Spatial and Temporal Distribution of Hairtail
(*Trichiurus japonicus*) in the Bungo Channel, Japan

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Abstract:
To ensure sustainable utilization of the hairtail (*Trichiurus japonicus*) fishery resources in the coastal and offshore waters of Japan, 15 acoustic surveys were conducted from 2007 to 2013 using a 38 kHz split-beam echo sounder. The hairtail was mainly distributed depth between 80 and 280 m in winter (particularly between 80–120 m), 60–280 m in depth (particularly between 120–160 m) in autumn, and 70–260 m in depth (particularly between 70–140 m) in summer. The average area backscattering coefficient (*s*a*) was higher in winter and spring between 2008 and 2009; in the other years it was highest in autumn. The average *s*a* significantly influenced by depth, temperature, salinity, and turbidity in univariate analyses (*p*<0.05). However, in linear regression analyses, the average *s*a* significantly increased only with increases in temperature and salinity, whereas the effects of depth and turbidity were not statistically significant.

Classification: Fisheries acoustics, Bioacoustics, Miscellaneous (measurements, etc.)
Keyword: *Trichiurus japonicus*, area backscattering coefficient, hairtail density

1. Introduction
The hairtail (*Trichiurus japonicus*) is a long and slender fish found throughout tropical and temperate waters worldwide.1) In Japan, hairtail migrate from south of Hokkaido to the coastal waters of the East China Sea around Japan, the Korean Peninsula, and the Yellow and Bohai seas.2) The hairtail is an important commercial species in...
Japan. The Bungo Channel and surrounding waters are the most productive hairtail fishing grounds in Japan, producing about 40% of the total catch. Although local fishermen have managed this fish resource independently, the catch has shown an apparent decline in recent years. Because hairtail fisheries are self-managed, they do not generate long-term scientific data conducive to statistical analysis, and policy formation in relation to resource management has been lacking; as a result, this industry is at risk of an over-fishing crisis. A clear understanding of the density and distribution of hairtail will help to facilitate sustainable use of this resource.

Species population parameters must be determined when estimating the density and distribution of fish schools. There is currently no estimation of the sustainable density of hairtail. The use of acoustic instruments in large areas can rapidly detect fish stocks and increase the efficiency and accuracy of population assessments. In the present study, we measured the area backscattering coefficient \( s_a \) and the distribution of hairtail from 2007 to 2013. We also assessed seasonal changes in hairtail \( s_a \) in the Bungo Channel and examined the effects of environmental factors on hairtail distribution.

2. Materials and methods

2.1 Data collection

Fifteen surveys (Table 1) were conducted from 2007 to 2013 in the Bungo Channel (ca. 33°22′N, 132°00′E) along the northern coast of Kyushu, Japan (Fig. 1). Five surveys were conducted from December to March (winter and spring), five were conducted from May to July (summer) and the remaining five were conducted from September to November (autumn). From 2007 to 2011, the surveys were performed using a Sonic KFC-3000 split-beam echo sounder (Sonic Co., Japan). In 2012 and 2013, a Sonic KCE-300 split-beam echo sounder was used in the surveys. The raw acoustic data were collected using a 38 kHz echo sounder. The echo sounder was calibrated with a 38.1 mm standard sphere before each survey.

Table 1. Seasons of acoustic surveys in the Bungo Channel, Japan.

| Season          | Year and month of survey |
|-----------------|--------------------------|
| Winter and Spring | 2007 Mar. 2008 Mar. 2009 Feb. 2010 Mar. 2011 Mar. 2012 --- 2013 --- |
| Summer          | 2007 May 2008 Jun. 2009 --- 2010 May 2011 Jul. 2012 Jul. 2013 |
| Autumn          | 2007 Nov. 2008 --- 2009 Nov. 2010 Nov. 2011 Oct. 2012 Sep. 2013 |

Fig. 1. Survey area in the Bungo Channel, Japan. The rectangle made with the dotted line indicates the Bungo Channel; the solid black line indicates the isobath.
Acoustic surveys were conducted from 5:00 (dawn) to about 17:00 (sunset) for 3 to 4 days per survey. Hairtail have a vertical diurnal migration property; they usually feed near the surface during the nighttime and migrate to the bottom in the daytime. Consequently, various tilt angles were observed during the nighttime; these angles will affect the accurate estimation of standing stock. Unstable situations must be avoided when collecting acoustic data from the hairtail record; thus, acoustic surveys were conducted during the day. The speed of the boat was maintained at ca. 5 knots during the observations.

