Characteristics of a Pacific herring *Clupea pallasii* spawning bed off Minedomari, Hokkaido, Japan

HIROSHI HOSHIKAWA,1* HISAMI KUWAHARA,2 KEN-ICHIRO TAJIMA,3 TADASHI KAWAI,4 TOMONORI KANETA1 AND FUJINORI TSUDA1

1Hokkaido Central Fisheries Experimental Station, Yoichi, Hokkaido 046-8555, 2Fisheries Research Agency (NRIFE), Ebidai, Hasaki, Ibaraki 314-0321, 3Hokkaido Institute of Mariculture, Shikabe, Hokkaido 041-1404 and 4Hokkaido Nuclear Energy Environmental Research Center, Kyowa, Hokkaido 045-0123, Japan

**ABSTRACT:** The spawning bed selection of herring *Clupea pallasii* off Minedomari, Atsuta, on the west coast of Hokkaido, Japan, is discussed in relation to the topography of the rocky shore and wave conditions during the spawning season. From 1998 to 2003, herring have spawned their eggs mainly on the leaves of the seagrass *Phyllospadix iwatensis* Makino in almost the same site on the rocky shore off Minedomari in the Atsuta area. The site is connected to a valley-like feature offshore. Wave conditions were surveyed at Minedomari during the spawning season in 2000 and the wave height was estimated from 1998 to 2003, except for in 2000, using the correlation of wave height between Minedomari and Ishikari Bay New Port, approximately 18 km south-west of Minedomari. Herring spawned under calm conditions, during which the wave height was approximately 0.5 m off Atusta and Aoshima and was 0.18–1.28 m off Minedomari. The distribution of water particle velocity on the sea bottom surface as a result of ocean waves off the Minedomari area, which was estimated based on the wave height and the topography of the coast, suggested herring could swim easily into the shallower area along the valley-like feature off Minedomari. Therefore, topographical features are thought to be one of the reasons why herring have used Minedomari as a spawning bed. Additionally, seepage of freshwater from the bottom, which was observed in this area, could also be the reason why herring spawn in Minedomari repeatedly.

**KEY WORDS:** herring, spawning bed selection, topography, wave condition.

**INTRODUCTION**

Pacific herring *Clupea pallasii* deposit eggs on vegetation in the intertidal and subtidal zones.1–7 Ishikari Bay herring, which is a local population of the Pacific herring along the north-west coast of Hokkaido, Japan, also spawn on vegetation, especially on the seagrass *Phyllospadix iwatensis* Makino and on the Sargassum algae *Cystoseira hakodatensis* (Yendo) Fensholt and *Sargassum confusum* C. Agardh.8,9 Although rich vegetation covers most of the Atsuta coast, dense spawning beds of herring are restricted to certain areas, such as Minedomari (Fig. 1).8 Therefore, other factors, such as topography, wave conditions and the effect of the Ishikari River and other small rivers, might also be important to the spawning bed selection of herring in this area.

In the present study, the spatial distribution of the spawning bed was examined, underwater observations were made, the bottom topography off Minedomari was surveyed and the wave height off the coast was measured during the spawning season. Based on these data, the reasons why herrings spawn eggs off Minedomari year by year are discussed in relation to the wave conditions and other environmental conditions.

**MATERIALS AND METHODS**

**Study area**

Field investigations were conducted along the coast of Atsuta, Ishikari Bay, located on the west coast of Hokkaido, northern Japan, from February to April during 1998–2003 (Fig. 1; Table 1). From Atsuta to Minedomari, there is a natural platform-like rocky shore. But from Mourai to the mouth of the Ishikari River, the coast is a sandy beach except for only a
narrow area just south of Mourai. The sea bottom slope is steep in the northern part and gentle in the southern part of this coast. The rocky shore is covered by dense vegetation. *Laminaria* spp. (*Laminaria religiosa* Miyabe in Okamura, *Laminaria ochotensis* Miyabe in Okamura and *Laminaria cichorioides* Miyabe in Okamura) were dominant in the biomass, followed by *C. hakodatensis* and *P. iwatensis*. These species accounted for approximately 90% of the biomass. *Laminaria* spp. were distributed in the exposed zone at the edge of the platform, *C. hakodatensis* was found in the sheltered zone and *P. iwatensis* was found in the intermediate zone on the rocky shore. Minedomari was selected as the main study area because four dense spawnings occurred between 1998 and 2003. There is a small harbor and the rocky shore, which is shallower than approximately 1 m, is well developed on both sides of the harbor. A small river, the Minedomari River, flows into the sea just south of the harbor. There are some groove-like channels running from north-west to south-east on the south of the harbor and river. The channels are approximately 2.0–3.0 m wide and deep at the seaward mouth and taper to approximately 1.0 m wide and 0.5 m deep at the shoreward edge.

