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Relation	

Seasonal bathymetric distributions of three coastal flatfishes: estimation from logbook data for trawl and gillnet fisheries

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Highlights

- Catch-per-unit-effort data of bottom trawls and gillnets for three flatfishes were analyzed.
- Catchability by gillnets showed species specific seasonal patterns.
- Logbook data in commercial fisheries provide useful information on the seasonal bathymetric distributions.

Abstract

The present study aims to clarify the seasonal bathymetric distributions of three coastal flatfishes (stone flounder, marbled flounder, and Japanese flounder) that are caught mainly by bottom trawls and gillnets off the coast of Fukushima, Japan, by using logbook data. All three species were found to have specific spawning depths, i.e., depths of 40–80 m, 20–40 m, and 10–60 m for stone, marbled, and Japanese flounders, respectively, with extremely high catch-per-unit-effort during their spawning seasons, reflecting spawning ground formation. Furthermore, Japanese flounder showed a tendency to expand their distribution offshore to depths deeper than 100 m after October. These results indicate interspecific variations in migration and aggregation patterns. Using logbook data and considering the seasonal catchability of each fishing gear enabled us to understand the seasonal bathymetric distribution of each species and the depths of their spawning grounds.

Keywords: CPUE; flatfish; inshore-offshore migration; hotspot; spawning ground

1. Introduction

Seasonal changes in fish distribution are important factors for determining the location of operations in capture fisheries. For fish species that aggregate on spawning grounds, appropriate fisheries management measures, such as spatial or temporal limitations, are required to avoid reduced reproduction due to intensive fishing (van Overzee and Rijnsdorp, 2015; Sadovy de Mitcheson, 2016). To achieve sustainable fisheries, it is necessary to understand in detail the seasonal changes in distribution and the annual life cycle, including spatiotemporal patterns in spawning ground formation. Describing seasonal patterns in marine fish distributions is often unrealistic for only researchers to carry out; it is difficult to collect sufficient samples and data from a vast area in surveys conducted by research vessels. Data collection by commercial fisheries is extremely efficient and can be used for application in fisheries management (Óskarsson et al., 2009; Melvin et al., 2016).

Three coastal flatfishes, stone flounder *Platichthys bicoloratus* (Pleuronectidae), marbled flounder *Pseudopleuronectes yokohamae* (Pleuronectidae), and Japanese flounder *Paralichthys olivaceus* (Paralichthyidae) are commercially important species in Japan. Spawning seasons for stone and marbled flounders peak in December–January (Hatanaka and Iwahashi, 1953; Tsuruta, 1991), while those for Japanese flounder peak in June–August (Kurita, 2012). For stone flounder, it is empirically understood that they usually inhabit sandy areas with depths of 20–60 m and that they aggregate in silt or muddy-sand areas with depths of 20–50 m for spawning in Sendai Bay, northern Japan (Omori and Tsuruta, 1988; Tsuruta, 1991). Marbled flounder usually inhabit depths of 30–80 m (Omori, 1974), and its main spawning ground is estimated to occur at depths of 30–40 m in Sendai Bay (Takahashi et al., 2006). Japanese flounder moves seasonally and aggregates in shallow areas, especially during its spawning season (Shibata et al., 2017). The above information is insufficient to comprehensively understand the distribution of each species. To implement better fisheries management, it is necessary to understand in detail the seasonal distribution patterns of each species.

Catch-per-unit-effort (CPUE) analysis is often performed to investigate the distribution characteristics of target fish. In the case of multiple fishing gears operating in capture fisheries, comprehensive analysis of the CPUE with different gears is one of the issues that needs to be resolved. The three flatfishes are caught by gillnets and trawls in the Joban area, which is the study area. As the trawl is an active fishing gear while gillnet is a passive fishing gear, it is not possible to simply compare CPUEs between these two gear types. The CPUE of passive fishing gear would be affected not only by the abundance of the target species but also by fish behavioural activities. In fact, Japanese flounder shows seasonal changes in their swimming activity (Nakatsuka et al., 2014).

The purpose of this study was to reveal seasonal changes in the distribution depth of stone flounder, marbled flounder, and Japanese flounder from the logbook data (operation records and catches) of commercial fisheries. For the operation records of fishermen, the trawl and gillnet vessels were extracted as samples to obtain detailed information on the water depth and catch of the target fishes through a logbook. In addition, the body size of landed individuals was measured at the fish market and verified the differences in fish body sizes between fishing gear types (Clement et al., 2014). Furthermore, to evaluate the validity of considering depths with high CPUEs as spawning grounds, both the collected depths and the gonad status of landed marbled flounder at the market were examined around spawning seasons.

2. Materials and Methods

2.1. Study area and logbook data collection

Joban area and Sendai Bay (35° 45' N–38° 25' N) are an area with a wide continental shelf in the longitudinal direction, and coastal flatfish species are mainly caught by otter trawls and gillnets. Gillnet fisheries are usually operated at depths shallower than 50 m, while bottom trawls are operated mostly at depths deeper than 40 m. The trawl fisheries are prohibited in July and August. For Japanese flounder, a size limitation of less than 30 cm in total length (TL) has been implemented (Tomiyama et al., 2008). To minimize the influence of the latitudinal environmental gradient, such as temperature, the sample vessels and logbook data to be analysed were limited to those from the latitudes between 37° 20' N and 38° 10' N (Fig. 1). There were approximately 40 bottom trawl vessels (30 vessels belonging to Soma-Futaba Fisheries Association and 10 vessels belonging to Iwaki-City Fisheries Association) and 250 gillnet vessels operating in this area in 2008 and 2009. Of these vessels, 7 trawl vessels (6.6 to 47.6 ton) and 39 gillnet vessels (4.8 to 6.6 ton) were selected as samples. Each vessel recorded the location and time of each operation, effort (towing duration for bottom trawls and net length for gillnets) and catch (kg) of the principal fishes. These records from January to December 2008 and 2009 were used to determine the CPUE of each species (catch per 1 h haul for bottom trawls and catch per 500 m length for gillnets) for each operation.

Notably, the fishermen recorded principal species, and therefore, no record for target species did not always indicate the absence of them. In 2008 and 2009, stone flounder, marbled flounder, and Japanese flounder accounted for 1.4 and 1.5%, 0.8 and 1.1%, and 2.4 and 5.4% of trawl catches, respectively, and for 11.0 and 8.3%, 9.1 and 8.6%, and 12.2 and 14.3% of gillnet catches, respectively, at the Soma-Haragama Fish Market (37° 50' N, 140° 58' E; Supplementary Table S1).

2.2. Logbook data analyses

The CPUE at 10 m depth classes were analysed on the basis of the water depth at the operation location (average water depth between positions of net entering and lifting). The catchability was assumed to be constant regardless of the season for the bottom trawls, but the catchability was changeable in association with the seasonal changes in swimming activity of the fish for gillnets. Vessel size was not considered for trawl fisheries because it was excluded from the linear mixed models for the CPUEs of all three species, in which vessel size was used as an explanatory variable, and month, depth class, and vessel were used as random variables, based on the Akaike information criterion (AIC). Similarly, soak time and/or mesh size could affect the CPUE in gillnet fisheries, but we assumed these effects to be negligible (Fig. S1). To comprehensively understand the depth-CPUE relationships, we analysed the CPUEs of the different gears in three steps.

