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Weight-based yield per recruitment and spawning-biomass per recruitment analyses of Pacific cod *Gadus macrocephalus* off the Pacific coast of southern Hokkaido, Japan

Running title: Weight-based YPR and SPR of Pacific cod

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Abstract:
The present study assessed the stock state of Pacific cod *Gadus macrocephalus* caught off the coast of southern Hokkaido, Japan. Weight-based yield per recruitment (YPR^W) and spawning-biomass per recruitment (SPR^W) analyses were used for this assessment. The current fishing mortality (average from 1998 to 2000) was 0.65 and weight at first capture was 0.5kg B.W. Under these fishing pressures, the YPR of Pacific cod in southern Hokkaido was 1.06kg/recruitment and %SPR was 6.9%. The %SPR was lower than the critical limit at 20%SPR. The main reason that values of both YPR and %SPR were not optimum would be that the weight at first capture was too small. Raising the weight at first capture was thought to be a better strategy from the biological viewpoint and reducing fishing mortality to 0.3 would be the next alternative strategy from the fisheries management viewpoint.

***KEYWORDS*: *Gadus macrocephalus*, Pacific cod, SPR, stock assessment, weight-based, YPR.**

INTRODUCTION

Pacific cod (*Gadus macrocephalus*) is caught mainly in northern Japan and is one of the most important commercial species in Hokkaido and Aomori prefecture (Fig. 1). The Pacific cod that is distributed in the Pacific fishing grounds of Hokkaido comprises two stocks; one distributed off Southern Hokkaido and the other off Eastern Hokkaido.[1] Southern Hokkaido stock is caught by trawl net, long lines, gillnet, set net, etc, with two thirds of the catch made through use of trawl net and long line. The body weight composition of fish caught by trawl net and long line is quite similar.[2] Biological features of Pacific cod caught around Hokkaido have been reported, for example growth,[3,4] maturity,[5] feeding habits,[6,7] reproductive behavior[8] and migration[9,10], but population estimation and fishery management studies have not been reported except by Ueda *et al*.[11]

Fishing mortality and biomass of Pacific cod in southern Hokkaido have been estimated using weight-based virtual population analysis (WPA).[11,12] In this population, the annual age data was not available. The age of Pacific cod is usually estimated from otoliths.[3,4] To obtain an otolith, the head of the fish has to be broken. It is difficult to collect a sufficient number of otoliths from Pacific cod because the fish is large and expensive. Annual age composition is often estimated from annual body length composition using annual age-length keys. However, the body length of these fish is also difficult to measure because they are landed in closed foam polystyrene boxes. Alternatively, the body weight of Pacific cod is usually measured in the market for pricing purpose so these statistics can be used. Thus the weight-based approach is the only way to estimate the biomass for Pacific cod in southern Hokkaido.

The fishing mortality of Pacific cod in southern Hokkaido has been estimated[11] and evaluation should be made as to whether overfishing is occurring or not. For this purpose, yield per recruitment (YPR) and spawning-biomass per recruitment (SPR) analyses have been widely used.[13-18] YPR analysis was originally devised by Beverton and Holt,[19] and gives strategies to avoid growth-overfishing.[20] SPR analysis is suggested by Sissenwine and Shepherd[13] and gives strategies to avoid recruitment-overfishing.[20-22]

Although model parameters of conventional YPR and SPR models are age-specific, selectivity and maturity are thought more likely to be related to body size than age.[23] Conventional models have assumed that all individuals in a stock have the same growth rates, but there are generally fairly large individual variations in growth and these should be incorporated in the models.[15]

Thus for this stock, body size-based YPR and SPR analyses should be applied considering growth variation. A backward weight transition probability was estimated for WPA.[11] This probability $P_{k,i}^{b}$ was defined as the probability that a fish grows from weight class i to k in the previous year. The forward weight transition probability can be estimated by a similar procedure. Using the forward weight transition probability instead of the backward weight transition probability, YPR and SPR can be calculated considering these growth variations.

