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Recruitment forecasting model of the Japanese Pacific walleye pollock *Theragra chalcogramma*, incorporating the ocean environmental factors

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ABSTRACT
This study analyzed recruitment fluctuation in the Pacific stock of walleye pollock *Theragra chalcogramma*. Here, we present a recruitment forecasting model that includes ocean environmental factors. We used the water temperatures in the Funka Bay as the independent variables. We tested whether the fluctuations in recruitment and spawning stock biomass could be reproduced using this model. Further, we investigated the effects on abundance and catch when the age of first capture was increased and the fishing mortality coefficient (*F*) was reduced. Fluctuations in recruitment and spawning stock biomass in the model reproduced the fluctuations observed in the data, indicating that fluctuations in recruitment can be reproduced by manipulating only the spawning stock biomass and water temperatures in the Funka Bay. The density-dependent effect is not necessarily required to explain the fluctuations. Increasing the age of the first capture and reducing *F* was necessary and the resultant effects were compensational.

Keywords: Funka Bay, Fishing mortality coefficient, Japanese Pacific walleye pollock, recruitment forecasting model, stock-recruitment relationship, *Theragra chalcogramma.*

1. Introduction
The walleye pollock *Theragra chalcogramma* is one of the important bottom fish resources in the northern seas surrounding Japan. It is divided into the following stocks: northern Japan Sea stock, Nemuro Strait stock, southern Okhotsk Sea stock, and Japanese Pacific stock [1-5]. Of these, the most abundant is the Japanese Pacific stock, and its main spawning area is the Funka Bay [6-13]. However, in recent years, the abundance of walleye pollock has remained at low levels. Particularly after 2002, there has been a tendency for the population to decrease, and in 2007, populations hit the lowest level since 1981 (Fig. 1) [1]. According to the Fisheries Agency of Japan, the population level is low and population size is decreasing [1].
Japan introduced a total allowable catch (TAC) system in 1996 [14], which includes the catch of walleye pollock. In order to determine a proper TAC, it is necessary to clarify the mechanisms of population dynamics of the target fish [15]. Generally, environmental factors and spawning stock biomass (SSB) have an effect on population dynamics [16]. Although the current TAC system in Japan mainly assumes the density effect of SSB on recruitment size, in order to evaluate the allowable biological catch (ABC), changes in the ocean environment may have an extremely important influence on population dynamics [15,16]. However, the effects of the ocean environment on the population dynamics have not yet been elucidated.
The purpose of this study was to create a new recruitment prediction model that includes the ocean environmental factors and to evaluate the effects of catch management by manipulating the age of first capture and the fishing mortality coefficient.

2. Materials and methods
2.1 Estimation of the population size and fishing mortality coefficient
This study employed age at catch, natural mortality coefficient per year (M = 0.40 for 57 0-year old, M = 0.35 for 1-year old, M = 0.30 for 2-year old, and M = 0.25 for 3-year 58 old and older ages), and age-specific maturity rate taken from “Resources evaluation of the 2007 Japanese Pacific walleye pollock regional population” [1]. The data were used to estimate the age-specific fishing mortality coefficient per year (*F*) and population size by using virtual population analysis (VPA).

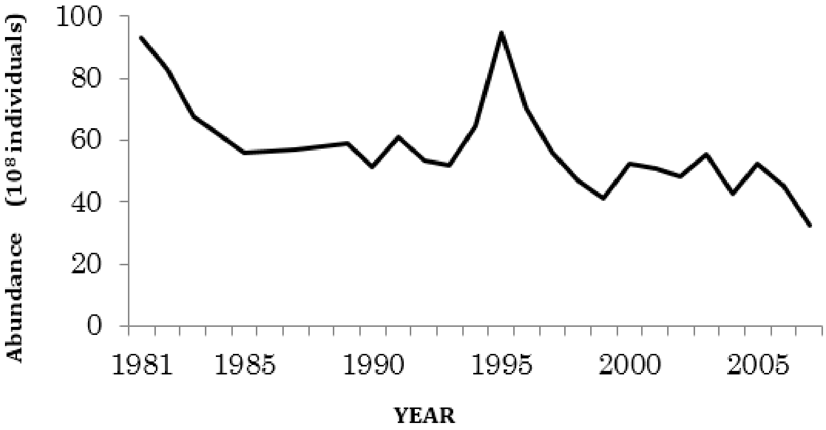

Fig 1: Abundance of the Japanese Pacific walleye Pollock 1981-2007 quoted from the "Resources evaluation of the 2008 Japanese Pacific walleye Pollock group"

The population size, catch number, and fishing mortality coefficient of year t, at age a were denoted as $N_{a,t}$, $C_{a,t}$, and $F_{a,t}$, respectively. Fish aged 8 years or more were treated as the "plus-group," indicated by 8+. Here, we assumed that the terminal F of each age in 2007 was equal to the average F from 2002 to 2006, and the fishing mortality coefficient of the 8+ group in each year was equal to that of the fish at age 7 years [1].

