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An Evaluation of the Natural Mortality Schedule Assumed in the PBF 2008 Stock Assessment and Proposed Changes

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Abstract

The stock status of Northern Pacific bluefin tuna (PBF), *Thunnus orientalis,* was recently evaluated by the PBF Working Group (WG) of the International Scientific Committee (ISC) for Tuna and Tuna like Species. The stock status remains uncertain and the WG is investigating the possibility that there may be a model mis-specification. This paper focuses on natural mortality. It reviews the scientific process leading to the PBF natural mortality (M) schedule assumed for the 2008 PBF assessment. It also provides a critical evaluation of the assumptions and proposes an alternative natural mortality schedule for PBF.

In the absence of direct estimates of M for PBF beyond age-0 (1+ years), the WG adopted a vector based on assumptions made for southern bluefin tuna (SBT). This choice should be re-visited and revised considering the differences that exist between the life-history of PBF and SBT. The adoption for PBF of the SBT estimate of M=0.12 yr^{-1} for the 4+ year old adult fish seems the most problematic. The later is based on the long life-span of SBT (maximum age of 42) which does not seem to be the case for PBF (maximum observed age of 21 years). In addition, while the mean age at maturity for SBT varies from age 8-12 years, PBF begins to mature at age 3 and are fully mature at age 5. It seems reasonable to assume that such an early investment on reproduction would result in higher natural mortality levels for mature PBF. An alternative M estimate for the adult fish (3+ year) could be taken as the median value (M=0.27) obtained across a large suite of life-history based methods. Estimates of natural mortality for ages 1 and 2 also

need to be revised. We propose comparisons with SBT base on length rather than age.

Background

The stock status of Northern Pacific bluefin tuna (PBF), *Thunnus orientalis*, was evaluated by the PBF Working Group of the International Scientific Committee (ISC) for Tuna and Tuna like Species (Anonymous, 2008). The assessment was conducted using Stock Synthesis II (SS2; Methot 2005) which consists of an age-structured integrated (fitted to many different types of data) catch-at-length model. The stock status was uncertain. On one hand, the current levels of fishing mortality were estimated to be greater than commonly used biological reference points and the age structure of the population was found to be sharply truncated in favor of younger fish. On the other hand, the biomass which is mainly represented by recruits has fluctuated without trend over the assessment period (1952-2004).

Several regional fishery management organizations (including the IATTC, SPC and the US-PMFC) use the Spawning Biomass Ratio (SBR) - the ratio of the current spawning biomass to unfished spawning biomass (S_0) – as a reference quantity to characterize stock status. In the 2008 PBF assessment, SBR was found to be below 5% during the entire dynamic period of the assessment (1952-2005). Most noticeably, the base case model estimated SBR at around 3% in 1952. If true, these results would imply that the stock had already been highly depleted in the early 1950s, and that the population has been composed mostly by recruits since then. Another striking result is an extremely high estimate derived for the unfished spawning biomass (S_0). As an explanation, the WG concluded that the unreasonable S_0 estimate should be disregarded because of density-dependent changes in growth and maturity that may have occurred at higher stock levels during the pre-exploited period of the fishery. However, Piner *et al.* (2008) simulated a series of scenarios of density-dependence and concluded that these could not explain the high estimate of S_0.

An alternative hypothesis explaining the unreasonable high S_0 estimate and low levels of SBR is that these are a result of model mis-specification. Specifically, it may be that a mis-specification of one or more of the assumptions made about natural mortality, growth, and selectivity parameterization, when combined with fitting to the available size composition and CPUE data, results in an overly depleted stock at the start of the model, and upwardly biased estimates of S_0 (Piner *et al.*, 2008). If that is the case, it seems reasonable to assume that virgin recruitment (R_0) is also biased, therefore compromising the population dynamics and derived management quantities. Depending on how the model is mis-specified, other important management quantities (e.g. fishing mortality reference points that are dependent on the assumed natural mortality) may also be biased.

The ISC-PBF WG will meet on December 10-17, Ishigaki, Japan, with the aim of re-examining input values used for biological parameters in the 2008 stock assessment model, the model itself, and to promote research to improve estimates of PBF life history parameters. This paper reviews the scientific process leading to the PBF natural mortality (M) schedule assumed for 2008 PBF assessment. It provides a critical evaluation on these assumptions and proposes an alternative natural mortality schedule for PBF.