In this paper, we assessed the state of this Pacific cod stock using weight-based YPR and SPR analyses.

MATERIALS AND METHODS

Weight-based YPR and SPR analyses have similar procedures to the WPA.[11] The procedure of WPA needs the growth curve, length-weight relationship and the variation of weight. Then we made the backward weight transition probability and estimated the population number using this probability. On the other hand, although weight-based YPR and SPR models need the same growth curve, length-weight relationship and variation of weight, they use the forward weight transition probability instead of the backward one.

Growth curve

We used the same parameters used in WPA[11] for von Bertalanffy's growth curve of the Pacific cod in southern Hokkaido, which was reported in Hattori *et al.*:[4]

$$l_t = 96.6\left\{1 - e^{-0.259(t+0.087)}\right\} \tag{1}$$

where l is body length (cm) and t is age (yr).

From equation 1, the relationship between l_{t+1} and l_t is

$$l_{t+1} = 0.772 \cdot l_t + 22.042 \tag{2}$$

The weight-length relationship was also the same as the relationship used in WPA:[11]

$$w = 5.67 \times 10^{-5} \cdot l^{2.624} \qquad (n{=}101,\ r^2{=}0.65) \tag{3}$$

where w is body weight (kg).

From equations 2 and 3, the relationship between w_{t+1} and w_t is described as follows:

$$w_{t+1} = 5.67 \times 10^{-5} \left\{ 0.772 \left(\frac{w_t}{5.67 \times 10^{-5}} \right)^{\frac{1}{2.624}} + 22.042 \right\}^{2.624} \tag{4}$$

Weight transition probability

The body weight of individuals of weight class i was assumed to be w_i, which was the midpoint of the class i.

We denote w'_i as the mean body weight of the individuals in weight class i in the previous year. We derived w'_i from the relationship between w_i and w'_i, which was derived from equation 4 after replacing w_t with w_i and w_{t+1} with w'_i:

$$w'_i = 5.67 \times 10^{-5} \left\{ 0.772 \left(\frac{w_i}{5.67 \times 10^{-5}} \right)^{\frac{1}{2.624}} + 22.042 \right\}^{2.624} \tag{5}$$

We defined the forward weight transition probability $P^f_{k,i}$ as the probability that a fish grows from weight class i to k in the next year, which was assumed to be a part of normal distribution with mean body weight w'_i and standard deviation $\sigma_{w'_i}$ as:

$$P^f_{k,i} = \int_{w_k^L}^{w_k^U} \frac{1}{\sqrt{2\pi\sigma^2_{w'_i}}} \exp\left(-\frac{\left(x - w'_i\right)^2}{2\sigma^2_{w'_i}} \right) dx \tag{6}$$

where w_k^U and w_k^L were the upper and lower limits of weight class k.

The standard deviation $\sigma_{w'_i}$ was proportional to w'_i with the coefficient of variation being 0.161.[11]

Table 1 shows the forward weight transition probabilities. The weight class interval was set at 0.5 kg and weight classes analyzed were from 0.0-0.5kg to 7.5+kg. Body weights of 7.5kg and over were all included in the 7.5+kg weight class.

Weight-based YPR model

We assumed that a stock recruits only into the weight class 1 in year 0. Recruitment (R) is represented as:

$$R = N_{1,0} \tag{7}$$

where N is the population number.

The population numbers are calculated sequentially using the following equation:

$$N_{k,j+1} = \sum_{i=1}^{I} (P_{k,i}^{f} e^{-(F_{k,j}+M)} N_{i,j}) \tag{8}$$

where k and i are weight classes, j is year, F is fishing mortality and M is natural mortality. P is weight transition probability mentioned above. M was set at 0.2 which was used in WPA.[11] In this paper, fishing mortality and natural mortality mean instantaneous rates of fishing and natural mortalities respectively.