The population sizes at ages 0–6 years were obtained using the following equation:

$$N_{a,t} = N_{a+1,t+1}e^{M} + C_{a,t}e^{\frac{M}{2}} \quad (1)$$

The population sizes at ages 7 and 8+ years are expressed using the following equations [1], assuming $F_{8+,t} = F_{7,t}$:

$$N_{7,t} = \frac{C_{7,t}}{C_{7,t}+C_{8+,t}}N_{8+,t+1}e^{M} + C_{7,t}e^{\frac{M}{2}} \quad (2)$$

And

$$N_{8+,t} = \frac{C_{8+,t}}{C_{8+,t}+C_{7,t}}N_{8+,t+1}e^{M} + C_{8+,t}e^{\frac{M}{2}} \quad (3)$$

Moreover, the population size at age 8+ years was also calculated using the following:

$$N_{8+,t+1} = (N_{7,t} + N_{8+,t})e^{-(F_{8+,t}+M)} \quad (4)$$

By combining equations (2), (3), and (4), the following equation was obtained:

$$N_{8+,t+1} = \frac{C_{7,t}+C_{8+,t}}{e^{F_{8+,t}}-1}e^{-\frac{M}{2}} \quad (5)$$

Then, $N_{8+,2008}$ was calculated from equation (5) by assuming the value of $F_{8+,2007}$ and the population sizes of fish aged 7 and 8+ years from 1981 to 2007 by using equations (2) and (3), respectively.

The fishing mortality coefficient was obtained from the following equation:

$$F_{a,t} = -\ln\left(1-\frac{C_{a,t}e^{\frac{M}{2}}}{N_{a,t}}\right) \quad (6)$$

The following equation was used for calculating the population size in 2007:

$$N_{a,t} = C_{a,t}e^{\frac{M}{2}} / \left(1-e^{-F_{a,t}}\right) \quad (7)$$

2.2 Relationship between environmental change and reproduction

Recruitment was defined as the population size at age 0 years. Environmental factors were the Arctic Oscillation (AO), Pacific Decadal Oscillation (PDO), and mean water temperature of the Funka Bay (the spawning ground) from 1981 to 2007. The AO, PDO, and water temperature were downloaded from the National Oceanic Atmospheric Administration [17], Japan Meteorological Agency [18], and Japan Ocean Data Center [19], respectively.

The weight $W_{a,t}$(g) and maturity rate $m_{a,t}$ at age a in year t were used to calculate the spawning stock biomass in year t SSB_t [1]. On the basis of the assumption that the sex ratio equaled 1 from 1981 to 2007, SSB_t was obtained using the following equation:

$$SSB_t = \frac{1}{2}\sum_{a=0}^{8+} m_{a,t}N_{a,t}W_{a,t} \quad (8)$$

First, we attempted to create models of reproductive success of the Pacific regional population of walleye pollock by following linear and non-linear models (Ricker model):

Linear model: $R_t = aSSB_t + b$ (9)

And

Ricker model : $R_t = aSSB_te^{(-bSSB_t)}$; (10)

in the above equations, a and b are constants.

Secondly, the environmental factors that correlated significantly with recruitment size were employed as explanatory variables of the reproduction function. In this study, the mean water temperature of the Funka Bay was calculated for each of the four seasons, that is, the mean water temperature was taken as the average water temperature from December to March (spawning season, winter), April to June (spring), July to September (summer), and October to November (autumn), at depths from 0 to 400 m. The correlation coefficient was calculated between the recruitment size and environmental variables (mean water temperature of each season, AO and PDO).