PBF M schedule assumed in 2006

The PBF age-specific (annual) natural mortality schedule assumed by the WG in 2006 was: 1.6 for age-0, 0.4 for age-2, and 0.25 for 3-year old fish and older (Table 1, Figure 1). The 1.6 yr^{-1} estimate for the 0 year old fish is the only estimate in the schedule that was determined empirically from tagging data (Takeuchi and Takahashi, 2006). The 0.25 value for the 3+ year old fish was derived from life-history based methods. The intermediate values of 0.8 and 0.4 yr^{-1} taken for the 1- and 2-year old fish were interpolated.

Revised PBF M schedule for the 2008 stock assessment

At the ISC PBF-WG meeting in December 2007, Shimizu, Japan, the group performed an in-depth review of the assumptions on natural mortality for PBF (see Appendix 8, Discussion of Natural Mortality, Anonymous, 2007). The 2006 M schedule was replaced by new a vector which was mainly derived based on comparisons made with Atlantic bluefin tuna (*Thunnus thynnus*, ABT) and southern bluefin tuna (SBT, *Thunnus maccoyii*) (see Table 1 and Figure 1). The review indicated that there are very few empirical estimates of M for the three bluefin species. It was noted that “the available empirical estimates are 1.6 for age-0 fish of PBF (Takeuchi and Takahashi, 2006), 0.456-0.474 for age-1 and 0.253-0.295 for ages 2 and older for SBT (Polacheck *et al*., 1997)”. An M value of 0.12 for ages 4 and older is assumed for SBT. A fixed M value of 0.14 is assumed for all ages of ABT.

The review also included a comparative analysis of cohort survival schedules among the three bluefin populations. Results of the analysis indicated that there were fewer survivors of old fish with the PBF 2006 M schedule when compared with SBT and ABT (Figure 2). Furthermore, it was noted that "the PBF 2006 schedule would require a reduction of 0.541 with the existing age-specific pattern to match results from the southern bluefin tuna M schedule".

The final PBF M schedule adopted by the WG for the 2008 assessment is summarized below (from Appendix 8, Anonymous 2007):

Age	M	Rationale
0	1.6	Empirical estimate, PBF tagging (Takeuchi and Takahashi, 2006)
1	0.46	Empirical estimate, SBT tagging, average range (Polacheck, 1997)
2	0.27	Empirical estimate, SBT tagging, average range (Polacheck, 1997)
3	0.2	Linear interpolation from age 2 and age 4 estimates
4+	0.12	Adopted from SBT

A critical evaluation of the 2008 PBF M schedule

The estimate of M_0=1.6 yr^{-1} adopted in 2008 for the 0-year PBF seemed reasonable since it was obtained directly from a tagging analysis (Takeuchi and Takahashi, 2006). However, the PBF M values assumed in 2008 beyond age-0 are not based on PBF empirical data. In the absence of direct estimates of M for PBF beyond age-0 (1+ years), the WG adopted a vector based on assumptions made for SBT (Polacheck *et al.*, 1997). This choice should be re-visited and revised considering the differences that exist between the life-history of PBF and SBT, described below.

Natural mortality for juveniles is often attributed to predation. Predation mortality is likely to be highly dependent on the size of the fish. By age one, PBF are relatively large (approximately 60 cm) and are therefore outside the range of all but the largest predators. Therefore, the predation component of natural mortality is likely to be small for PBF age one and older. Age one PBF are about the size of an age two SBT. Unless there is some other physiological factor affecting M that is age based, any comparisons with SBT should be made relative to size rather then age.

The adoption for PBF of the SBT estimate of M=0.12 yr^{-1} for the 4+ year old fish seems problematic. The later is based on the long life-span of SBT (not just the maximum age of 42, but large numbers of 25 and 30 year old fish that are caught in the fishery; Farley *et al*., 2001). Such high longevity for SBT has been validated with carbon-bomb otolith analysis (Kalish *et al*., 1996). In contrast, there is no evidence of such high longevity for PBF. The maximum age observed in a sample of sectioned otoliths from 520 PBF individuals (47-260 cm in FL) collected in waters of Japan and Taiwan was of 21 years (Shimoze *et al*., 2008). These results strongly suggest that the cumulative adult natural mortality levels for PBF must be much higher than those for SBT.

