Hatching date, nursery grounds, and early growth of juvenile walleye pollock (*Theragra chalcogramma*) off northern Japan*

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Walleye pollock (*Theragra chalcogramma*) is widely distributed in the North Pacific Ocean and plays an important role in coastal subarctic ecosystems. The Japanese Pacific population of this species is one of the most important demersal fishes for commercial fisheries in northern Japan. The population is distributed along the Pacific coast of Hokkaido and the Tohoku area (Fig. 1), which is the southern limit of distribution of the species in the western North Pacific. In Funka Bay, the main spawning ground for this population, pollock spawn from December to March (Kendall and Nakatani, 1992). Planktonic eggs and larvae are transported into the bay, where juveniles usually remain until late July when they reach 60–85 mm in total length (Hayashi et al., 1968; Nakatani and Maeda, 1987). These juvenile pollock then migrate from Funka Bay eastward to the Doto area off southeastern Hokkaido (Honda et al., 2004). Many studies on eggs, larvae, and juveniles of the species have been conducted in or near Funka Bay, but little information is available on the ecology of the early life stages in the Tohoku area. Hashimoto and Ishito (1991) suggested that eggs are transported from Funka Bay southward to the Tohoku area by the coastal branch of the Oyashio Current, but there has been no study to verify this hypothesis.

The aim of the present study was to examine, by using otolith daily growth ring analysis, regional differences in hatching date, body size, and early growth of juvenile pollock in Funka Bay and the Tohoku area and to elucidate the importance of Tohoku area as a nursery ground for the Japanese Pacific population of pollock.

Materials and methods

The present study was carried out from Funka Bay to the Tohoku area. We divided the study area into four regions, Funka Bay, east of Tsugaru Strait, northern Tohoku, and southern Tohoku (Fig. 1). East of Tsugaru Strait region is located between Funka Bay and the Tohoku area. Sampling was done at a total of 54 stations mostly in late May during three years, from 1999 to 2001: 10 for 1999, 23 for 2000, and 21 for 2001 (Table 1). In Funka Bay, sampling stations were set up only at the bay mouth area because there was a lot of fishing gear inside the bay. Pollock juveniles were collected with a midwater trawl (NST-92-K1, Nichimo Co., Ltd., Shinagawa, Tokyo) onboard the RV *Wakataka Maru* of the Tohoku National Fisheries Research Institute (TNFRI).

The midwater trawl, which had a round mouth opening with a diameter of about 20 m, was towed only during the day. The overall length of the net was 98.3 m and it had a variable-size mesh of 14 m (stretched) in the forward section to 3 mm (square mesh) at the codend. All tows were made at an average ship speed of 4 knots. The horizontal tows were carried out in 1999, whereas the double oblique tows were made from the surface to near the bottom (10–20 m above the bottom) in 2000–2001. The sampling biases of the net were not investigated, but biases may have been neglible for two reasons. First, our net had a larger mouth opening than that of the Methot trawl (5 m^2) used for collecting late larval and early juvenile stages of walleye pollock (Brodeur et al., 1995). Second, we could sample juveniles that hatched from mid-December to mid-April in our survey and the juveniles were thought to be from eggs that spawned throughout the whole spawning season (December to March) in Funka Bay.

Pollock juveniles were sorted from the codend samples and preserved in 95% ethanol diluted with seawater for otolith daily-growth analysis. Total length (TL) of some pollock was measured to the nearest 0.1 mm on board the vessel, whereas the same length of preserved fish was similarly measured in the laboratory. The following formula was used to change TL of preserved fish to TL of fresh fish:

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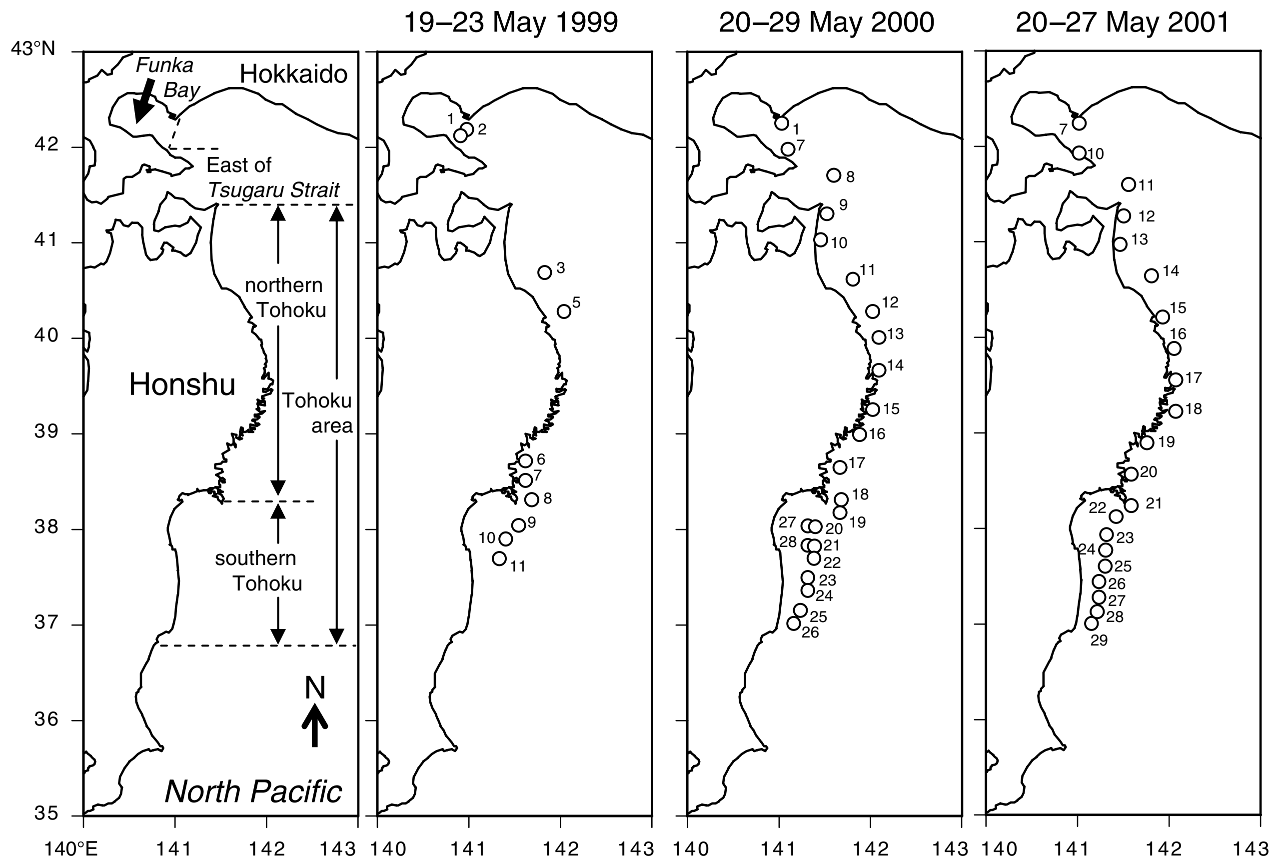

Figure 1

Sampling stations (open circles) for walleye pollock (*Theragra chalcogramma*) caught with a midwater trawl net in four regions off the Pacific coast of northern Japan in May 1999–2001. Arabic numerals indicate station numbers (see Table 1).

$$TL\ of\ fresh\ fish = 1.0126(TL\ of\ preserved\ fish) + 1.7934\ [n=97,\ r^2=0.974].$$

To study the daily otolith increment of our sample, we employed the methods established by Nishimura and Yamada (1984), Bailey and Stehr (1988), Yoklavich and Bailey (1990) and Bailey et al. (1996). Sagittal otoliths, hereafter called "otoliths," from the juveniles were embedded in epoxy resin on glass slides and ground with carbon paper (no. 800–1200) perpendicularly to the otolith flat plane along the long axis (frontal section). Polished otoliths were selected if they included the otolith nucleus on the ground surface and were thin enough to transmit light under a light microscope. Then 1171 specimens were polished with lapping film, cleaned, and observed. Early narrow increments were counted under 600× or 1000× magnification. As the increments increased in width, the magnification was changed to 400×. Hatching date was estimated by subtracting the number of increments from the sampling date.