The catch number for weight class i in year j is represented as:

$$C_{i,j} = \frac{F_{i,j}}{F_{i,j}+M}(1-e^{-(F_{i,j}+M)})N_{i,j} \tag{9}$$

The cumulative yield derived from the recruited stock is represented as:

$$Y = \sum_{i=1}^{I} \sum_{j=0}^{J} C_{i,j} w_i \tag{10}$$

The maximum year J was set at 25 years. The number for recruited population decreases approximately to zero in the 25th year.

The yield per recruitment (YPR) is calculated as:

$$\text{YPR} = \frac{Y}{R} = \frac{1}{R} \sum_{i=1}^{I} \sum_{j=0}^{J} C_{i,j} w_i \tag{11}$$

Weight-based SPR model

Spawning biomass for weight class i in year j is represented as:

$$S_{i,j} = N_{i,j} w_i m_i \tag{12}$$

where m_i is maturity rate for the fish in weight class i. In this equation, spawning is assumed to be linear to body weight of fish.

The mature body length of female Pacific cod in southern Hokkaido was 57cm.[5] Using this information, the mature body weight of Pacific cod in southern Hokkaido was calculated as 2.3kg by equation 3. To calculate SPR, we set the maturity rate for weight class i m_i at 0 for weight classes smaller than 2.0kg, at 0.4 for 2.0-2.5kg and at 1.0 for weight classes greater than 2.5kg.

The cumulative spawning-biomass derived from the recruited stock is represented as:

$$S = \sum_{i=1}^{I} \sum_{j=0}^{J} N_{i,j} w_i m_i \tag{13}$$

The spawning-biomass per recruitment (SPR) is calculated as:

$$\text{SPR} = \frac{S}{R} = \frac{1}{R} \sum_{i=1}^{I} \sum_{j=0}^{J} N_{i,j} w_i m_i \tag{14}$$

Current fishing mortality

To assess the current fishing mortality, we used the average fishing mortality of recent years selected from the fishing mortality from 1994 to 2000 obtained from Ueda *et al.*[11] (Table 2). Because the fishing mortality seemed to have changed from the lower (earlier) period to the higher (later) period, we divided the seven years into two periods, and we used the average of the later period as the current fishing mortality. To choose the best boundary year between the two periods, we compared the sum of residual squares between the fishing mortality of the year and the average fishing mortality of that year's period, for all possible boundary years. The sum of residual squares had a minimum value when we divided into 1994-1997 and 1998-2000. We examined the difference between the average fishing mortalities of earlier and later periods. The average of the later period (0.65) was significantly larger than the earlier period (0.40) (one tailed *t*-test, P=0.0103), so we used 0.65, which was the average of the later period, as the current fishing mortality.

Current weight at first capture

Because the fishing mortality for the weight class 1-2kg was the highest of all the other classes,[11] Pacific cod caught in southern Hokkaido was thought to be full-recruited at 1kg. Although the minimum body weight of caught Pacific cod measured was about 400g,[2] individuals less than 500g are very rare, so we assumed the weight at first capture to be the 0.5-1.0kg of the weight class.

RESULTS

The yield per recruitment estimated by the weight based YPR analysis was 1.06kg/R under the current fishery (Fig. 2). The YPR was maximized (1.18kg/R) at 0.30 of fishing mortality F when weight at first capture w_c was fixed at the current status, or maximized (1.64kg/R) at w_c=3.5kg when F was fixed at the current status. These results suggest that although reducing fishing mortality raises the yield only by 11%, an increase of weight at first capture raises the yield by a maximum of 55%.

The percentage of spawning-biomass per recruitment with fishing to that without fishing estimated by the weight based SPR analysis was 6.9% in the current fishery (Fig. 3). The %SPR was 20% at F=0.32 and 30% at F=0.22 when w_c was fixed at current fisheries status. The %SPR was 19.0% at w_c=2.0kg and 29.4% at w_c=3.0kg when F was fixed at current fisheries status. Both decreasing fishing mortality and/or increasing fishing size at first capture led to an increase of the spawning biomass.

DISCUSSION

The %SPR was between 5.1% (1999) and 19.7% (1995) from 1994 to 2000 (Table 2). In these seven years, the average %SPR was 11.7% and annual %SPR was constantly less than the critical level of 20%.[21] This result suggests that fisheries in southern Hokkaido would have a considerable impact on the stock state of Pacific cod.