The maximum observed age depends on total mortality (Z), which includes fishing mortality. Therefore, an alternative hypothesis is that PBF has a much higher exploitation rate than SBT as indicated by the 2008 assessment. However, the hypothesis of a much lower longevity for PBF is consistent with the information available on the reproduction biology of PBF and SBT. Specifically, the large differences observed in the age at maturity of both species strongly support the hypothesis of higher levels of natural mortality for adult PBF. Information on mean age at maturity for SBT varies from age 8 years (152 cm) (Farley and Davis, 1998) to age 12 years (Mori *et al*., 2001). In contrast, PBF begins to mature at age 3 and are fully mature at age 5 according to the maturity vector given in the most recent ISC assessment (Anonymous, 2008). It seems reasonable to assume that such an early investment on reproduction would result in higher natural mortality levels for mature PBF. In fact, age of maturity is used as a predictor of natural mortality (Jensen, 1996). Higher levels of natural mortality are also associated with higher growth rates (Beverton and Holt, 1959; Jensen, 1996). Reported values of the von Bertalanffy K parameter for SBT range between 0.106 and 0.184, but most are close to 0.14-0.15 (Fishbase). These are lower than the estimate of K=0.195 obtained for PBF (Shimoze *et al*., 2008).

Comparisons of natural mortality rates between PBF and Atlantic bluefin (ABT) are also invalid. As pointed out by Fromentin and Powers (2005), "…in the absence of direct estimates of M for ABT, the M vector of SBT is generally taken for the east Atlantic and Mediterranean ABT assessments, whereas a constant M of 0.14 is taken for the west Atlantic." The same life-history considerations that we raise for PBF when developing assumptions on natural mortality based on SBT, can also be pointed out for ABF. While ABF have been found to mature between 8 and 12 years in the Western Atlantic and Gulf of Mexico, they seem to mature much earlier (4-5 years) in the Mediterranean Sea (Mather *et al*., 1995; Fromentin and Powers, 2005). Nevertheless, very similar values of adult natural mortality (M_0=0.12 and 0.14) are taken for both sides of the ocean. Therefore, an SBT based assumption may not be the best choice of adult M for ABT of the Eastern Atlantic and Mediterranean Sea.

To conclude, the current assumption of M=0.12 taken from SBT for adult PBF (age 4+ years) seems unreasonable and should to be re-visited by the WG. In fact, the survivorship curves for SBT or ABT should not have been considered as references to derive the M schedule for PBF (see Figure 2 below and ISC Information Paper PBF-WG/07-3). As noted above, there are marked differences among the life-histories of the three species, particularly for PBF which seems to mature very early (around 3 yrs) and attain a much shorter longevity (maybe half) than SBT. Furthermore, the extremely high value of M assumed for PBF of 0 yrs (M_0=1.6) is much higher than that assumed for SBT (around 0.4). This results in strong differences between the survivorship curves of both species.

Given the arguments presented above, it seems very likely that the unrealistically low (<5%) depletion (SBR) levels estimated in the 2008 PBF assessment during the entire dynamic period (1952-2005), are due to a model mis-specification of PBF adult natural mortality, at least. To better illustrate this point, a subset of the average yearly size composition data of the Japanese longline fishery (1994-1999) is presented in Figure 3. The proportions at length have been weighted by the CPUE so that the absolute scale of the y-axis is an indicator of the relative abundance between years. There are no fish above 200 cm observed in the size composition data of 1994. Apparently, a strong cohort enters in the fishery in 1996 and moves through in subsequent years, with some fish above 200 cm being caught. According to the data, this cohort is rapidly depleted to about 20% in less than 3 years due to the cumulative effect of natural mortality (M) and fishing mortality (F). The figure illustrates how fast the PBF cohorts decline due to effect of total mortality (Z=M+F). With such low and unrealistic levels of adult natural mortality assumed (M=0.12), the model can mostly attribute these sharp declines of the adult stock to intense fishing mortality (F). This could at least partially explain the unrealistic depletion levels.