Daily growth-ring diameter is the index of body length at an age because a significant linear relationship exists between log-transformed body length and otolith length data for pollock juveniles (Nishimura and Yamada, 1988). In the present study, we measured the short otolith radius (SOR) along the long axis obtained from a frontal section and used the SOR from the nucleus to the 30th ring (SOR 30) as the index of early growth. SOR 30 was measured for the specimens collected in 2000, by using the otolith daily growth ring analyzing system (Ratoc System Engineering Co., Ltd., Shinjuku, Tokyo). The Mann-Whitney *U*-test was used to identify differences in SOR 30 groups. We were not able to use analysis of covariance (ANCOVA) because an interaction was found by analysis of variance (ANOVA) in size-at-age relationships among regions in 2000 ($P<0.0001$) and 2001 ($P=0.035$). Comparisons of specific growth rate (SGR) for the juveniles were made between our regions by the Mann-Whitney *U*-test or ANOVA. Comparisons of means were made using Scheffe's test. SGR values of individual fish were calculated by using the following formula (Ricker, 1979):

$$SGR = \frac{(\ln L_2 - \ln L_1)\times 100}{t_2 - t_1},$$

Table 1

Summary of midwater trawl surveys in May of 1999–2001. SST=sea surface temperature, OB= oblique tow, HZ=horizontal tow.

Station no.	Sampling date	Depth (m)	SST (°C)	Towing time (min)	Method	Number of fish	CPUE (fish/h)
1	19 May 1999	69	7.2	63	HZ	6	5.7
2	19 May 1999	69	7.2	70	HZ	129	110.6
3	21 May 1999	99	10.6	72	HZ	4	3.3
5	21 May 1999	108	10.7	84	HZ	19	13.6
6	23 May 1999	97	11.2	88	HZ	0	0
7	23 May 1999	124	11.8	74	HZ	0	0
8	23 May 1999	136	11.6	93	HZ	0	0
9	22 May 1999	106	14.7	98	HZ	0	0
10	22 May 1999	102	16.4	84	HZ	0	0
11	22 May 1999	100	17.1	49	HZ	0	0
1	20 May 2000	84	8.4	45	OB	730	973.3
7	21 May 2000	101	8.3	57	OB	173	182.1
8	21 May 2000	111	9.6	48	OB	399	498.8
9	21 May 2000	90	10.1	42	OB	0	0
10	22 May 2000	123	10.8	50	OB	6	7.2
11	22 May 2000	111	9.2	51	OB	17	20.0
12	22 May 2000	107	10.9	54	OB	69	76.7
13	25 May 2000	121	11.3	62	OB	90	87.1
14	25 May 2000	151	10.9	48	OB	14	17.5
15	25 May 2000	138	10.9	43	OB	163	227.4
16	26 May 2000	122	11.0	49	OB	57	69.8
17	26 May 2000	133	13.1	48	OB	81	101.3
18	26 May 2000	143	13.7	51	OB	24	28.2
19	26 May 2000	121	14.3	51	OB	22	25.9
20	27 May 2000	104	12.5	48	OB	62	77.5
21	27 May 2000	122	13.7	48	OB	37	46.3
22	27 May 2000	130	12.8	57	OB	29	30.5
23	27 May 2000	97	12.5	44	OB	37	50.5
24	27 May 2000	105	12.9	51	OB	11	12.9
25	28 May 2000	77	9.7	60	OB	11	11.0
26	28 May 2000	102	9.9	50	OB	35	42.0
27	29 May 2000	69	13.3	47	OB	144	183.8
28	29 May 2000	82	12.6	45	OB	15	20.0
7	20 May 2001	71	10.2	55	OB	51	55.6
10	20 May 2001	103	7.6	39	OB	2371	3647.7
11	22 May 2001	117	10.4	48	OB	1	1.3
12	22 May 2001	90	11.0	40	OB	0	0
13	22 May 2001	176	10.5	48	OB	10	12.5
14	23 May 2001	109	10.3	51	OB	11	12.9
15	23 May 2001	104	10.6	52	OB	106	122.3
16	23 May 2001	120	13.1	45	OB	117	156.0
17	24 May 2001	141	11.7	60	OB	19	19.0
18	24 May 2001	147	11.5	44	OB	6	8.2
19	24 May 2001	108	10.7	23	OB	2	5.2
20	25 May 2001	130	10.5	31	OB	0	0
21	25 May 2001	115	11.2	23	OB	2	5.2
22	25 May 2001	112	11.6	45	OB	1	1.3
23	25 May 2001	104	12.0	22	OB	0	0
24	26 May 2001	120	13.4	42	OB	0	0
25	26 May 2001	125	12.0	57	OB	0	0
26	26 May 2001	97	12.1	35	OB	0	0
27	27 May 2001	106	15.7	35	OB	0	0
28	27 May 2001	100	19.1	52	OB	0	0
29	27 May 2001	103	19.6	21	OB	0	0

