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Environmental habitat use and migration of Plecoglossidae and Osmeridae fish

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The life histories of Plecoglossidae and Osmeridae fish collected from Japanese fresh, brackish, and seawaters were studied by examining the strontium (Sr) to calcium (Ca) ratios in their otoliths. The Sr:Ca ratios in the otoliths changed with the salinity of the habitat. The fish living in a freshwater environment showed consistently low Sr:Ca ratios throughout the otolith. The fish were identified as a standard freshwater type. In contrast, fish collected from the intertidal zone showed higher otolith Sr:Ca ratios than those in the standard freshwater type, and the ratios fluctuated along the growth phase. In the present study, in addition to the representative migration pattern reported previously, other migration patterns were found to show consistently high Sr:Ca ratios throughout the otolith in several Osmeridae fish. Those results indicate that these fish have a flexible migration strategy with a high degree of behavioural plasticity and an ability to utilize the full range of salinity throughout their life history.

Keywords: smalts, oyu, otolith, migration, environmental habitat use

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INTRODUCTION

Fish that migrate between freshwater and seawater are called diadromous. The migration patterns of such species differ, and show seasonal and life cycle variations. Only one per cent of all fish in the world are diadromous (McDowall, 1988). Crossing the important habitat barrier from freshwater to seawater or vice versa during migration requires major physiological changes for survival. Diadromous fish have been subdivided into three categories (Myers, 1949): catadromous (fish that migrate into the sea to reproduce), anadromous (fish that migrate from the ocean to fresh water to breed) and amphidromous (fish that migrate between the sea and fresh water to feed). Many diadromous species support important commercial and/or recreational fisheries. Thus, information on diadromous migrations can provide basic knowledge for both fish migration studies and fishery management, allowing effective and sustainable use of fish resources.

Smelts (family Osmeridae) are small, elongate, silvery shoaling fish, and usually of compressed and slender form. The life cycle of this species is variable being semelparous and iteroparous. This family encompasses 15 species in six genera, which are widely distributed in all oceans (McDowall, 1988). The family shows complex and variable migratory patterns throughout its life cycle.

Family Plecoglossidae encompasses 2 species in one genus. Ayu *Plecoglossus altivelis altivelis* is an amphidromus osmerid fish with an annual life cycle. Its distribution ranges throughout the Japanese Archipelago and partially along the far-eastern continental coast. The ayu is a small fish growing to about 250 mm. It is distinctive and specialized among the freshwater salmoniforms in being herbivorous. In addition to the typical amphidromous ayu, land locked populations are also known to inhabit Lake Biwa (Azuma, 1973) and several other lakes in Japan. Thus, this species also shows complex and variable migratory patterns as that of Osmeridae fish. Recent chemical analytic techniques have enabled identification of the life history events of individual fish by detecting trace elements in the microstructure of their otoliths (Arai, 2002). Strontium (Sr) incorporation in fish otoliths is of special interest for its potential utility as an indicator of past environmental (temperature and salinity) and physiological conditions (ontogeny) (Arai, 2002). The deposition of Sr in fish otoliths during growth varies between freshwater, brackish water and marine habitats. In fact, otolith microchemical analyses can reconstruct the migratory history throughout the ayu lifespan (Arai, 2006). However, knowledge of migration in Plecoglossidae and Osmeridae fish remains at a rudimentary level compared to the information for other diadromous fish.

The objective of the present study was to reveal the migratory histories of Plecoglossidae (one species, *Plecoglossus altivelis*) and Osmeridae (four species, *Osmerus dentex*, *Spirinchus lanceolatus*, *Hypomesus japonicus* and *H. nipponensis*) fish collected in Japan by using the Sr:Ca rates in their otoliths.

MATERIALS AND METHODS

Specimens of Plecoglossidae and Osmeridae fish were collected in fresh, brackish and seawater environments in Japan during 2002 and 2004 (Table 1). The ayu *Plecoglossus altivelis*,

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Shishamo smelt *Spirinchus lanceolatus* and surf smelt *Hypomesus japonicus* were collected in seawater environments that had a full range of salinity. The rainbow smelt *Osmerus dentex* was collected in a brackish water lake with a salinity ranging from 18 to 31. The pond smelt *Hypomesus nipponensis* was collected in three salinity environments: an inland freshwater lake, a brackish water lake that was connected to the Pacific Ocean by a 6 km long intermittent river through which seawater enters the lake by tidal flow, and a bay with full seawater. A total of 35 specimens were used in the present study, and these specimens were classified by their migration patterns based on a previous report (McDowall, 1988) and their sampling location (Table 1). The otolith microchemical analysis has a potential as a powerful tool to reconstruct the minute environmental life history for each fish, although the sample sizes of each species examined seem to be rather small (five fish for each species). Thus, we used five fish for each species in the present study.