Oceanographic information and the geographic position (latitude/longitude) were collected at fixed stations along each acoustic transect. At least 15 stations were surveyed in 2007–2011, and 18 stations in 2012 and 2013. A conductivity-temperature-depth profiler (CTD, Alec Electronics Co., Kobe, Japan) was used to profile the physical characteristics of the water column at the same time during each transect survey. Temperature (°C), turbidity (nephelometric turbidity units, NTU), and salinity (practical salinity units, psu) were binned in 1 m depth increments from the bottom to the surface prior to analysis. Temperature categories were defined in 0.01°C increments, salinity in increments of 0.01 psu, and turbidity in increments of 0.01 NTU.

### 2.2 Data analysis

The extraction of the hairtail echo was done according to the following steps.

First, researchers who had studied the overwintering migration of the hairtail (in 2007–2011) and experienced fishermen who had been catching the hairtail for 20 to 30 years (in 2012–2013) determined whether the echo track represented hairtail or not based on the shape of fish schools of hairtail in the repercussion of the echo sounder and recorded the latitude and longitude of the echo track. The tracks of the hairtail were slender, stratified, and located near the sea bottom, and were clearly distinguished from other fish tracks, and the reflection intensity was weak (Fig. 2). The distributing echo near the rugged sea floor did not belong

![Hairtail echogram. The colored bar indicates the volume backscattering strength (Sv). The yellow line is the sea bottom, and the green line indicates 0.75 m above the sea bottom.](image)

| Variable              | Specification            | KFC3000 | KCE300 |
|-----------------------|--------------------------|---------|--------|
| Survey period         | 2007–2011                | 2012–2013|        |
| Frequency             | 38 kHz                   | 38 kHz  |        |
| Beam width (deg.)     | 8.4                      | 8.5     |        |
| Pulse duration (ms)   | 0.6                      | 0.6     |        |
| Ping rate (s)         | 4                        | 5       |        |
to the hairtail’s echo as judged by the experienced captain and researchers. The area of the rugged sea floor accounted for a small proportion of the total survey area, and the reflection intensity was weak in this area. If the distributing echo near the rugged sea floor belonged to the hairtail’s echo, excluding this data would not have affected the results of this study. Several longline fishing operations were conducted in 2012 to confirm whether or not the shape of the repercussion represented hairtail.

Second, it was reported that the distribution of hairtail was about 10 m away from the sea bottom during the daytime.\(^8\) The mean depth of the area in 15 surveys was approximately 121.41 m in this study. This mean depth was substituted into the dead zone formula of Ona and Mitson (1996), resulting in a dead zone depth of 0.71 m in the present case. Therefore, the range of data analysis was set as 0.75 to 10 m above the sea bottom. The echo track of the hairtail was only analyzed in this range.

Finally, in order to remove the echo of other species to facilitate the identification of hairtail, the preanal length (PAL) of 1 cm for hairtail with swimming ability\(^{12}\) was substituted in the target strength (TS) relationship,\(^{13}\) and a minimum signal threshold of -68.3 dB was applied in the data analysis to exclude small targets such as plankton. Data were excluded when the signal was weaker than this value.

According to the above three conditions, the hairtail echo was determined in the echogram.