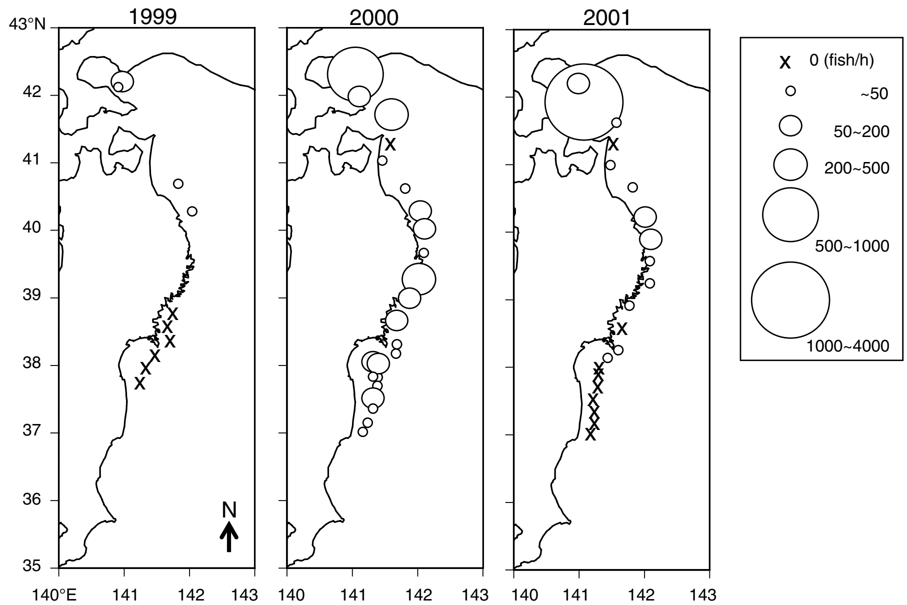

Figure 2

Distribution of catch per unit of effort (CPUE) (fish/hour) for walleye pollock (*Theragra chalcogramma*) caught with a midwater trawl net in May 1999–2001 off the Pacific coast of northern Japan.

where L_2 and L_1 = body length at time t_2 and t_1, respectively.

In this study, we defined L_1 = 4.6 mm at hatching (t_1=0) according to Nishimura and Yamada (1988) and L_2= TL of fish at the number of otolith increments (t_2). All tests were evaluated for significance at the P=0.05 level.

Results and discussion

Distribution of juveniles

In 1999, juvenile pollock were collected only from Funka Bay to northern Tohoku, but no fish were sampled in southern Tohoku (Fig. 2). In 2000, juvenile pollock were caught in abundance at almost all sampling stations: highest catch per unit of effort (CPUE) was recorded at a station in Funka Bay (973 fish/h) and many juveniles were found in northern and southern Tohoku (max: 227 and 184 fish/h, respectively). In 2001, the juvenile distribution was similar to that in the previous year, but few juveniles were caught in southern Tohoku. These results show interannual variability in the distribution of juvenile walleye pollock between 1999 and 2001.