In the first step, the CPUE of the gillnets was corrected by taking seasonal catchability into consideration. Both types of fishing gear were used at various depths, with overlapping usage at depths from 40 to 50 m irrespective of species or season (Table S2); thus, the ratio between the CPUEs of trawls and gillnets in this depth class was determined for each species in each month. Preliminarily, the data were excluded from the analysis when the number of CPUE data at each depth class was less than three for each fishing gear (Table S2). The conversion coefficient (CC) was obtained by a linear mixed model for the CPUE of bottom trawls divided by the CPUE of gillnets, assuming a periodic function by fitting "sin ($2\pi \times M / T$)" and "cos ($2\pi \times M / T$)". M is the month in order, and T is the number of months in one cycle. Year was included as a random factor. The response variable is the median bottom trawl CPUE / median gillnet CPUE at depths of 40–50 m each month. The median was used because CPUE was not necessarily normally distributed and extreme outliers were often observed (Fig. 2). The initial explanatory variables were sin ($2\pi \times M / 6$), sin ($2\pi \times M / 12$), cos ($2\pi \times M / 6$), and cos ($2\pi \times M / 12$) to take both semi-annual and annual cycles into account. A model was created for each fish species, and model selection was performed using the AIC corrected for small sample sizes (AICc).

In the second step, the CPUEs of the gillnets was corrected by the CC, which was obtained by the model for each month, and were pooled with the CPUEs of the trawl. Then, the median integrated CPUE for each species in each depth class was determined for each month to clarify the seasonal changes in the bathymetric distributions. Data less than three were excluded.

In the third step, the spatial CPUE patterns during spawning seasons were analysed to explore the spawning sites. We drew the spatial distribution of the median integrated CPUEs of the gillnets and trawls in longitudes and latitudes at 2' grid scales for each species. Data from December and January were used for stone and marbled flounders, as these months align with their spawning seasons. For Japanese flounder, the peak in spawning season was considered to be from June to August (Kurita, 2012), but high CPUEs were observed from May to July rather than June to August (see results). Additionally, the peak in the hatch period was observed between May and July (Oshima et al., 2010). Thus, the data from May to July were used for Japanese flounder. The data from 2008 and 2009 were pooled, and the data in grid cells with less than three per square were excluded.

Bottom water temperature was investigated as one of the factors affecting the distribution of each species. Monthly data on bottom water temperatures were obtained from five stations with depths of 20–140 m along the latitude of 37° 50' N and from one station with a depth of 3 m (37° 49' N, 140° 58' E) by Fukushima Prefectural Fisheries Experimental Station. The relationship between the water depth and the water temperature from January 2008 to December 2009 was drawn with contour diagrams. Although substratum is an important factor affecting flatfish distribution (Able and Fodrie, 2015), effects of substratum were not considered because substrata were mostly sand and gravel at depths <100 m and were mostly fine sand at depths ≥100 m in the study area (Aoyagi and Igarashi, 1999).

2.3. Fish market survey

To determine the body size of fish caught by each fishing gear, fish market surveys were conducted 3–7 times per month at the Soma-Haragama Fish Market from January 2008 to December 2009. The TL of landed fish was measured to the nearest 1 cm. Because the operating depths were different between gillnet and trawl fisheries, TL frequency distributions of each species were compared between the two fisheries by the Kolmogorov-Smirnov two sample test.

2.4. Validation of spawning depths

Approximately 30–50 individuals of adult female marbled flounder were sampled for measurements every month at the Soma-Haragama Fish Market from November 2008 to February 2009 and from December 2009 to February 2010 (298 individuals in total; 162 by gillnets and 136 by trawls; 242 to 503 mm TL). Females were extracted by palpation on the blind side (Tomiyama, 2013). The location of collection and the depth at collection were given by fishermen for each sample. Female marbled flounder are classified as "total spawners" (Murua and Saborido-Rey, 2003; McBride et al., 2015) because they ovulate and spawn all developed oocytes in a single event (Sato, 1971), and the individuals before and after spawning can be clearly distinguished from the appearance of their gonad. In addition, an individual with hydrated eggs can be regarded as occurring immediately before spawning. According to the classification of maturity for marbled flounder (Tanda et al., 2008), the maturity levels of adult female marbled flounder were classified into three groups, i.e., "Developing" (yellow- or orange-coloured ovary), "Ripe" (ovary filled with hydrated oocytes), and "Spent" (post-spawning). These groups corresponded with the classification of maturity for winter flounder *Pseudopleuronectes americanus* (McBride et al., 2013), a congeneric species to marbled flounder, i.e. "Developing", "Ripe" including "Ripe and running", and "Spent" including "Resting". The depth of the collected water of each group was investigated. Preliminarily, immature individuals were excluded.

3. Results

3.1. Seasonal changes in the CPUE based on different gears

We analysed approximately >10,000 and >800 records of gillnet and trawl logbooks, respectively (Table 1). The logbook data showed that stone flounder, marbled flounder, and Japanese flounder were collected from depths of 11–119 m, 5–116 m, and 3–186 m, respectively. Collection records at depths ≥80 m were observed in most months for all species, and no clear seasonal bias was detected. For stone flounder, the CPUE of the gillnet increased as the depth increased from 20 to 50 m regardless of the season, and the CPUE of the trawl was high at depths from 40 to 80 m from October to January (Fig. 2). A high CPUE for stone flounder was observed in December and January for both fishing gears. For marbled flounder, the CPUE of the gillnet often peaked at depths of 20–30 m and showed especially high values in December–February, while the CPUE of the bottom trawl showed relatively low values and tended to be low in deeper areas. For Japanese flounder, the CPUE of the gillnet was high from May to September. The CPUE of the bottom trawl decreased as the depth increased from 50 to 100 m in most months, while the CPUE increased as the depth increased from 100 to 150 m from February to May.

The ratio of the CPUEs between trawls and gillnets at depths of 40–50 m changed seasonally for all species (Fig. 3). In stone flounder, the ratio was low during February–April and high during June–November. In marbled flounder, the ratio tended to be high in March and September–November. In Japanese flounder, the ratio was high during November–April. The selected linear mixed models for the CC, fitted to the data of these ratios, were expressed by the following formulas (Table 2):

Stone flounder: $\mathrm{CC} = 1.263 - 0.842 \times \sin\left(2\pi \times \frac{M}{12}\right)$

Marbled flounder: $\mathrm{CC} = 3.409 - 1.366 \times \sin\left(2\pi \times \frac{M}{12}\right) - 2.100 \times \cos(2\pi \times \frac{M}{6})$

Japanese flounder: $\mathrm{CC} = 5.147 + 2.143 \times \sin\left(2\pi \times \frac{M}{12}\right) + 2.893 \times \cos(2\pi \times \frac{M}{12})$

3.2. Seasonal changes in the bathymetric distribution

The biomass, expressed by the integrated CPUE of gillnets and trawls, was particularly high at depths of 40–80 m and 20–40 m for stone flounder and marbled flounder, respectively, during their spawning season of December–January (Fig. 4). For stone flounder, high CPUEs (>4 kg h^{-1}) were chiefly observed at depths from 30–80 m from October to January, while similarly high CPUEs were also observed at depths from 50–80 m in June. For marbled flounder, extremely high CPUEs (>10 kg h^{-1}) were observed at depths from 20–40 m from January to April 2008 and from January to February 2009, while relatively high CPUEs (>5 kg h^{-1}) were often observed at depths from 10–50 m throughout the year. For Japanese flounder, the CPUEs were extremely high (>10 kg h^{-1}) at depths from 10–40 m from April to June in 2008 and at depths from 10–60 m from May to June in 2009. High CPUEs were also observed at depths from 10–60 m from November 2008 to January 2009 and from September to December 2009. The distributions of all species seemed to expand to deeper areas from September to December. It should be noted that the distribution at depths of ≥50 m could not be drawn from June to September because bottom trawls are prohibited from July to August.