Proposed changes on M

The proposed modifications of the M schedule for the PBF base case stock assessment model are summarized below and illustrated in Figure 4. In addition, one sensitivity analysis on M is also proposed to be included in the PBF assessment. The rationale for the proposed modifications is described in the text below.

Age	M	Rationale
Base case		
0	1.60	Empirical estimate, PBF tagging (Takeuchi and Takahashi, 2006)
1	0.31	Empirical estimate, SBT tagging, average range for 2 yrs (Polacheck, 1997), age 1 PBF about same size as age 2
2	0.27	Equal to adult M, large size of about 100 cm.
3+	0.27	Median from indirect methods
Sensitivity		
0	0.39	Empirical estimate, SBT tagging, average range (Polacheck, 1997), see ISC PBF-WG/07-3 Information Paper
1	0.31	Empirical estimate, SBT tagging, average range for 2 yrs (Polacheck, 1997), age 1 PBF about same size as age 2
2	0.27	Equal to adult M, large size of about 100 cm.
3+	0.27	Median from indirect methods

Age 0

Without any other scientific information being available, the estimate of M_0=1.6 yr^{-1} adopted in 2008 for the 0-year PBF seemed reasonable since it was obtained directly from a tagging analysis (Takeuchi and Takahashi, 2006). However, a natural mortality value of 1.6 yr^{-1} seems too high for fish ranging about 20-60 cm (Shimoze *et al.*, 2008). It is difficult to conceptualize such high natural mortality value for any tuna species. The WG should review this assumption carefully. Specifically, the assumptions about emigration, tag-related mortality, reporting rate, and tag shedding should be re-visited. On this subject, the researchers of the IATTC, NMFS and the TOPP program have started a collaborative effort to analyze PBF historical convention tagging and more recent archival tagging data to improve the estimates of natural mortality. These results will be presented at future meetings. Scientists from other agencies and programs involved on PBF tagging are invited to participate.

While no updated tagging analysis are available for PBF, it seems reasonable to adopt the estimate of M_0=1.6 proposed by Takeuchi and Takahashi (2006) (Figure 4). However, a sensitivity run assuming a lower M value for the 0 age-class should also be reported in the assessment. The alternative value of M_0=0.39 for SBT could be used (geometric mean of five estimates from Pollacheck *et al.*, 2007; see ISC PBF-WG/07-3 Information Paper) (Figure 4). The concerns expressed above regarding comparisons between PBF and SBT are minimal for similar size young fish, which are not reproductively active yet.

Age 1-2 years

In the absence of direct estimates available from tagging analysis for 1-2 yr old PBF, one approach would be to use the tagging estimates available for SBT (M_1=0.34 and M_2=0.31, geometric mean of five estimates from Polacheck *et al.*, 2007; see ISC PBF-WG/07-3 Information Paper). However, age 1 PFB tuna are about the same size as age 2 SBT, so a second alternative would be to make PFB age 1 M the same as SBT age 2 M, then make PFB age 2 M equal adult M. This choice seems more appropriate (Figure 4).

Adult fish (age 3+)

Given the PBF life-history peculiarities presented above and their differences with SBT, the WG should seek alternative assumptions for PBF adult M to those taken from SBT (M=0.12). Rather, M estimates that are more consistent with the life-history of PBF should be taken. The estimate of M=0.25 assumed by the WG in 2006 for PBF adult natural mortality seems a reasonable approximation. An alternative M estimate for the adult fish (3+ year) could be taken as the median value (M=0.27) obtained across a large suite of life-history based methods (Table 2): Hoenig (1983), Pauly (1980), Chen and Watanabe (1989) and Jensen (1996). In fact, Takeuchi (2008) had already presented very similar and even higher M values obtained from the use of indirect methods (Jensen, 1996; Chen and Watanabe, 1989) applied to the recent PBF age and growth estimates of Shimoze *et al*. (2008).