While the biomass of Pacific cod in southern Hokkaido from 1994 to 2000 increased,[11] the main factor affecting this increase was not fisheries management but the increase of recruitment, which could not be controlled. Results of YPR and SPR analyses suggest that increasing fishing size at first capture would lead to an increase of yield and spawning biomass even if recruitment was not increased.

Considering the current fisheries status, it is difficult to enlarge the size at first capture because Pacific cod are caught with other fish including walleye pollock (*Theregra chalcogramma*), which are much smaller than Pacific cod. To maximize YPR if the size at first capture cannot change, the fishing mortality should be decreased from 0.65 to 0.30, which means about a 50% reduction of the fishing effort. While the yield would be increased to 11% at equilibrium with half of the current effort, that means that fisheries productivity would increase substantially. In addition, the %SPR would increase nearly threefold (from 6.9% to 21.2%). These results are achieved under the constant recruitment condition. If recruitment relates to spawning biomass, decreasing fishing mortality is potentially effective in increasing biomass and yield of Pacific cod in southern Hokkaido.

To calculate the weight transition probability, the standard deviation $\sigma_{w_i'}$ was assumed to be proportional to w_i' with the coefficient of variation being 0.161.[11] Because this value is derived from the relationship between body weight belonging to a body length class and its standard deviation,[11] this standard deviation is essentially not the same to that is necessary to equation 6. The coefficient of variation of 0.161, therefore, is alternative information to calculate the forward weight transition probability. For example, if mark-recapture data is available, the suitable standard deviation is derive from the relationship between the body weight of marking and recapturing.

To calculate the weight transition probability, the body weight of individuals in next year was assumed to be normal distributed and that's variance was assumed to be linear to mean body weight. For that reason, the weight transition probability had many minus-growth parts especially in large weight classes (Table 1), and this may be unrealistic. Assuming other distribution (e.g. gamma distribution) could avoid minus-growth, but considerable decrease of recruited population number in large weight classes has a small influence on calculation of YPR and SPR, and it is not surprising that many biological variables are approximately normal distributed.[24]

In this paper, we estimated YPR and SPR using a weight-based model. If there are no individual variations of growth, the estimated YPR and SPR should be equal to the estimators of the age-based model. Ueda and Matsuishi[25] reported that estimates of weight-based YPR (SPR) were slightly different to estimates of age-based models. Weight-based YPR and SPR, incorporating the individual growth variations as weight transition probability, seemed to be more reasonable than the age-based model. The procedure of YPR and SPR estimation should incorporate the growth variation, and the individual based model would be one of the best ways of doing this,[15] but the computation load is fairly large. Although our method needs information about the growth variation adding to the parameters required for the age-based YPR and SPR, this method incorporates the variation of individual growth in a simple manner and could be applied for various stocks.

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Captions of figures and tables

Fig. 1 Location and fishing area of Pacific cod in southern Hokkaido, Japan.

