

Stock recruitment relationships of the North Pacific blue shark¹

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Abstract

This working paper provides stock-recruitment relationships of blue shark (*Prionace glauca*) in the North Pacific. We developed a pre-recruit survival model for the early life history of blue sharks and combined it with an existing model for the reproductive ecology of teleost species. We used biological data collected from wide areas of the western North Pacific between 2010 and 2016 to estimate key biological parameters. The model provides a point estimate for steepness, which is a fraction of unfished recruitment when spawning stock biomass is 20% of the species' unfished spawning stock biomass. We conducted numerical simulations to incorporate uncertainties in the biological parameters. The mean values and their standard deviations for steepness were 0.67 (standard deviation = 0.081) for the Beverton-Holt model. The curves showed a steep slope around the lower spawning biomass. These results suggest that the stock-recruitment relationship in North Pacific blue shark was high density-dependent and that its productivity is higher than that of other pelagic sharks.

Introduction

The blue shark (*Prionace glauca*) is a large, highly migratory oceanic pelagic shark found throughout the world in tropical and temperate seas (Nakano and Stevens, 2008), and it is the world's most abundant pelagic shark species (Nakano, 1994; Nakano and Seki, 2003).

Stock assessment of North Pacific blue shark that was conducted in 2014 using a stock synthesis model with the function of a low-fecundity stock-recruitment relationship (LFSR) (Taylor et al., 2013). It was found that the parameters (i.e. shapes) of the LFSR had a large impact on the stock status concerning whether the stock biomass had become overfished or was being overfished (ISC, 2014). In particular, it is unclear how density dependence influences the relationships between spawning biomass and recruitment. It is therefore urgently essential to clarify the stock-recruitment relationships for North Pacific blue shark.

This document paper provides stock-recruitment relationships of blue shark (*Prionace glauca*) in the North Pacific.

Materials and Methods

We develop a pre-recruit survival model for the early life history of blue sharks and combine it with an existing model for the reproductive ecology of teleost species. Mangel *et al.* (2010) derived equations of steepness (h) from an age-structured model with Beverton-Holt:

$$h = \frac{\alpha_s(1-r)\bar{W}_f}{4+\alpha_s(1-r)\bar{W}_f} \quad \text{for the Beverton-Holt model} \quad (1)$$

where the unit of α_s is new individuals per spawning biomass, r is a sex ratio, and \bar{W}_f is the expected surviving mature biomass per recruit.

The most significant difference between teleost species such as tunas and pelagic sharks is their reproductive strategy. The former produces eggs that hatch outside the body of the female, and the latter produces eggs that hatch inside the body and the female then gives birth to live young. We seek to develop a model that accounts for the pre-recruit survival of blue shark while accounting for differences in the survival rate at four distinct life history stages before recruitment: fertilized eggs (stage 0), embryos inside the body of female fish (stage 1), neonates immediately after pupping (stage 2), and pre-recruit neonates (stage 3). We use a product of the survival rates at each stage:

$$S_{pre} = S_0 S_1 S_2 S_3 \quad (2)$$

where S_{pre} is a pre-recruit survival rate and S_x is a survival rate at stage x (i.e. from 0 to 3). The survival rates at stages 0 and 1 are considered extremely high, because the survival is not dependent on competition, predation, or environmental influences. On the other hand, the survival rates of embryos at stages 2 and 3 are subject to the influences of an extreme environment that cause high natural mortality in these embryos. We suppose that the natural mortality of embryos at stage 3 is size (or age)-dependent, and we estimate the values using a modified equation proposed in the stock assessment of Atlantic yellowfin tuna (*Thunnus albacares*) in 2016. The Method II (Walters *et al.*, 2016) is defined as

$$M(a) = \frac{M_T(a_{max}-a_c)}{\ln\left(\frac{L_c}{L_c+L_\infty(\exp(k(a_{max}-a_c))-1)}\right)} \ln\left(\frac{L(a)}{L(a)+L_\infty(\exp(k)-1)}\right) \quad (3)$$

where M_T is a Target-M defined as a mean natural mortality from the age at first full recruitment (a_c) to maximum age (a_{max}), and L_c is the body length at a_c . Here, the definition of the ‘‘first full recruitment’’ is used as an alternative meaning of the first estimated age for the calculation of the Target-M (i.e. age 0). We used a value of 0.23 as the Target-M that estimated from the meta-analysis for the natural mortality of blue shark in the world oceans (Campana *et al.*, 2004). Justification for the use of the Equation (3) is described in Semba and Yokoi (2016).

We also modify the other parts of the model proposed by Mangel *et al.* (2010). New individuals per spawning biomass is expressed by

$$\alpha_s = \frac{\psi(L(a))S_{pre}S_{cycle}}{W(a)} \quad (4)$$

where $\psi(L(a))$ is litter size, S_{cycle} is the frequency of reproduction in a year, and $W(a)$ is the mass. In addition, viviparous elasmobranchs are commonly known to have a next gestation without a resting period after parturition (Castro, 2009). The frequency of reproduction is calculated from $S_{cycle} = 1/y$ where y is a reproductive period (gestation + ovulation + resting) in a year.