Then, a reproduction model was constructed with the function SSB_t and environmental factors:

$$R_t = f(SSB_t) + g(X_{1,t}, X_{2,t}, \ldots, X_{n,t}) + \varepsilon_t \quad (11)$$

Here, $f(SSB_t)$ expressed the linear and Ricker models. R_t, $X_{i,t}$, and ε_t expressed the recruitment size, the ith environmental factors, and error term in year t, which normally distributes with mean 0 and variance σ^2. In this study, we called equation (11) as an addition model. Akaike information criterion (AIC) [20] was used for model selection.

2.3 Reproducing the abundance and catch

This study attempted to simulate the population sizes and documented catch numbers from 1981 to 2007. First, the population size in 1981 at ages 0 to 8+ years estimated using VPA was referred to as the initial population size. Second, the population size at ages 1–8+ years in the following year was obtained using the following equation:

$$N_{a,t} = N_{a-1,t-1} e^{-F_{a-1,t-1}-M} \quad (12)$$

Third, the population size at age 0 years in the following year was calculated from the reproduction model. Moreover, the catch number from 1981 to 2007 was also calculated from the following equation:

$$C_t = N_t F_t (1 - e^{-F_t - M}) / (F_t + M) \quad (13).$$

This process was repeated until the year reached 2007.

2.4 Fluctuations of the abundance and catch by changing the fishing mortality coefficient

By using the same method described above, the population size and catch were calculated, after changing the age at first capture and the age-specific fishing mortality coefficient ($F_{a,t}$). Although the age of the first capture was 0 years in the actual fishery, here we assumed that it was caught by age 1 year ($F_0 = 0$), age 2 years ($F_{0,.} = F_{1,.} = 0$), or age 3 years ($F_{0,.} - F_{2,.} = 0$), and $F_{a,t}$ was changed as $\alpha F_{a,t}$ ($0.7 < \alpha < 0.9$), which was calculated using VPA.

3. Results

3.1 Estimates of the population size and fishing mortality coefficient of Japanese Pacific walleye pollock

Figure 2 shows an estimate of the population size at age 0 years from 1981 to 2007. This was also the recruitment size. The results agree well with the estimated result from the “Resources evaluation of the 2008 Japanese Pacific walleye pollock regional population” [1]. Recruitment size fluctuated greatly yearly.

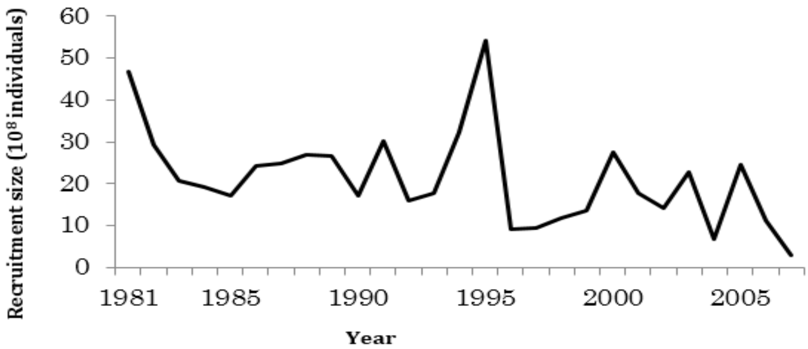

Fig 2: Estimate of the recruitment size of the Japanese Pacific walleye Pollock from 1981 to 2007

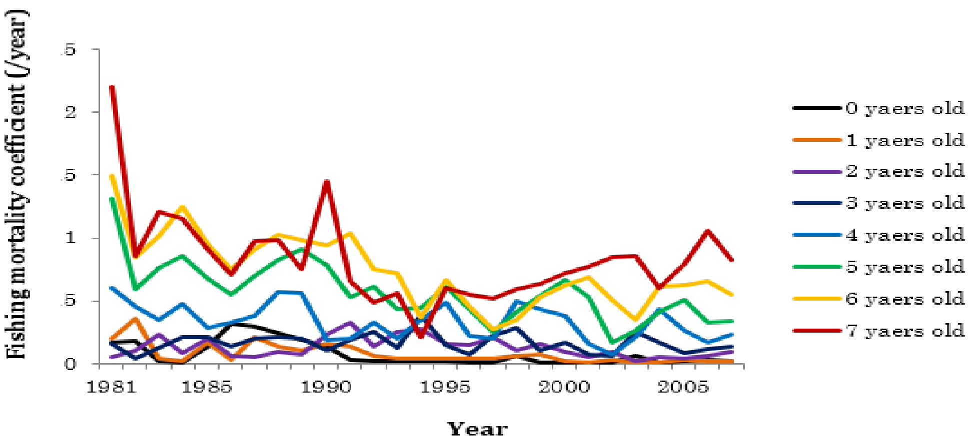

Fig 3: Estimate of the fishing mortality coefficient of each age from 1981 to 2007

