1 **Title: Vertical movement of spawning cultured chub mackerel (*Scomber japonicus*)**
2 **in a net cage**

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1 **Abstract**

2 Vertical behavior of cultured chub mackerel, *Scomber japonicus*, in a net-cage
3 was investigated using depth data logger and infrared video camera footage during the
4 spawning and non-spawning seasons. Marked differences in the vertical distributions of
5 spawning and non-spawning mackerel were observed. Non-spawning mackerel swam
6 near the bottom of the net-cage during the daytime, coming up to shallow waters during
7 night-time. However, spawning mackerel remained near the bottom of the net at all
8 times except for brief, night-time visits to the surface for gamete release. Spawning
9 events started with the school of fish whirling near the surface, before two or three fish,
10 possibly the female followed by the males, darted upward and away from the school at
11 high speed. Once away from the school, the fish swam in a tight circle two or three
12 times before releasing their eggs and sperm. Estimation of the timing of spawning
13 events based on back-calculations of egg development and then correlating these data
14 with changes in vertical movements revealed that there were 26 events over a three-day
15 period, and that most events occurred between sunset and midnight. Differences in the
16 depth distribution between the spawning season and the non-spawning season could
17 potentially be used as new indicator for the spawning period in chub mackerel reared
18 under artificial conditions. These results could help us to better understand the spawning
19 season in mackerel and allow us to increase the sustainability of the natural reproductive
20 process in captivity.

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22 **Keywords:**

23 aquaculture; spawning behavior; depth distribution; data logger; bio-logging

24

1 **1 Introduction**

2 Chub mackerel, *Scomber japonicus*, is a cosmopolitan species that is widely
3 distributed in the temperate waters of the Atlantic, Indian and Pacific oceans
4 (Hernandez and Ortega, 2000). The mackerel is an important fishery resource for the
5 numerous countries on the Pacific Ocean (Collette and Nauen, 1983). In the waters
6 around Japan, chub mackerel stocks decreased from 1980 before stabilizing at low
7 levels after 2000. The commercial catch has been managed by the total allowable catch
8 system (TAC) since 1997 (Fisheries Agency, Japan, 1997). Recently, chub mackerel
9 have received considerable attention as a new target species in Japanese aquaculture.
10 However, because seeding the mackerel used in aquaculture still depends on wild-
11 caught adults, the captive rearing methods that are currently employed are not yet
12 sustainable.

13 Recently, artificial reproduction of chub mackerel was attempted by applying
14 hormone injection to seedling production. Shiraishi et al. (2005) induced the production
15 of eggs by administering gonadotropin releasing hormone (GnRH). However, the
16 requirement for regular injections using this method makes it difficult to maintain
17 spawning behavior over an extended period. The Fisheries Laboratory at Kinki
18 University succeeded in closing the life-cycle the chub mackerel in land-based tanks
19 without hormone injection (Murata et al., 2005). However, ensuring consistency with
20 respect to spawning frequency, egg quality, and mass production has been difficult
21 (Murata et al., 2005; *pers. comm.*). Matsuyama (2006) clarified that the condition of the
22 rearing environment, especially the rearing space and the process of acclimation, have a
23 marked effect on stress and reproductive success in captive fish. In addition, artificial
24 reproduction may be facilitated by hormone administration or performed in land-based

1 tanks may limit the genetic diversity of the cultured fish. It is therefore important, to
2 develop natural spawning in net cages that do not require artificial treatment methods in
3 order to ensure stable egg production and better quality eggs. Surprisingly, even though
4 the spawning grounds, maturation, and larval ecology of the chub mackerel are well
5 known, relatively little is known about the *in situ* spawning behavior of this species
6 (Dickerson et al, 1992; Yukami et al., 2009).

7 The observation of spawning behavior provides us with an understanding of
8 the requirements for successful reproduction, including species-specific behavior,
9 spawning time, frequency, season, and how these are affected by the oceanic
10 environment; indeed, all of these aspects are fundamental to any successful aquaculture
11 initiative. Therefore, to better understand the reproductive characteristics of chub
12 mackerel under culture conditions, we observed the vertical movements of mackerel
13 maintained in a net-cage using depth data loggers and infrared video camera footage
14 during the spawning and non-spawning seasons, and then compared these behavior
15 patterns between seasons.