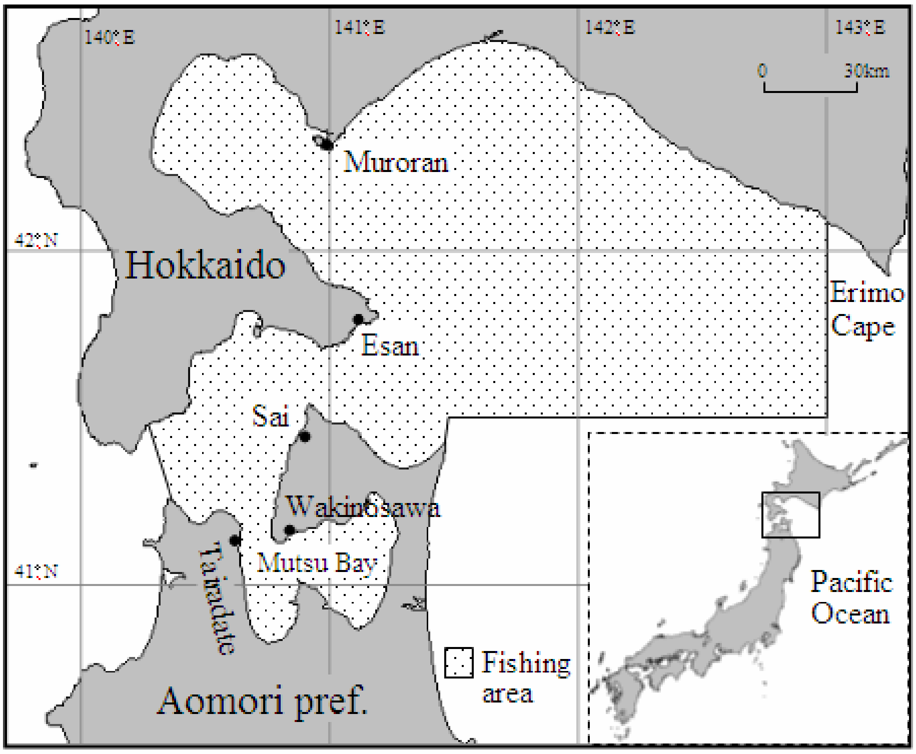

Fig. 2 The contour of weight-based yield per recruitment of Pacific cod in southern Hokkaido. A solid circle represents fishing mortality (0.65) and weight at first capture (0.5kg) of the current fishery (average from 1998 to 2000). Dotted lines represent constant fishing mortality (0.65) or weight at first capture (0.5kg).

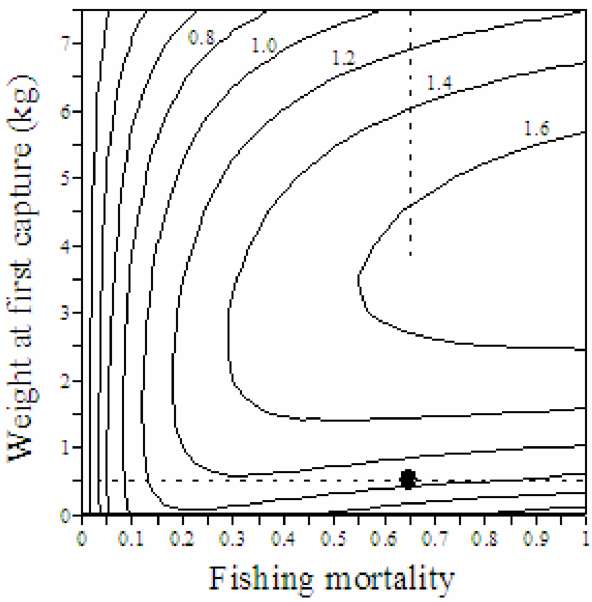

Fig. 3 The contour of the percentage of weight-based spawning-biomass per recruitment with fishing to that without fishing of Pacific cod in southern Hokkaido. A solid circle represents fishing mortality (0.65) and weight at first capture (0.5kg) of the current fishery (average from 1998 to 2000). Dotted lines represent constant fishing mortality (0.65) or weight at first capture (0.5kg).

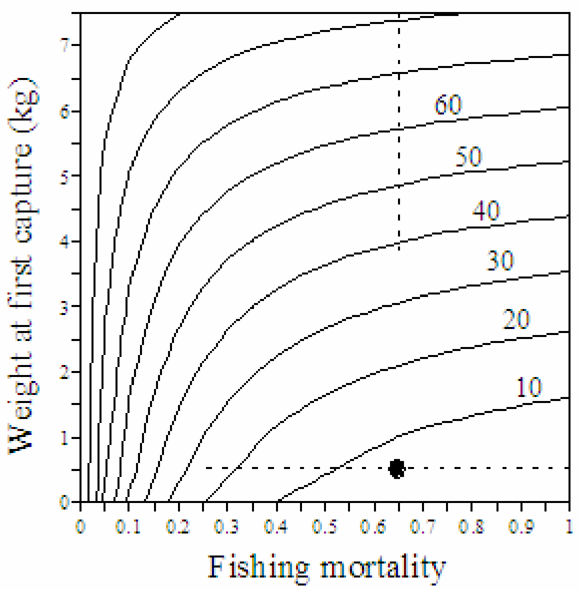

Table 1 Forward weight transition probabilities of Pacific cod in southern Hokkaido, where w_i is the midpoint of weight class i and w_i' and $\sigma_{w_i'}$ are mean and standard deviation of corresponding weight of next year respectively.