From 1981 to 1985, the recruitment size decreased greatly, and then from 1985 to 1993, the recruitment size fluctuated stably. From 1993 to 1995, the recruitment size greatly increased, but then it greatly decreased in 1996. From 1996 to 2007, the fluctuation amplitude of the recruitment size was smaller than that before. On the basis of the assumption that the year class in which the recruitment size exceeded 3 billion was the dominant year class, the populations of year classes 1981, 1994, and 1995 were considered as the dominant year classes. Figure 3 shows the yearly fluctuations of the fishing mortality coefficient at each age from 1981 to 2007. Generally, the fishing mortality coefficient of age 0 years was the lowest in all the year classes, and those of ages 5 and 6 years had a tendency to be higher than that of the other ages, except those of ages 7 and 8+ years.

3.2 Environmental change and reproduction relations

Table 1 shows the relationship of recruitment size to AO, PDO, and mean water temperature of the Funka Bay. Significant correlations were not found between the AO and PDO and recruitment size. However, a strong correlation was observed between the mean water temperature of the Funka Bay and recruitment size. Moreover, as shown in Table 2, a strong correlation was found in the relationship between the mean water temperature of the spawning season (December to March) and recruitment size, at a significance level of 0.1%, with a correlation coefficient of 0.66. However, the mean water temperature from October to November showed a low correlation between the temperature and recruitment.

The above results suggest that the water temperature of the spawning ground could have an influence on the fluctuation in recruitment size. Thus, the reproduction model developed here used the mean water temperature of three seasons (expect from October to November) in the spawning ground (the Funka Bay sea area), as well as the spawning stock biomass *SSB*. Table 3 shows the parameters and AIC of each model. We found that the AIC of the linear addition model was slightly smaller than that of the Ricker addition model. Therefore, we constructed a forecasting model by using the linear addition model. Further, we assumed the mean water temperature of three seasons (expect October to November) and that SSB might have the greatest influence; thus, the mean water temperatures and SSB were factored in here. We used multiple repression analysis. The water temperature from December to March, April to June, and July to September were denoted using $X_{1,t}$, $X_{2,t}$, and $X_{3,t}$ as independent variables of the reproduction model. The full model was defined as follows:

$$R = aSSB_t + b + \sum_{i=1}^{3}\left(c_i X_{i,t} + d_i SSB_t X_{i,t} + e_i X_{i,t} X_{i+1,t}\right), \quad (14)$$

where, $X_{4,t} = X_{1,t}$.

As a result, the AIC was 191, which was much lower than that obtained before. Consequently, the reproduction equation was chosen as follows:

$$R = 47.1 - 6.37X_{1,t} - 6.58X_{2,t} + 1.32X_{1,t}X_{2,t}. \quad (15)$$

The recruitment sizes estimated using VPA and predicted from equation (15) are shown in Figure 4. The fluctuations in recruitment size calculated using equation (15) were similar to those estimated using VPA (Fig. 5).

Table 1: Correlation coefficients between recruitment size and AO, PDO, and the mean water temperature of the Funka Bay.

	AO	**PDO**	**Funka Bay**
Correlation coefficient	-0.062	-0.098	0.48
p-value	0.76	0.62	0.011

Table 2: Correlation coefficients between recruitment size and mean water temperatures in 4 seasons of the Funka Bay sea area.

	December to March	**April to June**	**July to September**	**October to November**
Correlation coefficient	0.66	0.36	0.52	0.23
p-value	1.6×10^{-4}	0.062	0.005	0.24

Table 3 Parameters in the reproduction models estimated and Akaike information criterion (AIC)

Model	**Parameters**					
	a	b	$X_{1,t}$	$X_{2,t}$	$X_{3,t}$	AIC
Linear	-0.69	34.56				210.2
Ricker	5.48	0.08				209.8
Linear Addition	-0.24	-12.3	3.0	1.20	0.76	199.6
Ricker Addition	-1.21	-0.026	3.0	1.19	0.56	200

Fig 4: The recruitment sizes calculated by VPA and equation (12) from 1981 to 2007. Solid and dotted lines were those calculated by VPA and eq. 12, respectively

Fig 5: The population sizes calculated by VPA and equations (8), (12) and (15) from 1981 to 2007 Solid and dotted lines were those calculated by VPA and equations (8), (12) and (15), respectively.

