Weight-based virtual population analysis of Pacific cod *Gadus macrocephalus* off the Pacific coast of southern Hokkaido, Japan

Yuji UEDA,*a Yasuji KANNO AND Takashi MATSUISHI

Graduate School of Fisheries Sciences, Hokkaido University, Hakodate, Hokkaido 041-8611, Japan

ABSTRACT: Age-based population assessment is widely used, but there are cases where information on age or even body length of landed fish is difficult to collect. In the present study, the biomass and fishing mortality of the southern Hokkaido stock of Pacific cod *Gadus macrocephalus* was estimated directly from body weight composition, using weight-based virtual population analysis, from 1994 to 2000. The estimated biomass over 1 kg body weight was 5607 t in 1994 and increased to 7908 t in 2000. The increase was explained by an increase in recruitment.

KEY WORDS: *Gadus macrocephalus*, Pacific cod, stock assessment, weight-based virtual population analysis.

INTRODUCTION

Pacific cod *Gadus macrocephalus* is caught mainly in northern Japan and is commercially one of the most important species in the Hokkaido and Aomori Prefectures (Fig. 1). The Pacific cod that is distributed in the Pacific fishing grounds of Hokkaido comprises two stocks: one distributed off the Pacific fishing ground of southern Hokkaido (SH Pacific cod) and the other off Eastern Hokkaido.1 The SH Pacific cod spawn in Mutsu Bay from December to March,2 and in Kikonai Bay from December to January.3 The major fishing areas in southern Hokkaido are off Muroran, Esan on the Pacific coast, and Wakinosawa in Mutsu Bay. The types of fishing equipment that are most commonly used are trawl, long-line and set nets. In spite of the high commercial value, the biomass of the SH Pacific cod has not been assessed.

Virtual population analysis (VPA)4 is widely used for fish population assessment. Virtual population analysis estimates the population size, usually based on age compositions. However, age information is often difficult to collect. The age of cod is usually estimated from otoliths of caught fish. To get otoliths, the head of the fish must be broken. It is difficult to collect a sufficient number of otoliths from large, expensive fish such as cod. Often, age composition is estimated from body length using age-length keys. However, the body length of these fish is also difficult to measure because they are landed in closed foam polystyrene boxes. Even in these cases, body weight is always measured in the market for pricing purposes.

Ueda et al. developed weight-based virtual population analysis (WPA),5 which develops the length-based virtual population analysis method to use weight data.6 Weight-based virtual population analysis is a method of separable VPA that is similar to length-based methods.6–10 Age–length keys of SH Pacific cod are also not available on a yearly basis for the reason above, and WPA was used in the present study to estimate stock biomass.

In the present study, the biomass and fishing mortality of the SH Pacific cod are estimated and the stock state discussed.

MATERIALS AND METHODS

Population estimation using WPA requires catch-at-weight data, weight transition probability and natural mortality. The weight transition probability is estimated from the data of the weight-based growth curve and its variability.

Catch-at-weight data

The fishing area of the SH Pacific cod is shown in Fig. 1. The area consists of the waters stretching...
from the coast of Shiriuchi to Samani in Hokkaido, from Imabetsu to Higashidoori in Aomori prefecture, and the Erimo-nishi trawl fishery area. The catch-at-weight data of the SH Pacific cod were collected from slips preserved in three major fishing ports, namely, Muroran (trawl), Esan (longline) and Wakinosawa (set net) from 1994 to 2000.