**Survey for the spawning bed of herring on the Atsuta coast and estimation of the spawning period**

The herring fishery starts from early February or the end of January and continues to the end of March off the Atsuta coast every year. To clarify the spawning period, field observations were carried out every 7–10 days between February and April from 1999 to 2003 by snorkeling off Minedomari. The survey was carried out along transect lines 2–8 each time (Fig. 2). Surveys for the spawning bed distribution from Atsuta to Minedomari and the rocky shore off Mourai from the end of February to mid-March, the main herring fishing season, were also carried out by snorkeling.

Underwater observations were also conducted by scuba at a depth of 3 m off Minedomari on 10 April 1998 and on 21 February 2003. When eggs were found in the survey, samples were collected and the area of the spawning bed was measured. In the case of small beds, four or five samples were collected in the bed using a small quadrat (25 cm × 25 cm) and the area was measured using a tape measure. The area of large beds were measured using the transect lines off Atsuta in 2000 and off Minedomari in 1998, 1999 and 2003, and a theodolite (EDM GTS-2B; Topcon Co., Tokyo, Japan) off Aoshima in 2001 and off Minedomari in 2000. Seagrass and algae with eggs were collected using a small quadrat every 10–20 m along the transect lines and random sampling in the case of the theodolite surveys.

The eggs on the algae and seagrass were counted and all or some of the eggs were fixed in 5% formalin immediately in order to observe the developmental stage. The spawning period was estimated using the number of days from fertilization to each developmental stage. At least 100 eggs were observed from each sample. In the case of large spawning beds, the total number of eggs was estimated based on the mean density and the area of the bed.

Temperature during spawning season was measured using a small instrument Optic StowAway Temp Logger (Onset Co., Pocasset, MA, USA) in 1998 and 1999, and using an MDS-CT instrument (Alec Electronics Co., Kobe, Japan) from the end of January to May from 2000 to 2003. These instruments were set on the bottom near the channels at a depth of 0.7 m (Fig. 2).

**Locations of the spawning beds, bottom topography and wave conditions off Minedomari**

The boundary of the spawning bed was recorded along each transect line shown in Fig. 2 and the area of the bed was mapped using the data surveyed on 10 April 1998, 25 March 1999, 16 April 1999 and 21 February 2003. In 2000, the boundary was measured by a theodolite and the location of the beds was mapped.
Table 1  Spawning beds of herrings along the coast of Atsuta from 1998 to 2003