The parameters of the pre-recruitment model for blue shark were estimated based on the biological data. It is well known that embryo of blue shark occurs from the fertilized-eggs, and then the placenta is formed from the tissue of the embryo. Hence blue shark fundamentally has a same number of fertilized eggs, placenta, and embryos. The value of S_0 was estimated using the

occurrence rate of embryos from fertilized eggs for blue shark. We assumed that the embryos of blue shark were almost immortal at stage 1 (i.e. $S_1 \cong 1$), because we found that the total number of embryos before parturition was the same as the number of placenta for all pregnant females of blue shark ($n = 124$). Instead, we assumed that the embryos at stage 2 incurred natural mortality due to abnormalities such as prematurity or deformation. The values of S_2 were therefore estimated using the proportion of abnormal embryos. The values of S_0 and S_2 were assumed to be a normal distribution with average rates and standard deviations. The value of S_3 and the natural mortality after recruitment for females was estimated using Equation (2). The default values of all parameters are shown in Table 1.

A numerical simulation was conducted to estimate the steepness in a manner similar to Mangel *et al.* (2010) where the variation in steepness was created from the variation in survival. The computation of the numerical simulation was implemented using a code based on the R package (R Core Team, 2013).

The stock-recruitment relationship based on pre-recruit survival is currently available within the stock synthesis assessment platform (Taylor, 2013). It is therefore crucial for future stock assessments of North Pacific blue shark to specify the parameters (S_{frac} and β) using the output of the stock-recruitment relationships for the Beverton-Holt models in this study.

Additionally, we estimated the steepness and parameters of the Low-Fecundity Stock-Recruitment function for eight scenarios with regards to the reproductive cycle and maximum ages (See appendix).

Results

The mean values and their standard deviations (SD) for steepness were estimated using beta density, and the mean value of steepness was 0.68 (SD = 0.073) for the Beverton-Holt model. The curves showed a steep slope around the lower spawning biomass. The S_{frac} and β of LFSR were 0.981 and 0.292, respectively for the Beverton-Holt model. These results suggested that the stock-recruitment relationship of North Pacific blue shark was high density-dependent, and that productivity was higher than that of other pelagic sharks.

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Table 1. Default parameters based on biological data of the female blue shark.

No.	Function name	Parameter name	Symbol	Unit	Value	Reference	
1	von-Bertalanffy growth curve	Asymptotic size	L_{∞}	cm in PCI	256.3	Fujinami et al. (2016)	
		Growth rate	k	year ⁻¹	0.147		
		Theoretical age at length at 0	a_0	year	0.97		
2	Weight-length relationship		c_1		5.859	Fujinami et al. In press	
			c_2		3.093		
3	Length-based maturity ogives		c_3		24.52	Fujinami et al. In press	
			c_4		-0.16		
4	Littersize-length relationship		c_5		-45.54	Fujinami et al. In press	
			c_6		0.455		
5	Natural mortality	Theoretical equation		M	year ⁻¹	Not shown	Semba and Yokoi (2016)
			Target M	M_T	year ⁻¹	0.23	Campana et al. (2004)
		Gamma distribution		a_c	year	0	
				v		9.7	Mangel et al. (2010)
				λ		Not shown	
6	No function	Maximum age	a_{\max}	year	16	Fujinami et al. In press	
7	No function	Sex ratio	r		0.5	Nakano (1994)	
8	Pre-recruit survival	Normal distribution	Survival at stage 0	S_0	year ⁻¹	0.965	Estimated in this paper
		No function	Survival at stage 1	S_1	year ⁻¹	1	
		Normal distribution	Survival at stage 2	S_2	year ⁻¹	0.993	Estimated in this paper
		Theoretical equation		M	year ⁻¹	Not shown	Semba and Yokoi (2016)
9	Reproductive cycle	No function	Reproductive period	y		1	Fujinami et al. In press
			Days to recruit from partrition	d	day ⁻¹	365	Estimated based on Nakano (1994)
10	Stock-recruitment relationship	Unfished recruitment	R_0	Number in 1000	1000	Arbitrarily given	
		Unfished spawning biomass	B_0	tons	25000	Arbitrarily given	

Appendix

Table A1. Additional estimation of the steepness and parameters of the Low-Fecundity Stock-Recruitment function for eight scenarios with regards to the reproductive cycle and maximum ages. An empirical equation (Peterson and Wroblewski, 1984) and theoretical equation: Walter II (Walters et al. 2016) were used to estimate the natural mortality respectively and then steepness was estimated. Two reproductive cycles were used from Fujinami et al. In press and Joung et al. (2011), and three maximum ages were calculated from the theoretical two equations (Fabens, 1965 and Chin and Liu, 2013). Growth, maturity, litter size were used from Fujinami et al. (Fujinami et al. In press and Fujinami et al. 2016). Grey column shows the reference case in this study.

Empirical equation (Peterson and Wroblewski, 1984)	Walter-II methods (Walter et al. 2016) based on the Campana et al. (2004)							
	cycle=1	cycle=2	cycle=1	cycle=2	cycle=1	cycle=2	cycle=1	cycle=2
			tmax=16	tmax=16	tmax=19	tmax=19	tmax=24	tmax=24
Steepness	0.936	0.881	0.681	0.520	0.665	0.503	0.622	0.459
Sfrac	1.000	1.000	1.000	0.598	0.978	0.562	0.848	0.473
Beta	0.387	0.366	0.292	0.420	0.293	0.437	0.328	0.485

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