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ORIGINAL ARTICLE

Fisheries

Fishery characteristics of barfin flounder *Verasper moseri* in southern Tohoku, the major spawning ground, after the start of large-scale stock enhancement in Hokkaido, Japan

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Abstract Commercial landings of a rare pleuronectid flatfish, barfin flounder *Verasper moseri*, recovered drastically after large-scale stock enhancement in Hokkaido conducted since 2006. This study investigated commercial landings, fishing grounds, size distributions, and sex and age compositions of barfin flounder during 2007–2011 in southern Tohoku, their major spawning ground, which is over 700 km south of Hokkaido. Landings, mostly comprising stocked fish, increased drastically in southern Tohoku: from 2.0 tons in 2007 to 20.8 tons in 2010. Over 98 % of them were landed during January–April, with the peak period during February–March. Fishing logbook data of offshore bottom-trawl vessels during 2007–2010 revealed the upper continental slope off southernmost Tohoku as the main fishing ground (35°40′–36°50′N, annual weighted mean depth 267–299 m). Two size modes in the landings consisted of males (ca. 40 cm) and females (ca. 60 cm). The main age at fishery recruitment in southern Tohoku was younger for males (age 2+) than for females (ages 3+ and 4+), the result of which was that the female percentage was lowest at 1.5 % in 2009 and highest at 7.9 % in 2011. Our results showed clearly how the effectiveness of large-scale stock enhancement in Hokkaido extended to southern Tohoku in association with spawning migration of stocked barfin flounder.

Keywords Commercial landings · Fukushima Prefecture · Released seedlings · Southern Tohoku · Spawning ground · Spawning migration · Stock enhancement · *Verasper moseri*

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Introduction

Barfin flounder *Verasper moseri* is a large pleuronectid flatfish distributed in cold water areas around the northwestern Pacific [1]. This flounder, growing to 80 cm standard length [2], is a commercially valuable species in Hokkaido and Tohoku areas in Japan (Fig. 1) because of its palatability and high commercial price [2–4]. Nevertheless, the wild population of barfin flounder became extremely small after the 1970s [4, 5]. Wild barfin flounder have been captured only rarely from the 1980s onward. To recover their stock condition and to augment fishery catches, barfin flounder stock enhancement programs started in Hokkaido and Iwate prefectures (Fig. 1) from 1987 [6] and 1990 [7], respectively, resulting in the gradual increase of commercial landings at each locale.

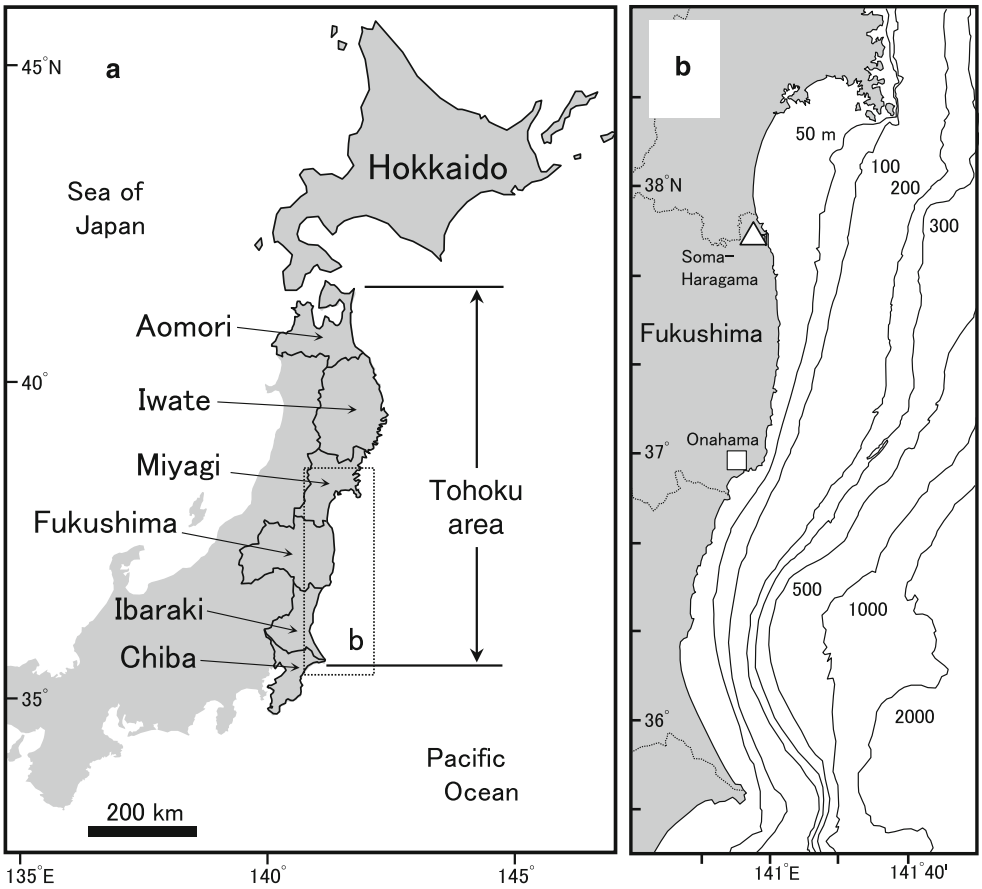

Fig. 1 Map of the study area. **a** Hokkaido and six prefectures (Aomori, Iwate, Miyagi, Fukushima, Ibaraki, and Chiba) located at the Pacific coast of eastern–northeastern Japan. Tohoku is indicated by *arrows*. **b** Map of southern Tohoku. Soma-Haragama (*open triangle*) and Onahama (*open square*) fish markets are shown in Fukushima Prefecture. *Isolines* show depth

Underpinned by refined hatchery technology for mass seedling production [8], a large-scale stock enhancement program, releasing more than one million seedlings annually, was implemented in southwestern Hokkaido since 2006 [9]. This stock enhancement activity has dramatically augmented commercial landings not only in Hokkaido, but also in Tohoku (Fig. 1), especially in southern Tohoku [9], where some tagged fish released in Hokkaido were recaptured previously [10, 11]. Recently, Kayaba et al. [9] detected that spawning grounds of stocked female barfin flounder (mainly > age 3) are formed at the upper continental slope off southernmost Tohoku during February–April. Results strongly suggest that barfin flounder migrate repeatedly over 700 km from feeding grounds off Hokkaido to spawning grounds off southern Tohoku [9]. However, increase of wild fish has not been confirmed yet [12], although spawning stocked females were detected in southern Tohoku [9]. In addition, comparison of fishery characteristics of barfin flounder in southern Tohoku before and after the large-scale stock enhancement program in Hokkaido can show clearly how and when the effects of the program extend to southern Tohoku.