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Survey date</th>
<th>Estimated spawning date</th>
<th>Depth (m)</th>
<th>Area (m²)</th>
<th>Mean egg density n (×10⁴/m²)</th>
<th>Total No. eggs (×10⁶)</th>
<th>Species of vegetation on which herring spawned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>Minedomari</td>
<td>10 April</td>
<td>26–28 March</td>
<td>0.4–2.0</td>
<td>13 250</td>
<td>24.2</td>
<td>3207</td>
<td>Phyllospadix iwatensis, Cystoseira hakodatensis</td>
</tr>
<tr>
<td></td>
<td>Minedomari</td>
<td>25 March</td>
<td>1–2 March</td>
<td>0.4–1.2</td>
<td>10 650</td>
<td>9.6</td>
<td>1022</td>
<td>Phyllospadix iwatensis, Cystoseira hakodatensis</td>
</tr>
<tr>
<td></td>
<td>Minedomari</td>
<td>16 April</td>
<td>8 April</td>
<td>0.3–1.0</td>
<td>4 500</td>
<td>7.5</td>
<td>338</td>
<td>Phyllospadix iwatensis, Cystoseira hakodatensis</td>
</tr>
<tr>
<td></td>
<td>Kotan</td>
<td>9 April</td>
<td>1–2 March, 8 April</td>
<td>0.4–1.2</td>
<td>800</td>
<td>ND</td>
<td>ND</td>
<td>Phyllospadix iwatensis</td>
</tr>
<tr>
<td></td>
<td>Mourai</td>
<td>16 April</td>
<td>20 March–8 April, 11–12 April</td>
<td>0.5–1.2</td>
<td>35</td>
<td>ND</td>
<td>ND</td>
<td>Phyllospadix iwatensis</td>
</tr>
<tr>
<td>2000</td>
<td>Minedomari</td>
<td>21 March</td>
<td>18 March</td>
<td>0.4–1.0</td>
<td>2 455</td>
<td>15.5</td>
<td>381</td>
<td>Phyllospadix iwatensis</td>
</tr>
<tr>
<td></td>
<td>Minedomari</td>
<td>21 March</td>
<td>18 March</td>
<td>0.5–1.2</td>
<td>7 256</td>
<td>19.6</td>
<td>1422</td>
<td>Phyllospadix iwatensis</td>
</tr>
<tr>
<td></td>
<td>Atsuta</td>
<td>6 April</td>
<td>18 March</td>
<td>0.5–1.8</td>
<td>24 000</td>
<td>2.8</td>
<td>672</td>
<td>Cystoseira hakodatensis</td>
</tr>
<tr>
<td>2001</td>
<td>Minedomari</td>
<td>24 February</td>
<td>Early February</td>
<td>0.5–1.0</td>
<td>25</td>
<td>ND</td>
<td>ND</td>
<td>Phyllospadix iwatensis</td>
</tr>
<tr>
<td></td>
<td>Minedomari</td>
<td>10 March</td>
<td>5–6 March</td>
<td>0.5–0.7</td>
<td>35</td>
<td>3.7</td>
<td>1</td>
<td>Phyllospadix iwatensis</td>
</tr>
<tr>
<td></td>
<td>Atsuta</td>
<td>26 March</td>
<td>26 March</td>
<td>1.0</td>
<td>50</td>
<td>1.0</td>
<td>1</td>
<td>Phyllospadix iwatensis</td>
</tr>
<tr>
<td></td>
<td>Kotan</td>
<td>30 March</td>
<td>26 March</td>
<td>1.1–1.2</td>
<td>200</td>
<td>ND</td>
<td>ND</td>
<td>Phyllospadix iwatensis</td>
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<tr>
<td></td>
<td>Kotan</td>
<td>30 March</td>
<td>26 March</td>
<td>0.7–0.8</td>
<td>350</td>
<td>ND</td>
<td>ND</td>
<td>Phyllospadix iwatensis</td>
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<tr>
<td></td>
<td>Aoshima</td>
<td>8 April</td>
<td>26 March</td>
<td>0.4–1.5</td>
<td>55 000</td>
<td>5.4</td>
<td>2970</td>
<td>Phyllospadix iwatensis, Cystoseira hakodatensis, Sargassum confusum</td>
</tr>
<tr>
<td></td>
<td>Mourai</td>
<td>18 March</td>
<td>4–7 March</td>
<td>0.8–1.0</td>
<td>1 000</td>
<td>20.7</td>
<td>207</td>
<td>Phyllospadix iwatensis</td>
</tr>
<tr>
<td>2002</td>
<td>Minedomari</td>
<td>17 February</td>
<td>6–7 February</td>
<td>0.7</td>
<td>35</td>
<td>2.8</td>
<td>1</td>
<td>Phyllospadix iwatensis</td>
</tr>
<tr>
<td></td>
<td>Mourai</td>
<td>18 March</td>
<td>Early February</td>
<td>0.7</td>
<td>150</td>
<td>7.7</td>
<td>12</td>
<td>Phyllospadix iwatensis</td>
</tr>
<tr>
<td>2003</td>
<td>Minedomari</td>
<td>21 February</td>
<td>2–4 February</td>
<td>0.3–1.3</td>
<td>13 500</td>
<td>7.8</td>
<td>1053</td>
<td>Phyllospadix iwatensis, Sargassum confusum, Mazzaella japonica</td>
</tr>
<tr>
<td></td>
<td>Minedomari</td>
<td>1 March</td>
<td>14–15 February</td>
<td>2.5–3.0</td>
<td>50</td>
<td>6.3</td>
<td>3</td>
<td>Mazzaella japonica, Tichocarpus crinitus</td>
</tr>
<tr>
<td></td>
<td>Kotan</td>
<td>25 February</td>
<td>Early February</td>
<td>1.0</td>
<td>2 025</td>
<td>4.8</td>
<td>97</td>
<td>Phyllospadix iwatensis</td>
</tr>
</tbody>
</table>