The body weights of 112 individual fish were measured at Muroran market and relationships were derived between the number of individuals in a box and the mean body weight of an individual as shown in Fig. 2:

\[ g_d = 13.6 \cdot n_d^{0.888} (n = 39, r = 0.91) \]  
\[ g_s = 14.7 \cdot n_s^{1.125} (n = 67, r = 0.92) \]

where \( g_d \) and \( g_s \) are the body weights in a deep box and a shallow box, respectively, and \( n_d \) and \( n_s \) are the numbers in a deep box and a shallow box, respectively. The data for \( n_d = 1 \) (six individuals) were not used for deriving the relationship because the range of body weights for this category was very wide (12.4–15.1 kg). The body weight for \( n_d = 1 \) was set at 13.6 kg, which was the mean. The standard deviations of \( g_d \) and \( g_s \) (\( \sigma_d \) and \( \sigma_s \), respectively) were

\[ \sigma_d = 0.320 \cdot g_d - 0.602 \ (n = 39, r = 0.96) \]  
\[ \sigma_s = 0.126 \cdot g_s + 0.031 \ (n = 67, r = 0.72) \]

It was assumed that the body weights of individuals in a box were normally distributed. The probability \( \rho_{n_d,k} \) that the body weight of an individual of category \( n_d \) belonged to the weight class \( k \) was

\[ \rho_{n_d,k} = \frac{1}{\sqrt{2\pi}\sigma_d} e^{-(x_{k}-\mu_d)^2/2\sigma^2_d} \ dx \]

similarly, for \( \rho_{n_s,k} \),

\[ \rho_{n_s,k} = \int_{w_k^U}^{w_k^L} \frac{1}{\sqrt{2\pi}\sigma_s} e^{-(x_{k}-\mu_s)^2/2\sigma^2_s} \ dx \]

where \( w_k^U \) and \( w_k^L \) are the upper and lower limits of weight, respectively, for individuals of weight class \( k \). In the present study, weight classes of 1–2 kg, 2–3 kg, . . . , 6–7 kg and ≥7 kg were considered, so \( w_k^U \) and \( w_k^L \) were defined as boundary values among adjacent weight classes.

The numbers of individuals in a box (\( n \)), the numbers of boxes (\( b \)) and the types of boxes (deep [\( d \)] or shallow [\( s \)]) are recorded on fishing slips at Muroran market. The catch-at-weight of Pacific cod in weight class \( k \) (\( C_k \)) was derived as follows:

\[ C_k = \rho_{n_d,k} n_d b_d + \rho_{n_s,k} n_s b_s \]
At Esan market, boxes filled with fish are classified into six categories depending on the body weight of individuals: $3S < 1 \text{ kg}$, $1 \text{ kg} \leq 2S < 2 \text{ kg}$, $2 \text{ kg} \leq S < 3 \text{ kg}$, $3 \text{ kg} \leq M < 5 \text{ kg}$, $5 \text{ kg} \leq L < 10 \text{ kg}$ and $10 \text{ kg} \leq 2L$. The $3S$ data were not used because a biomass of more than $1 \text{ kg}$ was estimated in the present study. The total weights of fish in a box and in the various categories are recorded on slips. For example, when the total weight is $6.4 \text{ kg}$ and the category is $M$, the box contains two fish of $3.2 \text{ kg}$, because similar sized fish are packed in a box.

For the $2S$ category, the number of fish in a box could not be calculated naturally because, when the total weight of fish in the box was $9.0 \text{ kg}$ and the category was $2S$, the box could potentially contain from five ($1.8 \text{ kg} \times 5$) to nine ($1.0 \text{ kg} \times 9$) individual fish. For this category, the number of fish in a box was calculated by dividing the total weight of fish in the box by $1.5 \text{ kg}$, which was the midpoint between $1 \text{ kg}$ and $2 \text{ kg}$.

At Wakinosawa market, fish are also packed in boxes. The total weight of fish in a box and the number of fish in a box are recorded on slips. Using this information, the catch-at-weight of Pacific cod landed in Wakinosawa was calculated by dividing the total weight of fish in a box by the number of fish in a box. For example, when the total weight was $6.4 \text{ kg}$ and the number of fish was two, the box contained two fish of $3.2 \text{ kg}$.