Inada and Murakami (1993) suggested that the pollock catch and distribution in the Tohoku area are strongly affected by the coastal branch of the Oyashio Current but little information is available on the relationship between oceanographic conditions and juvenile distribution and abundance in this area. The southern limit of the coastal branch characterized by the position of 5°C at 100 m depth has been regarded as an index to show the strength of the current (Ogawa, 1989). Thus we examined annual changes in the position of southern limit of the coastal branch based on water temperature data (TNFRI[1]). In April, the coastal branch of the Oyashio Current mostly stagnated in northern Tohoku in 1999 and 2001 but there were some annual variations, but it went far south to southern Tohoku in 2000 (Fig. 3A). It is likely that the juvenile distribution in May of the three years from 1999 to 2001 is associated with the southern limit position of the coastal branch of the Oyashio Current in April. Kitagawa et al.[2] reported the recruitment index of age-0 pollock based on bottom trawl surveys in the Tohoku area. We compared the recruitment index (X, $\times 10^3$ fish) given by Kitagawa et al.[2] with the latitude of the southern limit of the coastal branch of the Oyashio Current (Y) and, as a result, a significant relationship was observed in the 1995–2001 data (Y=46.653X$^{-0.019}$, r^2=0.960, Fig. 3B). This result may indicate that abundant recruitment is brought by

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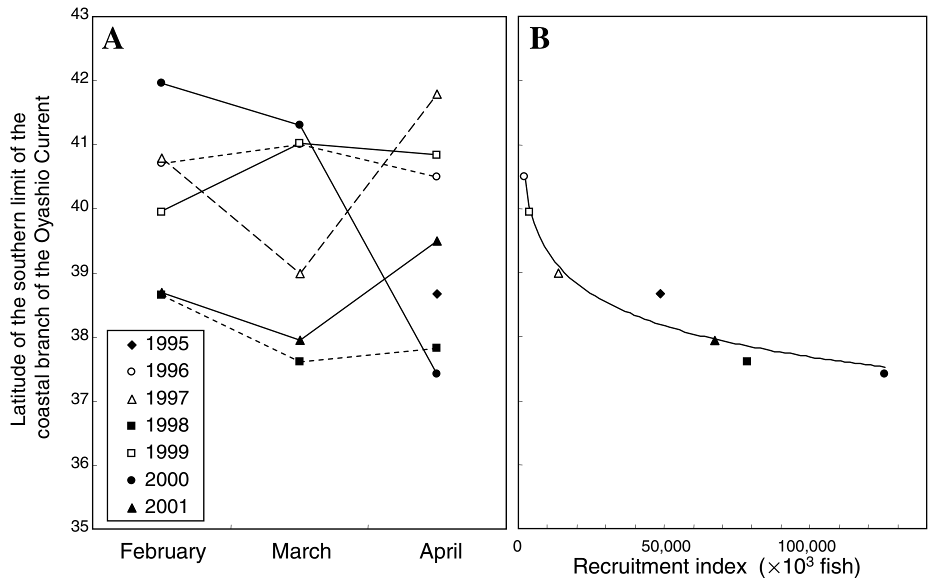

Figure 3

Monthly change in the latitude of the southern limit of the coastal branch of the Oyashio Current (**A**), and the relationship between recruitment index of age-0 walleye pollock (*Theragra chalcogramma*) in the Tohoku area and the latitude of the southern limit of the coastal branch of the Oyashio Current (**B**). This figure is drawn according to the water temperature data from the Fisheries Oceanography Division of the Tohoku National Fisheries Research Institute (TNFRI) (see text). The data on the recruitment index are from Kitagawa et al.[2] (see general text).

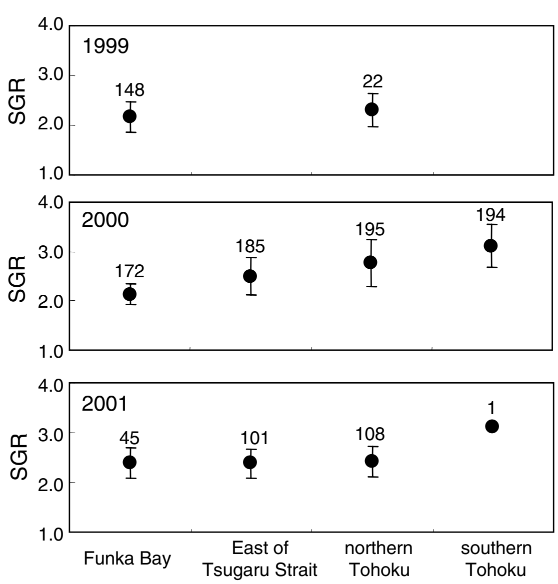

Figure 4

Specific growth rate (SGR) for walleye pollock (*Theragra chalcogramma*) from four regions off the Pacific coast of northern Japan in 1999–2001. Vertical bars indicate standard deviation and arabic numerals indicate number of samples.

a strong coastal branch of the Oyashio Current in the Tohoku area.