The spatial distribution during spawning seasons differed between species (Fig. 5). High CPUEs (>4 kg h^{-1}) of stone flounder were chiefly observed around depths of 50 m in areas north of 37° 32' N, while the hotspot (CPUE >15 kg h^{-1}) for marbled flounder was observed around depths of 30 m at 37° 30–32' N and 37° 52–58' N. For Japanese flounder, high CPUEs (>8 kg h^{-1}) were observed everywhere at depths of approximately 50 m or shallower.

The water temperature at depths of <20 m peaked in August–September, while at depths of ≥40 m, it peaked in October–November (Fig. 6). The CPUE was low for all three species at water temperatures above 20 °C.

3.3. Length frequency distribution for different fishing gears

The body size distribution was similar between fishing gears for all three species (Fig. 7). Gillnet fishermen usually use larger meshed gillnets from April to August to harvest large Japanese flounder migrating to shallow waters for spawning; therefore, larger-sized Japanese flounder and marbled flounder were caught by gillnets during this period (Fig. S2). Significant differences in the length-frequency distribution throughout the survey period were observed between fishing gears for all species (stone flounder: $D = 0.17$, $p < 0.001$; marbled flounder: $D = 0.075$, $p < 0.001$; Japanese flounder: $D = 0.18$, $p < 0.001$). The proportion of large fish was greater in trawls than in gillnets for stone flounder, while this proportion was greater in gillnets than in trawls for marbled flounder and Japanese flounder (Fig. 7). However, the TLs of the landed fish were similar for both types of gears for all fishes, i.e., 23–66 cm and 21–68 cm in trawls and gillnets, respectively, for stone flounder; 17–56 cm and 21–58 cm in trawls and gillnets, respectively, for marbled flounder; and 30–94 cm and 30–91 cm in trawls and gillnets, respectively, for Japanese flounder.

3.4. Verification of the spawning ground of marbled flounder

Depths of collection for female flounder in all three maturity classes were observed from 28.5 to 120 m around the spawning season (Fig. 8). Most of the "Ripe" individuals who possessed hydrated oocytes were caught by gillnets at depths of <45 m except for only 2 individuals caught by trawls. On the other hand, individuals in other stages were caught evenly between fishing gears: 72 and 87 "Developing" individuals or 62 and 60 "Spent" individuals were collected by trawls and gillnets, respectively. A large proportion of the "Developing" individuals caught by trawls were from depths of <60 m, while "Spent" individuals caught by trawls were mostly from depths of ≥60 m.

4. Discussion

This study revealed that spawning grounds inferred from the CPUE were located at different depths for stone flounder (depths of 40–70 m) and marbled flounder (20–40 m), whereas their spawning seasons were common from December to January (Table 3). To date, the two species have been thought to spawn at similar depths (Table 3). Although a hotspot of stone flounder was found near 38° N at depths of approximately 30 m during the spawning season (Fig. 5a), low abundance was observed in other locations with similar depths, implying that this depth was not common for spawning grounds of stone flounder. On the contrary, the ripe females of marbled flounder with hydrated oocytes in their ovaries were caught mainly from depths of 30–45 m, indicating the validity of regarding depths with high CPUEs as spawning grounds. Additionally, many "Developing" and "Spent" individuals occurred over a broader depth range than "Ripe" individuals (Fig. 8). This result suggests aggregation to spawning grounds before their spawning and the emigration to deeper areas after spawning, although their emigration to deeper waters after spawning was not observed from the CPUE analyses (Fig. 4). Thus, such supportive information would be important. Japanese flounder have been thought to spawn at depths of approximately 20 m during June and July (Table 3), but a high CPUE was observed at depths of 10–60 m (Figs. 2c, 5c), suggesting broader spawning grounds for this species. Such aggregational behaviours associated with spawning have been elucidated through logbook data analyses for hairtail *Trichiurus lepturus* (Cheng et al., 2001) and barfin flounder *Verasper moseri* (Wada et al., 2014). Similarly, migration to shallow waters for spawning and post-spawning emigration to deeper waters were observed in turbot *Psetta maxima* through a tagging study (Florin and Franzén, 2010). Spawning aggregation would be general for most pleuronectid and paralichthyid flatfishes, but such efforts to elucidate spawning aggregations should be promoted further.

The ratio of CPUEs between gillnets and trawls suggested a seasonal periodicity in the swimming activity of each species. That is, the activity of stone flounder was high in February–April and low in August–October, while that of marbled flounder was high in December–February and May–June. Japanese flounder seemed to be active from June to September. This high swimming activity could be related to their mating behaviour, aggregation to spawning grounds, or emigration to deeper areas after spawning (Hunter et al., 2009). In southern Japan, swimming activity of Japanese flounder, as evaluated by a data logger, increased during their spawning season of January–March (Nakatsuka et al., 2014). However, high CPUEs of Japanese flounder were observed from April to June (Fig. 4), while the peak in the spawning season in the study area was considered to be from June to August (Kurita, 2012). This inconsistency may indicate that CPUE itself does not reflect the swimming activity or spawning seasons. It is also unclear why the catchability of marbled flounder by gillnets was high from May–June. One possible explanation is that feeding activity of marbled flounder, inferred from stomach contents weight and daily ration, was highest in June (Takahashi et al., 2018). Similarly, low feeding activity of Japanese flounder from March to April (Tomiyama and Kurita, 2011) might be corresponded with relatively low swimming activity during this period. Additionally, the swimming activity inferred from the CC, e.g. high swimming activity under low CC, might have been affected by depth. We determined the CC at the depth class from 40–50 m for all species, but swimming activity might be higher at shallower depths because of higher water temperatures (Fig. 6). Further studies on swimming activity in relation to depth are expected.

It should be noted that gillnets are usually set over night. Visual predators, including pleuronectid and paralichthyid flatfishes, remain on the bottom and forage food usually traveling small distances during the day (Olla et al., 1972; Tsuruta and Omori, 1976; Gibson et al., 2013), but they swim more actively during the night than during the day (Miyazaki et al., 1997; Solmundsson et al., 2003; Kawabe et al., 2009). Marbled flounder and its congeneric winter flounder spawn eggs during the night (Sato, 1971; Stoner et al., 1999), although the spawning behaviour of Japanese flounder as suggested by data loggers was mainly observed during the day (Yasuda et al., 2013). Furthermore, the flatfishes may be able to find refuge from gillnets by their visual senses during the day. Such difference in catchability between day and night should be considered for analyses of CPUE by passive fishing gears.