The sagittal otoliths were extracted from each fish, embedded in epoxy resin (Struers, Epofix), and mounted on glass slides. The otoliths were then ground to expose the core using a grinding machine equipped with a diamond cup wheel (Struers, Discoplan-TS), and polished further with OP-S suspension on an automated polishing wheel (Struers, RotoPol-35) equipped with a semi-automatic specimen mover (Struers, PdM-Force-20). Finally, they were cleaned and rinsed with deionized water prior to examination.

For electron microprobe analyses, all otoliths were platinum/palladium coated by a high vacuum evaporator. The otoliths from all specimens were used for a 'life-history transect' analysis of Sr and Ca concentrations, which were measured along the line of the longest axis of each otolith from the core to the edge using a wavelength dispersive X-ray electron microprobe (JEOL JXA-8900R), as described in Arai *et al.* (1997, 2004). Wollastonite ($CaSiO_3$) and Tausonite ($SrTiO_3$) were used as standards. The accelerating voltage and beam current were 15 kV and 1.2×10^{-8} A, respectively. The electron beam was focused on a point 10 μm in diameter, with measurements spaced at 10 μm intervals.

Differences among data were tested first by analysis of variance (ANOVA) and then with Scheffé's multiple range tests for pairwise comparisons (Sokal & Rohlf, 1995), although this limited the number of fish for each species.

RESULTS

The Sr:Ca ratios in the otoliths of the ayu *Plecoglossus altivelis* increased just outside the core and remained high until the portion 400–500 μm from the otolith centre (Figure 1). The ratios subsequently decreased outward to the edge. The Sr:Ca ratios measured along a transect from the core to the edge of the otoliths of the rainbow smelt *Osmerus dentex*, Shishamo smelt *Spirinchus lanceolatus* and surf smelt *Hypomesus japonicus* collected in high saline environments showed consistently high Sr:Ca ratios, averaging 7.0×10^{-3}, 11.2×10^{-3} and 7.0×10^{-3}, respectively, with no transition point from low to high or from high to low values in the ratio (Figure 1). The otolith Sr:Ca ratios in the pond smelt *Hypomesus nipponensis* varied among locations (Figure 1).

In Miyako Bay, three of the five specimens collected showed relatively high Sr:Ca ratios from the core to the edge, averaging 10.8×10^{-3} (Figure 1). Two out of five specimens showed similar Sr:Ca values to the other three specimens from the core to the portion 800–1200 μm from the otolith centre, averaging 8.7×10^{-3}. Thereafter, the ratio increased abruptly, and maintained high values, averaging 14.8×10^{-3}, with several fluctuations towards the edge of the otolith. In Lake Ogawara, the otolith Sr:Ca ratios were relatively high from the core to the edge, averaging 4.3×10^{-3} (Figure 1). The Sr:Ca ratios measured along a transect from the core to the edge of the otoliths of the Lake Ashinoko pond smelt collected from a freshwater environment showed consistently low Sr:Ca ratios, averaging 1.3×10^{-3} (Figure 1).

In order to determine the environmental habitat use among species, the mean Sr:Ca ratios along the life history transect were compared, with further comparison carried out by dividing each site for the Japanese smelt (Figure 2). Significant

Table 1. Plecoglossidae and Osmeridae. Specimens used for otolith microchemistry analyses.

