Annual changes in the hatching period of the dominant cohort of larval and juvenile ayu *Plecoglossus altivelis altivelis* in the Shimanto Estuary and adjacent coastal waters during 1986–2001

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**ABSTRACT:** Larval and juvenile ayu from seven year-groups (1986, 1987, 1992, 1995, 1996, 1999 and 2000) were collected in the Shimanto Estuary and adjacent coastal waters. The present study focuses on the variation among year-groups in the hatching period estimated by age determination using the otolith. The hatching period of the dominant cohorts in the 1986, 1987 and 1992 year-groups occurred from late October to mid-November. A delay of the hatching period of the dominant cohort was observed from the 1995 year-group, which occurred in late November to early December, and the dominant periods in the 1996, 1999 and 2000 year-groups were observed from early to late December. It appears that the delay of the hatching period of dominant cohorts was not due to a delay of spawning, but a high mortality of early hatched larvae. The water temperature in autumn in the coastal waters adjacent to the Shimanto River has tended to rise over the past 20 years and this trend was especially notable in the late 1990s. The delay in the hatching period of the dominant cohort observed from the 1995 year-group was likely to be related to the rise in seawater temperatures in autumn.

**KEY WORDS:** ayu, hatching period, mortality, Shimanto Estuary, water temperature.

**INTRODUCTION**

The ayu *Plecoglossus altivelis altivelis* is an amphidromous fish with a life span of 1 year. The fish mature in autumn and spawn in the lower reaches of rivers. Newly hatched yolk-sac larvae drift down into estuarine and coastal waters, where they remain throughout the larval and early juvenile stages.1–4 In spring, juveniles ascend the rivers, where they feed chiefly on periphyton and grow over the summer.

The maturation of ayu is controlled strongly by day length,5 so spawning periods are roughly fixed each year according to latitude.6 However, minor annual changes in the spawning period, especially in its peaks, are observed in relation to other annually varying biotic and abiotic conditions, such as water temperature,7,8 precipitation,8,9 and body size.6,10,11 Moreover, Takahashi et al.12 showed that mortality rates varied markedly between early and late-hatching ayu larvae. Therefore, the hatching periods of the dominant cohort of ayu surviving until the late larval and juvenile stages are expected to fluctuate annually. We found a marked change in the hatching period of the dominant cohort, through otolith analysis, in the Shimanto Estuary and adjacent coastal waters from 1986 to 2001 and, in the present paper, we report these annual changes and discuss a possible factor leading to the changes.

**MATERIALS AND METHODS**

Larval and juvenile ayu from seven year-groups (1986, 1987, 1992, 1995, 1996, 1999 and 2000) were collected in the waters adjacent to the banks of the Shimanto Estuary and adjacent coastal waters (surf zone) from October 1986 to April 2001 (Table 1). In the present study, the population that originated from one spawning season from
autumn to winter is defined as a ‘year-group’ (e.g. the population hatched from October 1986 to February 1987 is the 1986 year-group). Samplings were conducted using a small seine net (1 × 4 m, 1 mm mesh) for the 1986, 1987 and 1992 year-groups, and using an aqua lamp (light trap; 100 W) for the 1996, 1999 and 2000 year-groups (Table 1). To confirm whether any sampling biases occurred with the change of sampling gear, both types of gear were used for the 1995 year-group. Details of the sampling methods and sites for the 1986–1999 year-groups are provided in previous publications. However, for the 1995 and 1996 year-groups, samples in the center of flow in the estuary were not used in the present study because sampling in the center of flow was not conducted for other year-groups. The method and sites for the 2000 year-group were the same as the 1999 year-group. A total of 52,082 larval and juvenile ayu were caught (Table 1). The number of fish caught shown in Table 1 does not reflect the resource size of each year-group, because the samplings were varied in effort (e.g. types of gear, number of sampling times, number of stations) for different year-groups.

After measuring body length (BL; notochord length in preflexion and flexion larva; standard length in post-flexion larva and juveniles), age determinations using the otolith (sagitta) were made only for specimens over 10 mm BL and hatching dates were estimated from the age (days) and the date of capture.

