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Migration of adult Pacific herring, *Clupea pallasii*, around spawning ground revealed by an automated ultrasonic telemetry system

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Abstract— Pacific herring (*Clupea pallasii*) spawn in coastal waters of northern Japan in winter and spring. Although Pacific herring are an important target species of coastal fisheries, few studies have reported their migration around their spawning ground. In this study, ultrasonic transmitters were attached to 16 adult herring specimens, which were then released into Miyako Bay, Iwate Prefecture, Japan, in 2015 and 2016. Four automated receivers were deployed around the spawning ground in the inner bay, and the behaviors of four individuals were monitored successfully. Adult herring stayed mainly in deeper waters during the day but moved to shallower spawning areas intermittingly at night. It is likely that the fish did not spawn immediately upon reaching the spawning grounds but rather stayed around the spawning grounds for a certain period of time before spawning.

Key words: Pacific herring, spawning migration, biotelemetry, Miyako Bay

Introduction

Pacific herring (*Clupea pallasii*) spawn in the coastal waters of northern Japan in winter and early spring (*e.g.*, Kobayashi 1983, Takayanagi and Ishida 2002, Tanaka and Takayanagi 2002). Although Pacific herring is one of the important fishery species, recent herring fishery in Japan has depended on several small local stocks (*e.g.*, Ishikari Bay stock) since the largest stock of herring disappeared in 1954 (reviewed by Kobayashi 2002). In Miyako Bay (Fig. 1), the local herring stock, Miyako herring, was successfully established in the 1990s due to the release of artificially produced juveniles into the bay since 1984 (Okouchi et al. 2010).

Miyako Bay, which is located in the mid-Sanriku region of the Pacific coast of northern Japan, has a narrow configuration, with a width of approximately 4 km at the bay mouth and a depth of approximately 10 km. Eelgrass areas around Akamae (Noda et al. 2017) and Kanehama (Okada and Furukawa 2013) and a reef and sandy area around Horinai (Okada and Furukawa 2013) are distributed contiguously in the inner bay (see Fig. 1).

Larvae and juveniles of Miyako herring inhabit the inner area of Miyako Bay (Yamane 2011, Murase 2016). The herring gradually move toward the central portion of the bay with the seasonal rise in water temperature and then leave the bay to feed in northern Funka Bay in southern Hokkaido (Yawata et al. 1991, Okouchi and Chimura 2001). Miyako herring mature at the age of 2 years and return to the coastal waters of the bay to spawn (Okouchi and Chimura 2001, Nagakura et al. 2014) during January and May (Chimura et al. 2009). Pacific herring spawn adhesive eggs that are attached to seaweeds and seagrasses in shallow estuary areas (Hoshikawa et al. 2001) to increase hatching success (Taylor 1971). Fertilized eggs attached to *Zostera japonica* and *Zostera marina* were collected in 2013 and 2016 at Stn D in Miyako Bay (Yamane et al. 2019, see also Fig. 1), the main eelgrass area in the bay (Okada and Furukawa 2013), suggesting that the spawning grounds of Miyako herring are located in the shallow area of the bay.

Examining the movements of adult herring around spawning grounds can provide detailed information about their reproductive ecology, but few studies have examined these movements in Miyako Bay. Ultrasonic telemetry systems are well-known methods for tracking the movements of fish species (*e.g.*, Metcalfe and Arnold 1997, Espinoza et al. 2011, Bishop and Eiler 2017). Since the late 20th century, miniaturization of transmitters in ultrasonic telemetry systems has facilitated research into various aspects of the behavioral ecology of fish species, such as anguillids (*e.g.*, Carr and Whoriskey 2008) and salmonids (e.g., Lacroix and McCurdy 1996).

