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Short Note

Life history patterns of silver eels *Anguilla japonica* collected in the Sanriku Coast of Japan

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Abstract—The migratory history in the silver eel stage of the Japanese eel, *Anguilla japonica*, collected in the mouth of Kozuchi River along the Sanriku Coast of Japan, was examined using the otolith microstructure and analysis of strontium (Sr) and calcium (Ca) concentrations with wavelength dispersive X-ray spectrometry by an electron microprobe. The line analysis of Sr : Ca ratios along the life history transect of each otolith showed a peak (ca $12–15\times10^{-3}$), which corresponded to the period of their leptocephalus and early glass eel stages in the ocean. The mean Sr : Ca ratios from the elver mark to the otolith edge indicated that there were eels with several general categories of migratory history, that included sea eels that never entered freshwater (average Sr : Ca ratios, $\geq6.0\times10^{-3}$) and others that had entered freshwater for brief periods, but returned to the estuary or bay. This evidence of the occurrence of sea eels in this northern area indicates that Japanese eels of the Sanriku Coast do not necessarily migrate into freshwater rivers during recruitment as glass eels at the beginning of their growth phase, and even those that do enter freshwater may later return to the marine environment.

Key words: *Anguilla japonica*, migration, otolith Sr : Ca ratios, marine resident, silver eels

Introduction

The Japanese eel, *Anguilla japonica* Temminck & Schlegel is widely distributed in East Asia, from Taiwan in the south, through eastern China, Korea, and up to the Pacific coast of Hokkaido Island, Japan (Tesch 1977). The life cycle of *A. japonica* has five principal stages, which are the leptocephalus, glass eel, elver, yellow eel and silver eel stages (Bertin 1956). The eel spawns in waters to the west of the Mariana Islands and their leptocephali drift within the North Equatorial and Kuroshio Currents to the continental shelves (Tsukamoto 1992). They leave these currents after metamorphosing into glass eels and have traditionally been considered to all migrate up freshwater streams where they grow to the pre-adult silver eel stage. Then during the silver eel stage, their gonads begin maturing and they start their downstream migration into the ocean and back out to the spawning area where they spawn and die.

However, Tsukamoto et al. (1998) found yellow and silver eels of *Anguilla japonica* in marine areas adjacent to their typical freshwater habitats that have never migrated into freshwater and have spent their entire life history in the ocean. Furthermore, Tsukamoto and Arai (2001) found an intermediate type between marine and freshwater residents of *A. japonica*, which appear to frequently move between different environments during their growth phase. This discovery of marine ("sea eels") and estuarine ("estuarine eels") residents of *A. japonica* suggests that anguillid eels do not all have to be catadromous and calls into question the generalized classification of diadromous fishes.

In this study we measured Sr : Ca ratios in the otoliths of silver eels collected at the almost northernmost edge of their species range, the Sanriku Coast of Japan, where there is little information available about the migration and habitat use by *Anguilla japonica*. Thus, the objective of this study was to reconstruct the life history of *A. japonica* just before its spawning migration to open ocean.

Materials and Methods

Specimens of *Anguilla japonica*, were collected by fishing in the mouth of Kozuchi River (39°N, 141°E), Iwate Prefecture of the Sanriku Coast of Japan in August 2007. A total of 12 specimens were collected, and their total length (TL), body weight (BW) and gonad-somatic index (GSI) were measured. To distinguish developmental stage of female eels, each individual was classified as either a yellow (<1.0) or silver eel (>1.0) using GSI, following Utoh et al. (2004).

Five specimens were categorized as female silver eels by GSI of each eel, and were further used in the otolith analyses.

Several introduced species of *Anguilla*, e. g. *A. anguilla* and *A. rostrata* have been found in Japanese waters (Aoyama et al. 2000, Okamura et al. 2008). These species cannot identify using morphological characters only due to some of these are overlapped among those species. Thus, we used genetic characters to identify the species.

Species identification of each eel was carried out using polymerase chain reaction-restriction fragment length polymorphism (PCR-RFLP) analysis of the mitochondrial 16S rRNA gene as described by Aoyama et al. (2000), and all eels were confirmed to be *A. japonica*.

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). Finally, they were rinsed with deionized water prior to examinations.

For electron microprobe analyses, all otoliths were Pt–Pd coated by a high vacuum evaporator. The life-history transect analysis of Sr and Ca concentrations, were measured along a line down 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. (2003a, b). Wollastonite ($CaSiO_3$) and Tausonite ($SrTiO_3$) were used as standards, and 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.

Following the electron microprobe analysis, the otoliths were repolished to remove the coating, etched with 1% HCl and thereafter stained with 1% toluidine blue. The age of the specimens was determined by counting the number of blue-stained transparent zones following the method of Arai et al. (2003a, b). The positions of the transparent zones were then correlated to elemental analysis points (Fig. 1). The relative ages at particular elemental analysis points could then be assigned.