1 2 **Materials and Methods**

2 2.1 *Monitoring the behavior of Chub mackerel*

3 The spawning season of cultured chub mackerel, *S. japonicus* is from late
4 March to July and mainly between May and June (Murata et al., 2005). The behavior of
5 cultured 2 year-old chub mackerel was recorded during the spawning season (3 to 9
6 June 2011) and the non-spawning season (2 to 8 Dec. 2011) in a net cage off the coast
7 of the Fisheries Laboratory at Kinki University, Wakayama Prefecture, Japan. To
8 monitor the behavior of the mackerel in the net cage, we used a DST-micro data logger
9 (diam: 8.3 mm, length: 25.4 mm, weight: 1.9 g in water, Star Oddi, Iceland). The data
10 logger recorded depth at 6 s intervals for three days. During the spawning season, after
11 checking the appearance of the genital papilla and release of eggs and sperm in response
12 to gentle pressure applied to the abdomen, 11 females and nine males were selected and
13 fitted with data loggers (Table 1). During the non-spawning season, 12 of 20 fish were
14 fitted with data loggers, but we were unable to identify the sex of the fish (Table 1).
15 Data-loggers were surgically implanted into the peritoneal cavity of each fish within 3
16 mins of cool-water anesthesia (6°C). In addition, the total length (TL), fork length (FL)
17 and body weight of each were measured. The fish were then transferred to a recovery
18 tank, given 10 min to recover from the anesthesia and stress associated with tagging,
19 before being released into an experimental net-cage measuring 7 m² by 4.7 m deep. The
20 fish were fed artificial pellets (Nishin Marunbeni, Japan) at 10:00 every day. The data
21 logger recordings were initiated 5 days after tagging in order to exclude the effects of
22 tagging trauma and handling during the first five days. After 8 days of experiments, all
23 of the fish were recaptured from net-cage and the data loggers were retrieved. Data were
24 downloaded and analyzed using IGOR Pro 6.2 (WaveMetrics, Lake Oswego, OR, USA).

1 To describe the surface behavior of chub mackerel during spawning, we also recorded
2 the behavior using an infrared video camera (HDR-XR520V, SONY) from above the
3 water from 23:00 to 05:00 during operation of the data loggers.

5 *2.2 Egg sampling and assessment of egg development*

6 To ensure that only mackerel eggs were collected, and to prevent
7 contamination by other fish eggs, a plastic sheet was placed around the net cage from
8 the surface to a depth of 1.5 m from 2 days before starting each experiment in both the
9 spawning and non-spawning seasons. Egg collection was performed in this surface
10 water using a square sample net (mesh: 1 mm, mouth: 50 cm², depth: 100 cm deep) at
11 03:00 during operation of the data loggers in each season. The collected eggs were then
12 immediately transferred to the laboratory and observed under a light microscope. Eggs
13 >1 mm in diameter were selected and developmental stage was determined based on the
14 categories of Murata et al. (2005).

3 Result

We analyzed the data that were obtained from 10 of 11 females and 7 of 9 males in the spawning season; one of the females and two of the males were excluded from the analysis as depth sensor recordings exceeded the depth of net-cage. We successfully retrieved data from all 12 of the mackerels during the non-spawning season and analyzed all of the data. Water temperatures ranged from 20.0 to 21.0°C ($20.9 \pm 0.4^\circ\text{C}$, mean $\pm$ S.D.) and 21.7 to 24.0°C ($22.7 \pm 0.6^\circ\text{C}$) during the spawning and the non-spawning experiments respectively.