Additionally, ultrasonic telemetry systems have revealed

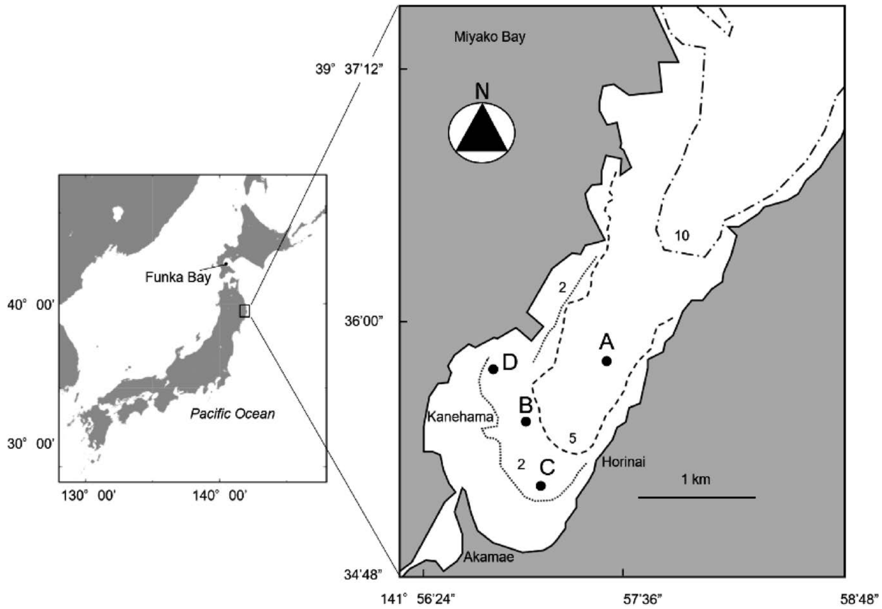

Fig. 1. Study area in Miyako Bay on the Pacific coast of northern Japan. Letters (A–D) indicate the locations of the receiver settings. Adult herring were collected and released at Stn A. Numbers represent the bottom depth (m).

the horizontal and vertical spawning migrations of adult Atlantic herring (*C. harengus*) (Lacoste et al. 2001, Langård et al. 2015) and Pacific herring (Eiler and Bishop 2016, Bishop and Eiler 2017, Tomiyasu et al. 2018) around their spawning grounds. Based on these previous studies, it should be possible to observe the spawning migration of adult herring in inner Miyako Bay. Therefore, the goal of this study was to examine the spawning migration of individuals around the shallow area of the bay using automated ultrasonic transmitters.

Materials and Methods

Fish collections

Specimens of adult herring were collected using a set net at Stn A (Fig. 1) in late January and late February of 2015 and in January of 2016. Some of these individuals were fitted with transmitters and released at Stn A. Others were transported to the laboratory, where their total length (TL, mm) was measured. The maturation stage was determined based on the condition of the gonads, according to Yamamoto (2001), by examining the gonads visually: "immature I", tight ovary with no observation of eggs by unaided eye; "immature II", tight ovary with opaque eggs; "mature", loose and elastic ovary with running, transparent yellow or orange eggs; and "postmature", loose ovary with clouded eggs. The ages of the fish were determined by counting the opaque zones in the sagittal otoliths under a stereoscopic microscope following the method of Eklund et al. (2000).

Deployment of hydrophone receivers

Vemco (Canada) model VR2w hydrophone receivers and Vemco model V13–1H coded acoustic transmitters (length, diameter, weight, and transmitter power of 36 mm, 13 mm, 6 g, 153 dB, respectively) were used to monitor horizontal movements of the herring. Four receivers were deployed in the inner area of Miyako Bay (Stns A–D, Fig. 1). Stn A (water depth c. 9 m) was the site of the sampling and release of adult fish with transmitters. Stn B (water depth c. 5 m) was located in the middle of the inner bay. Stn C (water depth c. 2 m) was located in the eastern shallow area, which is the putative feeding grounds for larvae and juveniles (Yamane 2011, Murase 2016), and Stn D (water depth c. 2 m) was located in the western shallow area, where fertilized eggs were collected (Yamane et al. 2019). The receivers at Stns A and B were slung from a set net and on an oyster raft, respectively. The receivers at Stns C and D were moored using buoys and anchors. The receivers were placed on January 15, 2015, and January 15, 2016, and retrieved on March 12, 2015, and March 18, 2016, respectively. The maximum receiving distance of a signal of the receivers is approximately 1 km (diameter), and the maximum transmitting distance of the transmitters is approximately 700 m (diameter) (https://vemco.com/range-calculator/), but these distances change according to sea conditions, obstacles, and/or passing ships around survey area. For example, Field et al. (2011) examined the maximum detection distances of V13–1H transmitters after the deployment of VR2w receivers at reefs, and reported that the distance varied between 250 m and 455 m depending on the locations.