Weight class i (kg)	w_i	w_i'	$\sigma_{w_i'}$	Weight class k (kg)															
				0.0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	2.5-3.0	3.0-3.5	3.5-4.0	4.0-4.5	4.5-5.0	5.0-5.5	5.5-6.0	6.0-6.5	6.5-7.0	7.0-7.5	7.5+
0.0-0.5	0.25	0.96	0.16	0	0.59	0.41	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5-1.0	0.75	1.69	0.27	0	0.01	0.23	0.63	0.13	0	0	0	0	0	0	0	0	0	0	0
1.0-1.5	1.25	2.29	0.37	0	0	0.02	0.20	0.50	0.26	0.03	0	0	0	0	0	0	0	0	0
1.5-2.0	1.75	2.83	0.46	0	0	0	0.03	0.20	0.41	0.28	0.07	0	0	0	0	0	0	0	0
2.0-2.5	2.25	3.33	0.54	0	0	0	0.01	0.05	0.21	0.35	0.27	0.09	0.01	0	0	0	0	0	0
2.5-3.0	2.75	3.82	0.61	0	0	0	0	0.01	0.08	0.21	0.31	0.25	0.11	0.02	0	0	0	0	0
3.0-3.5	3.25	4.28	0.69	0	0	0	0	0	0.03	0.10	0.21	0.28	0.23	0.11	0.03	0.01	0	0	0
3.5-4.0	3.75	4.73	0.76	0	0	0	0	0	0.01	0.04	0.12	0.21	0.26	0.21	0.11	0.04	0.01	0	0
4.0-4.5	4.25	5.17	0.83	0	0	0	0	0	0	0.02	0.06	0.13	0.21	0.23	0.19	0.10	0.04	0.01	0
4.5-5.0	4.75	5.61	0.90	0	0	0	0	0	0	0.01	0.03	0.07	0.14	0.20	0.22	0.17	0.10	0.04	0.02
5.0-5.5	5.25	6.03	0.97	0	0	0	0	0	0	0	0.01	0.04	0.09	0.15	0.20	0.20	0.16	0.09	0.06
5.5-6.0	5.75	6.45	1.04	0	0	0	0	0	0	0	0.01	0.02	0.05	0.10	0.15	0.19	0.18	0.14	0.16
6.0-6.5	6.25	6.86	1.10	0	0	0	0	0	0	0	0	0.01	0.03	0.06	0.11	0.15	0.18	0.17	0.28
6.5-7.0	6.75	7.26	1.17	0	0	0	0	0	0	0	0	0.01	0.02	0.04	0.07	0.12	0.15	0.17	0.42
7.0-7.5	7.25	7.67	1.23	0	0	0	0	0	0	0	0	0	0.01	0.02	0.05	0.08	0.12	0.15	0.55
7.5+	7.75	8.06	1.30	0	0	0	0	0	0	0	0	0	0.01	0.02	0.03	0.06	0.09	0.13	0.67

Table 2 Fishing mortality and the percentage of weight-based spawning-biomass per recruitment with fishing to that without fishing of Pacific cod in southern Hokkaido from 1994 to 2000. Fishing mortality was estimated by Ueda *et al.*[11]

Year	1994	1995	1996	1997	1998	1999	2000
Fishing mortality	0.492	0.319	0.467	0.341	0.563	0.769	0.615
$\%SPR^W$	10.9	19.7	11.8	18.2	8.8	5.1	7.6