Recently, Wada et al. [13] analyzed bottom-trawl fishery data of barfin flounder in southern Tohoku, and detected the main fishing grounds (35°40′–36°35′N, mean 278 m depth), season (January–April), and size distribution (male, ca. 43 cm; female, ca. 60 cm) of barfin flounder during 2000–2006, when the effects of the large-scale stock enhancement had not extended to southern Tohoku. However, they were unable to show the seasonal/annual variation of fishing grounds and/or size distributions during the study period mainly because of the lower quantities of landings (maximum of 1.1 tons in 2006 in Fukushima Prefecture) compared with other flatfishes [14]. As a next step, detailed quantitative analyses considering annual/seasonal changes in fishery catches in southern Tohoku after the large-scale stock enhancement in Hokkaido are necessary to develop and propose reliable fishery management systems by which spontaneous reproduction of stocked barfin flounder can be enhanced, and consequently, restore the wild barfin flounder population promptly.

In this study, we conducted intensive market surveys, fishing logbook data analyses, and measurement of obtained samples during 2007–2011 to show the seasonal/annual changes in commercial landings, fishing grounds, size distributions, and sex and age compositions of barfin flounder in southern Tohoku after the large-scale stock enhancement in Hokkaido.

Materials and methods

Fishery statistics

Annual landings and annual quantities of released seedlings in Hokkaido and five prefectures in Tohoku (northern Tohoku: Aomori, Iwate, and Miyagi prefectures; southern Tohoku: Fukushima and Ibaraki prefectures) during 2000–2011 were reanalyzed from Kayaba et al. [9] to show area-specific fishery characteristics clearly. Furthermore, to reveal the seasonal variation of commercial landings of barfin flounder in southern Tohoku, monthly variations of landings in Fukushima and Ibaraki prefectures achieved using respective fishing methods [offshore trawl (≥15 ton vessel), coastal trawl (<15 ton vessel), gillnet, and others] from January 2007 to March 2011 were calculated from fishery data compiled by the Fishery Office of the Fukushima and Ibaraki Prefectural Governments.

Fishing logbook data analyses

To detect the annual and seasonal changes in the fishing grounds of barfin flounder in southern Tohoku, daily fishing logbook data of four offshore bottom-trawl vessels (19–42 tons) of Fukushima Prefecture were analyzed during 2007–2010, following the method described in Wada et al. [13]. Offshore bottom-trawl vessels of Fukushima Prefecture analyzed in this study have permission to operate in broader fishing areas from southern Iwate Prefecture to northern Chiba Prefecture (Figs. 1, 4). Therefore, the obtained results reliably reflect the characteristics of fishing grounds of barfin flounder throughout southern Tohoku. The records, written by a chief fisherman, included data reflecting the (1) fishing dates, (2) location of fishing grounds (Loran-A or latitude and longitude, and depth), (3) net-entering and net-hauling times for each operation, and (4) catches (nearest 0.1 kg) of a maximum of 15 species for each operation. The total effort (towing hours for trawling, h) and total catch (kg) of barfin flounder were summed monthly for each 5 min of latitude/longitude (35°30′–38°55′N, 140°40′–142°15′E). Then the catch per unit effort (CPUE, kg/h) for each 5 min of latitude/longitude was calculated based on a database of the fishing logbook data compiled using spreadsheet software (Excel 2010; Microsoft Corp.). Because more than 99 % of all catches were landed in January–May in southern Tohoku (Fig. 3), the CPUE maps are depicted as monthly for January–May in 2007–2010.

To compare the annual variation in collected depth distributions of barfin flounder caught at southernmost Tohoku (35°40′–36°50′N), the major fishing grounds [9], CPUEs for every 50 m depth during 2007–2010 were calculated annually, following Wada et al. [4]. Also, the mean collected depth (m) weighted by CPUE (weighted mean depth, WMD) for each month (January–May) or year (2007–2010) was calculated following the equation described in Hattori et al. [15]. In this study, CPUE, instead of fish density [15], was used in the calculation as below

$$\mathrm{WMD} = \frac{\sum(\mathrm{CPUE}_i \times D_i)}{\sum \mathrm{CPUE}_i}$$

where CPUE_i stands for CPUE (kg/h) at depth i (D_i) (i 107–457 m).

Market surveys and analyses of obtained samples

Market surveys were conducted about three times a week at the Soma-Haragama fish market (SHFM, Fig. 1), the largest fish market in Fukushima Prefecture [13, 14], to reveal the size distribution and sex composition of barfin flounder. No commercial size limitation for barfin flounder has been implemented in Fukushima Prefecture [13]. At SHFM, total length (TL) (nearest cm) and weight of barfin flounder were measured. Then the existence of abnormal pigmentation and body coloration of the blind side (white or yellow) were recorded (Fig. S1). Stocked barfin flounder could be clearly distinguished from wild ones by the occurrence of permanent abnormal pigmentation patterns on the blind side, which wild fish are lacking [2]. Sex discrimination of released barfin flounder based on the skin coloration on the blind side (male, yellow; female, white) was proved with probability of greater than 90 % [17]. Annual changes in female percentages were calculated based on body coloration data with no correction. The total size distributions of landed fish in southern Tohoku (Fukushima and Ibaraki prefectures) each year were estimated as

$$N_{ij} = n_{ij} \times \frac{\mathrm{SWtotal}_j}{\sum w_j}.$$

Therein, N_{ij} is the estimated number of barfin flounder at size i (i 29–70 cm TL) landed in southern Tohoku in year j (j 2007–2011), n_{ij} is the total number of barfin flounder at size i surveyed at SHFM in year j, w_j represent the total weight of barfin flounder surveyed at SHFM in year j, $\mathrm{SWtotal}_j$ stands for the statistical landed weight of barfin flounder in southern Tohoku in year j.

Some of the landed fish (total $n = 604$) were purchased randomly at SHFM and Onahama fish market (Fig. 1) during January–April in 2008–2011. The sex and age were determined respectively by visual observation of gonads and by counting the translucent zones of the sagittal otolith [18]. In this study, 1 June, not 1 April [9, 18], was defined as the birth date and was used as the start-day for age determination to assign the same release cohort landed

Table 1 Mean size, standard deviation, and number of samples of male and female barfin flounder at each age purchased during January–April in 2008–2011

Sex	Category	Age (years)[a]				
		1	2	3	4	5
Male	Mean TL (cm)	35.8	40.5	44.7	48.1	
	SD	1.69	2.47	2.5	3.06	
	n	9	401	83	7	0
Female	Mean TL (cm)		51.2	55.8	60.1	64.7
	SD		3.74	4.4	3.59	3.25
	n	0	5	43	43	13

TL total length, *SD* standard deviation

[a] Birth date was defined to be 1 June

during January–May to the same age, subsequently, to interpret the results of age composition more clearly. During 2007–2010, 99.1 % (83.6 %) of the total catches in southern Tohoku were landed from January to May (January–March). The age composition of barfin flounder landed in southern Tohoku during 2007–2011 was estimated by decomposing a mixture of normal length-frequency distributions of males and females during January–May in 2007–2011 at SHFM by application of a Bayesian model [19] using R software [20]. The mean size and standard deviation at each age (ages 1–5) of males and females determined from the obtained samples and used in the analysis are shown in Table 1.