The derived catch-at-weight data of Pacific cod landed in Muroran (trawl), Esan (long-line) and Wakinosawa (set net) are shown in Fig. 3. Individual fish weighing $7 \text{ kg}$ or more were included in a sink class ($\geq 7 \text{ kg}$). Trawl and long-line fisheries caught mainly the smallest weight class ($1–2 \text{ kg}$), whereas set net fisheries caught mainly mature fish in the $\geq 3 \text{ kg}$ weight class.

It was assumed that the selectivity for SH Pacific cod would remain unchanged for the period of the study, so the catch-at-weight data of the three fisheries were pooled and used for population estimation by WPA. The reasons for this were as follows. Fishing efforts of trawl, long-line and set net all decreased from 1995 to 2000 (Fig. 4). Fishing grounds differed slightly among fisheries but no remarkable changes in the fishing grounds of each fishery were observed (Y Ueda, pers. comm., 2000). The fishing seasons of these fisheries also did not

![Fig. 3 Yearly catch-at-weight of Pacific cod in southern Hokkaido.](image-url)
change during the period of the present study (Y Ueda, pers. comm., 2000). Therefore, the annual effort composition among the three fisheries changed very little.

The total catch of the SH Pacific cod was obtained from published fishery statistics (Aomori Prefecture, unpubl. data, 2002). It was assumed that the weight compositions of the three ports represented the weight composition of the fish caught in the fishing area of SH Pacific cod defined in Fig. 1, because the total yield of the three ports was 1607 t in 2000 and was 50% of the total yield of the fishing area of SH Pacific cod.

Growth curve and growth variability

Von Bertalanffy’s growth curve was used for Pacific cod caught in southern Hokkaido,

\[ l_t = 96.6 \left[ 1 - e^{-0.259(t + 0.087)} \right] \]  
(8)

where \( l \) is body length in cm and \( t \) is age in years. From equation 8, the relationship between \( l_{t+1} \) and \( l_t \) is

\[ l_{t+1} = 0.772 l_t + 22.042 \]  
(9)

Both samples used for the growth curve and the length–weight relationship belonged to SH stock. The relationship between \( l \) and weight (\( w \), kg) was derived as follows:

\[ w = 5.67 \times 10^{-5} l^{2.624} \]  
(10)

This relationship was derived from 101 Pacific cod individuals landed at Wakinosawa, Sai and Taira-date fishing ports in the Mutsu Bay area from December 1995 to February 1996.

The relationship between body weight belonging to a weight class and its standard deviation was investigated. The standard deviation was calculated as follows. Observed body length data were classified into length classes of 54.1–63.1 cm, 63.1–70.4 cm, 70.4–76.7 cm and 76.7–82.2 cm. These length classes corresponded to weight classes of 2–3 kg, 3–4 kg, 4–5 kg and 5–6 kg from the following equation, which was derived from equation 10:

\[ l = \left( \frac{w}{5.67 \times 10^{-5}} \right)^{1.624} \]  
(11)

For each length class, the standard deviation of observed body weights was calculated. Standard deviations for the weight classes 1–2 kg, 6–7 kg and ≥7 kg could not be calculated because each sample size was either one or zero. A linear relationship was found between the midpoint of weight class \( i \) (\( w_i \)) and its standard deviation (\( \sigma_{wi} \)) (Fig. 5):

\[ \sigma_{wi} = 0.161 w_i \]  
(12)

Weight transition probability

It was assumed that the probability that the weight of fish in the previous year in weight class \( k \) (\( p_k \)) was represented by a normal distribution with average weight \( w_i \) and standard deviation \( \sigma_{wi} \):

\[ p_k = \int_{w^l_k}^{w^u_k} \frac{1}{\sqrt{2\pi\sigma_{wi}^2}} e^{-\frac{(x-w_i)^2}{2\sigma_{wi}^2}} dx \]  
(13)

where \( w^l_k \) and \( w^u_k \) are the upper and lower limits of weight, respectively, for individuals of weight class \( k \).