Early growth of walleye pollock

There was no difference in SGR between Funka Bay and northern Tohoku in 1999 (U-test, P=0.111, Fig. 4). Also, no regional differences were found among all regions in 2001 (ANOVA, P=0.526). For 2000, however, there were significant differences in SGR among all four regions (ANOVA, $P<0.0001$) and even between all pairs (Scheffe's test, $P<0.0001$).

In 2000, the SOR 30 values ranged from 30–58 μm for the juveniles collected in Funka Bay and east of Tsugaru Strait (Fig. 5). However, two different SOR 30 groups were found for the samples from northern and southern Tohoku (U-test, $P<0.0001$): one with SOR 30 values ranging from 30–60 μm and the other with values greater than 68 μm. Fish of the former group (low-growth group) had the same SOR 30 range as those from Funka Bay and east of Tsugaru Strait. The latter group (high-growth group) was observed only in the Tohoku area. Positive linear regressions were found in size-at-age relationships for low- and high-growth groups ($P<0.0001$, Fig. 6) and the difference of the SGR was significant between these two groups (U-test, $P<0.0001$).

These results indicate that the surveys of juvenile walleye pollock in May 2000 caught two growth groups:

the low-growth group that probably spawned in Funka Bay mixed with the high-growth group that was probably produced locally in the Tohoku area. This mixing of the two groups could have occurred primarily because of either advection or migration. Assuming that this interpretation is correct, it would be important for local fisheries managers to take account of these variations especially if the years of extra production from the Tohoku area expand the exploitable stock.

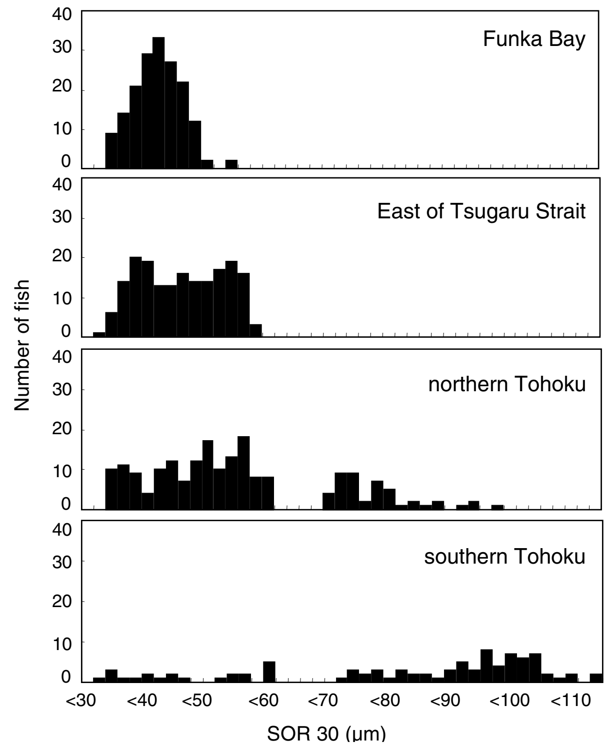

Figure 5

Frequency distribution of the short otolith radius from the nucleus to the 30th ring (SOR 30) for walleye pollock (*Theragra chalcogramma*) collected in four regions off the Pacific coast of northern Japan in 2000.