3.1 Spawning behavior

Infrared video camera recordings successfully captured the spawning behavior of cultured chub mackerel in the surface waters of the net-cage. A single spawning event typically consisted of the following five stages (Fig. 1):

1. The school of fish gradually ascends to the surface layer of the net-cage moving in a circular manner (Fig. 1A).
2. While the school of fish is moving in this circular manner near the surface, two or three fish dart out of the school at high speed, possibly a female followed by one or two males (Fig. 1B).
3. Away from the main school, these fish then swim in a tighter circle two or three times before the single female and male(s) release their eggs and sperm, which then float on the surface (Fig. 1B).
4. These fish then return to the main school immediately after spawning.
5. After some time spent spawning in this way, the whirling school gradually descends to the deeper water in the net-cage.

3.2 Vertical movement of chub mackerel in a net cage during the spawning and the non-spawning seasons

Figure 2 shows time-series data obtained for mackerel depth in net-cage during the spawning season. In the spawning season, male and female mackerel typically remained at the bottom of the net-cage and moved vertically within a range of 3.5-4.5 m during the day and night. However, all mackerel ascended to a depth of approximately 3.5 m before sunrise and sunset. During nighttime in the second and third days, the male and female mackerel frequently moved for short duration from the bottom of the net-cage to the surface layer in a synchronized manner. The duration of one such vertical movement was 52.7 ± 10.1 s. Conversely, vertical movements to layers above the middle layer of water during the daytime were only recorded at feeding on the third day, and this behavior was not synchronized. The duration of these vertical feeding movements was 40.5 ± 8.4 s, which differed significantly from that observed at nighttime (Mann-Whitney U-test, $P < 0.001$).

On the other hand, in the non-spawning season, vertical movements by mackerel exhibited a diel periodicity. Figure 3 shows the time-series data obtained for mackerel in the net-cage during the non-spawning season. The mackerel generally swam near the bottom of the net cage (around 3.5 m) during the daytime and near the surface (1 - 2 m) during the nighttime. On the first and second days of the experiment, the swimming depth of the mackerel gradually increased to 2.5 - 3 m at 2:00 to 3:00 during nighttime, and then rapidly ascended to around 1-3 m before sunrise and then to the bottom layers after sunrise. On the third day, the fish remained near the surface (1 - 2.5 m) all night, but their lower depths also increased overnight.

Figure 4 shows the vertical distribution of the mackerel during the daytime

1 and the nighttime in both seasons. Although the mackerel remained at around 4 m
2 during the day time in both seasons, marked differences in swimming behavior were
3 observed at nighttime between the two seasons. Specifically, the fish at nighttime
4 remained near the bottom (3.0 - 4.5 m) in the spawning season (96.3 %) considerably
5 more than the fish in the non-spawning season (14.2 %). Mean swimming depth of the
6 mackerel in the non-spawning season and the spawning season were 2.81 ± 0.87 and
7 3.94 ± 0.14 m, respectively (Mann Whitney U-test, $P < 0.0001$, Table 1).

8 9 *3.3 Development stage of collected eggs and estimated spawning time*

10 We successfully collected mackerel eggs on the second and third days in the
11 spawning season. The development stages of the collected eggs were 1-cell, 32-cell, 64-
12 cell, 128-cell and early morula stage on second day, and 1-cell, 32-cell, 64-cell and
13 early morula and morula stage on the third day. Estimating spawning time based upon
14 back-calculation of egg development following Murata et al. (2005), revealed that the
15 vertical movements of the mackerel to the surface water occurred in the estimated
16 spawning time. However, on the third day, several vertical movements did not in synch
17 with estimates of spawning time. The synchronized vertical movement of both males
18 and females to depths above 1 m (Fig. 2), which were considered in this study to
19 represent spawning events, were estimated to have occurred 26 times (0 times on the
20 first day, 12 times on the second day, and 14 times on the third day). Some of the
21 estimated spawning events were observed within a short time interval. The frequency of
22 spawning events over 24 hours, calculated by aggregating the data collected over 3 days,
23 is shown in Fig. 5. Most spawning events occurred from after sunset to midnight.