Data on flow in the lower reaches of the Shimanto River and water temperatures in the coastal waters adjacent to the river from 1986 to 2001 were collected from the Ministry of Construction and the Kochi Prefectural Fisheries Experimental Station, respectively. Catches of ayu in the Shimanto River were based on the Annual Statistics of Fishery Products in Kochi reported by the Ministry of Agriculture, Forestry and Fisheries.

### RESULTS

**Body length of specimens used for age determinations**

Size–frequency distributions of the specimens used for age determinations are shown in Fig. 1. Modal sizes of specimens in the 1986, 1987 and 1992 year-groups, which were collected using the seine net, were 10–12 or 12–14 mm BL in the estuary and 16–18 mm BL in coastal waters. A few fish over 20 mm BL were caught in the estuary (4–28%), but fish > 20 mm BL were relatively abundant in coastal waters (48%). Modal sizes of the 1995, 1996,
Comparison of sizes and hatching dates between two sampling gears

The size distributions and hatching date distributions of larval and juvenile ayu in the 1995 year-group, which was collected using both the seine net and aqua lamp (Table 1), were compared between the two sampling gears (Fig. 2). The modal sizes of samples collected using the seine net and aqua lamp were 10–12 and 14–16 mm BL, respectively. Fish over 20 mm BL were collected abundantly by the aqua lamp (47%) in comparison with the seine net (18%), but no significant difference was found between the two samples ($P > 0.05$, Kruskal–Wallis test).

The hatching dates of both samples ranged from early November to mid-January (Fig. 2). Although the distribution patterns of hatching date were somewhat different between the two samples, little difference was found in the hatching periods of the dominant cohort. There was no significant difference between the two samples ($P > 0.05$, Kruskal–Wallis test).

Hatching dates

The frequency distributions of hatching dates of ayu in the seven year-groups collected in the estuarine and coastal waters are shown in Fig. 3. Although the 1995 year-group was collected by both the seine net and aqua lamp (Table 1; Fig. 2),
only data of the sample collected using the aqua lamp are given in Fig. 3. The hatching periods of the dominant cohort in the 1986, 1987 and 1992 year-groups were observed from late October (the 1992 year-group) to mid-November (the 1986 year-group) and few fish hatched after the beginning of December. A delay in the dominant hatching period began to appear from the 1995 year-group. In the 1996 and 1999 year-groups, fish hatched in October and November were scarce and the hatching period of the dominant cohort was observed in late December. In the 2000 year-group, the hatching period of the dominant cohort occurred slightly, but not significantly \((P > 0.05)\), earlier compared with the 1996 and 1999 year-groups and was observed in early December. Hatching terminated in mid-March in this year-group. The peak occurrences of yolk-sac larvae in the 1987, 1992, 1996 and 2000 year-groups, which were based on previous studies and unpublished data (Takahashi I, unpubl. data, 2001), were observed from late October to mid-November (Fig. 3).

**River flow and seawater temperatures**

The flow of the Shimanto River fluctuated from October to November between the years and was generally stable from December to February (Fig. 3). The mean flow from October to November was high in 1987, 1999 and 2000 (approximately 73–127 m³/s) and was low in 1986, 1992, 1995 and 1996 (approximately 18–49 m³/s).

Annual changes in the mean water temperature in the coastal waters adjacent to the Shimanto River from October to November, when the hatching periods of the dominant cohort in the 1986, 1987 and 1992 year-groups were observed (Fig. 3), are shown in Fig. 4. Water temperatures
have tended to rise over the past 20 years, with repeated annual changes. High water temperatures have been recorded intermittently from 1994 to 2000.

**Catch of ayu**

The catch of ayu in the Shimanto River tended to decrease after the 1980 year-group (Fig. 5). The catches of the 1994–1999 year-groups have been reduced and have hovered between 250 and 400 ton.

