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## Estimation of steepness of PBFT -By using biological features

Shigehide Iwata, Hiromu Fukuda, Osamu Abe and Yukio Takeuchi

National Research Institute of Far Sea Fisheries, Fisheries Research Agency  
5-7-1 Orido, Shimizu, Shizuoka 424-8633, Japan

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## **Summary**

The spawner-recruitment relationship, i.e. relationship between spawning stock biomass (SSB) and recruitment ( $R$ ), is a fundamental issue in stock assessments. Since recruitment is one of the important indices to evaluate stock status as well as a benchmark for fish management. One important parameter which describes the Stock Recruitment relationship is steepness (Mace and Doonan, 1988). Steepness is defined as the fraction of recruitment from an unfished population ( $R_0$ ) to the recruitment level when the spawning stock biomass is reduced to 20% of its unfished level ( $B_0$ ). In the stock assessment model, steepness plays an important role, providing information on stock-recruitment relationship. However, accurate estimate of steepness is hard to make, due to the uncertainties associated with biological parameters and difficulty in making data consistent with definition in the model. Mangel et al. (2010) presented the direct estimation method from biological information. In this document, we calculate steepness of Pacific Bluefin tuna using deterministic part of Mangel's procedures in estimating steepness, which would provide basis for discussing settings of stock assessment model. The calculated steepness of PBF is close to one. In application of this method, the problem is related to uncertainties in biological parameters, especially those in the early life period. Duration of "early life period" comes from the growth parameter ( $a_0$ ), in the Mangel's procedure, which determined as the theoretical age when an individual would have been of length 0. The definition of the parameters in the model has a lot of uncertainties and ambiguities, especially in the definition of early life period. It is recommended to use steepness ranging, 0.8-1.0 for PBF sensitivity analysis, to compromise our results with Mangel's results (Mangel et al., 2010).

## **Materials and methods**

### **Concept of steepness**

The definition of steepness, as the fraction of recruitment from an unfished population ( $R_0$ ) to the recruitment level when the spawning stock biomass is reduced to 20% of its unfished level ( $B_0$ ), is firstly proposed by Goodyear (1977, 1980). After that Mace and Doonan (1988) assumed that reproduction follows a Beverton-Holt stock recruitment relationship so that when spawning biomass is  $B$ , the resulting recruitment  $R(B)$  is,

$$R(B) = \frac{B}{\alpha + \beta B}$$

where  $\alpha$  and  $\beta$  are parameters. Let us denotes steepness as  $h$ , then following relationships are satisfied;

$$R_0 = \frac{B_0}{\alpha + \beta B_0}, \quad hR_0 = \frac{0.2B_0}{\alpha + 0.2\beta B_0},$$

where  $B_0$  represents biomass without fishing and let us define  $R(B_0)_0$  as  $R_0$ .  $\alpha$  and  $\beta$  are determined by the followings;

$$\alpha = \frac{B_0}{R_0} \frac{1-h}{4h}, \quad \beta = \frac{5h-1}{4hR_0}.$$

In general, relatively a high value of steepness means that the stock recruitment relationship is sparse (low); stock recruitment curve being close to parallel to the X-axis.

### Model to derive steepness

In this document, the steepness of PBF is calculated deterministically by modified methods of Mangel et al., (2010) together with other biological information. Firstly,  $r$  denotes the fraction of female at birth.  $M$  denotes the rate of natural mortality and  $\alpha_p$  denotes the units of new biomass per existing spawning (female) biomass per time period. The steepness can be estimated by non-age-structured model as follows:

$$h = \frac{\frac{\alpha_p(1-r)}{M}}{4 + \frac{\alpha_p(1-r)}{M}}, \quad (1)$$

The equation (1) without sex ratio, derived from? Myears et al. (1999). This particular form is proposed by Mangel et al. (2010). Steepness of age structured model is as follows;

$$h = \frac{\alpha_s(1-r) \frac{\bar{W}_{f,m}}{M}}{4 + \alpha_s(1-r) \frac{\bar{W}_{f,m}}{M}}, \quad (2)$$

$\bar{W}_{f,m}$  is interpreted as the average biomass of a spawning female and  $\alpha_s$  denotes the expected number of new individuals per unit spawning biomass.