Results

Quantity of release and commercial landings

The fluctuation pattern of annual landings followed that of the number of release (Fig. 2). Landings in Hokkaido were below 20 tons during 2000–2006, becoming 34.7 tons in 2007, and reaching over 130 tons in 2008 and thereafter. The highest landing of 178.1 tons was recorded in 2010. In Tohoku, the release of seedlings was conducted only in Iwate Prefecture (Fig. 2). The quantities were around 120,000 during 2000–2010. Consequently, constant quantities of landings were recorded in Iwate Prefecture during 2000–2011 (2.2 ± 1.2 tons), which were higher than other prefectures in Tohoku during 2003–2007. During 2008–2011, a marked increase of landings was observed in Fukushima Prefecture, reaching a maximum of 19.4 tons in 2010. A gradual increase of landings was also found in Aomori Prefecture. The highest total landing of 30.5 tons was recorded in Tohoku in 2010. The landings in Hokkaido and Tohoku decreased in 2011 partly because of the influence of the Great East Japan Earthquake and tsunami,

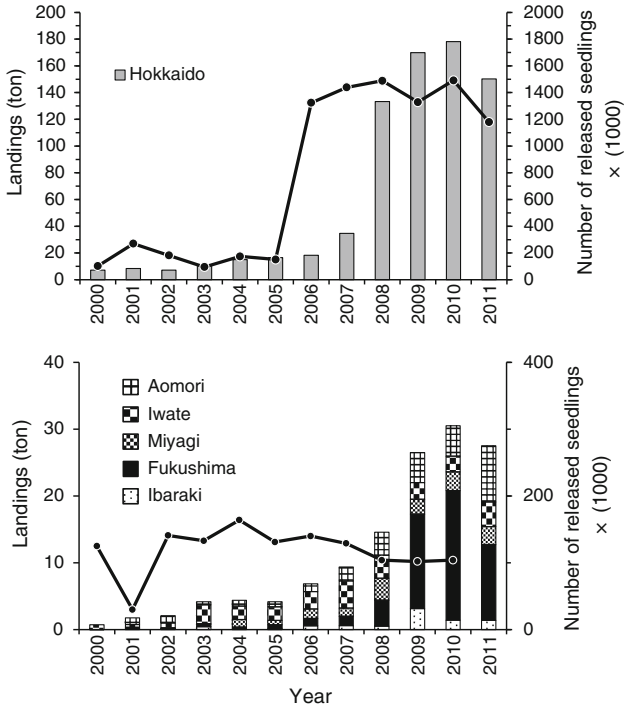

Fig. 2 Annual changes of commercial landings (bar graphs, *left axis*) of barfin flounder in Hokkaido (*upper*) and five prefectures in Tohoku (*lower*) during 2000–2011. *Black line graphs* with *black circles* (*right axis*) show annual changes of the number of released seedlings in Hokkaido (*upper*) and Iwate (*lower*) prefectures. *Vertical bars* of *upper and lower panels* show different scales

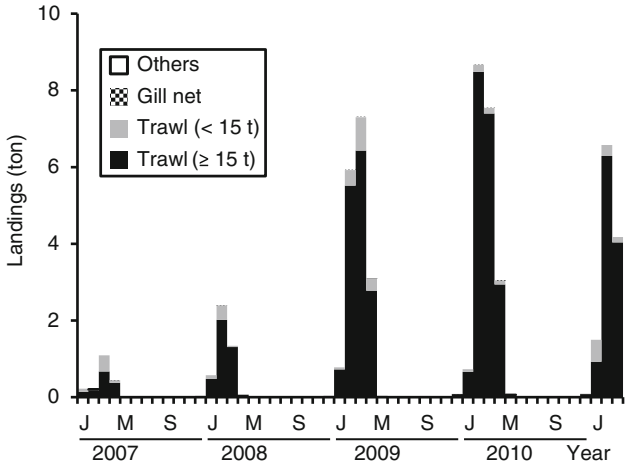

Fig. 3 Monthly variations of fishery landings for respective fishing methods in southern Tohoku (Fukushima and Ibaraki prefectures) during 2007–2011. *J*, *M*, and *S* on the *x*-axis, respectively, represent January, May, and September

and the subsequent Fukushima Dai-ichi Nuclear Power Plant accident that occurred on and after 11 March 2011 [16].

Monthly changes of barfin flounder landings in southern Tohoku during 2007–2011 are depicted in Fig. 3. Although the monthly absolute values of the landings differed among years depending on the total landings for each year (Fig. 2), the seasonal fluctuation patterns were quite characteristic and similar among years. Results except for 2011, when data after 10 March did not exist, indicated that almost all catches (98.8 %) were landed during January–April. Particularly, February (38.7 %) and March (36.8 %) were the peak months. Almost all fish (99.8 %) were caught using bottom-trawl fisheries. Particularly, offshore bottom-trawl fisheries operated by larger bottom-trawl vessels (≥15 tons) accounted for the highest proportion (92.2 %), whereas gillnet fisheries (0.11 %) and others (0.02 %) comprised a much lower proportion.