Length-frequency distribution and hatching date

The length-frequency distribution and hatching date composition for juvenile pollock among regions were similar in 1999 and 2001 but were different in 2000 (Figs. 7 and 8). In 2000, large fish over 40 mm TL, designated as forming part of the low-growth group, constituted the majority of the samples from Funka Bay, and much smaller fish of the same group (<40 mm TL) were widely distributed in waters from east of Tsugaru Strait to southern Tohoku. All juveniles from Funka Bay were categorized as low-growth group fish that hatched between late December and late February, and juveniles of the low-growth group that hatched after March 1 were caught widely from east of Tsugaru Strait to southern Tohoku in 2000. These results appear to indicate that late hatching fish originating from Funka Bay were transported to the Tohoku area by the strong coastal branch of the Oyashio Current after March 2000.

Nakatani and Sugimoto[3] showed that only fish hatching in January and February survived in Funka Bay in summer, whereas pollock usually spawn between December and March. Nakatani (1998) thus assumed that late hatching fish (after early March) would not be able to consume enough food during their settlement stage because the abundance of copepodids of *Pseudocalanus* spp., the main food for juveniles below 30 mm TL, decreases in late May and because late hatching fish cannot eat *Neocalanus plumchrus* due to its large size. Therefore, he suggested that there are two critical periods for walleye pollock during their early larval and settlement stages in Funka Bay. Considering these results, we suggest that when late hatching fish were transported to the Tohoku area, their survival rates were higher than those of juveniles that remained in Funka Bay.

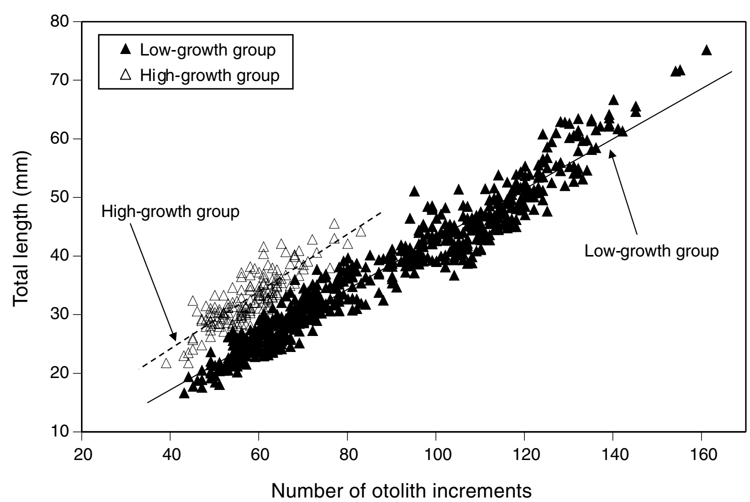

Figure 6

Size-at-age relationship for two growth groups of walleye pollock (*Theragra chalcogramma*) collected in 2000. Low- and high-growth groups were divided according to the SOR 30 distribution (see text and Fig. 5). The regression lines for each growth group are as follows: low-growth group: $TL=0.017+0.429\times age$ [$r^2=0.941$, $n=594$, $P<0.0001$]; high-growth group: $TL=4.694+0.486\times age$ [$r^2=0.715$, $n=152$, $P<0.0001$].

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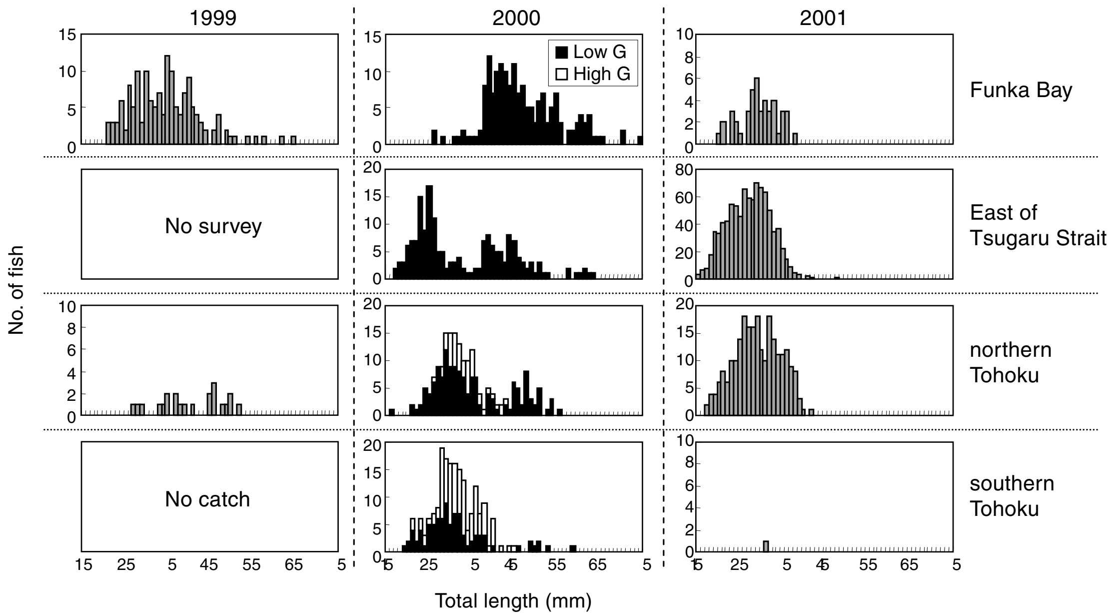