Let us consider,  $\alpha_p$ ,  $\alpha_s$ , and  $\bar{W}_{f,m}$ . In the equations (1) and (2), relationship among these parameters, i.e.  $\alpha_p = \bar{W}_{f,m} \alpha_s$ , is satisfied implicitly. Therefore, once  $\alpha_p$  is calculated, reminders are trivial.

### Details of calculation

Using Mangel et al. (2010), let us consider two periods; early life period and grown-up periods. Various biological characteristics and parameters seem to be quite particular natural mortality different in PBF between these two periods. Fish in the second period, grown-up period, follows most of the biological parameters estimated to the adult fish. However fish in the early life period are considered to have very distinct parameters. This period (early life period) represents time duration, in days, i.e.  $d_m$  days after hatch:  $d_m$  is defined by using von Bertalanffy parameter (age at which size is zero:  $a_0$ )

as,  $-365 \times a_0$ . Second period (adult period) is after  $d_m$  days. To find  $\alpha_p$ , let us assume a female fish of age  $a$ , with mass during adult period  $w(a)$ , length during adult period  $L(a)$ , and probability of being mature  $p_m(a)$  by age, where  $W(0)$  means the initial weight of adult period.  $F_B(w)$  is defined as batch fecundity of this individual in a single spawning event and  $s_f$  represents spawning frequency. Each egg is expected to contribute  $w(0) \times S_l(d_m)$  to new biomass so that  $\alpha_p$  can be derived as follows;

$$\alpha_p = \frac{F_B(a) \times W(0) \times S_l(d_m) \times s_f}{W(a)} \quad (3)$$

$w(0)$  is interpreted as  $\bar{w}_{f,m}$  (Mangel et al., 2010).

Next let us see the detail of dynamics during early life period and adult. We calculate the temporal change of survival rate by using the dry weight of egg – natural mortality relationship (McGurk, 1986). Let us define wet mass  $w_l(d)$  of a larva at an age (interval of days) and assume exponential growth during early life period,

$$w_l(d) = w_l(0) \times \exp(k_l d),$$

where  $k_l$  is determined by  $k_l = \log(w_l(d)/W(0))/d_m$ , since it is defined the individual grows from initial weight of early life period  $w_l(0)$  to initial weight of adult period  $W(0)$  during  $d_m$  days of early life period.

To compute an expected mass that an egg contributes to future biomass, the survival of individuals during early life period has to be decided, before being entered to the population dynamics model. The conversion factor from dry weight,  $w_{dry}$ , to wet weight is

$$w_l = 4.76 \times w_{dry} \text{ (Kamler, 1994).}$$

$M_l(w_{dry})$  is defined as a daily mortality rate of an individual of dry mass  $w_{dry}$ . McGurk (1986, Equation 7) concluded empirically that if  $M_l(w_{dry})$  denotes a daily mortality rate of an individual of dry mass  $w_d$ . If  $w_{dry}$  is less than 0.00504(g), then

$$M_l(w_{dry}) = 2.2 \times 10^{-4} \times w_{dry}^{-0.85}$$

or by McGurk (1986, Equation 2),

$$M_l(w_{dry}) = 5.26 \times 10^{-3} \times w_{dry}^{-0.25}.$$

Assuming survival at day  $d_m$  (after early life period) with probability  $S_l(d)$  (with  $S_l(0) = 1$ ); natural mortality at age  $a$ ,  $M_a(d)$  (with  $M_a(0) = 0$ ) and accumulated mortality are

$$S_l(d) = \exp(-\sum_{j=0}^d M_l(w_{dry}(w_l(j))))), \quad M_a(d) = \sum_{j=0}^d M_l(w_{dry}(w_l(j))). \quad (4)$$

In the adult period, the weight and fork length relationship is considered as follows;

$$W(a) = 0.001 \cdot L(a)^{2.4}, \text{ (Mangel et al., 2010)}$$

$$L(a) = L_\infty \{1 - e^{-k(a-a_0)}\}.$$

Individuals grow up following the above equation until they reach maximum age ( $a_{max}$ ).