The backward weight transition probability (\( P_{ki} \)) was defined as the probability that a fish would grow from weight class \( k \) to \( i \) in 1 year. The body weight of individuals of weight class \( i \) was assumed to be \( w_i \), which was the midpoint of the class \( i \). This assumption was also used by Sullivan et al. Using this assumption, the probability \( P_{ki} \) was calculated
using equation 13. \(w'_i\) was derived from the relationship between \(w_i\) and \(w'_i\), which was derived from equations 9 and 10 after replacing \(w_t\) with \(w_i\) and \(w_t-1\) with \(w'_i\):

\[
w_{t-1} = 5.67 \times 10^{-5} \left\{ \frac{1.295}{5.67 \times 10^{-5}} \left[ \frac{w_t}{5.67 \times 10^{-5}} \right]^{1.2624} - 28.552 \right\}
\]

(14)

\[
w'_i = 5.67 \times 10^{-5} \left\{ \frac{1.295}{5.67 \times 10^{-5}} \left[ \frac{w_i}{5.67 \times 10^{-5}} \right]^{1.2624} - 28.552 \right\}
\]

(15)

\(\sigma_{w'}\) was derived from equation 12. The parameters used to calculate the probability \(P_{k,i}\) are shown in Table 1.

Table 1 shows the backward weight transition probabilities in three cases. The first case is that the coefficient of variation (\(v\)) is 0.161, as shown in equation 12. The last two are given to examine the sensitivity when \(v\) is changed to 0.061 or 0.261.

Because of the absence of smaller weight classes from the probabilities, the sum of the probabilities in a row might not be 1. The weight class interval was set at 1 kg and the number of weight classes was seven.

**Natural mortality**

The natural mortality coefficient (\(M\)) was set at 0.2/year from the mean water temperature experi-
enced by Pacific cod in southern Hokkaido and from Pauly's equation.20

Weight-based virtual population analysis

The population size of SH Pacific cod from 1994 to 2000 was estimated, where the size was the number of individual fish weighing 1 kg or more. To derive estimates, the sum of the square residual between the observed catch in numbers and the corresponding WPA estimate was minimized using non-linear optimization. Estimates were the population size ($N$), fishing mortality at full-recruitment ($f$) and selectivity ($s$). Fishing mortality was calculated from the following equation:

$$\hat{N}_{ij} = \hat{f}_j \hat{s}_i$$  \hspace{1cm} (16)

where $j$ is the year. The detailed procedures for WPA are described in Ueda et al.5 Calculations were carried out using FORTRAN on a personal computer (Compaq Fortran, standard edition v6.5; Compaq Computer Corporation, Houston, TX, USA).

From the number of individuals $\hat{N}_{ij}$ estimated by WPA, the corresponding biomass $\hat{B}_{ij}$ was calculated from the following equation:

$$\hat{B}_{ij} = \hat{N}_{ij} w_i$$  \hspace{1cm} (17)

RESULTS AND DISCUSSION

The observed catch, corresponding estimates, population size, fishing intensity, selectivity and fishing mortality of the SH Pacific cod are shown in Table 3.

Estimated biomass

The biomass of SH Pacific cod weighing more than 1 kg was estimated to be 5607 t in 1994, increasing to 7908 t in 2000, when $v = 0.161$ (Fig. 6). The biomass of adult cod (>3 kg) varied slightly, between 3666 t in 1998 and 3127 t in 2000. This suggests that the increase in total biomass depends on the biomass of the young cod (1–2 kg weight class). The biomass of the young cod after 1998 increased

Table 3 The observed catch and estimates of population size, fishing mortality, fishing mortality at full-recruitment and selectivity of Pacific cod in southern Hokkaido, Japan