Fishing ground and depth distribution in southern Tohoku

Geographical distributions of fishing effort (operation hours, h) and monthly changes in CPUEs (kg/h) of barfin flounder during January–May in 2007–2010 are portrayed in Fig. 4. The total fishing efforts by the four offshore bottom-trawl vessels during January–May in 2007, 2008, 2009, and 2010 were, respectively, 11,488, 10,721, 11,191, and 10,796 h. Total catches of barfin flounder recorded in the fishing logbook data in 2007, 2008, 2009, and 2010 were, respectively, 11.5, 220.5, 845.0, and 2,610.0 kg. No catches were recorded in April or May in 2007 and 2008, or in May 2009. Almost all catches were made during January–April (99.7 % in total), with the peak months of February (40.2 %) and March (41.4 %). Trawling operations were found throughout southern Tohoku with depths of less than 810 m (Fig. 4). Higher efforts (>100 h) were detected from northern Ibaraki Prefecture to southern Miyagi Prefecture (36°45′–38°10′N) at depths of less than 200 m, and were also found for the area off southern Ibaraki Prefecture (35°30′–36°20′N) at depths of less than 300 m. In contrast, higher CPUEs of barfin flounder (>2.0 kg/h) were observed only off Ibaraki Prefecture (35°40′–36°45′N), although higher (1.6–6.1 kg/h) and lower (<0.24 kg/h) CPUEs were observed off Miyagi and Fukushima prefectures in March 2009 and in January 2008 and 2009, respectively (Fig. 4). The transition of monthly CPUEs in each year matched well with the relative value of the landings. The CPUEs became higher as the year progressed. Higher CPUEs (>10.0 kg/h) were found in April 2009 and February–April 2010 (Fig. 4). However, geographical locations of main fishing grounds where higher CPUEs within each year were found were slightly different among years. In 2007 and 2008, higher CPUEs (>1.0 kg/h) were observed only off northern Ibaraki Prefecture in February and March. In 2009, higher CPUEs (>2.0 kg/h) were also found off northern Ibaraki Prefecture in February, but those extended to southern Ibaraki Prefecture in March, and were only observed off southern Ibaraki Prefecture in April. In 2010, higher CPUEs (>2.0 kg/h) were formed off southern Ibaraki Prefecture in January. Then they extended to northern Ibaraki Prefecture during February–March. The highest value (22.5 kg/h) was found off southern Ibaraki Prefecture in April 2010 (Fig. 4).

Collected depth distributions expressed by CPUEs (kg/h) for every 50 m depth in each year from 2007 to 2010 are presented in Fig. 5. The CPUEs in the survey area (35°40′–36°50′N) were detected at 107–457 m. The highest mode was consistently found in 250–300 m depth range during the survey period of 2007–2010. However, different distribution patterns of CPUEs were found among years. In 2007 and 2008, CPUEs at 200–250 m depth range were quite small compared with those found in 250–300 m depth range, and no catches were found at depth less than 200 m. CPUE at 300–350 m depth range was about half of that found at 250–300 m depth range. In contrast, in 2009 and 2010, CPUEs at 200–250 m depth range were about half of those found at 250–300 m depth range, and smaller CPUE values were also observed at 150–200 m depth range. In addition, CPUEs at depths deeper than 300 m showed higher percentages compared with those found in 2007 and 2008. The monthly and annual WMD are summarized in Table 2. The monthly WMD during January–May in 2007–2010 ranged from 238 to 453 m. In February and March, corresponding to the peak months of landings (Fig. 3), the monthly WMD values were smaller in 2009 (238 m) and 2010 (259 m) than those in 2007 (280 m) and 2008 (283 m). The annual WMD values were higher in the order of 2008 (299 m), 2010 (290 m), 2007 (285 m), and 2009 (267 m).

Size distributions, and sex and age compositions in southern Tohoku

The estimated size frequency distributions of barfin flounder landed in southern Tohoku (Fukushima and Ibaraki prefectures) during 2007–2011 are depicted in Fig. 6. The numbers of surveyed fish at SHFM in 2007, 2008, 2009, 2010, and 2011 were, respectively, 287, 1,031, 4,086, 4,082, 3,938, and 1,797. The market survey rates (surveyed weight at SHFM per statistical total weight in southern Tohoku) were, respectively, 0.14, 0.26, 0.20, 0.19, and 0.16. The estimated numbers of fish landed in southern Tohoku in 2007, 2008, 2009, 2010, and 2011 were calculated, respectively, as 2,062, 4,030, 20,043, 20,930, and 11,302. Males and females with yellow and white coloration on their blind sides (Fig. S1), respectively, showed size frequency distributions peaked at around 40 and 60 cm in each year. The highest modes (mean sizes) for males in