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Table 1. Natural mortality (M) schedules assumed for Pacific bluefin (PBF), Atlantic bluefin (ABT), and Southern bluefin (SBT) tuna. PBF_2006 and PBF_2008 are the M schedules assumed for the 2006 and 2008 PBF assessments, respectively. M for SBT is the age-specific geometric mean of the six M vectors used for SBT (see Table 1 and Figure 1 of ISC Information Document PBF-WG/07-3). The proposed new schedule for the PBF base case model and a sensitivity run are also presented.

Age (yr)	PBF_2006	PBF_2008	ABT	SBT_AvgG	PBF_proposed	PBF_sens_proposed
0	1.60	1.60	-	0.39	1.60	0.39
1	0.80	0.46	0.14	0.34	0.31	0.31
2	0.40	0.27	0.14	0.31	0.27	0.27
3	0.25	0.20	0.14	0.28	0.27	0.27
4	0.25	0.12	0.14	0.25	0.27	0.27
5	0.25	0.12	0.14	0.23	0.27	0.27
6	0.25	0.12	0.14	0.20	0.27	0.27
7	0.25	0.12	0.14	0.18	0.27	0.27
8	0.25	0.12	0.14	0.16	0.27	0.27
9	0.25	0.12	0.14	0.14	0.27	0.27
10+	0.25	0.12	0.14	0.12	0.27	0.27

Table 2. Natural mortality schedules obtained from life-history based methods: Hoenig (1983), Pauly (1980), Chen and Watanabe (1989), Peterson and Wroblewski (1984) and Jensen (1996).

PBF - Natural mortality (M)

	Hoenig (1983)		Pauly (1980)		C&W (1989)	Jensen (1996)	
Age (yr)	amax=20	amax=25	Bayliff_91	Shimoze_91	Shimoze_91	$t_{mat=4}$	K_Shimoze_08
0	0.21	0.17	0.27	0.29	2.22	0.41	0.29
1	0.21	0.17	0.27	0.29	0.78	0.41	0.29
2	0.21	0.17	0.27	0.29	0.51	0.41	0.29
3	0.21	0.17	0.27	0.29	0.40	0.41	0.29
4	0.21	0.17	0.27	0.29	0.34	0.41	0.29
5	0.21	0.17	0.27	0.29	0.30	0.41	0.29
6	0.21	0.17	0.27	0.29	0.27	0.41	0.29
7	0.21	0.17	0.27	0.29	0.25	0.41	0.29
8	0.21	0.17	0.27	0.29	0.24	0.41	0.29
9	0.21	0.17	0.27	0.29	0.23	0.41	0.29
10	0.21	0.17	0.27	0.29	0.22	0.41	0.29
11	0.21	0.17	0.27	0.29	0.22	0.41	0.29
12	0.21	0.17	0.27	0.29	0.21	0.41	0.29
13	0.21	0.17	0.27	0.29	0.21	0.41	0.29
14	0.21	0.17	0.27	0.29	0.21	0.41	0.29
15	0.21	0.17	0.27	0.29	0.21	0.41	0.29
16	0.21	0.17	0.27	0.29	0.20	0.41	0.29
17	0.21	0.17	0.27	0.29	0.20	0.41	0.29
18	0.21	0.17	0.27	0.29	0.20	0.41	0.29
19	0.21	0.17	0.27	0.29	0.21	0.41	0.29
20	0.21	0.17	0.27	0.29	0.21	0.41	0.29
mean M (3+ yrs)	0.21	0.17	0.27	0.29	0.24	0.41	0.29
median (3+ yrs)	0.21	0.17	0.27	0.29	0.22	0.41	0.29
Grand mean (3+ yrs)	0.27						
Grand median (3+ yrs)	0.27						