It was assumed that catch efficiency is constant in the bottom trawls regardless of the season. However, water temperature may affect fish behaviour and the catchability of the fish by active gear (Ryer, 2008; Gibson et al., 2013), indicating the possibility that the CPUE of trawls are affected by the seasonality of the swimming activities of fish. The catchability of bottom trawls also differs between the daytime and nighttime (Petrakis et al., 2001; Ryer, 2008; Fujiwara et al., 2009). Thus, taking seasonality and diurnality of the catchability even in the trawls into account would improve the accuracy of seasonal distribution through the CPUE analyses.

Data loggers can provide supportive information (Kurita et al., in preparation). The logger indicated that off-bottom frequency and activity of Japanese flounder increased around their spawning season (Shibata et al., 2009; Nakatsuka et al., 2014). Seasonal migration of other flatfishes has been estimated by the loggers and satellite tags (Loher and Seitz, 2006; Florin and Franzén, 2010; Armsworthy et al., 2014; Le Bris et al., 2017; Seitz et al., 2017). Using loggers has many advantages, such as being able to directly record the water temperature experienced by individual fish. Because using data loggers for many individuals of multiple species is unrealistic, biologging should be used to obtain such supportive information for logbook data analyses to understand the distribution and movement patterns of the target fish species.

This study analysed the distribution of adult fish, as most fish of the three flatfishes caught by commercial fisheries were adults in the study area. The landed individuals were mostly larger than the minimum size at maturity; the minimum sizes at maturity in males and females are 16 and 22 cm TL, respectively, for stone flounder (estimated from standard length, Uehara and Shimizu, 1999), 20 and 27 cm TL for marbled flounder (estimated from standard length, Hatanaka and Iwahashi, 1953), and 35 and 44 cm TL for Japanese flounder (Kitagawa et al., 1994). The results of this study, including the spatial distribution patterns during spawning seasons (Fig. 5), are expected to contribute to reproductive conservation. Because the spawning depths largely differ between stone flounder and marbled flounder with their overlapping spawning seasons, the conservation of spawning fish or spawning grounds should be considered for multiple species simultaneously. Implementing a spawning closure for only one fish species may lead to increased fishing pressure on other fish species (Rijnsdorp et al., 2012). Another strategy for fisheries management is to propose a marine protected area (MPA) that effectively protects adult and immature fish by analysing hotspots of respective spawners and juveniles (Grüss et al., 2019). Our analyses did not detect the patterns in relation to the body sizes of the fish, but the size- or age-related segregation or distribution are future issues.

Fishery-dependent data, such as those analysed in this study, have possible limitations regarding the interpretation of fish distributions. For example, fishing efforts may concentrate on attractive areas. Indeed, CPUE, which was the basis of the distribution data, is affected by the species targeted by the fishermen (Quirjins et al., 2008) and the power of the fishing vessels (Rijnsdorp, 2000). Even if there are such limitations, fishery-dependent data could be a powerful source for understanding fish distributions and movement (Bourdaud et al., 2017), which are expected to be applied to sustainable fisheries and the conservation of exploited fish. It should be noted that the reliability of data depends largely on fishermen (Sampson, 2011). This study selected cooperative fishermen for the survey, and their records were highly reliable. Cooperation from fishermen is indispensable for fishery-based analyses.

This study described the distribution characteristics of three flatfishes from two-year data analyses, but long-term analysis will be more important in the future. For example, the habitats of summer flounder *Paralichthys dentatus* have moved northward as determined by analysing fishery information for approximately 40 years (Perretti and Thorson, 2019). Because the spatial distribution of fishes is assumed to change due to global warming, it is necessary to continuously collect abundance data with continuous analyses for the distribution patterns of fishes.

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Table 1
Number of observations and total catch of logbook records

Gear/Year	Stone flounder		Marbled flounder		Japanese flounder	
	N	Catch (kg)	N	Catch (kg)	N	Catch (kg)
Trawl						
2008	737	6,817	412	1,908	1,653	17,676
2009	790	5,830	462	2,349	2,222	30,585
Gillnet						
2008	5,852	59,059	5,970	55,325	6,460	70,871
2009	4,961	34,630	5,600	43,894	6,232	63,043

Table 2

Results of the analysis of deviance in the linear mixed models for the CPUE conversion coefficient (median of trawl CPUE / median of gillnet CPUE) of stone, marbled, and Japanese flounders

Species	Error source	df	Chi-square	*p*
Stone flounder	sin (2π × M / 12)	1	15.75	<0.001
Marbled flounder	sin (2π × M / 12)	1	6.06	0.014
	cos (2π × M / 6)	1	16.37	<0.001
Japanese flounder	sin (2π × M / 12)	1	5.05	0.025
	cos (2π × M / 12)	1	7.91	0.0049

Analysis of deviance was carried out using Type II Wald Chi-square tests. The initial explanatory variables were sin (2π × M / 6), sin (2π × M / 12), cos (2π × M / 6), and cos (2π × M / 12). M was the month in order. Year was incorporated as a random variable. The final model was selected on the basis of the Akaike information criterion for small sample size (AICc).

Table 3

Bathymetric information on the distribution of the three flatfish adults based on empirical knowledge and the results of the present study around the Joban area

Species	Spawning ground	Habitat	Reference
Stone flounder	20–30 m	20–60 m	Omori and Tsuruta (1988)†
	20–50 m		Tsuruta (1991)†
	20–50 m	15–100 m	Unpublished‡
	40–80 m	11–119 m	Present study
Marbled flounder		30–80 m	Omori (1974)
	30–40 m		Takahashi et al. (2006)
	20–50 m	20–50 m	Unpublished‡
	20–40 m	5–116 m	Present study
Japanese flounder	Around 20 m		Yusa (1979)†
		40–200 m	Unpublished‡
	10–60 m	3–186 m	Present study

† Empirical information

‡ Fukushima Prefectural Fisheries Experimental Station, unpublished report on the basis of logbook data (1987)

Figure captions

Fig. 1. Map of the study sites. A dashed square shows the study area (37° 20' to 38° 10' N, depth < 150 m).

Fig. 2. Catch per unit effort (CPUE) of (a) stone flounder, (b) marbled flounder, and (c) Japanese flounder in each month for each depth class. Data from 2008 and 2009 were pooled based on the assumption that the effects of spawning aggregations superseded the differences in abundance between the two years. Certain data ($N < 3$ for each year) were excluded from the analysis. Solid (blue) and open (red) boxes indicate trawl and gillnet fisheries, respectively.

Fig. 3. Monthly changes in the ratio of catch per unit effort (CPUE) between trawl and gillnet fisheries for (a) stone flounder and (b) marbled flounder. Open circles and triangles denote data from 2008 and 2009, respectively. CPUE was the amount of capture per 1 h haul in trawl fisheries or that per net length of 500 m in gillnet fisheries. The median CPUE at depths of 40–50 m was used to determine the ratio. Dashed lines indicate the fitted curves by periodic functions.