Species	Sampling location	Migration pattern*	No. fish examined	Total length (mm) Mean ± SD	Otolith radius (μm) Mean ± SD	Migration pattern estimated from otolith Sr:Ca ratios
Plecoglossus altivelis	Miyako Bay, Iwate, Japan	Amphidromous	5	120 ± 20.6	1018 ± 86.6	Amphidromous
Osmerus dentex	Lake Akkeshi, Hokkaido, Japan	Anadromous	5	224 ± 25.8	2534 ± 288	Non-anadromous
Spirinichus lanceolatus	Pacific Ocean, Hokkaido, Japan	Anadromous	5	160 ± 22.1	1646 ± 189	Non-anadromous
Hypomesus japonicus	Miyako Bay, Iwate, Japan	Marine resident	5	106 ± 2.6	1525 ± 293	Marine resident
Hypomesus nipponensis	Miyako Bay, Iwate, Japan	Anadromous	5	91.8 ± 8.5	1453 ± 528	Anadromous/ estuarine resident
	Lake Ogawara, Aomori, Japan	Anadromous	5	84.5 ± 2.4	1216 ± 240	Estuarine resident
	Lake Ashinoko, Yamanashi, japan	Freshwater resident	5	91.5 ± 11.6	1282 ± 376	Freshwater resident

*McDowall (1988)

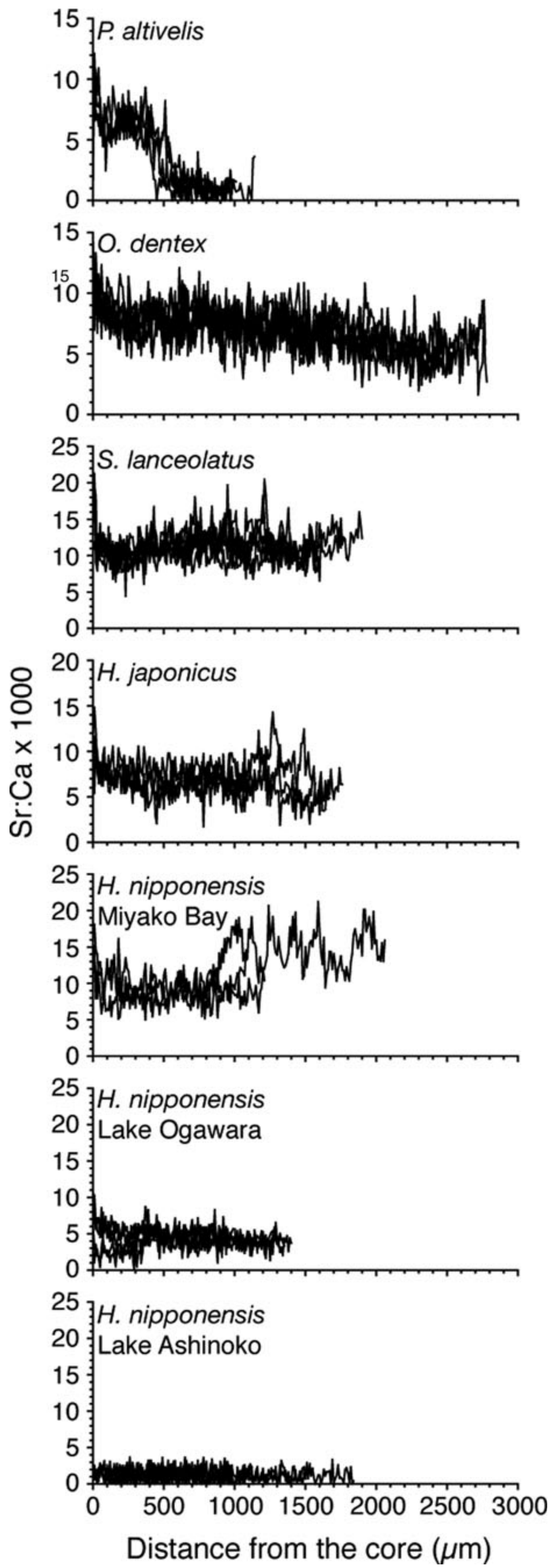

Fig. 1. Transects of otolith strontium:calcium (Sr:Ca) ratios measured with a wavelength dispersive electron microprobe from the core to the edge of the otoliths of Plecoglossidae and Osmeridae fish. Each line represents all data for the corresponding 10 μm segment.