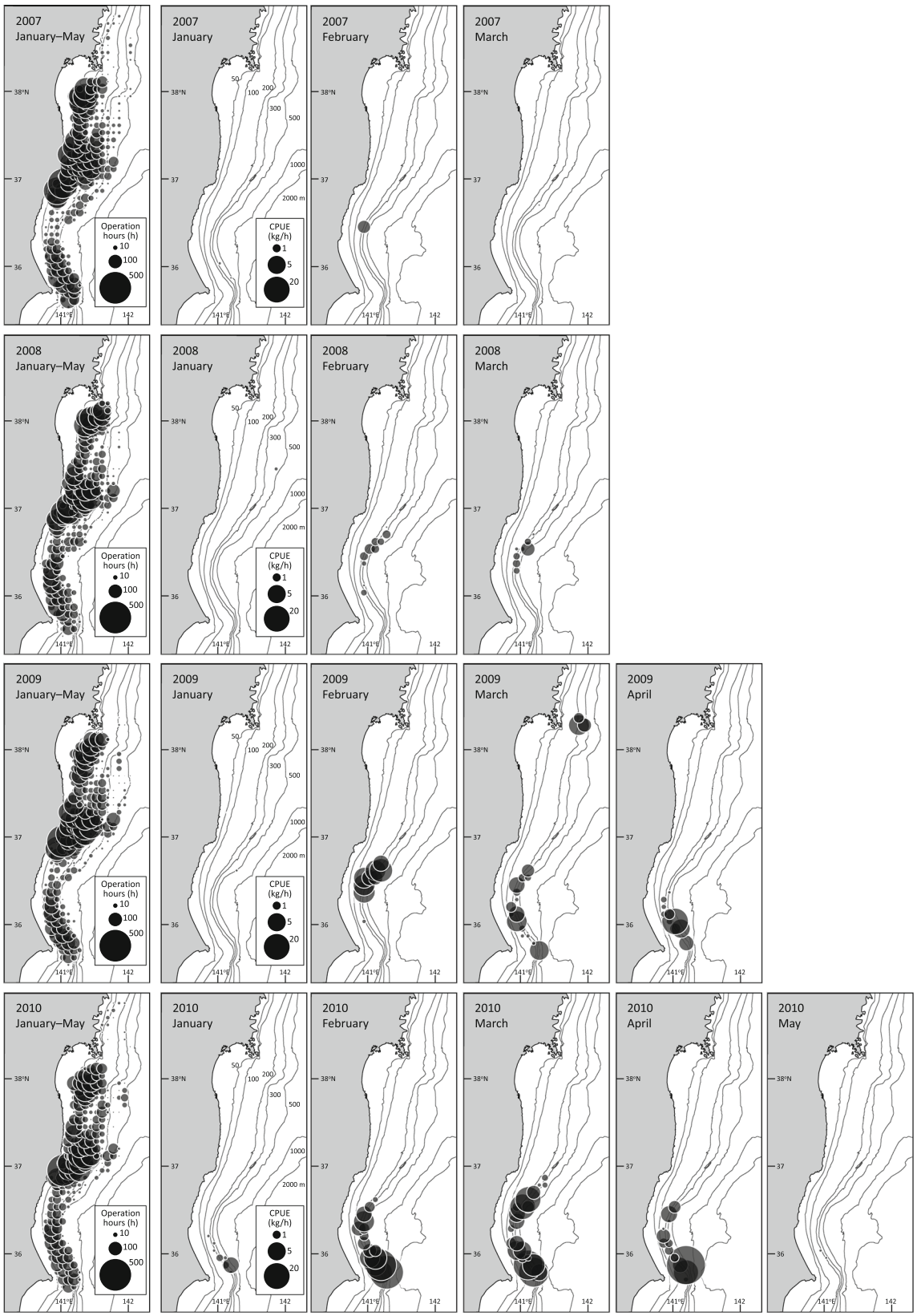

Fig. 4 Total operation hours of bottom trawling (*left*), and monthly changes in catch per unit effort (kg/h) of barfin flounder (others) by four offshore bottom-trawl vessels during January–May in 2007–2010 shown for every 5 min of longitude and latitude. *Isolines* represent depths

2007, 2008, 2009, 2010, and 2011 were, respectively, 40 (40.1), 40 (40.5), 39 (39.2), 40 (40.8), and 39 cm TL (41.1 cm TL), whereas those for females were, respectively, 60 (58.1), 60 (59.0), 60 (57.9), 54 (56.6), 57 cm TL (57.4 cm TL). The peak size of males were consistent during 2007–2011, however, different size frequency distributions were shown among years. The percentage of males with <40 cm, 40–45 cm, ≥45 cm TL were, respectively, 41.2, 47.1, 11.7 % in 2007, 39.8, 48.6, 11.6 % in 2008, 56.9, 41.1, 2.0 % in 2009, 34.4, 56.1, 9.6 % in 2010, and 35.4, 49.4, 15.2 % in 2011. All the measured barfin flounder have abnormal pigmentation and/or unclear black bands on dorsal and anal fins in the blind side. These results indicated that stocked fish occupied a much higher proportion among landings.

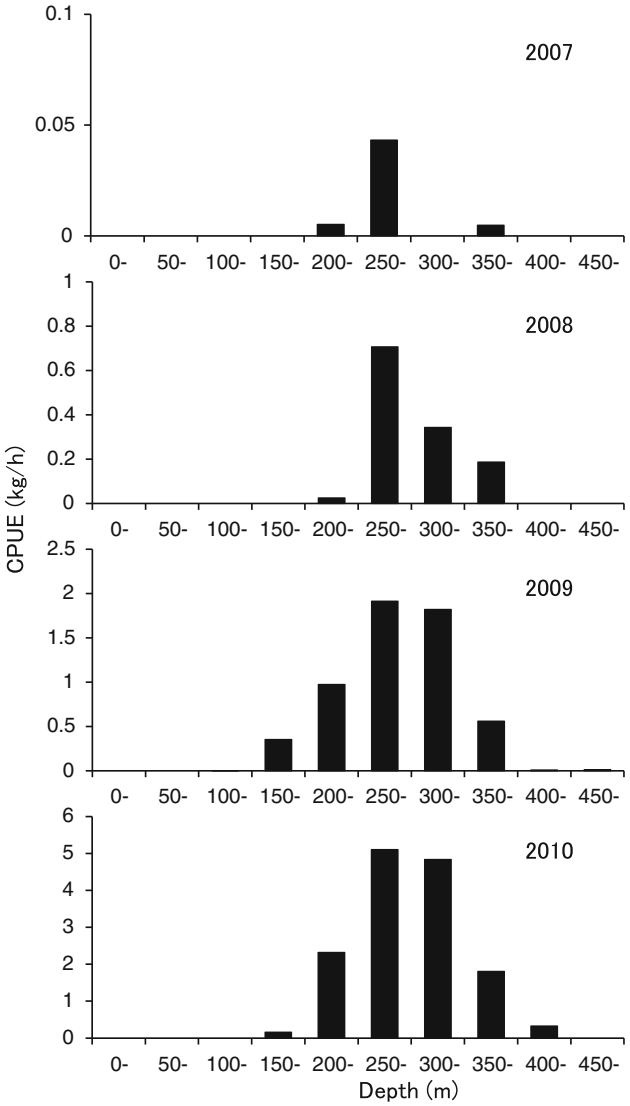

Fig. 5 Collected depth distributions of barfin flounder at southernmost Tohoku (35°40′–36°50′N) during 2007–2010, expressed by catch per unit effort (CPUEs, kg/h) for every 50 m depth. *Vertical bars* of each figure show different scales

Large differences were found in the number of landed fish between males and females (Fig. 6). The number of males was much higher than that of females, resulting in the low female percentages during the surveyed period. The female percentages fluctuated among years. The lowest and highest percentages were observed, respectively, in 2009 (1.5 %) and 2011 (7.9 %) (Fig. 7).

The estimated percentages of males and females at each age landed in southern Tohoku during 2007–2011 are presented in Table 3. Males were of ages 1–4. The 2 year old fish occupied higher percentages (≥77.6 %) in each year. Particularly, the highest percentage of 91.3 % for 2 year old fish was recorded in 2009 when seedlings of the 2006 year class were recruited to the bottom-trawl fishery in southernmost Tohoku (Fig. 2). Females were of ages 2–5. Higher percentages were observed for age 4 during 2007–2009 (≥43.4 %), and for age 3 in 2010 and 2011 (≥50.4 %). The highest percentage of 59.1 % for 3 year old fish was found in 2010 when mass-released seedlings of 2006 year class were caught at southernmost Tohoku (Fig. 4; Table 3).