Fig. 4. Catch per unit effort (kg per 1 h haul of trawl) of stone flounder (a), marbled flounder (b), and Japanese flounder (c) in relation to depth and season. The medians of CPUE data at each depth class each month were used. The CPUE in the gillnet fisheries was corrected and included. Data fewer than three at each depth class each month were excluded. It should be noted that trawl fisheries are prohibited during July and August and therefore data at deeper areas (>60 m deep) were not available for these months.

Fig. 5. Spatial distribution of the integrated CPUEs of gillnets and trawls (kg per 1 h haul of trawl) during the spawning seasons; (a) stone flounder in December and January, (b) marbled flounder in December and January, and (c) Japanese flounder from May to July. The median CPUE data for each 2' grid square were drawn. Data with fewer than three in each grid square for each month were excluded. The data from 2008 and 2009 were pooled. A dashed square shows the study area.

Fig. 6. Bottom water temperature (WT) in relation to depth and season in 2008 and 2009.

Monthly data obtained by Fukushima Prefecture were used.

Fig. 7. Frequency distribution of the total length of landed (a) stone flounder, (b) marbled flounder, and (c) Japanese flounder that were found at the market in 2008 and 2009, shown by Gaussian kernel density estimates (biased cross validation for bandwidth selection). Red and blue lines show the gillnet and trawl fisheries, respectively. The sample sizes (the number of individuals measured at the market) were (a) 5871 and 8343, (b) 12429 and 7475, and (c) 35811 and 45086 for gillnets and trawls, respectively.

Fig. 8. Collected depths of mature female marbled flounder from November 2008 to February 2009 and from December 2009 to February 2010. (a) Developing (yellow- or orange-coloured ovary), (b) Ripe (clear ovary with hydrated oocytes), and (c) Spent. Red and blue bars denote gillnets and trawls, respectively. Numerals show sample sizes.

Fig. 1

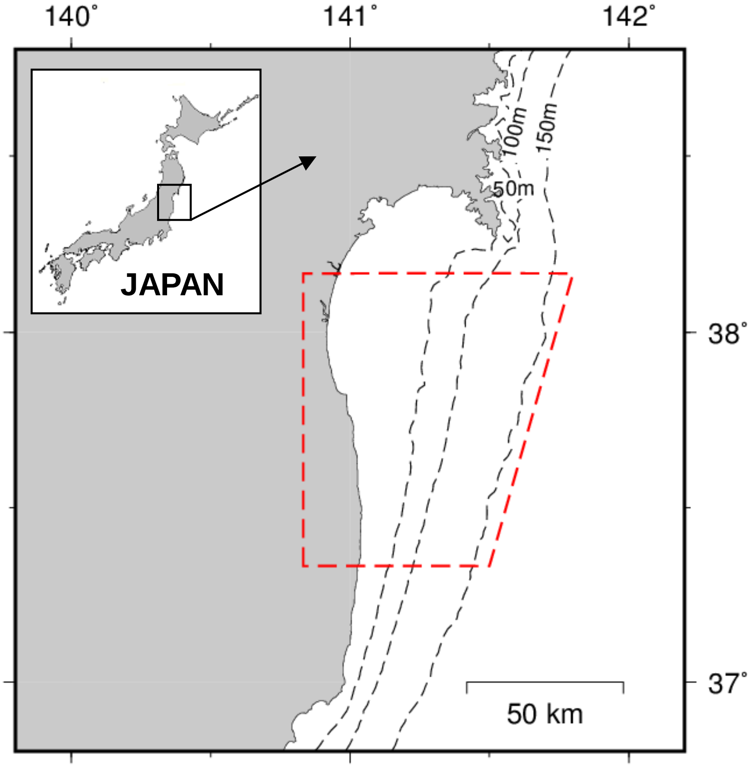


Fig. 2

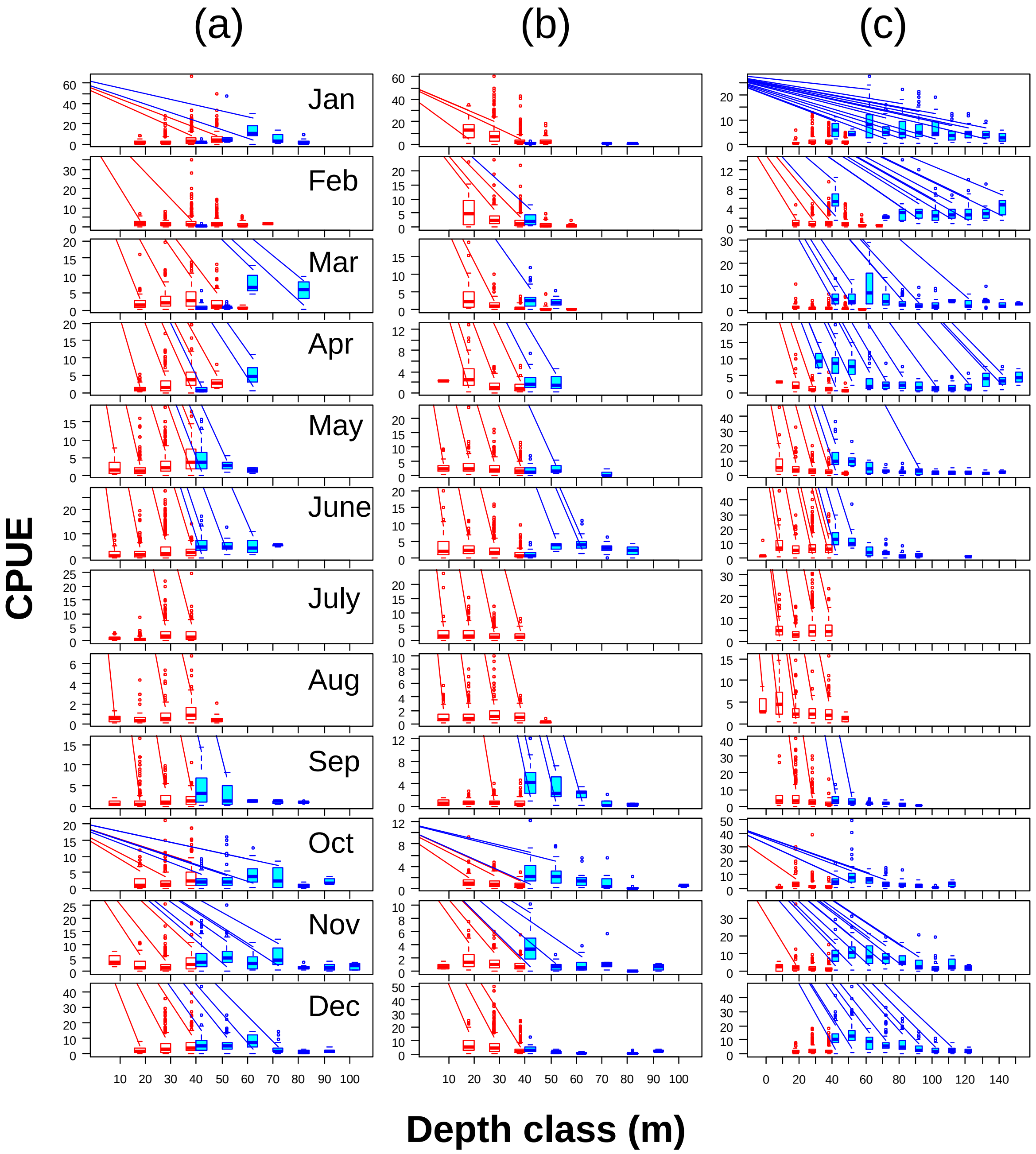

(a)
(b)
(c)
Jan
Feb
Mar
Apr
May
June
July
Aug
Sep
Oct
Nov
Dec
CPUE
10 20 30 40 50 60 70 80 90 100
10 20 30 40 50 60 70 80 90 100
0 20 40 60 80 100 120 140
Depth class (m)