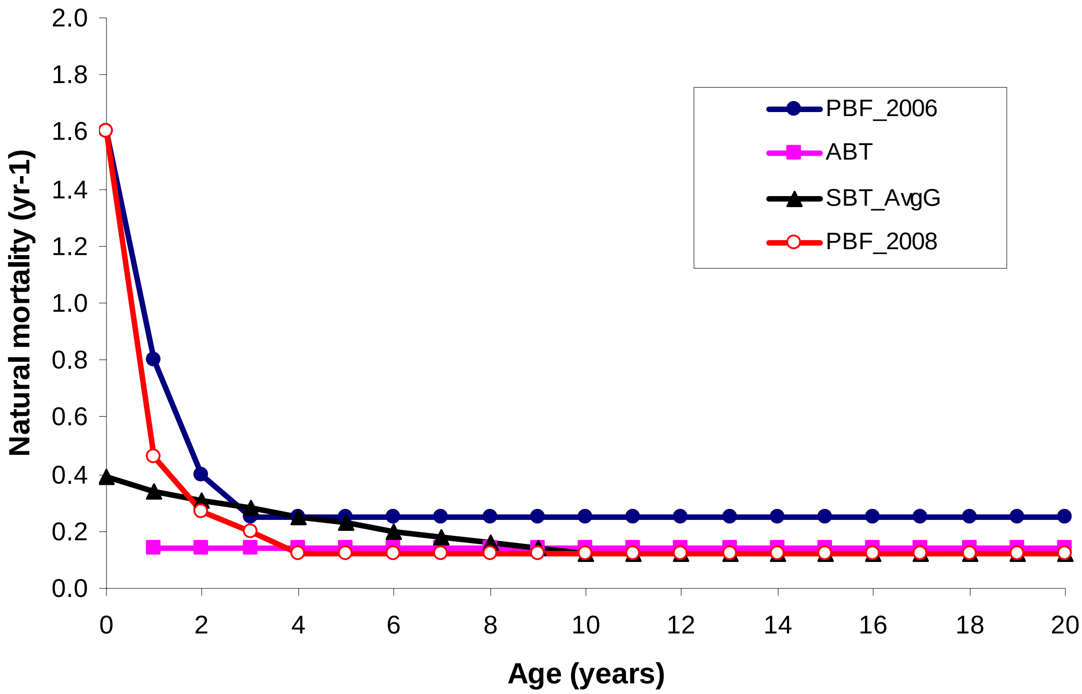
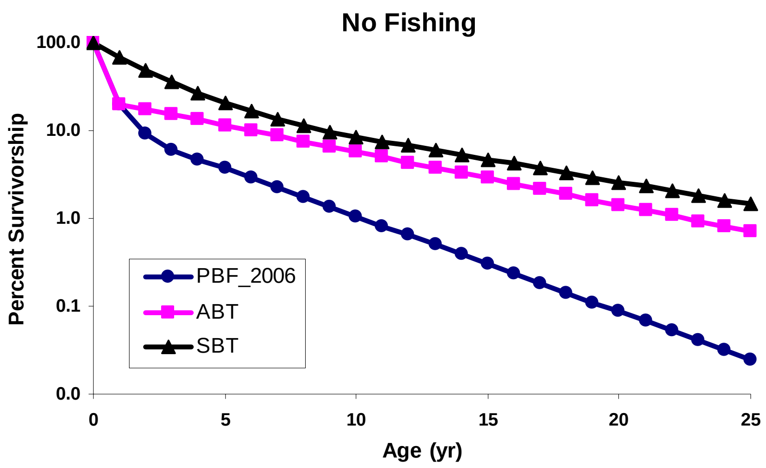


Figure 1. Natural mortality (M) schedules assumed for Pacific bluefin (PBF), Atlantic bluefin (ABT), and Southern bluefin (SBT) tuna. PBF_2006 and PBF_2008 are the M schedules assumed for the 2006 and 2008 PBF assessments, respectively. Average M for SBT is the age-specific geometric mean of the six M vectors used for SBT (see Table 1 and Figure 1 of ISC Information Paper PBF-WG/07-3).