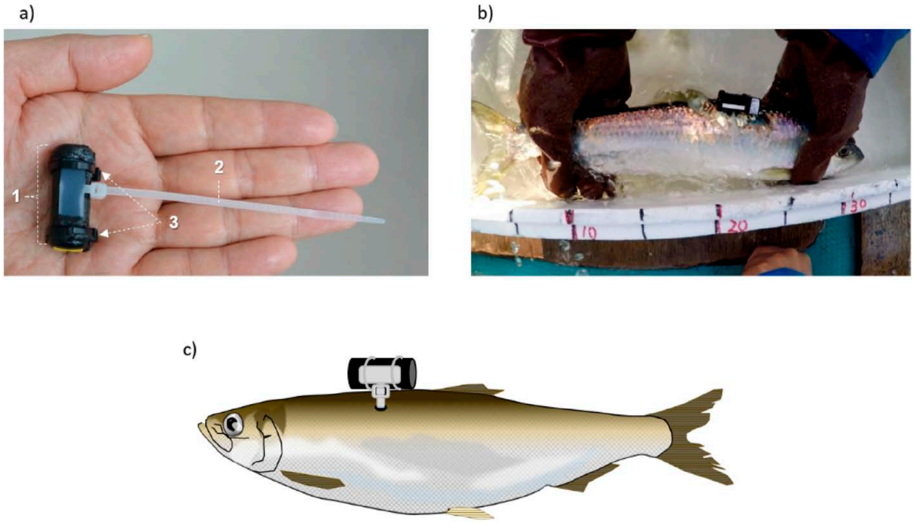

Fig. 2. a) A transmitter (1) attached to an indication tag of a white clamping band (2). The indication tag was reinforced by two small black clamping bands (3) and waterproof double-sided tape. b) Adult herring with an attached transmitter. c) Illustration of a herring with an attached transmitter.

Preparation and attachment of transmitters

Herring have small body size and are very sensitive to handling. In this study, transmitters were attached externally instead of by surgical implantation. To mount a transmitter on a fish trunk quickly, a clamping band with a flat indication tag was set using waterproof double-sided tape (Fig. 2a). Adult herring were captured using a set net near Stn A on January 26 and 28 and February 2, 4, 6, and 20, 2015, and on January 18, 20, 21, 22, 26, 27, 28, and 30, 2016. To minimize the effects of transmitter attachment to the fish, the attachment procedure was conducted in a styrene box filled with seawater. A transmitter was attached only to healthy fish with no visible bodily injury. After the TL (cm) of the fish was measured, a hole was made by penetrating a needle through the dorsal trunk in front of the dorsal fin, a location that would not result in interference with the swimming movement. The clamping band with transmitter tag was passed through the hole (Fig. 2b, c). The time duration from fish sampling to transmitter attachment for each individual was less than one minute. After observing the swimming behavior of the fish with a transmitter attached in a cage floating on the surface for a few minutes, individuals exhibiting normal swimming behavior were released at Stn A.

Data analysis

The automated receivers were retrieved in March, and the data recorded by the receivers were downloaded. Tracked individuals were typically shielded temporarily from the receivers by obstacles, such as an oyster or seaweed raft, so the signal from the individual included intermittent interruptions. When a signal was received continuously by a specific receiver, the individual was considered to be dead, and these data were excluded from the analysis. We set the sunrise as 7 AM and sunset as 5 PM referring the website of National Astronomical Observatory of Japan (https://www.nao.ac.jp/). The frequency of signal detection numbers during daytime (from 7 AM to 5 PM) and nighttime (from 5 PM to 7 AM) of each station was calculated and compared with the other stations.

Results

Fifteen adults were collected in 2015, and four of these were released after transmitters were attached. In 2016, 13 of 39 adults collected were affixed with transmitters and released. The numbers of individuals collected and released at each sampling date are shown in Table 1. Signals were received from 16 individuals over the two-year experiment. The signals from 10 of the 16 fish were recorded continuously by specific receivers, and these individuals were excluded from the following analyses. Three of the released adults were recaptured after their release: one was recaptured after four days in 2015, and one of the others were recaptured the next day, and the other was recaptured after 13 days in 2016 (see Table 1). Relatively large adults (>33 cm TL) in 2015 and smaller adults (28–33 cm TL) in 2016 were used in this experiment (Fig. 3; Table 1).