Fig. 3

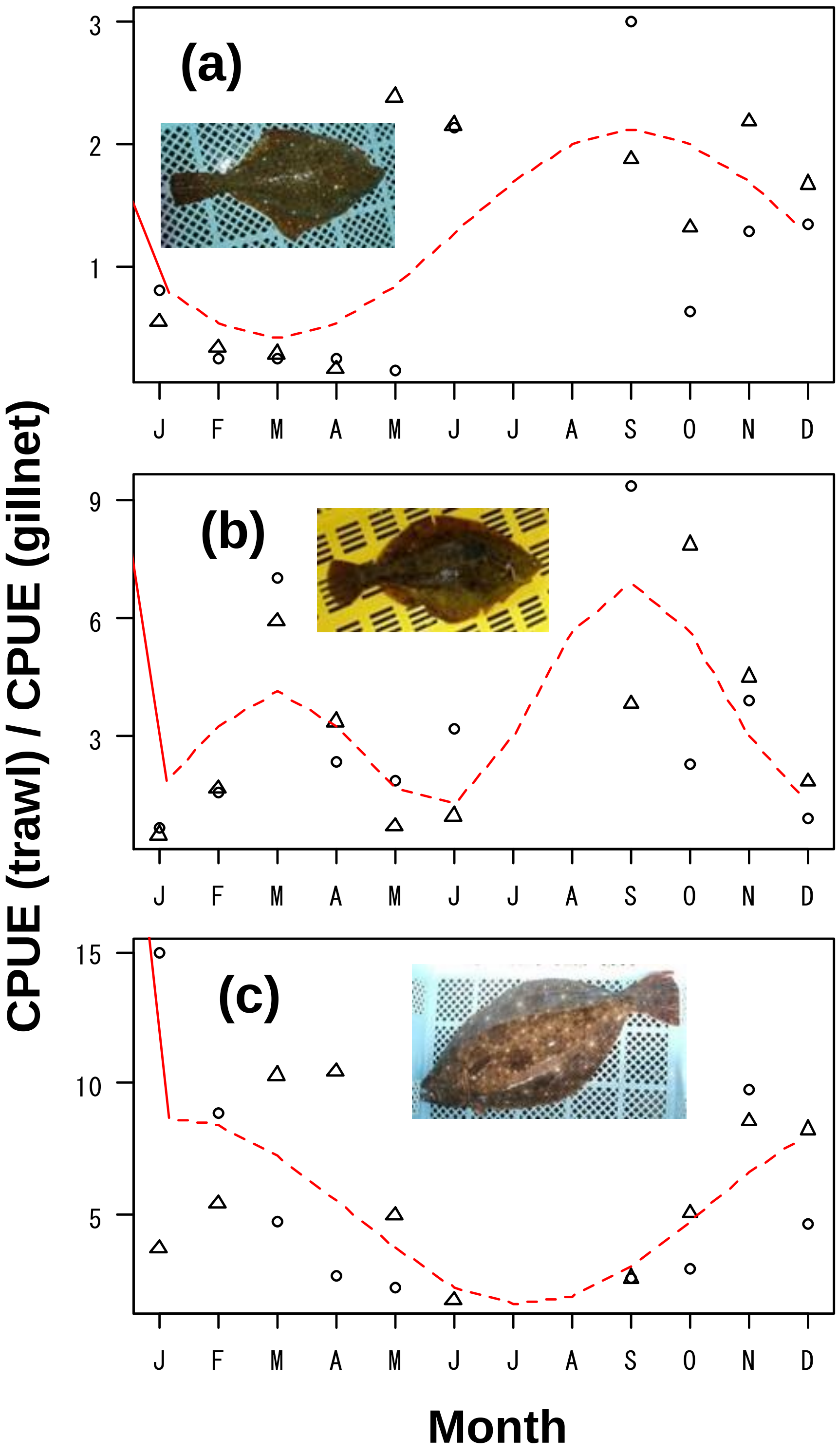

(a)
(b)
(c)
3
2
1
9
6
3
15
10
5
J F M A M J J A S O N D
CPUE (trawl) / CPUE (gillnet)
Month