Raw acoustic data were analyzed in Echoview 4.9 (Myriax Pty, Ltd., Hobart, Tasmania). The \(s_a\) values at one-nautical-mile intervals were obtained by echo integration for a series of consecutive layers encompassing the water column between 10–0.75 m above the sea bottom. This study used \(s_a\) to represent hairtail density and analyzed the temporal and spatial distribution of hairtail. Analyses of acoustic survey data did not use the conventional method of TS regression equations to calculate the standing stock of hairtail mainly because the influence of various biological factors of hairtail including tilt angle,\(^{14-16}\) physiology,\(^{17}\) and others on TS remains unknown. The variability of TS measurements potentially affects the accuracy of standing stock estimates. Therefore, a range of fun-

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Fig. 3. Horizontal distribution of \(s_a\) of hairtail. Summer: May–July; autumn: September–November; winter and spring: February–March. The solid black line indicates the survey transect.
Fundamental acoustic research on hairtail is needed to estimate the precise standing stock of hairtail.

Hairtail density may be related to many factors, but the main determinant is difficult to establish. Previous studies have reported that depth, temperature, salinity, and turbidity influence the distribution of hairtail. Therefore, this study made use of environmental factors to infer possible changes in the density of hairtail by investigating the relationships between acoustic density and temperature, salinity, turbidity, and depth. Relationships between $s_a$ and these marine environmental variables were assessed by simple linear regression analysis. The relationships between the $s_a$ of hairtail and environmental variables were assessed using univariate analysis of variance by SPSS software (SPSS, Inc., Chicago, IL).

3. Results
3.1 Spatial distribution

In terms of the horizontal distribution, during summer, hairtail were dispersed and not particu-
larly concentrated in specific waters, especially in 2012 and 2013 (Fig. 3). However, they tended to be distributed in deeper waters and more intensively concentrated at the deepest isobaths in the autumn. At this time, the $s_a$ value was higher than in other seasons. In winter and spring, the hairtail were still concentrated in deep waters.

In terms of the vertical distribution, Fig. 4 shows that the average $s_a$ was mainly distributed depth between 80–280 m in winter (especially in the 80–120 m range); in autumn the average $s_a$ was distributed between 60–280 m in depth (especially in the 120–160 m range), while in summer the average $s_a$ was distributed between 70–260 m (especially in the 70–140 m range). This shows that the hairtail distributed in the water layers fall into two groups; whatever the season, one group permanently remains between 70–120 m. As the seasons change, a group emerges that gradually migrates to deeper waters. Because fish migrate toward the deep sea, the average $s_a$ shows significant differences in all water layers. Seasonal and depth impact analysis for $s_a$ was performed using ANOVA. The results showed that $s_a$ showed significant differences depending on the season, depth, and the interaction of season and depth (seasonal, $F=52.48$, $p<0.001$; depth, $F=3.50$, $p<0.05$; seasonal* depth, $F=2.64$, $p<0.05$). The average $s_a$ in 2008 and 2009 was highest in winter and spring; in the other years it was highest in autumn (Fig. 5). In other words, the average $s_a$ showed the least seasonal changes in summer, reached a peak in autumn, and was slightly lower in winter than in autumn.

### 3.2 Environmental variables and hairtail density

Univariate analysis of variance revealed that $s_a$ was significantly affected by depth, temperature, salinity, and turbidity (Table 3). Post-hoc comparisons (Scheffe’s tests) showed that $s_a$ was increased at higher water temperatures and that the fish were mainly distributed in waters of 20.7–24.4°C in temperature, 32.87–33.24 psu in salinity, and low turbidity (0.27–2.73 NTU).