A)



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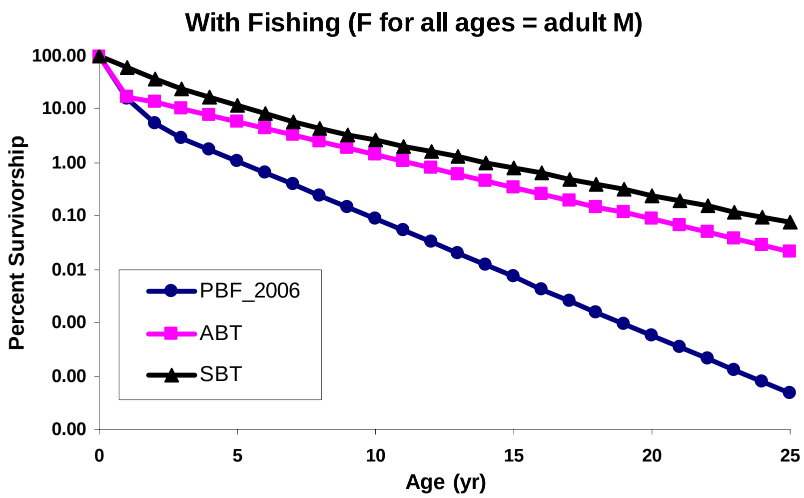

Figure 2. Percent survivorship at age for Pacific bluefin (PBF), Atlantic bluefin (ABT), and Southern bluefin (SBT). A) absence of fishing, *i.e*. F=0; B) with fishing (F for all ages was set to the respective M at age 10). For Atlantic bluefin (ABT), age 0 is not used in the stock assessment. ABT M for age 0 is set at the same rate as that for PBF. Average M for Southern bluefin (SBT) is the age-specific geometric mean of the six M vectors used for SBT (see Table 1 and Figure 1 of ISC Information Paper PBF-WG/07-3).