ND, no data.
Characteristics of a herring spawning bed

To measure the bottom current speed at the entrance of grooves, the same wave height meter, with a biaxial electromagnetic current meter equipped, was set at a depth of 3 m from the bottom from 24 January to 31 March 2001 (Fig. 2).

Distribution of water particle velocity on the sea bottom surface as a result of ocean waves off the spawning bed

The distribution of the water particle velocity on the sea bottom surface as a result of ocean waves off the Minedomari area was calculated using the wave height data measured off Minedomari in 2000. The wave field, including the surf zone, was calculated with the energy balance equation. The field used for the calculation was 1600 m along the coast by 1000 m across the coast, and was subdivided into 4000 small squares for which the length of one side was 20 m. The wave orbital velocity on the seabed was calculated using the small amplitude wave theory. We used the characteristic wave values of wave height, wave period and wave direction to obtain the bottom wave velocity during the spawning period. They were 0.5 m, 5.0 s and northwest, respectively, based on the results of the wave heights surveyed off Minedomari during the spawning season.

RESULTS

Distribution of spawning beds and spawning period along the coast of Atsuta

In the period from 1998 to 2003, large spawning beds of herring were observed off Atsuta (2000), Aoshima (2001) and Minedomari (1998, 1999, 2000 and 2003) (Table 1). Small spawning beds were also recognized off Kotan (1999, 2001 and 2003), Minedomoari (2001 and 2002), and Mourai (1999, 2001 and 2002). Spawning occurred off Minedomari twice, in early March and again in early April, in 1999. In the case of Minedomari in 2000, two spawning beds appeared in the same period, a small one located near the harbor and a large one located along the area of the groove-like channels.

Almost all the beds were located in areas shallower than 2.0 m except for one small bed off Minedomari in 2003, which was located at a depth of 2.5–3.0 m.

One of the common points to all the spawning beds was the dense vegetation. Herring deposited eggs mainly on the seagrass P. iwatensis, followed by C. hakodatensis, S. confusum, Sargassum miyabei Yendo and Mazzaella japonica (Mikami) Hommersand in Hommersand et al. Another common
point was the occurrence of small rivers and brooklets near the beds.

The mean daily water temperature was 2–3°C in February, 4–6°C in March, 6–9°C in April and 10–13°C in May. The spawning periods of large beds were estimated based on the developmental stage of eggs or embryos and water temperature as follows: 26–28 March 1998, 1–2 March and 8 April 1999, 18 March 2000, and 2–4 February 2003 off Minedomari; 18 March 2000 off Atsuta; and 26 March 2001 off Aoshima.

The mean density of herring eggs was from 10 000 eggs/m² to 242 000 eggs/m². The total number of eggs estimated in each large bed was 3207 million eggs in April 1998, 1022 million eggs in March and 338 million eggs in April 1999, 381 million eggs and 1422 million eggs in March 2000, and 1053 million eggs in February 2003 off Minedomari; 672 million eggs in April 2000 off Atsuta; and 2970 million eggs in April 2001 off Aoshima (Table 1).

**Distribution of spawning beds and bottom topography off Minedomari**

Herring spawned off Minedomari every year after 1998, although there were differences in the size of spawning beds. The locations of the beds from 1998 to 2003 are shown in Fig. 3. All spawning beds were formed to the south of the Minedomari harbor within approximately 200 m of the harbor. The name ‘spawning ground’ was used for the place according to Aneer.16

A narrow but dense spawning site was found at 3 m in depth in front of the Minedomari River on 21 March 2003 by scuba diving observation. The area was approximately 50 m², but mean egg density was 63 000 eggs/m². The value was the same as that of the bed in the shallow area off Minedomari. The diver observed the seepage of fresh water at the bottom of the spawning site on 21 February. The seepage had disappeared by the observation on 1 March. It seemed that the fresh-water seepage from the bottom was limited to only a short period responding to the snow melting season.