**DISCUSSION**

**Bias of the estimated hatching dates with changes in sampling gear**

In the present study, sampling gears were changed from seine net to aqua lamp from the 1995 year-group (Table 1). This change may have influenced the hatching date distributions of samples collected in the estuary and coastal waters. In fact, the size–frequency distributions were somewhat different between the two sampling gears, indicating a bias due to gear selectivity. However, in the 1995 year-group the dominant periods of hatching hardly differed between the two sampling gears, although the size–frequency distributions were somewhat different between the two samples. Moreover, the same phenomenon was found in samples from the 1986 and 1996 year-groups collected in both the estuary and coastal waters. It is unlikely that the change of sampling gear had any effect on the estimates of the hatching period of the dominant cohort. We conclude that the sampling biases can be ignored, as long as we discuss changes in the hatching period of the dominant cohort.

**Annual changes in the hatching period of the dominant cohort**

The hatching periods of the dominant cohort, estimated by the age determinations, in the 1986, 1987 and 1992 year-groups ranged from late October to mid-November. The peak occurrences of yolk-sac larvae in the downstream migration in the Shimanto River were observed in late October for the 1992 year-group and in early November for the 1987 year-group. Thus, in these year-groups, there is little difference in the dominant period between the occurrence of yolk-sac larvae and the hatching date distribution of larvae and juveniles that survived in the estuary and coastal waters. A delay in the hatching period of the dominant cohort began to be observed from the 1995 year-group. In the 1996 year-group, the dominant period occurred in late December, which was approximately 2 months later compared with the 1992 year-group. Similar circumstances were found for the 1999 and 2000 year-groups, although the hatching period of the dominant cohort in the 2000 year-group was slightly earlier. In contrast, the peak occurrences of yolk-sac larvae in both the 1996 and 2000 year-groups were found in mid-November. Therefore, it seems that the peak occurrence of yolk-sac larvae has not changed substantially from 1986 to 2000, whereas considerable changes have appeared in the hatching period of the dominant cohort surviving in estuarine and coastal waters. We have reported previously that larvae hatched abundantly in November 1996 (1996 year-group) suffered a high mortality in the period before reaching 10 mm BL in estuarine and coastal waters. These results suggest that the delays in the hatching period of the dominant cohort in the 1995–2000 year-groups were due to the mortality of the early hatched larvae and not to a delay in spawning. Maturation of ayu is triggered by day length, so that the spawning period seems not to change greatly.

If river flow is high, larvae hatched during this period may be transported to outside of our study site (the estuary and adjacent coastal waters). Therefore, there is a possibility that river flow affected the hatching date distributions of ayu collected in the estuary and adjacent coastal waters. However, the fluctuations in river flow during the hatching period were not related closely to changes in the observed hatching
period of the dominant cohort. For example, although the peak occurrence of yolk-sac larvae in the 1996 year-group was found to be in mid-November, when river flow was low, there were few fish hatched in November found in estuarine and coastal waters. This suggests that the transport of larvae by the river flow had little effect on annual changes in the hatching period of the dominant cohort.

We supposed that one factor leading to the high mortality of early hatched larvae (hatched in October and November) in the 1996 year-group was the high water temperature in coastal waters from October to November 1996 because water temperatures over 20°C have been shown to increase the mortality of reared larval ayu. The water temperature in the coastal waters adjacent to the Shimanto River in autumn tended to increase from the 1980s and was especially high from 1994. The same tendency is also noticeable for the whole area of Tosa Bay from 1994. When river flow was low, there were few fish hatched in November found in estuarine and coastal waters. This suggests that the temperatures over 20°C have been shown to increase the mortality of reared larval ayu. Therefore, the delay in the hatching period of the dominant cohort surviving in the estuarine and coastal waters, which was observed from the 1995 year-group, roughly correspond to the rise in seawater temperature in autumn. In addition, delays in the observed hatching period of the dominant cohort will lead to a reduction of the resource, because the delays were due to the mortality of early hatched larvae. The reduction of catches of ayu in the 1994–1999 year-groups in the Shimanto River may support this conjecture. We suppose that the delays in the observed hatching period of the dominant cohort in recent years can be attributed to higher water temperatures in the coastal waters in autumn from 1994. However, not all changes in hatching periods of the dominant cohort can be explained by fluctuations in water temperature. For example, hatching periods of the dominant cohort differed between the 1987 and 1995 year-groups, despite similar water temperatures, suggesting the existence of other factors in addition to water temperature that affect hatching period. It is necessary to conduct further investigations over a wider area to confirm this.

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