Linear regression analysis was also used to examine correlations between $s_a$ and environmental variables, and the following equation was obtained:

$$ Y = -0.30 (X_{depth}) + 0.18 (X_{temperature}) - 0.34 (X_{salinity}) $$

Fig. 5. Estimates of average $s_a$ ($m^2/m^3$) in the Bungo Channel between 2007 and 2013. The bar chart in gray indicates summer. The bar chart in black indicates autumn. The bar chart in white indicates winter and spring.
+0.08 (Y_{turbidity}) + 1.495. The correlation coefficient between \( s_a \) and the environmental variables was \( R = 0.62 \), and the coefficient of determination \( (R^2) \), sum of squares of the regression, and sum of squares of the residual were 0.38, 87.26, and 142.81, respectively \( (p<0.05) \), indicating that \( s_a \) was strongly and positively correlated with environmental variables. The \( s_a \) significantly increased with increasing temperature and salinity \( (\beta = -0.18 \) and \( -0.34 \), respectively) whereas the effects of depth and turbidity were not statistically significant. These results suggest that higher temperatures \( (ca. 20.7–24.4^\circ C) \) and salinity \( (33.24–33.56 \) psu) are favorable for hairtail growth and thus are associated with higher resource density.

4. Discussion

4.1 Spatial distribution

The spawning periods for hairtail in the Bungo Channel occur from May to June and from September to October. During the summer in this area, hatching can occur in 48 h when water temperatures are \( ca. 26–28^\circ C \). Juvenile hairtail inhabit coastal waters and migrate to deeper areas when they mature. Those that hatch in spring and summer migrate to deeper waters in autumn after 4–5 months of growth; the distribution and density trends observed here were consistent with that pattern. Hairtail that hatched during September and October (autumn) exhibited low growth rates from November to March when water temperatures were low. Thus, we speculated that hairtail that hatched in autumn migrated to deeper waters the following summer (Fig. 3). However, lower survival rates occurred in fish that were juveniles during winter, so the \( s_a \) of hairtail was not significantly higher during summer. The fish remained in shallow waters during summer, while in autumn they stayed in deeper areas and were present at relatively higher densities (Fig. 4). Presumably, during the process of growth and development, the feeding habits of hairtail change from planktophagy to ichthyophagy to suit their physiological requirements and resource availability. In winter, some hairtail migrate to offshore waters and some to deeper areas, which can explain the decline in density observed here.

4.2 Environmental variables and \( s_a \)

Environmental factors also affect the distribution of hairtail (Table 3). Higher water temperatures can promote marine productivity, thus providing abundant food for juvenile fish. In addition, such temperatures are conducive to reproductive development and lead to accelerated spawning rates, a prolonged larval growth period, and increased spawning efficiency. Therefore, temperature is an important factor affecting the
and distribution of hairtail. The turbidity and salinity of seawater are affected by runoff from terrestrial areas. Hence, because larvae stay in shallow coastal waters to feed during the planktonic period, runoff characteristics affect the distribution of larvae and thus juveniles. Adults have also been shown to feed in harbors and estuaries, and many organisms in such waters are susceptible to turbidity and salinity. Therefore, we predict that the distribution of adult hairtail is also indirectly affected by turbidity and salinity. Therefore, we predict that the distribution of adult hairtail is also indirectly affected by turbidity and salinity. However, the factors affecting hairtail distribution are complex; we will examine additional environmental factors in future studies to improve our understanding of these dynamics.

4.3 Hairtail habits and TS relationships

TS measurement for hairtail was only reported by Zhao. That study was conducted in both day and night, and the targets were only juvenile hairtail. From an ecological point of view, hairtail feed in the nighttime, so the tilt angles of hairtail may be very changeable. TS would be very unstable if the experiment was conducted at nighttime. In addition, prey may also be recorded along with hairtail when they are feeding, leading to erroneously strong TS values erroneously being obtained. If in situ TS measurements are not conducted with care, several fish may be identified as just one fish, producing erroneously strong TS values. In Zhao, the standing stock of hairtail was evaluated based on the TS relationship, which may lead to errors, so acoustic surveys were carried out in the daytime and the targets were adult fish in this study. Therefore, the TS relationship used by Zhao was not suitable for evaluating the standing stock of hairtail in this study. A high rate of estimation accuracy is also needed in investigations of hairtail in Bungo Channel waters so that the use of PAL and the determination of TS can be confirmed. In the future, additional measurements of hairtail TS will be performed to establish suitable values for estimating the standing stock in the Bungo Channel.

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