Discussion

Our study demonstrated clearly that barfin flounder landings of five prefectures in Tohoku increased drastically after large-scale stock enhancement in Hokkaido conducted since 2006 (Fig. 2). A particularly interesting

Table 2 Monthly and annual mean distribution depth (m) weighted by CPUE (WMD) of barfin flounder caught at southernmost Tohoku (35°40′–36°50′N) during January–May in 2007–2010

Year	Month					
	January	February	March	April	May	January–May
2007	260 (3.0)	280 (5.0)	352 (0.5)			285 (8.5)
2008		300 (157.0)	283 (63.0)			299 (220.0)
2009	453 (1.2)	284 (307.0)	238 (300.0)	243 (200.0)		267 (808.2)
2010	242 (87.0)	301 (1,015.0)	259 (1,125.3)	286 (372.6)	269 (3.1)	290 (2,603.0)

The values in parentheses show total catch weights recorded in the fishing log book data

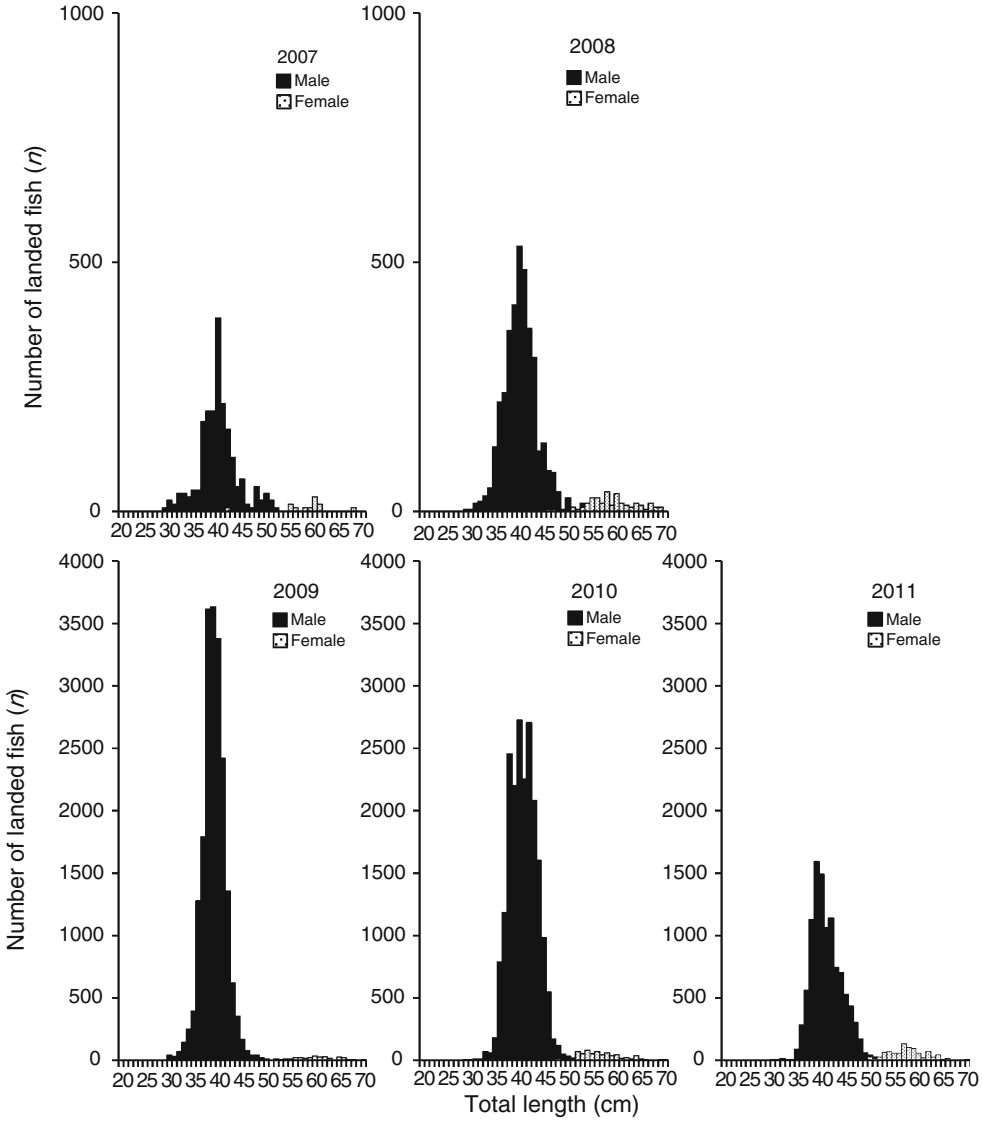

Fig. 6 Estimated total size frequency distributions of barfin flounder landed in southern Tohoku (Fukushima and Ibaraki prefectures) during 2007–2011. *Black* and *hatched bars,* respectively, represent males and females with yellow and white body coloration on the blind side (see Fig. S1). *Vertical bars* of the *upper two and the lower three* figures show different scales

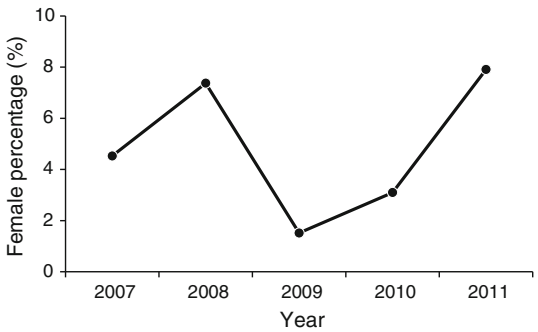

Fig. 7 Annual variation of female percentages of barfin flounder landed in Fukushima Prefecture during 2007–2011

finding is that the most marked increase occurred in southern Tohoku, especially in Fukushima Prefecture, about 700 km south from Hokkaido. Landings of barfin flounder were quite small in the 1980s and 1990s [4, 9] and also small in the early 2000s, when over 100,000 seedlings were released annually in Iwate Prefecture (Fig. 2). In addition, microsatellite DNA analysis revealed that over 80 % of samples collected from southern Tohoku in 2008 were fish released from Hokkaido [21]. These results indicate that most barfin flounder caught off southern Tohoku originated from seedlings released in Hokkaido.

The landings in southern Tohoku were consistently made using offshore bottom-trawl fishery at the upper continental slope off Ibaraki Prefecture during January–April each year (Fig. 4). These results probably reflect the fact that many mature adults migrated from Hokkaido after December [9] and congregated to southern Tohoku where suitable water temperature conditions for gonadal maturation and ovulation probably exist [9, 13]. The settled areas for spawning matched well with the main fishing grounds

Table 3 Percentage age composition and estimated total numbers of male and female barfin flounder landed in southern Tohoku (Fukushima and Ibaraki prefectures) during January–May in 2007–2011

Sex	Year	*n*	Age (years)[a]				
			1	2	3	4	5
Male	2007	1,860	8.5	77.6	9.7	4.3	0
	2008	3,622	6.1	80.3	10.3	3.4	0
	2009	19,539	6.2	91.3	2.2	0.3	0
	2010	20,158	2.0	84.6	12.9	0.5	0
	2011	10,399	1.4	80.3	17.1	1.3	0
Female	2007	87	0	6.1	39.4	52.7	1.9
	2008	295	0	2.9	39.0	43.4	14.8
	2009	298	0	8.2	31.1	44.0	16.7
	2010	633	0	6.8	59.1	30.2	4.0
	2011	892	0	4.1	50.4	41.4	4.1