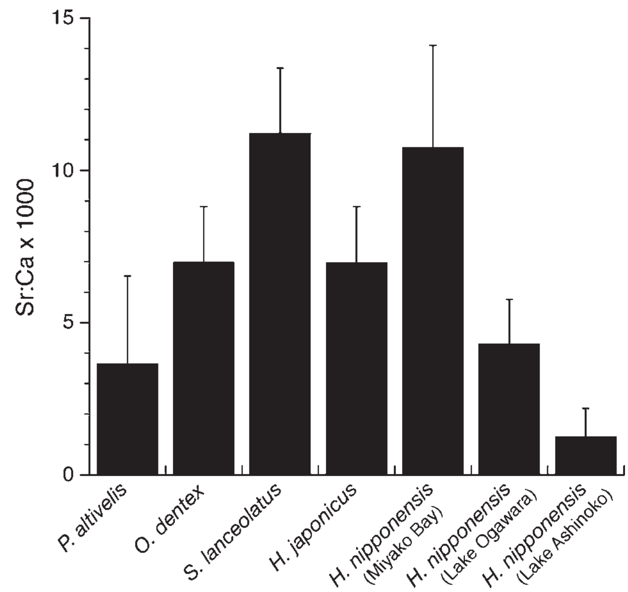

Fig. 2. Mean otolith strontium:calcium (Sr:Ca) ratios ($\pm$SD) measured in Plecoglossidae and Osmeridae fish.

differences occurred among 18 of 21 combinations ($P <$ 0.0005–0.0001), except for the combinations between *P. altivelis* and *H. nipponensis* from Lake Ogawara ($P > 0.5$), between *O. dentex* and *H. japonicus* ($P > 0.5$), and between *S. lanceolatus* and *H. nipponensis* from Miyako Bay ($P > 0.5$).

DISCUSSION

In the present study, the interpretation of Sr:Ca patterns is based on the assumption that the elemental composition of the otoliths of Plecoglossidae and Osmeridae fish within a freshwater/brackish/marine system is correlated with the salinity of the ambient water (Arai, 2002). It seems that our results support this assumption. Physiological condition, environmental parameters, and water chemistry each has the potential to influence the change of the Sr:Ca ratio in the otolith (Arai, 2002). In Plecoglossidae and Osmeridae fish otoliths, however, the Sr:Ca ratio did not seem to be significantly affected by physiological condition and temperature, because freshwater-, estuarine- and marine-resident samples showed consistently high Sr:Ca ratios (Figure 1; Table 1). All fish in pond smelt from the freshwater environment of Lake Ashinoko showed consistently low Sr:Ca ratios throughout the otolith (Figure 1). These samples provide a standard freshwater life history type as estimated from the otolith Sr:Ca ratios. Furthermore, all fish in ayu showed typical amphidromous migration patterns because changes in the Sr:Ca ratios in their life history transect just overlap the migration pattern reported previously. However, almost all of the other fish collected from the brackish water and intertidal zone environments showed higher otolith Sr:Ca ratios throughout their otoliths (Figure 1). These fish might experience different salinity environments during their migration in habitats. Thus, the differences in the Sr contents found in the otoliths collected from freshwater or brackish (sea) water environments were probably due to salinity effects.

The life history transect of the Sr:Ca ratios in rainbow smelt and Shishamo smelt showed that these fish maintained consistently high Sr:Ca ratios from the core to the otolith edge, with no low Sr:Ca values around the otolith core. Although rainbow smelt and Shishamo smelt were thought to have an anadromous migration pattern, their mean Sr:Ca values were the same or greater than that of surf smelt, which is a marine fish (Figure 2). These findings strongly suggest that the higher Sr:Ca ratios in the otolith core region found in rainbow smelt and Shishamo smelt could mean that the fish were not exposed to fresh or brackish water during spawning and hatching. Thus, these fish are non-anadromous (Table 1), which means that they are able to live their entire lives in coastal waters and do not have to migrate to freshwater areas.

In conclusion, the Sr:Ca ratios in the otoliths of Plecoglossidae and Osmeridae fish differed significantly among freshwater, brackish water and seawater habitats, and can be used as an environmental indicator to detect an individual's migratory history between brackish water, seawater and freshwater. In the present study, in addition to the representative migration patterns reported previously, other migration patterns such as non-anadromous and estuarine resident (Table 1) were found based on high Sr:Ca ratios throughout the otolith in rainbow smelt, Shishamo smelt and pond smelt, indicating that these fish have flexible migration strategies with a high degree of behavioural plasticity and an ability to utilize the full range of salinity throughout their life history.

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