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Catch ($n$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1–2</td>
<td></td>
<td>310 064</td>
<td>174 313</td>
<td>302 441</td>
<td>243 055</td>
<td>550 598</td>
<td>716 483</td>
<td>972 533</td>
<td></td>
</tr>
<tr>
<td>2–3</td>
<td></td>
<td>101 741</td>
<td>115 203</td>
<td>219 821</td>
<td>111 737</td>
<td>114 666</td>
<td>211 804</td>
<td>167 706</td>
<td></td>
</tr>
<tr>
<td>3–4</td>
<td></td>
<td>96 683</td>
<td>107 009</td>
<td>70 365</td>
<td>105 835</td>
<td>74 566</td>
<td>162 199</td>
<td>104 920</td>
<td></td>
</tr>
<tr>
<td>4–5</td>
<td></td>
<td>56 429</td>
<td>59 782</td>
<td>31 337</td>
<td>38 587</td>
<td>55 744</td>
<td>70 995</td>
<td>66 108</td>
<td></td>
</tr>
<tr>
<td>5–6</td>
<td></td>
<td>25 461</td>
<td>27 645</td>
<td>13 628</td>
<td>15 933</td>
<td>27 234</td>
<td>25 242</td>
<td>33 041</td>
<td></td>
</tr>
<tr>
<td>6–7</td>
<td></td>
<td>10 192</td>
<td>12 089</td>
<td>9 840</td>
<td>8 254</td>
<td>11 717</td>
<td>9 933</td>
<td>15 355</td>
<td></td>
</tr>
<tr>
<td>≥7</td>
<td></td>
<td>10 958</td>
<td>14 873</td>
<td>13 588</td>
<td>15 757</td>
<td>15 821</td>
<td>13 877</td>
<td>20 677</td>
<td></td>
</tr>
<tr>
<td>Population size ($n$)</td>
<td></td>
<td>869 091</td>
<td>829 153</td>
<td>962 726</td>
<td>981 081</td>
<td>1 339 121</td>
<td>1 440 943</td>
<td>2 314 622</td>
<td></td>
</tr>
<tr>
<td>1–2</td>
<td></td>
<td>418 197</td>
<td>415 486</td>
<td>471 544</td>
<td>471 153</td>
<td>547 679</td>
<td>602 822</td>
<td>523 692</td>
<td></td>
</tr>
<tr>
<td>2–3</td>
<td></td>
<td>266 985</td>
<td>257 803</td>
<td>290 395</td>
<td>297 240</td>
<td>322 586</td>
<td>324 898</td>
<td>313 744</td>
<td></td>
</tr>
<tr>
<td>3–4</td>
<td></td>
<td>186 971</td>
<td>174 957</td>
<td>191 623</td>
<td>195 798</td>
<td>219 532</td>
<td>198 742</td>
<td>175 563</td>
<td></td>
</tr>
<tr>
<td>4–5</td>
<td></td>
<td>125 451</td>
<td>112 980</td>
<td>122 086</td>
<td>115 925</td>
<td>136 701</td>
<td>124 433</td>
<td>85 120</td>
<td></td>
</tr>
<tr>
<td>5–6</td>
<td></td>
<td>78 866</td>
<td>64 698</td>
<td>76 190</td>
<td>61 870</td>
<td>67 112</td>
<td>74 849</td>
<td>50 780</td>
<td></td>
</tr>
<tr>
<td>≥7</td>
<td></td>
<td>37 202</td>
<td>73 133</td>
<td>48 150</td>
<td>73 038</td>
<td>48 133</td>
<td>33 218</td>
<td>58 741</td>
<td></td>
</tr>
<tr>
<td>Fishing mortality (per year)</td>
<td></td>
<td>0.492</td>
<td>0.319</td>
<td>0.467</td>
<td>0.341</td>
<td>0.563</td>
<td>0.769</td>
<td>0.615</td>
<td></td>
</tr>
<tr>
<td>1–2</td>
<td></td>
<td>0.346</td>
<td>0.225</td>
<td>0.329</td>
<td>0.240</td>
<td>0.396</td>
<td>0.541</td>
<td>0.432</td>
<td></td>
</tr>
<tr>
<td>2–3</td>
<td></td>
<td>0.365</td>
<td>0.237</td>
<td>0.347</td>
<td>0.253</td>
<td>0.418</td>
<td>0.571</td>
<td>0.456</td>
<td></td>
</tr>
<tr>
<td>3–4</td>
<td></td>
<td>0.425</td>
<td>0.276</td>
<td>0.404</td>
<td>0.295</td>
<td>0.487</td>
<td>0.664</td>
<td>0.531</td>
<td></td>
</tr>
<tr>
<td>4–5</td>
<td></td>
<td>0.443</td>
<td>0.287</td>
<td>0.420</td>
<td>0.306</td>
<td>0.506</td>
<td>0.691</td>
<td>0.533</td>
<td></td>
</tr>
<tr>
<td>5–6</td>
<td></td>
<td>0.323</td>
<td>0.209</td>
<td>0.306</td>
<td>0.223</td>
<td>0.369</td>
<td>0.504</td>
<td>0.403</td>
<td></td>
</tr>
<tr>
<td>6–7</td>
<td></td>
<td>0.390</td>
<td>0.253</td>
<td>0.370</td>
<td>0.270</td>
<td>0.446</td>
<td>0.609</td>
<td>0.487</td>
<td></td>
</tr>
<tr>
<td>≥7</td>
<td></td>
<td>0.492</td>
<td>0.319</td>
<td>0.467</td>
<td>0.341</td>
<td>0.563</td>
<td>0.769</td>
<td>0.615</td>
<td></td>
</tr>
</tbody>
</table>