4 Discussion

To our knowledge, this is the first study to examine the spawning behavior of chub mackerel in a net-cage under natural photoperiod and water temperature conditions. By examining and collecting eggs, we confirmed that mackerel fitted with data loggers spawned in the net-cage during the spawning season. Shiraishi et al. (2009) reported that female chub mackerel experience difficulties with final oocyte maturation or ovulation in captivity. Matsuyama (2006) proposed that the reason for failed natural spawning in captive mackerel was due to environmental stress caused by factors such as small rearing tanks (20-30 fish in 1-3t land-based tank) and lack of acclimation. In this study, the number of fish maintained in the net-cage (7 m² x 4.7 m) was limited to a total of 20 fish (males and females) in order to ensure that the fish had sufficient space for their reproduction and natural behavior. Additionally, data were recorded 5 days after the data loggers were implanted, which means that our results are unlikely to have been extensively influenced by the stress associated with implantation.

4.1 Spawning behavior, time and frequency

Spawning behavior of Chub mackerel in a net-cage was similar to that observed in Atlantic mackerel, *S. Scombrus*, bred in captivity. Walsh and Johnstone (1992) reported that small groups of Atlantic mackerel swam away from the school at high speed and spawned in an area somewhat removed from the main school. After spawning, the fish rejoined the school immediately. We also report, for the first time, that spawning events of chub mackerel are associated with a vertical movement of the school at nighttime, and that this movement was synchronized in both females and males. These characteristic vertical movements were confirmed as spawning events

1 using video camera footages recordings and by examining the developmental stages of
2 collected eggs.

3 Since *Scomber* spp. have floating eggs, the eggs of wild mackerel are usually
4 found in shallow seawater, between the surface and the thermocline (Sette, 1943;
5 Motoda, 1955). In addition, most pelagic fish have been reported to spawn the upper
6 thermocline at night, although the eggs sink gradually as the eggs develop. By spawning
7 at the surface, mackerel may avoid losses due to predators and egg feeders, and since
8 the pelagic eggs float on the water it is possible that the surface waters facilitate egg
9 dispersal. Additionally, spawning in smaller groups away from the main school may
10 prevent the mackerel from eating their own eggs. Walsh and Johnstone (1992) reported
11 that egg predation occurred in mackerel maintained in shallow tanks and that eggs were
12 found in the stomachs of fish; indeed, the stomach of one of the fish contained a total of
13 589 eggs.

14 In our study, spawning events were estimated to have occurred at nighttime
15 only, mainly from sunset to midnight. These spawning times agree with the active
16 spawning times of between 22:00-24:00 estimated for chub mackerel in the wild by
17 Yamada et al. (1998) and Shiraishi et al. (2005). We estimated that there were 26
18 spawning events in total, with 0, 12 and 14 events on the first, second and third days of
19 the experiment, respectively. However, we were unable to identify which fish were the
20 spawners and how many fish participated in each spawning event. It is not known
21 whether the fish spawn at all of the spawning events, because some spawning events
22 occur frequently and over a short time. The estimated spawning time on the third day of
23 the experiment did not coincide with the vertical movement of the school above 1 m
24 (02:30-04:00 on 9 June). These spawning events may have occurred in the middle or

1 bottom layers of the net-cage. Since it is possible that the frequency of spawning events
2 in our data might be overestimated, future studies using a higher sampling rate for depth
3 measurements or acceleration sensors for recording the body movements of fish (Tsuda
4 et al., 2006) need to be undertaken. Moreover, DNA fingerprinting of parents and eggs
5 could be a powerful tool to confirm ID of spawners..

6 In our study, no spawning events were recorded on the first day. The mean
7 water temperatures at 4 m on the first, second, and third days of the experiment were
8 23.1, 21.8 and 22.3°C, respectively. Murata et al. 2005 reported that the number of eggs
9 collected after spawning decreased rapidly at temperatures above 23°C, although the
10 mackerel in their study spawned at 20.8 - 24.2°C. Therefore, in conjunction with a
11 behavioral index developed from data logger information, temperature monitoring may
12 also be useful for estimating spawning days.