Figure 7

Total length-frequency distribution for walleye pollock (*Theragra chalcogramma*) from four regions off the Pacific coast of northern Japan in 1999–2001. Low G=low-growth group (solid bars); high G=high-growth group (open bars).

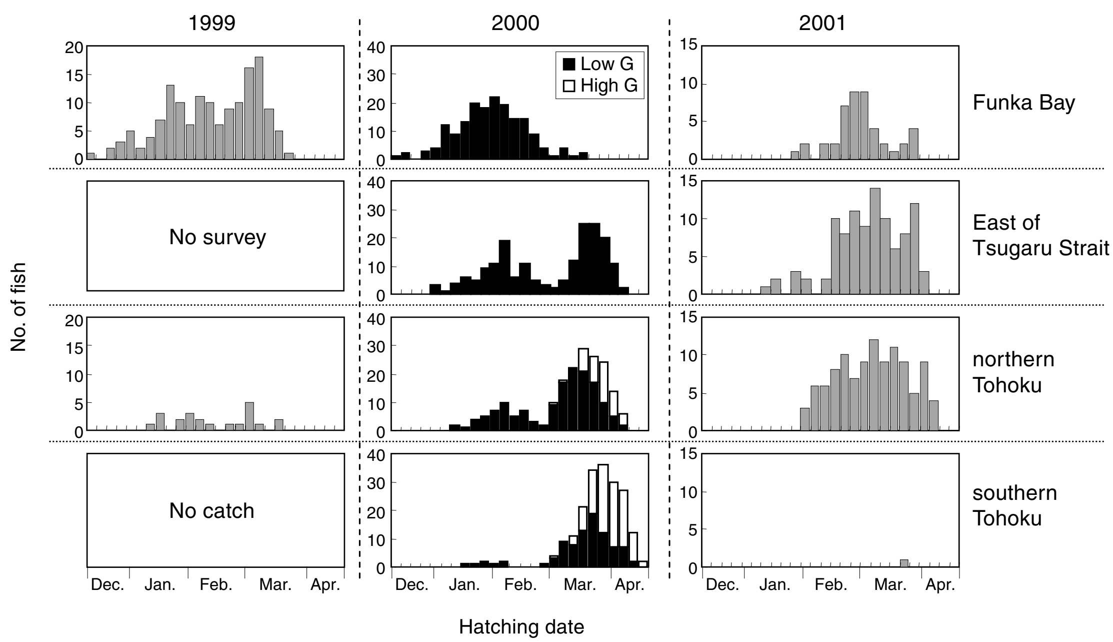

Figure 8

Hatching date composition for walleye pollock (*Theragra chalcogramma*) from four regions off the Pacific coast of northern Japan in 1999–2001. Low G=low-growth group (solid bars), high G=high-growth group (open bars).

We suggest that, in addition to the recruitment process in Funka Bay, an important recruitment process occasionally exists in the Tohoku area, and when the year-class strength of the Japanese Pacific population of pollock is strong, as in 2000 (Yabuki[4]), the Tohoku area becomes important as a nursery ground for the late hatching fish originating from Funka Bay.

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