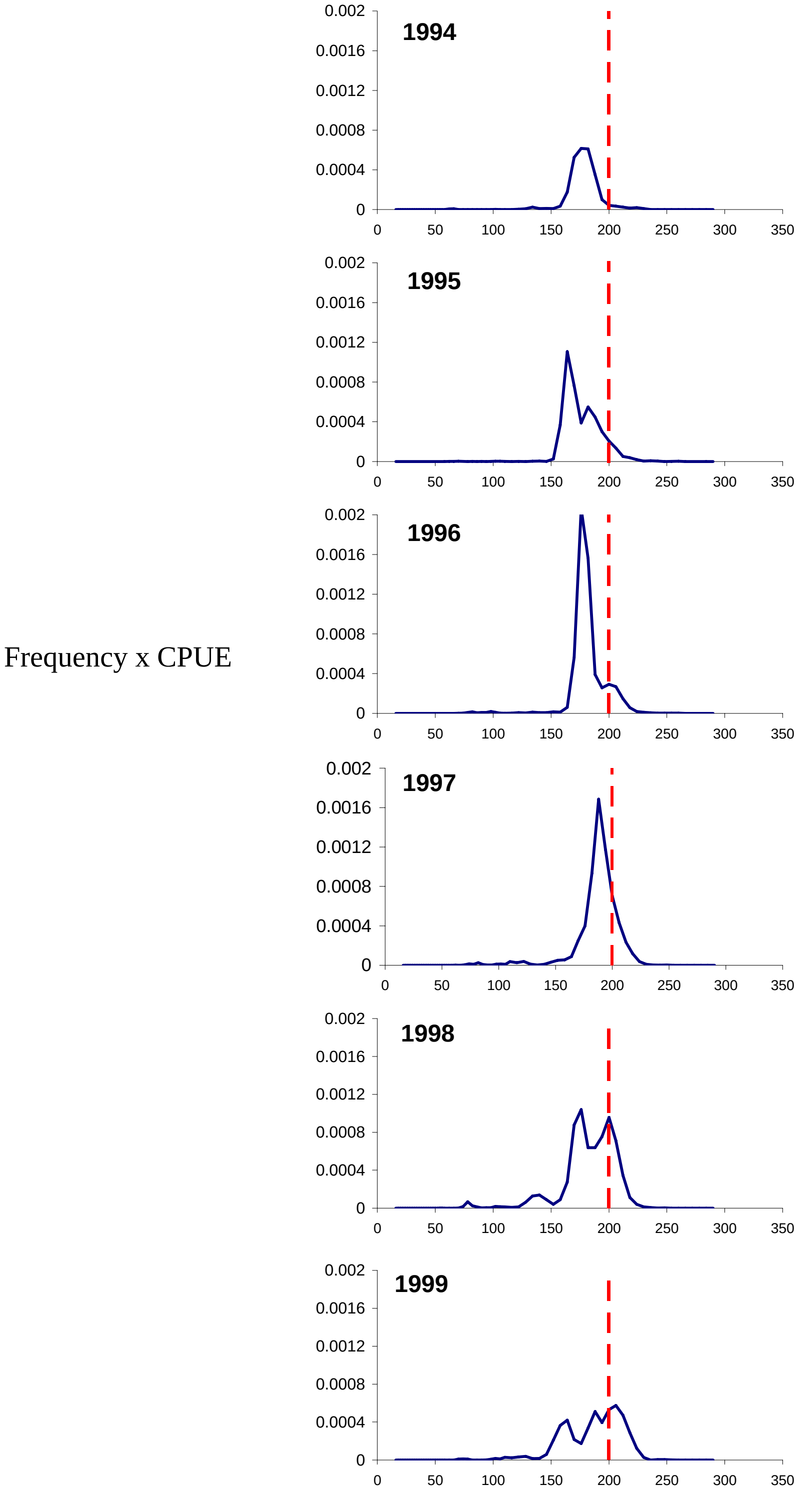

Figure 3. Average yearly size compositions of the Japanese longline fishery (1994-1999). The proportions at length have been weighted by the CPUE so that the absolute scale of the y-axis is an indicator of the relative abundance between years. The dashed vertical line is a reference line at 200 cm.

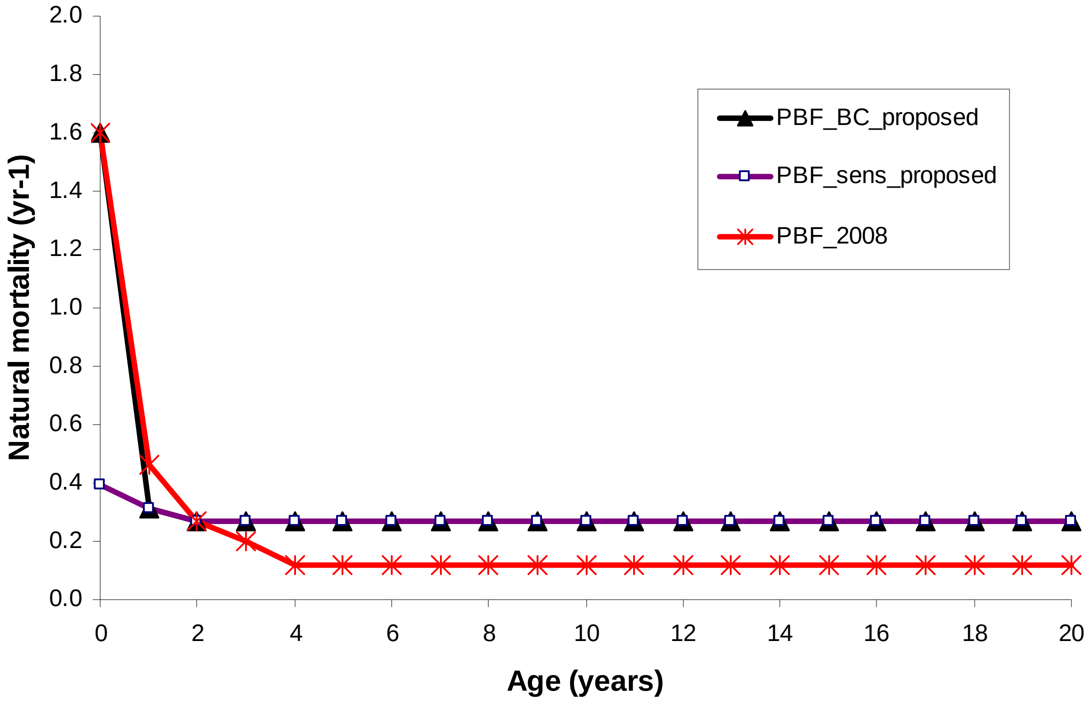

Figure 4. Proposed natural mortality (M) schedule for the PBF base case model (PBF_BC_proposed) and sensitivity run (PBF_sens_proposed). The M schedule assumed in the 2008 assessment (PBF_2008) is also shown.