The TL range of the retained individuals was 27.0–35.9 cm (n=11; mean ± SD=33.2 ± 2.5 cm) in 2015 and 26.0–38.3 cm (n=26; mean ± SD=34.1 ± 3.1 cm) in 2016. In 2015, five of the 11 individuals retained were mature; thus, the four released individuals were likely mature and immature individuals. Ten of the retained individuals (27.1–35.9 cm TL) were 3 years old, whereas the remaining one (27.1 cm TL) was 2 years old. According to the TL range of the four transmitter-attached individuals (33.0–36.0 cm TL), the individu-

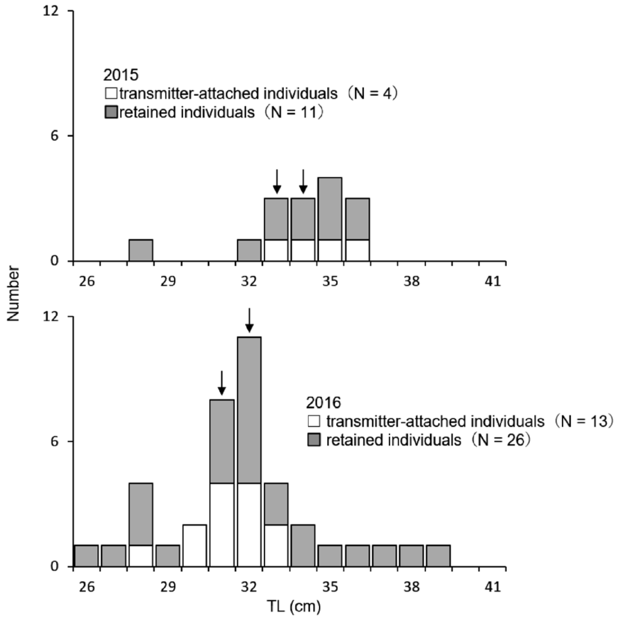

Fig. 3. The total lengths (TL) of herring collected in 2015 and 2016. Open columns indicate fish attached with a transmitter and then released; closed columns indicate fish that were retained. Arrows indicate the TLs of transmitter-attached individuals analyzed the behavior patterns.

Table 1. Collection date, number of herring collected, number of herring with a transmitter attached, and total length (TL) (range) of transmitter-attached herring.

Collection date	Collected number	Transmitter attached number	TL (range) of transmitter attached individuals (cm)
2015			
26 Jan.	4	0	—
28 Jan.	2	0	—
2 Feb.	3	3	33—36
4 Feb.	4	0	—
6 Feb.	1	1 (recaptured*)	35
20 Feb.	1	0	—
2016			
18 Jan.	8	7	31—33
21 Jan.	2	2 (both recaptured*)	28, 32
22 Jan.	7	3	30—33
26 Jan.	1	0	
27 Jan.	11	1	30
28 Jan.	7	0	—
30 Jan.	3	0	—

*The individuals unintentionally captured by commercially fishing and only transmitters were collected

als were considered to be 3 years old. In 2016, all 26 individuals retained were mature. Of these, seven (26.0–31.6 cm TL) were 2 years old, 15 (30.4–34.2 cm TL) were 3 years old, and three (TL 35.8–38.3 cm) were 4 years old. The age of one individual (TL 37.1 cm) could not be identified from its annual otolith increments. Judging from their TL range of 28–33 cm, the transmitter-attached individuals were thought to be 2 and 3 years old.

The signals from two individuals (No 1501: TL 33 cm and No 1502: TL 34 cm) in 2015 and two individuals (No 1609: TL 32 cm and No 1612: TL 31 cm) in 2016 were recorded for longer than three days (4 and 9 days in 2015 and 10 and 14 days in 2016), thus, these data were used for further analyses. In both years, signals from adult herring were detected mainly in deeper areas (Stns A and B), but relatively small numbers of signals were detected intermittently in shallower areas (Stns C and D; see Fig. 4). The individual No 1501 randomly migrated around Stns A, B, and C while No 1609 mainly stayed around Stn A (Fig. 4). The individuals Nos 1502 and 1612 showed relatively clear migration pattern that No 1502 migrated from Stn A to Stn B and then from Stn B to Stn C in 6 days. Individual No 1612 seemed to make two round trips between Stn A and Stn C via Stn B.

In 2015, the total number of signals on detection days from No 1501 tended to be higher at Stns A (n=1206), B (n=1935), and C (n=2374) than at Stn D (n=206). A comparison of the frequency of signal detection numbers during daytime and nighttime at the four stations showed that the frequency was higher during daytime than nighttime at Stn A, whereas it was higher during nighttime than daytime at Stns B, C and D (Fig. 5). The number of signals from No 1502 was higher at Stns A (n=1769) and B (n=4794) than at Stns C (n=364) and D (n=265). The frequency of signal detection number was higher during daytime than nighttime at Stns A and D, but it was higher during nighttime than daytime at Stns B and C (Fig. 5).