Finally, relationship between batch fecundity ( $F_B$ ; million eggs) and fresh gonad mass ( $M_G$ ;g) is

$$F_B = 3.24 \times 10^5 \times L(a) - 5.21 \times 10^7.$$

The probability that a fish is mature at age  $a$  is,

$$p_m(a) = e^{(a-a_{50})/slope} / \{1 + e^{(a-a_{50})/slope}\},$$

where  $a_{50}$  is the age at which 50% of a cohort is mature (see Table 1). Usually, a *slope* is needed in the description of  $p_m(a)$ . However in the case of steepness value does not critically change depending on the value of *slope*. So we set the value of slope as 1. The age of 50% maturity,  $a_{50}$  is considered to be 5 in this study, since estimated length-at-50% maturity roughly corresponds to age 5 (Anon. 2008).

In this document, based on equation (3) and (4), we calculate a following approximate,

$$\tilde{\alpha}_p = \frac{\sum_a (F_B(a) p_m(a)) \times W(0) \times S_l(d_m) \times S_f}{\sum_a W(a)}.$$

## **Results and Discussions**

The parameters used in this analysis are shown in Tables 1, 2 and 3 except for the early life period which is defined as  $d_m = -365 \times a_0$ . The calculated steepness in relation to the length of early life period is shown in Table 4.

As seen in the Table 4, the estimated steepness is almost identical to one, regardless with growth parameters,  $M$  scenarios and early life period. Strictly speaking, the results of table 4 is robust for defined early life period depending on the growth parameter,  $a_0$ . This means that there should be little functional relationship between spawners and recruitments. Furthermore, the current setting of steepness (i.e. 1) in the stock assessment model for PBF in 2010 (anon. 2011) seems to be reasonable.

Now, let us discuss the possible sensitivity analysis. The analysis suggested the effect of the length of early life period, since assumptions of growth parameters in early life period affect the steepness estimates. For the steepness for Albacore, Figure 1 in Iwata et al.(2011) showed that the estimates of steepness depends on length of early life period for albacore. The length of early life period is defined by the growth parameters,  $a_0$ , in Mangel et al. (2010). In the Mangel's (2010) definition of length of early life period, the calculated steepness takes nearly one (see figure 1. a, b, c and d).

In this study, the early life period is defined as previously explained ' from the birth until maturing', however other many definitions; such as 14 days (crucial period for survival; Tanaka et al., 2006), 30 days (a turning point for swimming ability and behavior; Fukuda et al., 2010, 2011), or 100 days (a inflection point for growth rate in aquaculture; Miyashita et al., 2002). Therefore, the definition of the early life period

effects on the estimation of steepness, and definition of the early life period is problematic and difficult to set precisely.

The ambiguous dynamics of early life period also affects the calculation of natural mortality. For example, 0-age fish natural mortality for early life period follows the equation 2 in McGurk (1986) and the natural mortality for remained period of year is calculated as  $(365-d_m) \times (0\text{-age natural mortality}) / 365$ . As a result, the expected natural mortality through the 0-age fish for long early life period will change dramatically than the expected natural mortality for short early life period. In this meaning, the early life period suffers from the problem of ambiguity of definition and difficulty to set precisely.

Secondly, let us consider steepness calculated by using possible growth parameters, especially on the decision as to 'which is better, to use growth parameters which estimated by using all sex combined or female only', because male have similar parameters as sex combined, but the parameter for female is quite difference. Since, there is a possibility to set estimated steepness by using growth parameters for female only if sex structure will be incorporated into the stock assessment model. However, to apply the steepness for stock assessment model without sex structure is a reasonable choice unless the uncertainties in duration of early life period have been solved. Since it is not sure that early life period for female is appropriate. As an additional issue, current growth parameter during early life period remains uncertain, particularly there have been difficulties in reading ages on otoliths. in reading otolith. It is recommended to accumulate more research on growth curve for female and various biological knowledge of early life period for PBF.