We calculated the average Sr : Ca ratios for the values outside the elver mark, and according to the criteria of Tsukamoto and Arai (2001), we categorized the specimens into "sea eels" (Sr : Ca$\geq6.0\times10^{-3}$), "estuarine eels" ($2.5\times10^{-3}\leq$Sr : Ca$<6.0\times10^{-3}$) or "river eels" (Sr : Ca$<2.5\times10^{-3}$).

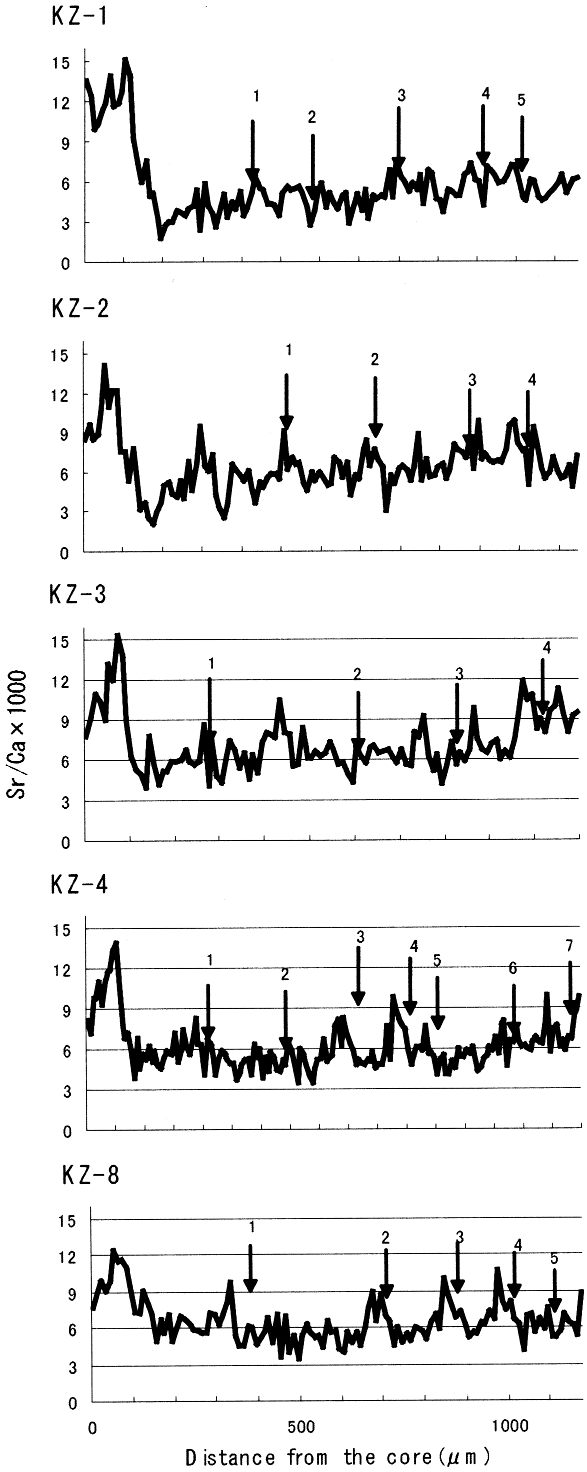

Fig. 1. Plots of the otolith Sr : Ca ratios along line transects from the core (0 μm) to the edge of the otoliths of all specimens collected in the river mouth of Kozuchi River, Iwate Prefecture, along the Sanriku Coast of Japan. The positions of the annual rings in the frontal plane of the sagittal otoliths and the estimated ages of the specimens are indicated as arrows. KZ indicates Kozuchi River.

Results and Discussion

The TL of silver eels ranged from 591 to 666 mm, with a mean$\pm$SD of 632$\pm$31 mm. The BW of those eels ranged from 258 to 465 g, with a mean$\pm$SD of 373$\pm$103 g. The age at maturation in the Sanriku area ranged from 4 to 7 yr, with a mean$\pm$SD of 5.2$\pm$1.3 yr and their GSI ranged from 1.05 to

1.35%, with a mean±SD of 1.17±0.13% in August. In Mikawa Bay, the lowest value of GSI (0.2) occurred in August, and then the values increased markedly in either October or November (Kotake et al. 2005). These results suggest that the maturation period would be different among habitats. The earlier start of downstream migration in northern silver eels is probably why the eels had higher GSI values in summer.

It is noteworthy that all eels were identified as females in the present study. Krueger and Oliveira (1999) concluded that increases in population density, and the resulting slower growth, the production of males in *A. rostrata*. In *A. japonica*, Kotake et al. (2007) reported that the most female-predominant area was in the coastal waters at Sanriku in the north (100%), the second most was Mikawa Bay in central Japan (95%), and the least was in the Amakusa Islands in the south (70%). The present study was consistent with these results, finding that the rate of females near the northern edge of the distribution was 100%.