[a] Birth date was defined to be 1 June

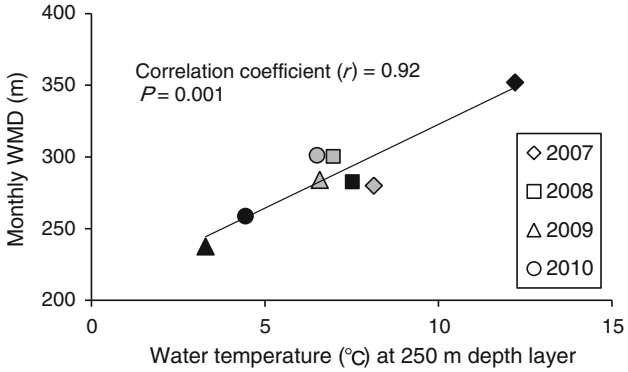

Fig. 8 Correlation between water temperature at the 250 m depth layer off southern Fukushima Prefecture (37°00′N, 141°36′E, 427 m bottom depth, Fig. S2) and monthly mean distribution depth (m) weighted by CPUE (WMD, Table 2) of barfin flounder caught at southernmost Tohoku (35°40′–36°50′N) during February–March in 2007–2010. *Grey* and *black graph* legends, respectively, show February and March in each year

for offshore bottom-trawl vessels registered in Fukushima Prefecture (Fig. 4). For that reason, a drastic increase of landings with high seasonality was found especially in Fukushima Prefecture (Figs. 2, 3), where the most numerous offshore bottom-trawl vessels (41 vessels) among five prefectures in Tohoku (Aomori 22; Iwate 14; Miyagi 26; Ibaraki seven) were assigned a license from the Fishery Office of the Japanese Government in 2011.

Annual and seasonal changes in fishing grounds

The annual catches of barfin flounder recorded in the fishing logbook data of offshore bottom-trawl vessels (Fig. 4) reflected well the increasing trend of landings in southern Tohoku (Fig. 3). The important finding is that the main fishing grounds of barfin flounder were formed consistently at southernmost Tohoku off Ibaraki Prefecture, as reported previously [13], irrespective of the operations of wide areas throughout southern Tohoku (Fig. 4). Swimming behavior above the seafloor and/or passage of deeper waters during spawning migration might explain why barfin flounder were rarely caught by bottom-trawl fisheries off Miyagi and Fukushima prefectures. However, detailed fishing logbook data analyses detected the annual variation of geographical locations of fishing grounds (Fig. 4) and depth distributions of barfin flounder (Fig. 5; Table 2). Because gonadal maturation and ovulation of barfin flounder are closely related to the ambient water temperature [8, 22], the seasonal/annual variation of geographical location of main fishing grounds might be related to the water temperature condition at the upper continental slope off southernmost Tohoku, where large variations of water temperature caused by the southward intrusion of the cold Oyashio east of Japan have been reported [23, 24]. Actually, large annual/monthly variations of water temperature off southern Fukushima Prefecture (Fig. S2) were recorded in the monthly monitoring surveys of R/V Iwakimaru (159 tons, Fukushima Prefectural Fisheries Experimental Station). The significantly positive correlation ($r = 0.92$, $P = 0.001$) between monthly WMD and water temperature at 250 m depth layer during February–March in 2007–2010 (Fig. 8) suggests that depth distributions extend to shallower areas in colder temperature conditions, as shown in 2009 (Fig. 5; Table 2).

Annual change in size distribution, and age and sex composition

Intensive market surveys and analyses of purchased samples revealed that size distribution, and age and sex compositions in southern Tohoku reflected well the fishery recruitment process of mass seedlings released in Hokkaido since 2006.

Otolith aging revealed that males and females can migrate and recruit to the fishery in southern Tohoku at ages ≥1+ and ≥2+, respectively (Table 3). In 2007 and 2008, when the mass seedlings have not markedly recruited to the fishery in southern Tohoku, the size of males showed a broad distribution (≥45 cm TL: 11.7 and 11.6 %, respectively) with a peak at 40 cm TL in both years. The higher female percentage in 2008 (7.4 %) than that in 2007 (4.5 %) reflects the fact that fishery recruits of females with ages 3–5 years corresponding to 2004–2002 year classes were better than those in 2007 (Table 3). However, the cause of this phenomenon cannot be clarified because fishery recruits of the same year class of 1 year younger ages (ages 2–4) were smaller in 2007. In 2009, the size of males showed a narrow (≥45 cm TL: 2.0 %) and large

distribution peaked also at 40 cm TL because of the massive fishery recruitment of 1 and 2 year old males corresponding to 2007 and 2006 year classes. In contrast, the female percentage showed the smallest 1.5 % in 2009 because, unlike the males, the total number of landed females had not increased (Fig. 6; Table 3). In 2010 and 2011, the sizes of males respectively showed slightly broad and positively skewed distributions (≥45 cm TL: 9.5 % and 15.2 %, respectively) probably because, in addition to the fishery recruitment of younger fish (ages 1 and 2), greater quantities of 3 year old fish of 2006 and 2007 year classes with larger sizes had recruited to the fishery (Table 3). In 2011, many mature females of 2006 and 2007 year classes (ages 4 and 3, respectively) had recruited to and caught by the bottom-trawl fishery, resulting in the highest female percentages of 7.9 %. However, this female percentage was much lower than that of released seedlings in the large-scale stock enhancement program in Hokkaido. The female percentages of age-0 seedlings (>1.5 million per year) produced in the Date Station of Hokkaido Aquaculture Promotion Cooperation during 2006–2010 ranged from 30.4 % in 2006 to 66.5 % in 2010 (weighted mean during 2006–2010: 48.6 %). (T. Matsuda, Mariculture Fisheries Research Institute, Hokkaido Research Organization, personal communication in 2014). As reported by Wada et al. [13], the male-biased sex ratio throughout the survey period in southern Tohoku might be partly explained by the fact that initial ages for migration from the waters near Hokkaido to southern Tohoku were older in females (Table 3), resulting in longer fishing mortality for remaining females than for migratory males. High fishing pressure for barfin flounder in Hokkaido was indirectly shown by a drastic increase of landings in Hokkaido after the commencement of large-scale stock enhancement (Fig. 2).