Fig. 4

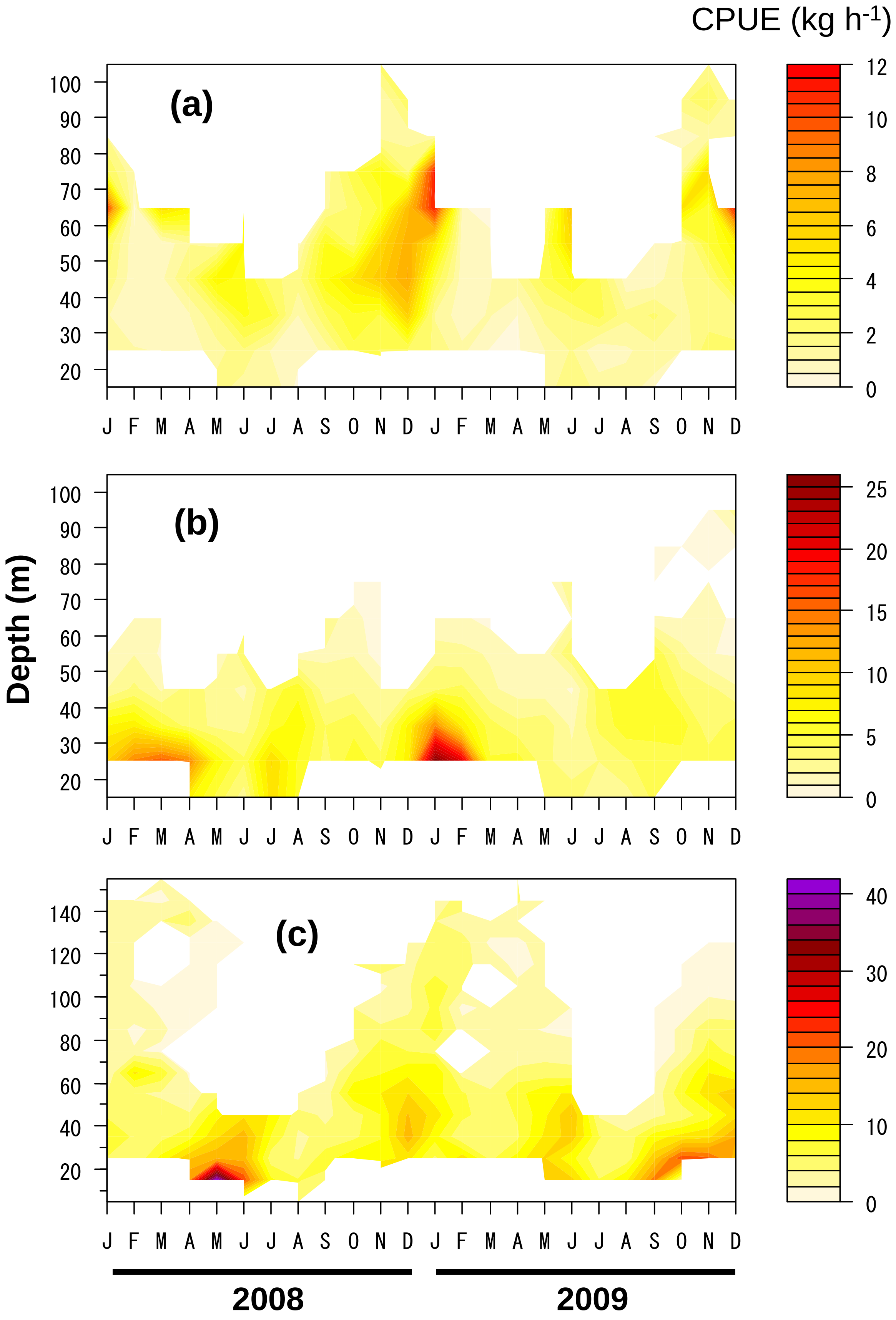

CPUE (kg h^{-1})
(a)
(b)
(c)
Depth (m)
100
90
80
70
60
50
40
30
20
140
120
0
2
4
6
8
10
12
5
15
25
30
40
J F M A M J J A S O N D J F M A M J J A S O N D
2008
2009

Fig. 5

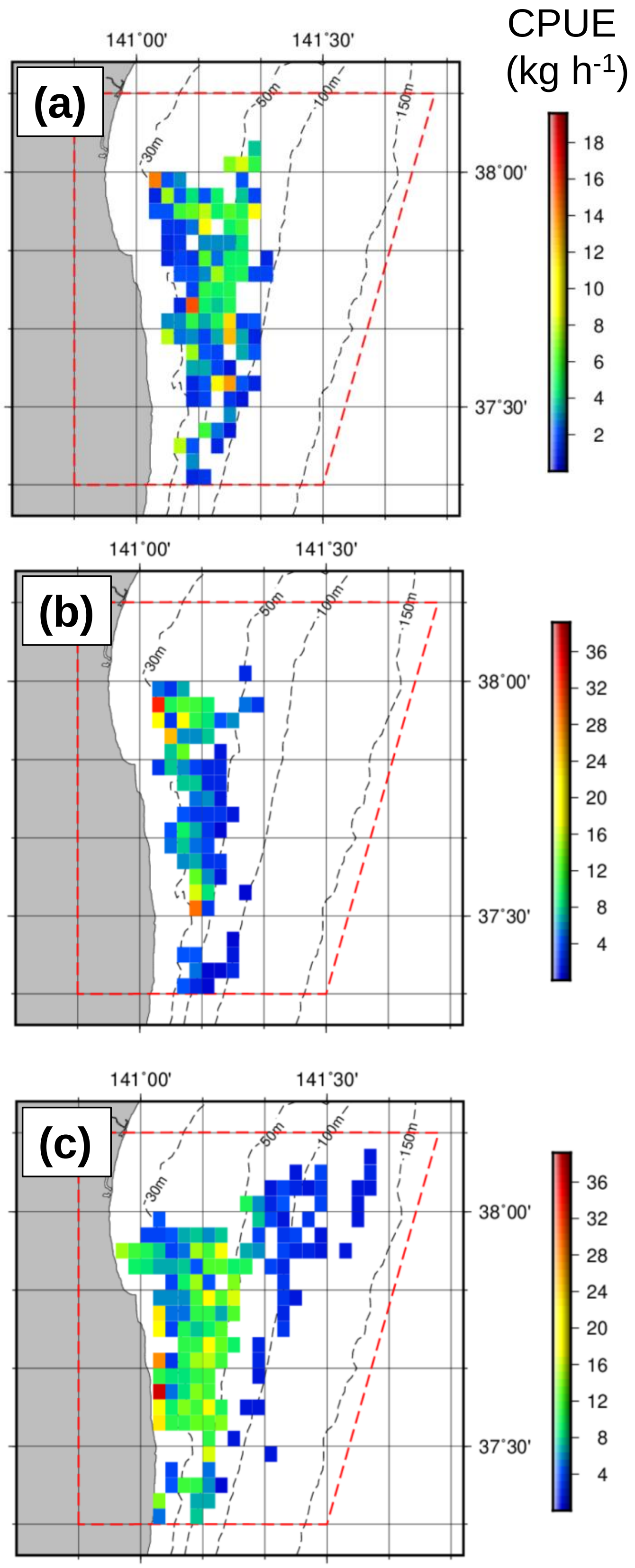

CPUE
(kg h-1)
(a)
141°00'
141°30'
38°00'
37°30'
30m
50m
100m
150m
18
16
14
12
10
8
6
4
2
(b)
141°00'
141°30'
38°00'
37°30'
30m
50m
100m
150m
36
32
28
24
20
16
12
8
4
(c)
141°00'
141°30'
38°00'
37°30'
30m
50m
100m
150m
36
32
28
24
20
16
12
8
4