In 2016, the total number of signals on detection days from No 1609 was higher at Stn A (n=4988) than at Stns B (n=1792), C (n=389), or D (n=646). For No 1612, higher numbers of signals were detected at Stns A (n=59442), B (n=5495), and C (n=3871) than at Stn D (n=489). In No 1609, frequency of signal detection number was higher during daytime than nighttime at Stn A, but most of the signals were detected during nighttime than daytime at Stns B, C, and D (Fig. 5). Signals from No 1609 were detected intermittently by the receivers for 13 days, and the individual was recaptured on day 14 after its release. For No 1612, the number of signals was higher during daytime at Stn A, but it was lower during daytime at Stns B, C, and D (Fig. 5).

Discussion

In this study, the behavior of adult herring around the spawning ground in Miyako Bay, Japan, was examined using an ultrasonic automatic telemetry system. Based on the length of the signal detection period from No 1609, mature adults appeared to remain in the coastal spawning grounds for at least half a month during the spawning season. All in-

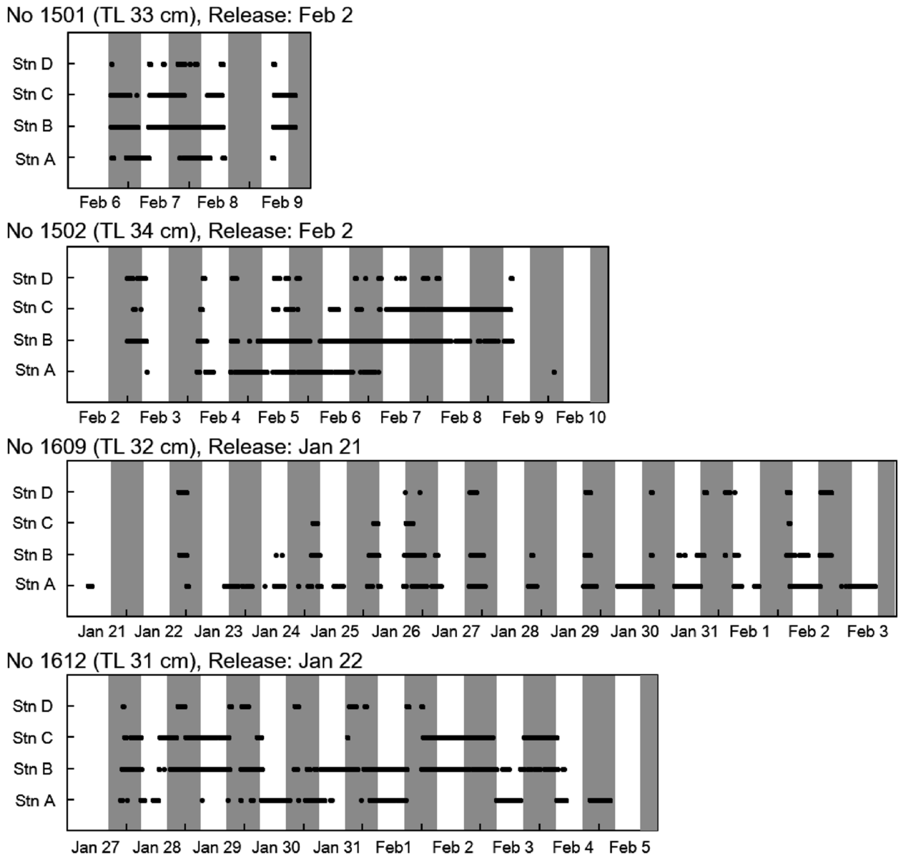

Fig. 4. Behavior patterns of adult herring at Stns A–D. Numbers indicate Nos of transmitter-attached individuals. Horizontal lines indicate the range of signal detection dates of each individual. Filled dots represent when signals from individuals were detected and at which receivers they were detected. Nighttime (5 PM to 7 AM) is indicated by the gray zone and daytime (7 AM to 5 PM) is indicated by the white zone.