Fishing mortality at full-recruitment (per year)

A plausible explanation for the increase in recruitment to the 1–2 kg weight class could be changes in environmental factors. On the Pacific coast of Tohoku, the catch per unit effort increased after 1997, especially in the Shiriyasaki trawl fishing area, adjacent to southern Hokkaido, which is the most northerly fishing ground of the Pacific coast of Tohoku, where the catch per unit effort increased after 1998.21 On the Pacific coast of Tohoku, the catch of Pacific cod fluctuates over a cycle of 11 years21 and correlates to the southern limit of waters with a water temperature of 8°C at a depth of 100 m with a lag of 2 years.22 This suggests that the fluctuation in biomass of Pacific cod is related to environmental factors, not only on the Pacific coast of Tohoku, but also in southern Hokkaido.

Sensitivity analysis on growth variability

The estimated biomasses were compared using three ν-values of growth variability. The maximum difference among the estimated biomasses was 1131 t in 1995 between ν = 0.061 and ν = 0.261, and this was 18.2% of the biomass estimate for ν = 0.061 (Fig. 7). The differences were not large from 1994 to 2000. Trends of yearly biomass estimates for ν = 0.061 and ν = 0.161 were nearly the same.

There were no large differences between biomass estimates for the three ν-values (Fig. 7). The weight transition probability with ν = 0.061 represents almost deterministic weight growth (Table 1). These results might suggest that rough assumption of deterministic weight growth (ν = 0) also enables WPA to estimate the yearly trend of biomass. Conversely, especially for large weight classes, the weight growth increments were not 1 kg/year. Although a short period, comprising only 7 years of biomasses, was estimated in this paper, the accumulated data of yearly estimated biomass will enable discussion of the stock-recruitment relationship of the SH Pacific cod in a few years. For North Sea cod Gadus morhua, the rate at which fish mature is size dependent.23 If this corresponds to SH Pacific cod, WPA is suitable for estimating spawning stock biomass.
Model fitting

Figure 8 shows the observed and estimated catch-at-weight from 1994 to 2000. The values of the correlation coefficient were between 0.897 \((P < 0.05; 1995)\) and 0.997 \((P < 0.001; 1999)\). Weight-based virtual population analysis showed a good match with actual catches in almost all years. The correlation coefficients were calculated except for in the largest weight class \((\geq 7 \text{ kg})\) and in the most recent year \((2000)\) because the observed and estimated catch-at-weight for this weight class and year have the same value in the WPA procedure.5