Finally, in this document, the steepness is estimated very close to one. However, this result is only by a deterministic case. Mangel et al. (2010) presented the frequency distribution of steepness by age structured production model (Figure 2. In Mangel et al., 2010). His results indicated possible range of steepness as 0.8-1.0. At the coming stock assessment, the value in range of 0.8 to 1.0 is recommended for the sensitivity analysis.

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Table 1. The parameters used in this document.

Symbol	Meaning	PBFT
$R$	Sex ratio	0.5
$A_m$	Maximum age in simulation	12
$Sr$	Spawning frequency	Every 3.3 days during 6 weeks = 12.73
$a_{50}$	Age at which 50% of a cohort is mature	5

Table 2. Natural mortality scenarios

Symbol	meaning	M scenario options
$M$	Average natural mortality	ISC 2008 $\{2.33+0.2(1+a_m)\}/(1+a_m)$
		$(M_0=1.6, M_1=0.46, M_2=0.27, M_3+=0.2)$
		ISC 2010 $\{1.986+0.25(1+a_m)\}/(1+a_m)$
		$(M_0=1.6, M_1=0.386, M_2+=0.25)$

Table 3. Growth parameter options

	Asymptotic size, $L_\infty$	Growth rate, $K$	Age at which size is 0, $a_0$	Early life history
Bayliff, 1994	320.5	0.1035	-0.7034	256
Shimose et al. (2009)	249.6	0.173	-0.254	92
Shimose et al. (2011) Both sexes	252.1	0.165	-0.259	94
Shimose et al. (2011) female only	240.5	0.192	-0.089	32

Table 4. The calculation results of steepness.

M average Growth curve	ISC 2008 M scenario (estimated steepness, $d_m$ )	ISC 2010 M scenario (estimated steepness, $d_m$ )
	Bayliff 1944	0.998985, 256
Shimose et al. (2009)	0.999883, 92	0.999941, 92
Shimose et al. (2012) Combine	0.999863, 94	0.999932, 94
Shimose et al. (2012) Female	0.999758, 32	0.99878, 32

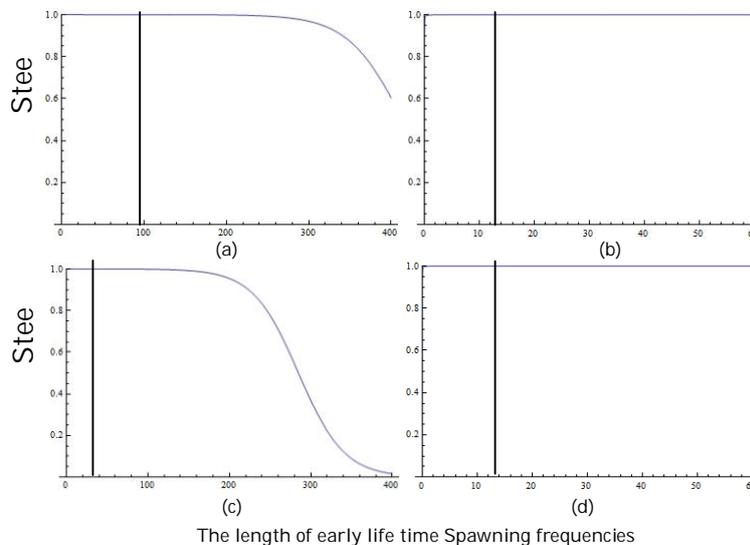


Figure 1. The sensitivity analysis for the longevity of early life history and Spawning frequencies. Vertical axis indicates the calculated steepness. All case obeys the M scenario of 2010. And (a, b) use the parameter combined two sex of Shimose et al. (2012) and (c, d) use the one combined female of Shimose et al. (2012). In (b) and (d), the longevity of early life history is 94 and 32 which comes from  $a_0$  of each growth parameter,  $a_0$ .