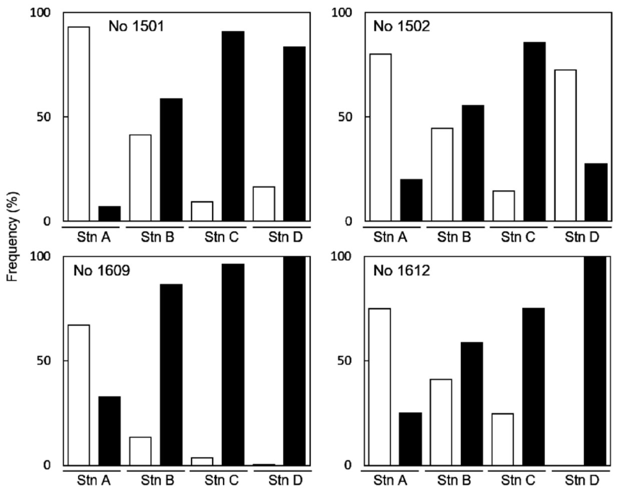

Fig. 5. Frequency of signal detection numbers from the adult herring during daytime (7 AM to 5 PM) and nighttime (5 PM to 7 AM) at Stns A–D. Numbers indicate Nos of transmitter-attached individuals. Nighttime is indicated by solid columns and daytime is indicated by open columns.

dividuals showed horizontal migrations such that individuals remained in deeper areas of the bay during daytime and migrated to shallower areas during nighttime, indicating that adults use the area as a spawning ground at that time.

Examination of the maturation stage of each individual revealed that 84% of individuals were mature, but some were immature. By tracking the movement of pre-spawning *Clupea harengus* using acoustic surveys in a semi-closed area in Norway, Langård et al. (2015) found that pre-spawning individuals gathered near the spawning grounds and moved toward the spawning grounds after the ovaries had filled the entire body cavity. In this study, some transmitter-attached individuals remained for weeks in the inner part of Miyako Bay, suggesting that immature individuals might have stayed there for a certain amount of time until they were mature enough to spawn.

Judging from the TLs, transmitter-attached individuals were considered to be 2 and 3 years old. Eiler and Bishop (2016) suggested the possibility that small-sized individuals show different migratory patterns than large-sized individuals, but no differences in movement between 2- and 3-year herring were observed in this study.

A comparison of the frequency of signals detected among the four hydrophone receivers in 2015 and 2016 showed that adults mainly swam near the deeper Stn A (c. 9 m depth) during daytime and moved to the shallower Stns

C (c. 2 m) and D (c. 2 m) during nighttime, with the exception of No 1502 that mainly swam around Stn D during daytime. For Stn B, the individuals except No 1609 remained near the station during both daytime and nighttime, whereas the No 1609 remained there mainly at nighttime. Because Stn B is located at the center of Stns A, C, and D (see Fig. 1), our data suggest that herring pass through the area of Stn B during diel migration. Pelagic fish species stay in deeper waters during daytime to avoid visual predators (Levy 1990, Clark and Levy 1988, Rosland and Giske 1994, Cardinale et al. 2003), and Pacific herring are known to spawn mainly during nighttime (Tamura et al. 1954) in coastal waters shallower than 2 m (Hoshikawa et al. 2001). Thus, Miyako herring likely stay in deeper areas during daytime to avoid predation but move to shallower areas during nighttime to spawn.

Additionally, the adult herring appeared to show repeated horizontal movements around the four receivers. A similar trend was observed by Langård et al. (2015) after adults were ready to spawn. This trend was interpreted as a change of movement from totalitarianism to individualism (Langård et al. 2015). Although the transmitter-attached individuals visited both Stns C and D (*i.e.*, shallower areas), fertilized eggs were found only at Stn D (Yamane et al. 2019). The main eelgrass area in Miyako Bay is located around Stn D (Okada and Furukawa 2013), indicating that the horizontal movement observed in this study may be exploratory behavior for substrates suitable for spawning.

We could not examine the bodies of recaptured individuals because the individuals were unintentionally captured by commercially fishing and only transmitters were stored. For this reason, we could not examine whether the transmitter-attached individuals spawned or whether the transmitter-attachment methods affected the condition of the individuals in this study. Tomiyasu et al. (2018) reported that one recaptured individual was in the process of spawning as a small amount of sperm was running out at the time. Tomiyasu et al. (2018) also reported that no serious inflammation was observed around the tag on recaptured individuals, but the method by which transmitters are attached may still severely damage the survival rate of herring. Konno (2016) suggested that using poly tubing (survival rate: 40%) instead of a clamping band (survival rate: 0%) to attach transmitters may increase the survival rate of herring. Although more than 30% of the herring to which transmitters were attached using a clamping band survived in this study, the survival rate would probably increase if the poly tube method was adopted.

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