13 14 *4.2 Vertical distribution of chub mackerel during the spawning and non-spawning* 15 *seasons*

16 In our study, the mackerel maintained in the net-cage showed clear difference
17 in their vertical distributions between the spawning season and the non-spawning
18 season (Fig. 4). In the non-spawning season, the mackerel remained in deep water
19 during the daytime and in shallow water during nighttime. Conversely, in the spawning
20 season, fish remained near the bottom of the net-cage the whole day and frequently only
21 moved above 1.5 m at nighttime to spawn. The difference in the depth distribution
22 between the spawning season and the non-spawning season could potentially be used as
23 a new indicator of the spawning period in chub mackerel maintained under culture
24 conditions.

1 In the non-spawning season, mackerel exhibited orderly and periodic changes
2 in vertical distribution. In the wild, the vertical distribution of members of the family
3 *Scombridae* (i.e. tuna, mackerels and bonitos) is primarily regulated by light intensity
4 and water temperature (Holland et al., 1990; Brill et al., 2002; Kitagawa et al., 2002;
5 Schaefer and Fuller, 2007); although no data are currently available for mackerel, it is
6 considered likely that they are similarly affected. In our study, the difference in
7 temperature between day and night in the non-spawning season was $<0.91^{\circ}\text{C}$. It is
8 possible that the mackerel in our study did not need to change their vertical distribution
9 in response to the movements of prey species because they were provided with food
10 regularly at 10:00 am. Consequently, the observed changes in vertical distribution may
11 have only been due to changes in light intensity. However, even if the mackerel are
12 restricted to shallow net-cages (4.7 m depth), their vertical movements may instinctive
13 behavior. On the other hand, the mackerel in the spawning season remained near the
14 bottom of the net-cage during day and night and exhibited only very limited vertical
15 movements at nighttime. This behavior might be typical for the spawning season as
16 spawning mackerel have to swim with mature gonads and they may save energy for
17 reproduction by limiting vertical movements. In addition, this behavior has the effect of
18 preventing the mackerel from eating their own eggs.

19 Our paper is the first to provide clear evidence of vertical changes in the
20 distribution of cultured chub mackerel between the spawning season and the non-
21 spawning season, and we also described spawning behavior in the net-cage in detail.
22 Taken together, it is possible that these characteristic behaviors will increase our
23 understanding of the spawning season in mackerel and contribute towards increasing the
24 sustainability of natural reproductive processes in captivity.

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1 **Figure legends**

2 **Fig. 1.** Spawning behavior of cultured chub mackerel in the net-cage (see Results for
3 detailed description).

4 **Fig. 2.** Time series data of swimming depth in 7 male (top) and 10 female (bottom)
5 chub mackerel during the spawning season. Water temperatures at 1 m (grey dashed
6 line) and 4 m (grey solid line) are also shown.

7 **Fig. 3.** Time series data of swimming depth in 12 chub mackerel during the non-
8 spawning season. Water temperatures at 1 m (grey dashed line) and 4 m (grey solid
9 line) are also shown.

10 **Fig. 4.** Depth distribution of chub mackerel during the non-spawning season (left) and
11 the spawning season (right). White bars indicate depth frequency during daytime and
12 black bars indicate the depth frequency during nighttime, in both seasons.

13 **Fig. 5.** Frequency of estimated spawning events of chub mackerel over 24 hours using
14 data aggregated over three days.

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Table 1 Characteristics of cultured chub mackerel surgically implanted with data loggers and mean diel swimming depth measurements.

Season	sex	Number of fish (analyzed)	Total length (cm)	Fork length (cm)	Body weight (g)	Mean swimming depth (m)		
						All time	During day	During night
Spawning season	Female	11 (10)	29.8±1.0	27.7±1.2	323.8±50.7	3.90±0.14	3.96±0.13	3.83±0.14
	Male	9 (7)	30.0±1.0	27.5±1.0	293.8±57.1	3.98±0.13	4.02±0.08	3.84±0.10
Non-spawning season	Unknown	12 (12)	29.6±1.5	28.0±1.4	266.6±45.9	2.81±0.87	3.66±0.07	1.97±0.10

A. Side view

in a net-cage

B. Top-down view

in a net-cage

Fig. 2 Tsuda et al.

Fig. 3 Tsuda et al.

Fig. 4 Tsuda et al.

Fig. 5 Tsuda et al.