Fig. 6

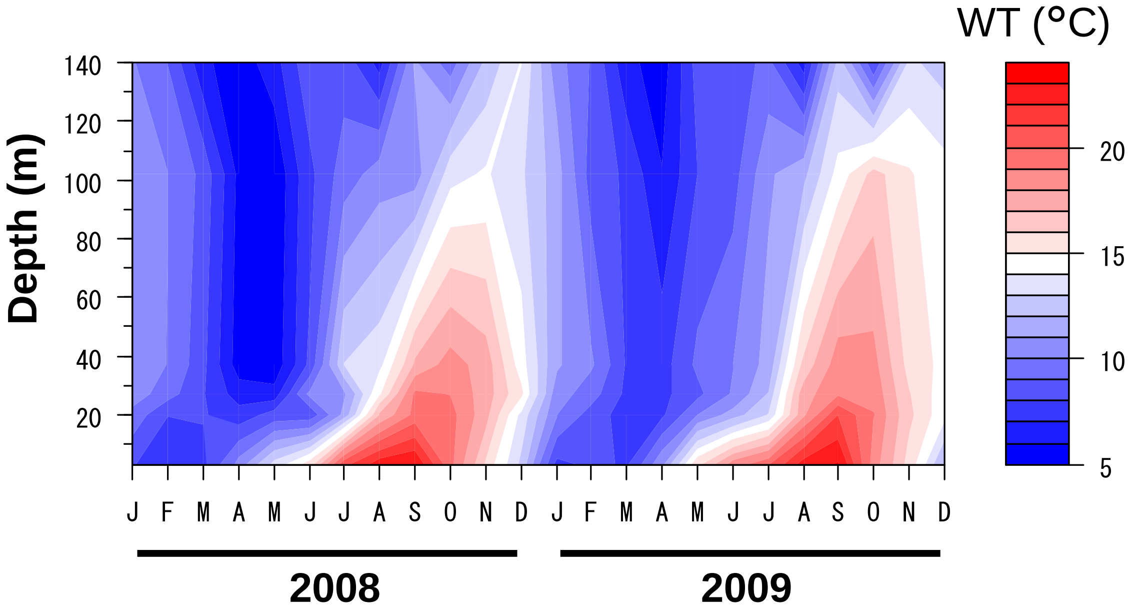

WT (°C)
20
15
10
5
Depth (m)
140
120
100
80
60
40
20
J F M A M J J A S O N D J F M A M J J A S O N D
2008
2009

Fig. 7

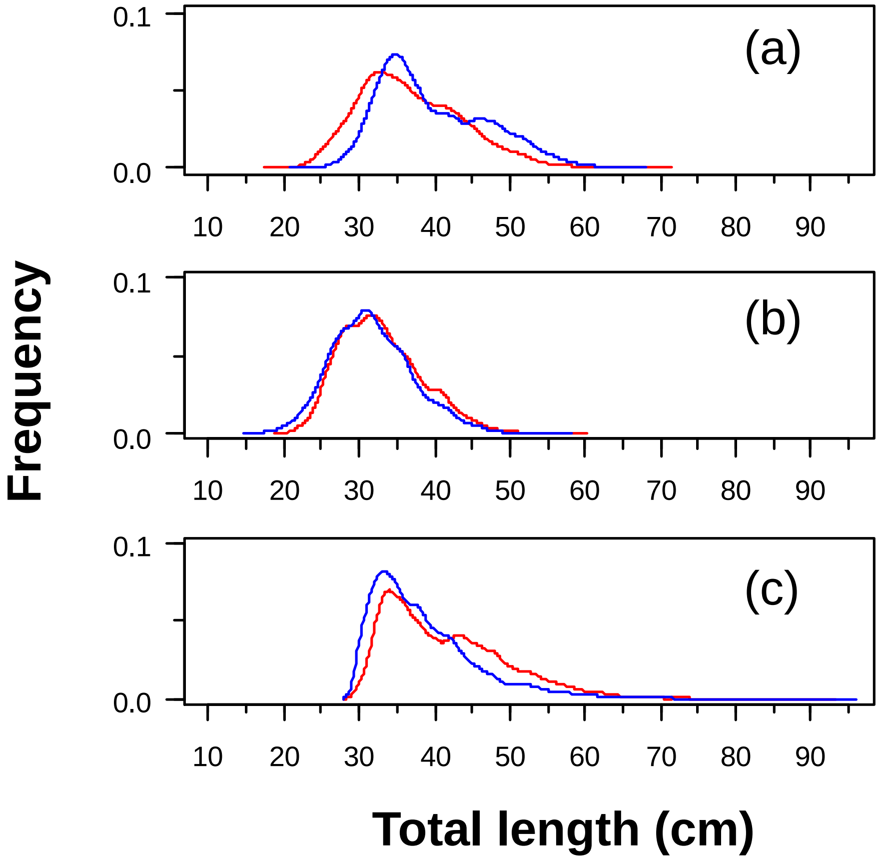
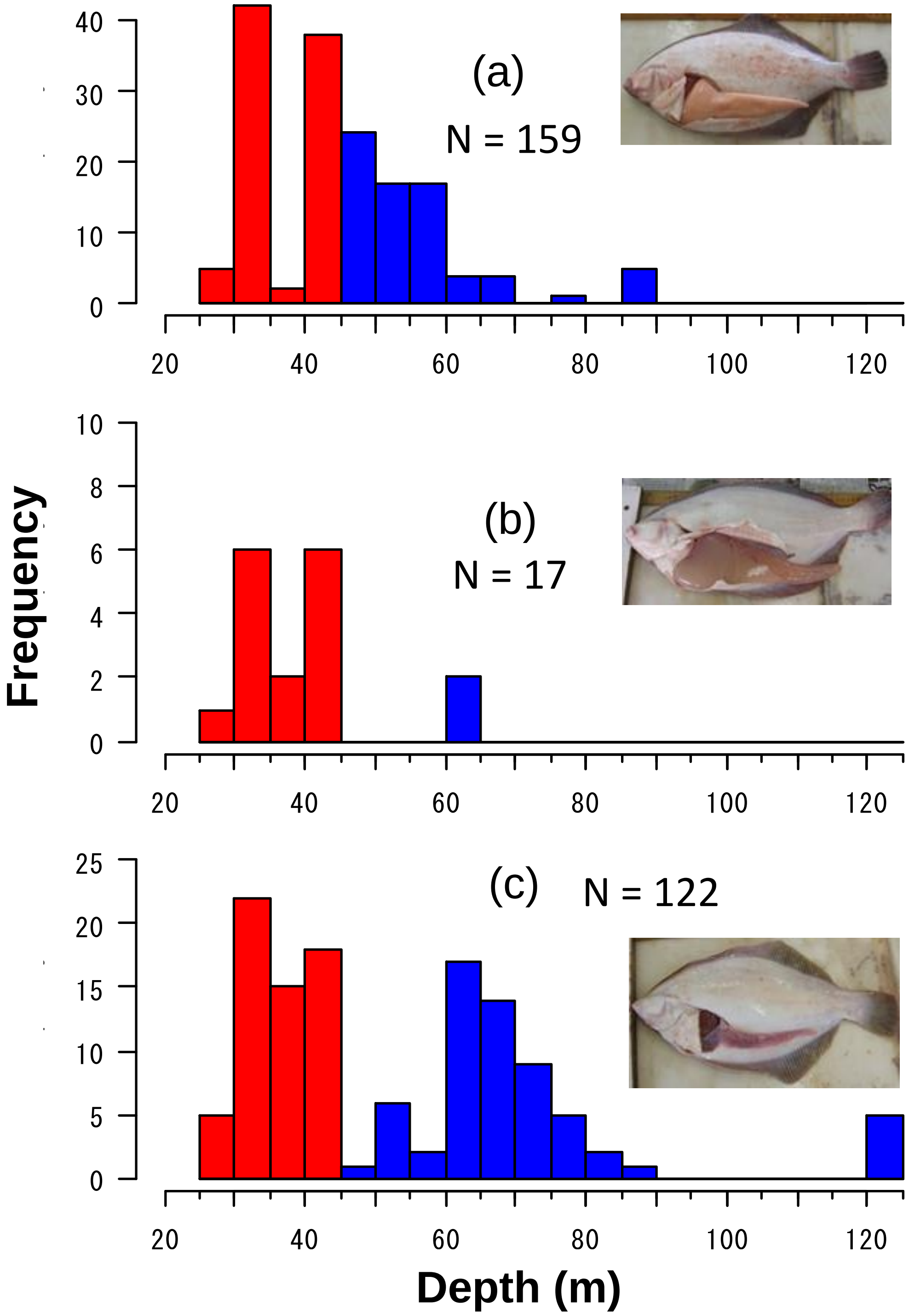

(a)
(b)
(c)
0.1
0.0
10 20 30 40 50 60 70 80 90
Frequency
Total length (cm)

Fig. 8


(a)
N = 159
(b)
N = 17
(c)
N = 122
Frequency
Depth (m)
0
10
20
30
40
0
2
4
6
8
10
0
5
10
15
20
25
20
40
60
80
100
120

Supplementary materials can be found at:

https://doi.org/10.1016/j.fishres.2020.105733