3.3 Reproducing the abundance and catch

Figure 5 shows the population sizes estimated using VPA and predicted using equations (8), (12), and (15), when the initial value used was the population size at each number in 1981. The trajectories were similar. Figure 6 shows the observed catch numbers and calculated using equations (8), (12), and (15). The fluctuations in both catch numbers were similar to each other.

Fig 6: The catch numbers observed and calculated by equations (8), (12) and (15) from 1981 to 2007 Solid and dotted lines were calculated by equations (8), (12) and (15) and observed, respectively

3.4 Fluctuations of the abundance and catch by changing the fishing mortality coefficient

Figure 7 shows the fluctuations in abundance estimated using VPA, evaluated for each F ($0.7F_{a,t}$, $0.8F_{a,t}$, and $0.9F_{a,t}$), for each age at first capture (1, 2, and 3 years) and their combinations. The patterns of these fluctuations were nearly the same. The abundance when the first capture age was increased to 1 year ($F_0 = 0$) and the $F_{a,t}$ was reduced by $0.8F_{a,t}$ was similar to the abundance when the first capture age was increased to 2 years ($F_0 = F_1 = 0$) and the $F_{a,t}$ was reduced by $0.9F_{a,t}$. We also found that the abundances were similar to each other when $F_0 = 0$ and $0.7F_{a,t}$, when $F_0 = F_1 = 0$ and $0.8F_{a,t}$, $F_0 = F_1 = 0$ and $0.7F_{a,t}$, and $F_0 = F_1 = F_2 = 0$ and $0.9F_{a,t}$. Figure 8 shows the fluctuation of the catch estimated using VPA, evaluated for each F ($0.7F_{a,t}$, $0.8F_{a,t}$, and $0.9F_{a,t}$), for each age at the first capture (1, 2, and 3 years), and their combinations. We found that the patterns of these fluctuations were similar and that it was easy to predict the catch.

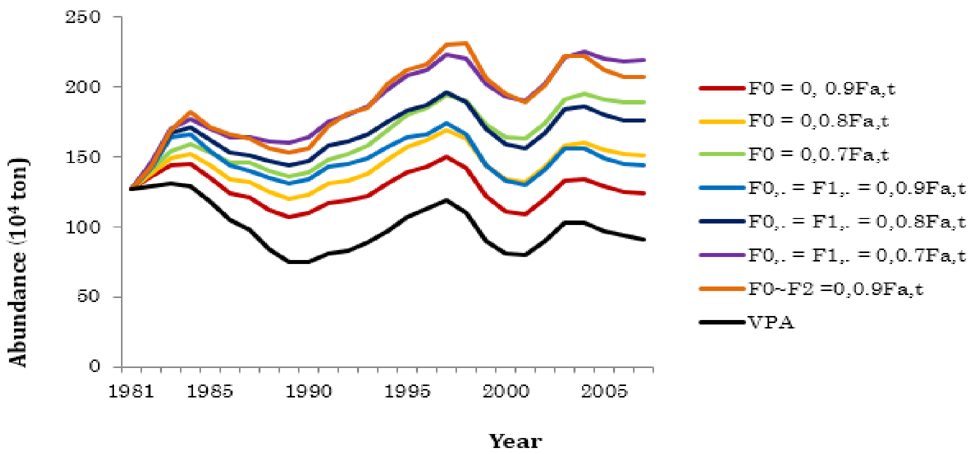

Fig 7: The fluctuations of the abundance by changing the fishing mortality coefficient from 1981 to 2007 and the age at first capture