Present situation and prospects

After the Fukushima Dai-ichi Nuclear Power Plant accident, the operations of bottom-trawl fisheries in Fukushima Prefecture were banned as a practical matter, except for trial fishing operations conducted within the restricted offshore areas off Fukushima Prefecture [16]. Ironically, the hazardous circumstances related to the accident might help protect the mature adults that congregate in southern Tohoku for spawning. Long-term monitoring not only of adults, but also of wild juveniles in Hokkaido and Tohoku is necessary to ascertain whether spontaneous reproduction of stocked barfin flounder can be practicable after the mass increase of matured adults in southern Tohoku. Our results showed clearly how the effectiveness of the large-scale stock enhancement in Hokkaido extended to southern Tohoku in association with spawning migration of stocked barfin flounder. This information will constitute a basis for developing and proposing reliable fishery management systems in Tohoku to protect the mature adults, to promote spontaneous reproduction, and subsequently, to enhance the stock biomass of barfin flounder in the future.

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References

1. Amaoka K, Nakaya K, Yabe M (1995) Barfin flounder *Verasper moseri* Jordan et Gilbert. In: Amaoka K, Nakaya K, Yabe M (eds) The fishes of northern Japan. Kita-Nihon Kaiyo Center, Sapporo, p 306 (in Japanese)
2. Andoh T, Watanabe K, Matsubara T (1999) Problems and perspectives in stock enhancement of barfin flounder (review). Bull Hokkaido Natl Fish Res Inst 63:19–33 (in Japanese with English abstract)
3. Takaya Y (2011) Recent situations about barfin flounder. Hokusuishi-dayori 54:1–5 (in Japanese)
4. Wada T, Kamiyama K, Kayaba T, Sasaki M (2011) Commercial landings and fishing areas of a depleted flounder *Verasper moseri* and other flatfish species in the Joban area, eastern Japan, during 1986–1999. Aquac Sci 59:489–497 (in Japanese with English abstract)
5. Sasaki M (1997) Fishery status and ecology of barfin flounder in the waters of Hidaka and Iburi areas, southwestern Hokkaido. Hokusuishi-dayori 38:7–12 (in Japanese)
6. Watanabe K, Suzuki S, Nishiki A (2001) Migration, growth and stock enhancement effects of hatchery-reared barfin flounder *Verasper moseri* juveniles released in Akkeshi Bay. Saibai Giken 28:93–99 (in Japanese)
7. Sasaki R, Nakai K (2006) Mark-recapture experiment using barfin flounder, *Verasper moseri* on the coast of Iwate Prefecture. Saibai Giken 34:1–6 (in Japanese with English abstract)
8. Kayaba T (2005) Studies of techniques of reliable production of seed of barfin flounder *Verasper moseri*. Sci Rep Hokkaido Fish Exp Stn 69:1–116 (in Japanese with English abstract)
9. Kayaba T, Wada T, Kamiyama K, Murakami O, Yoshida H, Sawaguchi S, Ichikawa T, Fujinami Y, Fukuda S (2014) Gonadal maturation and spawning migration of stocked female barfin flounder *Verasper moseri* off the Pacific coast of northern Japan. Fish Sci 80:735–748
10. Takaya Y, Yoshida H, Matsuda T, Murakami O (2009) Migration of hatchery-reared barfin flounder *Verasper moseri* with their age in the Pacific coastal waters off southwestern Hokkaido, Japan (Short paper). Sci Rep Hokkaido Fish Exp Stn 75:19–21 (in Japanese)
11. Yoshida H, Takaya Y, Matsuda T (2011) Age, total length and season of artificially reared barfin flounder, *Verasper moseri*,

released from Hokkaido and recaptured in waters off eastern Honshu from Aomori to Ibaraki prefectures. J Fish Technol 3:121–126 (in Japanese with English abstract)
12. Kayaba T (2013) Stock enhancement of barfin flounder *Verasper moseri*. In: Aritaki M (ed) Stock enhancement and risk management for coastal fishery resources. Monitoring on genetic diversity and efficiency of stock enhancement. Kouseisha-Kouseikaku, Tokyo, pp 9–21 (in Japanese)
13. Wada T, Kamiyama K, Shimamura S, Yoshida T, Kayaba T, Sasaki M (2013) Detection of fishing grounds, fishing season, and size distribution of stocked barfin flounder *Verasper moseri* in southern Tohoku, the Pacific coast of eastern Japan. Aquac Sci 61:39–46
14. Wada T, Kamiyama K, Shimamura S, Mizuno T, Nemoto Y (2012) Effectiveness of stock enhancement of a rare species, spotted halibut *Verasper variegatus*, in Fukushima, Japan. Aquaculture 364–365:230–239
15. Hattori T, Narimatsu Y, Ito M, Ueda Y, Kitagawa D (2008) Annual changes in distribution depths of bighand thornyhead *Sebastolobus macrochir* off the Pacific coast of northern Honshu, Japan. Fish Sci 74:594–602
16. Wada T, Nemoto Y, Shimamura S, Fujita T, Mizuno T, Sohtome T, Kamiyama K, Morita T, Igarashi S (2013) Effects of the nuclear disaster on marine products in Fukushima. J Environ Radioact 124:246–254
17. Misaka T, Sasaki M (2008) Sex discrimination of landed barfin flounder from the body coloration in the blind side. Kushirosuishi-dayori 89:8–11 (in Japanese)
18. Takaya Y, Matsuda T, Yoshida H (2004) Validation of age determination from otoliths of young barfin flounder (*Verasper moseri*) (short paper). Sci Rep Hokkaido Fish Exp Stn 66:11–13 (in Japanese)
19. Baba K, Sasaki M, Mitsutani N (2005) Estimation of age composition from length data by posterior probabilities based on a previous growth curve: application to *Sebastes schlegelii*. Can J Fish Aquat Sci 62:2475–2483
20. R Development Core Team (2013) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
21. Andoh T, Misaka T, Ichikawa T (2013) Genetic monitoring and conservation programs to maintain the genetic diversity. In: Aritaki M (ed) Stock enhancement and risk management for coastal fishery resources. Monitoring on genetic diversity and efficiency of stock enhancement. Kouseisha-Kouseikaku, Tokyo, pp 38–53 (in Japanese)
22. Kayaba T, Sugimoto T, Mori T, Satoh N, Adachi S, Yamauchi K (2003) Induced spontaneous spawning using an increased temperature stimulus in the cultured barfin flounder *Verasper moseri*. Fish Sci 69:663–669
23. Sekine Y (1988) Anomalous southward intrusion of the Oyashio east of Japan: 1. Influence of the seasonal and interannual variations in the wind stress over the North Pacific. Umi to Sora 64:19–30 (in Japanese with English abstract)
24. Shimizu Y, Yasuda I, Ito SI (2001) Distribution and circulation of the coastal Oyashio intrusion. J Phys Oceanogr 31:1561–1578