In the life history transect analyses, all otoliths had a central region with high Sr : Ca ratios that corresponded to the leptocephalus stage and showed lower, but in some cases variable Sr : Ca ratios after metamorphosis into the glass eel stage (Fig. 1). Each otolith had a peak in the Sr : Ca ratio ($12.2–15.2\times10^{-3}$) between the otolith core and out to about 150 μm (Fig. 1). Outside of the highest Sr : Ca values, all specimens had consistently high ranges of Sr : Ca values that were higher than 5×10^{-3} ($5.1\times10^{-3}–6.9\times10^{-3}$), suggesting a long-term residence in the sea with little, or more likely, no movement into freshwater. This study found that the Japanese eels caught near the northern edge of the range of this species were sea or estuarine eels had either lived in the bay during their entire growth phase until capture, or had entered freshwater only for relatively short periods. This finding suggests that *A. japonica* which recruits to this northern area have a flexible migration strategy with a high degree of behavioral plasticity to decide whether or not to enter freshwater or to return to the bay. A similar phenomenon was indicated in the otoliths of yellow and silver eels of *A. japonica* at other localities in the southern part of Japanese coastal waters (Tsukamoto et al. 1998, Tsukamoto and Arai 2001, Kotake et al. 2003, 2005). In Sanriku region, there were few capture migrating silver eels probably due to the low density compared to its southern area. Further study is mandatory using silver eels collected from fresh water to off shore of Sanriku region to understand their minute bahavior of the eels in northernmost edge of their species range.

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References

Aoyama, J., Watanabe, S., Miyai, T., Sasai, S., Nishida, M. and Tsukamoto, K. 2000. The European eel, *Anguilla anguilla* (L.), in Japanese waters. Dana 12: 1–5.

Aoyama, J., Watanabe, S., Nishida, M. and Tsukamoto, K. 2000. Discrimination of catadromous eels, genus *Anguilla*, using polymorphism analysis of the mitochondrial 16s ribosomal domain. Trans. Am. Fish. Soc. 129: 873–878.

Arai, T., Kotake, A., Ohji, M., Miller, M. J., Tsukamoto, K. and Miyazaki, N. 2003a. Occurrence of sea eels of *Anguilla japonica* along the Sanriku Coast of Japan. Ichthyol. Res. 50: 78–81.

Arai, T., Kotake, A., Ohji, M., Miyazaki, N. and Tsukamoto, K. 2003b. Migratory history and habitat use of Japanese eel *Anguilla japonica* in the Sanriku Coast of Japan. Fish. Sci. 69: 813–818.

Bertin, L. 1956. Eels—a biological study. Cleaver-Hume Press Ltd, London. Kotake, A., Arai, T., Ozawa, T., Nojima, S., Miller, M. J. and Tsukamoto, K. 2003. Variation in Migratory history of Japanese eels, *Anguilla japonica*, collected in coastal waters of the Amakusa Islands, Japan, inferred from otolith Sr/Ca ratios. Mar. Biol. 142: 849–854.

Kotake, A., Okamura, A., Yamada, Y., Utoh, T., Arai, T., Miller, M. J., Oka, H. P. and Tsukamoto, K. 2005. Seasonal variation in migratory history of the Japanese eel, *Anguilla japonica*, in Mikawa Bay, Japan. Mar. Ecol. Prog. Ser. 293: 213–221.

Kotake, A., Arai, T., Okamura, A., Yamada, Y., Utoh, T., Oka, H. P., Miller, M. J. and Tsuakamoto, K. 2007. Ecological aspects of Japanese eels, *Anguiila japonica*, collected from coastal areas of Japan. Zool. Sci. 24: 1213–1221.

Krueger, W. H. and Oliveira, K. 1999. Evidence for environmental sex determination in the American eel, *Anguilla rostrata*. Environ. Biol. Fish. 55: 381–389.

Okamura, A., Zhang, H., Mikawa, N., Kotake, A., Yamada, Y., Utoh, T., Horie, N., Tanaka, S., Oka, H. P. and Tsukamoto, K. 2008. Decline in non-native freshwater eels in Japan: ecology and future perspectives. Environ. Biol. Fish. 81: 347–358.

Tesch, F. W. 1977. The Eel. Biology and management of anguillid eels. Chapman and Hall, London.

Tsukamoto, K. 1992. Discovery of the spawning area for the Japanese eel. Nature 356: 789–791.

Tsukamoto, K. and Arai, T. 2001. Facultative catadromy of the eel, *Anguilla japonica*, between freshwater and seawater habitats. Mar. Ecol. Prog. Ser. 220: 265–276.

Tsukamoto, K., Nakai, I. and Tesch, F. W. 1998. Do all freshwater eels migrate? Nature 396: 635–636.

Utoh, T., Mikawa, N., Okamura, A., Yamada, Y., Tanaka, S., Horie, N., Akazawa, A. and Oka, H. P. 2004. Ovarian morphology of the Japanese eel in Mikawa Bay. J. Fish. Biol. 64: 502–513.