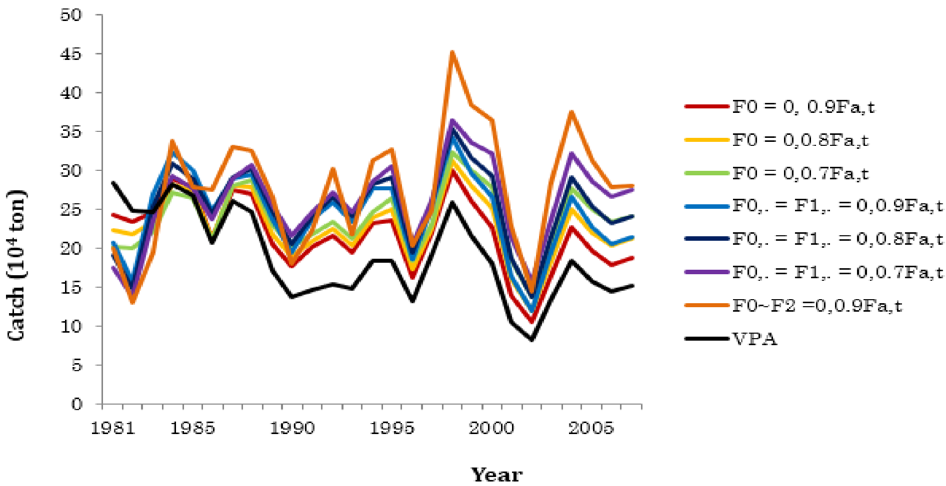

Fig 8: The fluctuations of the catch by changing fishing mortality coefficient the from 1981 to 2007 and the age at first capture

4. Discussion

The purpose of this study was to create a reproduction model that considered environmental factors for generating data of recruitment size, population size, and catch size. We also investigated the effects of changing the age of first capture and reducing the fishing mortality coefficient.

Recently, it has been reported that the walleye pollock population size is correlated with the environmental factors because water temperature influences reproduction of the northern Japan Sea walleye pollock stock, and thus, causing fluctuations in their population size [21].

In this study, we found a strong significant correlation between the mean water temperature of the Funka Bay and recruitment size, and we concluded that recruitment size would increase as water temperature of the Funka Bay rises. The water temperature around the Funka Bay during the early life stages strongly affects the recruitment size [22, 23]. Favorable environmental conditions during early life stages have been considered important for the survival of developing pollock [16], and high larvae survival rates are necessary for recruitment success [4, 16, 24]. This is similar to pollock recruitment success factors in the Gulf of Alaska [25].

Despite the clear correlation between water temperature and recruitment success, it is not clear whether water temperature directly influences recruitment size. In other words, water temperature may influence incubation, the survival during the early life stage, or the quantity of available food. Consequently, further studies are necessary to examine how water temperature affects fish abundance.

Year-class strength appeared to be the major factor driving changes in the biomass of pollock stock [23]. This study showed that recruitment sizes estimated using VPA fluctuated intensely (Fig. 2) and that the dominant year-classes (1981, 1991, 1994, and 1995) had the greatest effect on population size (Fig. 5).

However, Figure 2 shows that the recruitment size had the tendency to decrease in recent years. Therefore, the total population had a tendency to decrease. In contrast, age-specific F varied from 1981 to 2007 intensely, but no clear trend is observed (Fig. 3).

Figure 7 represents the fluctuations in population. From this figure, we see that changing the age of the first capture can have the same effect as reducing the F, and both changes can help gradually increase abundance. In Figure 8, the fluctuations of catch size changed in an orderly fashion and the changes were similar to each other. Accordingly, it was easy to predict the tendency of the catch size. Moreover, Figure 8 indicates that catch size also gradually increased by increasing the age of the first capture and reducing F. Thus, we can determine the F and age of the first capture that will stably increase recruitment size, population size, and catch size of the Japanese Pacific walleye pollock.

Sakuramoto and Suzuki [27] discussed that when the true model is the proportional model, there is a high probability that process and/or observation errors will result in the estimated stock-recruitment relationship model being misidentified as either the Ricker or Beverton and Holt model. In contrast, when the true model is the Ricker or Beverton and Holt model, process and/or observation errors seldom result in the proportional model being selected. This outcome suggests that if the proportional model is indeed identified as the fitting actual stock–recruitment relationship data, then there is a high probability that the relationship between recruitment size and egg production could instead be fit by using the proportional model.

In this study, we decided that the linear addition model was slightly better than the Ricker addition model, based on the AIC, although their values were almost same. Therefore, density-dependent effects intrinsic to the Japanese Pacific walleye pollock population may not be the main factors causing population fluctuations. It is possible to accurately reproduce the recruitment size, abundance, and fish catch by using the reproduction model chosen in this study. Therefore, the model proposed in this study is suitable for assessing the Japanese Pacific walleye pollock stock. In a further study, we will determine an appropriate fishing mortality coefficient F and age of the first capture based on the reproduction model and reduction of F, to gradually increase the recruitment size, population size, and catch of Japanese Pacific walleye pollock and stably sustain the population size.

5. Acknowledgments

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