Estimated selectivity and fishing mortality

The estimated selectivity was highest in the 1–2 kg weight class, and was lowest in the 6–7 kg weight class at 0.655 when the selectivity of the 1–2 kg weight class was standardized at 1 (Table 3). In southern Hokkaido, the target species of the trawl fishery is walleye pollock \(Theragra chalcogramma\). The age at full-recruitment for walleye pollock is 5 years in southern Hokkaido.24 The corresponding body weight is 0.52 kg.24 If this size corresponds to SH Pacific cod, not all individuals weighing less than 1 kg were fully recruited. The highest selectivity in the 1–2 kg weight class suggested that a body weight of 1–2 kg was the full-recruitment size for Pacific cod in southern Hokkaido.

The fishing mortality at full-recruitment was lowest in 1995 at 0.319 and highest in 1999 at 0.769 (Table 3). Fishing mortalities in recent years have tended to be larger than those in previous years, whereas fishing efforts have tended to decrease in recent years (Fig. 4). The reason for this might be that the increment of biomass is the cause of the increment in the fishing efficiency.

Retrospective analysis

A retrospective analysis for Pacific cod caught in southern Hokkaido was carried out. Three periods were analyzed: use of catch data during 1994–2000, 1994–1999 and 1994–1998 (Fig. 9). In the case of 1994–1999, the estimated biomass was smaller than the estimates of 1994–2000 in all years. In 1999, the biomass for 1994–1999 was 5595 t, which
was 21% smaller than the estimate for 1994–2000. An upward tendency was represented in both biomass estimates. In the case of 1994–1998, a downward tendency was represented. In 1998, the biomass for 1994–1998 was 3219 t, which was 54% smaller than the estimates for 1994–2000. Although the estimated biomass in 2000 could include errors, it is difficult to conclude that the biomass was over or underestimated from this analysis.

### Potential of weight-based virtual population analysis

Weight-based virtual population analysis was used in the present study to estimate the population size of Pacific cod off the Pacific coast of southern Hokkaido, Japan. Generally, body weight changes seasonally and varies between individuals of the same age, so the body weight of fish is less robust than age in estimating population size. The disadvantage of using weight for WPA can be overcome because the sample size of weight measurement is often much larger than that of age determination.

Ueda investigated the precision of the estimated population size in numbers by WPA from the above viewpoint. Weight-based virtual population analysis and VPA were applied to a simulated stock. The simulated stock included yearly fluctuations of growth, natural mortality, recruitment, fishing mortality and selectivity. The result was that when more than 20% of landed fish were weighed, the precision of WPA was similar to that of VPA. Stock fluctuations can be affected by factors that cannot be simulated (e.g., environmental factors). Ueda et al., who compared the estimate of WPA to that of VPA, showed that estimates of walleye pollock stock in southern Hokkaido were similar.

In the present study, catch-at-weight was derived from slips supplied from three main fishing ports. The catch at these fishing ports was 1949 t, which was 61% of the total catch in southeastern Hokkaido in 2000, so more than 20% of the total quantity of landed fish was measured, and the catch-at-weight was derived. Because of this, it was concluded that WPA is suited to estimating the biomass of Pacific cod in southern Hokkaido. Instead of using WPA, using a weight-age-key to transform catch-at-weight to catch-at-age might enable estimation of biomass using VPA. What cases are suitable for using WPA or VPA? This new subject will be investigated further in the future.

### ACKNOWLEDGMENTS

We thank the staff of Muroran Trawl Fisheries Cooperative Association and the Esan, Wakinosawa and Sai Fisheries Cooperative Association for allowing access to landing records. We also sincerely thank Dr Kunio Shirakihara and the two anonymous reviewers for many useful comments and suggestions. This paper was revised at Tohoku National Fisheries Research Institute, Hachinohe and we thank the staff there. This study was supported by Grants-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture of Japan, and from Aomori Prefecture.

### REFERENCES