The bottom topography off Minedomari is shown in Fig. 2. There is a valley-like feature in front of the harbor and area of groove-like channels. Although both sides show an irregular bottom, the bottom of the valley deepens with a smooth but steep slope to 6 m in depth.

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Fig. 3 Distribution of the spawning beds of herring off Minedomari, Atsuta, from 1998 to 2003.
Wave condition during spawning season

The wave height measured at Minedomari from February to the end of April 2000 varied from 0.2 m to 3.8 m. The change in wave height showed a similar pattern with that measured at Ishikari Bay New Port and there was a significant correlation ($r^2 = 0.879$) between the significant wave height at Minedomari and at Ishikari Bay New Port (Fig. 4). Therefore, the wave height converted from the data measured off Ishikari Bay New Port was substituted for Minedomari's wave height in the other years.

The mean of the significant wave height during the estimated period of large spawnings is shown in Fig. 5. The values at spawning at Atsuta and Aoshima were approximately 0.5 m or lower than the mean, which meant conditions were calm, but the wave height off Minedomari during the spawning period varied from 0.18 to 1.28 m. The bottom current speed at the connection zone between the valley and the groove-like channels was from 0.01 to 0.69 m/s (Fig. 6). The current speed under a given wave height was estimated using the relation between the significant wave height off Minedomari and the bottom current speed.

Distribution of water particle velocity on the sea bottom surface as a result of ocean waves off Minedomari

The bottom topography off Minedomari indicates that there is a wide valley-like feature at the bottom from 1 to 6 m in depth and the valley connects to the groove-like channels in the spawning ground off Minedomari (Fig. 7). The distribution of the water particle velocity on the sea bottom surface as a result of ocean waves showed there was a fast velocity zone at the edge of the rocky platform, except at the end of the valley connected to the spawning ground. The velocity at the edge of the platform was 0.8 m/s or more. However, the value at the end of the valley was less than 0.3 m/s. The current speed measured at the bottom at the valley end was 0.01–0.09 m/s, under the significant wave height of 0.5 m. Although the calculated result was
higher than the value actually measured, it seemed that calm conditions occurred frequently just off the spawning ground.

**DISCUSSION**

Spawning beds of herring were observed at almost the same site off Minedomari during 1998–2003. Along the coast of Atsuta, there is no spawning ground that herring use each year except for Minedomari and Mourai. However, the size of the spawning bed is always smaller off Mourai than off Minedomari.

One of the reasons why herring spawn off Minedomari year by year could be the topographical features. The distribution of water particle velocity on the sea bottom surface as a result of ocean waves off Minedomari indicates that the area off Minedomari is usually calm at the bottom and herrings could enter more easily into the shallow area through the valley-like topography to the spawning ground, compared with the edge of the rocky platform. Spawning occurred off Reuke in the Sea of Japan in Hokkaido, under calm conditions where the bottom current was 0.02 m/s. The calculated velocity in the present study was fast at the edge of the rocky shore but slow behind the edge of the shore where herring spawn frequently (Fig. 7).

The second reason why herring repeatedly use Minedomari as a spawning bed could be the seepage of freshwater from the bottom at a depth of 3 m. Underwater observations indicate that the egg density is higher around the freshwater seepage point. If such a seepage is limited to a short period, it would be difficult to make its existence clear. Field observations by scuba were carried out from 0.3 m to 12.0 m in depth from March to April in 1997 and 1998 along the coast of Atsuta. However, neither freshwater seepage nor herring eggs were observed in the surveys. Additionally, small rivers flow near the beds. The fresh water from such rivers might also affect the spawning bed formation of herring.

The effect of low salinity on the fertilization and hatching success of herring has been studied.
These studies have shown that the fertilization ratio (16.0%o), survival ratio till yolk sac absorption (16.4%o) and hatching rate (16.0%o, 16.4%o and 19.7–26.4%o) are high in the Pacific herring. In the Baltic herring, seepage of groundwater is thought as one of the key factors affecting the precise spawning bed selection.21 The detailed distribution of salinity under calm conditions and freshwater seepage from the bottom during the spawning period should be surveyed to investigate the mechanism of spawning bed selection in this area.

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