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Life history and migration of Sakhalin taimen, *Hucho perryi*, caught from Lake Akkeshi in eastern Hokkaido, Japan, as revealed by Sr:Ca ratios of otoliths

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Abstract Microchemical analysis of the strontium (Sr) and calcium (Ca) ratios of otoliths was conducted to determine the life history and migration of anadromous Sakhalin taimen, *Hucho perryi*. In 2008 and 2009, 10 specimens were sampled from Lake Akkeshi in eastern Hokkaido, Japan. Our results indicated that some specimens migrated to brackish waters during their early life history. Because the Sr:Ca ratios of the specimens in this study were all less than those of specimens of Sakhalin Island during a previous study, specimens of Lake Akkeshi may have migrated to brackish water, or remained in the ocean for only a short period.

Keywords *Hucho perryi* · Otolith · Sr:Ca ratios · Anadromous · Brackish water

Introduction

Populations of Sakhalin taimen, *Hucho perryi*, have decreased in recent decades; thus, this species has been registered as an IUCN endangered (CR) species since 2006 (IUCN 2009). *Hucho perryi* is the largest freshwater fish in Japan and is the only *Hucho* species with an anadromous form (Gritsenko et al. 1974; Holčík et al. 1988). In addition, this species is an iteroparous salmonid that spawns primarily from March to June in far upstream regions in Hokkaido Island (Fukushima 1994, 2001; Edo et al. 2000; Esteve et al. 2009). *Hucho perryi*, not only adults but also juveniles utilize wide range from the upstream to coastal waters as their habitats (Yamashiro 1965; Kimura 1966; Gritsenko et al. 1974; Kawamula et al. 1983; Sagawa et al. 2002, 2003; Edo et al. 2005; Honda et al. 2009). However there is little information about their migration pattern, especially for anadromous *H. perryi* (Arai et al. 2004; Honda et al. 2009). In Hokkaido, only fragmented catch data from brackish water lakes or coastal areas have verified the existence of anadromous fish (Yamashiro 1965; Kawamula et al. 1983; Edo et al. 2005; Suzuki et al. 2008), and some fish migrate downstream to lower reaches or coastal waters mainly in the spring and autumn (Kawamula et al. 1983; Edo et al. 2005; Honda et al. 2009).

The microchemicals in a given habitat are incorporated for the entire lifetime in fish otoliths, which control the acoustic and balance senses. Generally, the strontium (Sr) concentration in seawater is over 100 times greater than that in freshwater (Kennedy et al. 1997), with few exceptions (Kraus and Secor 2004; Limburg and Siegel 2006; Elsdon et al. 2008). Thus, the migratory history of individual specimens can be revealed by observing the Sr:calcium (Ca) ratios of otoliths (Arai 2002). Using this method, the life histories and migration of many salmonid species have been documented (Kalish 1990; Arai and Tsukamoto 1998; Volk et al. 2000; Arai and Miyazaki 2002; Arai and Morita 2005; Brenkman et al. 2007). Arai et al. (2004) analyzed the microchemicals in otoliths of *H. perryi* on Lake Aynskoye (not influenced by the rising tide via an intermittent river with 0 psu), Sakhalin Island, Russia, and revealed the existence of anadromous fish. The mean Sr:Ca ratio in the period which assumed to inhabit in saltwater (saltwater phase) of specimens captured at Lake Aynskoye showed ca. 6.0×10^{-3} and more (Arai et al. 2004). The ratio was almost four times higher than that of freshwater-reared specimens [$1.58 \times 10^{-3} \pm 0.74 \times 10^{-3}$ (Mean ± SD)]. Moreover, specimens that their Sr:Ca ratio increased drastically from the period which assumed to inhabit in freshwater (freshwater phase) to saltwater phase were observed, while specimens that their Sr:Ca ratio increased gently were also confirmed (Arai et al. 2004). However, the migratory patterns of *H. perryi* populations in Hokkaido within a river system containing a large brackish lake at the river mouth had not to date been examined. Therefore, we sought to assess the life history and migration of anadromous *H. perryi* migrating between the Bekanbeushi River system and Lake Akkeshi (brackish water lake) in eastern Hokkaido (Fig. 1) by examining otolith Sr:Ca ratios.

Materials and methods

Sampling fish. Sampling was conducted from April 2008 to May 2009; we only sampled *Hucho perryi* caught by local set net fisheries at Lake Akkeshi that were dead upon capture. Lake Akkeshi (circumference: 24.8 km, maximum depth: 7.0 m, salinity: ca. 25–30 psu; Hokkaido Institute of Environmental Sciences 2005) is a brackish water lake into which the stable population of *H. perryi* within the Bekanbeushi River system migrates. The lake is connected to Akkeshi Bay (i.e., the ocean; Fig. 1). In Lake Akkeshi, set-net fisheries targeting *Osmerus mordax dentex*, *Salangichthys microdon*, *Hypomesus japonicus*, and *Eleginus gracilis* are conducted every spring (20 March–30 June) and autumn (1 October–31 December). After measurements of fork length (FL, mm) and body weight (BW, g), the sex and maturity status (mature or immature) were confirmed by checking for gonads or remaining eggs or sperm. In addition, four freshwater-reared specimens (565–587 mm FL) were sampled as control fish from the Nanae Freshwater Laboratory, Hokkaido University, on 29 June 2009. We also sampled one specimen that was reared in both seawater and freshwater (827 mm FL, 5,700 g BW; the rearing duration and date of death were not recorded) from the Shibetsu Salmon Museum.

Elemental microanalysis of otoliths. Sagittal otoliths were extracted from each specimen, embedded in epoxy resin (Epofix; Struers, Copenhagen, Denmark), and mounted on glass slides. They were then ground to expose the core using a grinding machine equipped with a diamond cup wheel (Discoplan-TS; Struers). Otoliths were then polished further using an oxide polishing suspension on an automated polishing wheel (PdM-Force-20; Struers). For electron microprobe analysis, all otoliths were Pt–Pd-coated using a high-vacuum evaporator. All specimens were used for a “life history transect” analysis (transect analysis) of Sr and Ca concentrations, which were measured along the longest axis of each otolith from the core to the edge. An X-ray electron microprobe (JXA-8900R; JEOL, Tokyo, Japan) was used for the transect analysis, and Wollastonite ($CaSiO_3$) and Tausonite ($SrTiO_3$) were used as standard samples. The electric pressure and current values were 15 kV and 1.2×10^{-8} A, respectively, and the electron beam was focused on a point 10 μm in diameter with measurements spaced at 10-μm intervals.

The mean (±SD) Sr:Ca ratios of the four freshwater-reared control specimens were $1.98 \times 10^{-3} \pm 0.10 \times 10^{-3}$, and the transitions to saltwater phase were not confirmed for these specimens [C1–C4 in electronic supplementary material (ESM) Fig. S1]. Therefore, the ratio of 2.0×10^{-3} was considered to roughly indicate the freshwater life stage, and this value was used for comparisons to each specimen caught in Lake Akkeshi following Kuroki et al. (2006).

Results

In total, 10 specimens, two in April–May 2008, one in October 2008, and seven in April–May 2009, were caught from Lake Akkeshi. Body size and sex of the specimens are presented in

Table 1. The mean (±SD) and range in FL were 687 ± 103 mm and 452–826 mm, respectively, and the mean and range in BW were 3,730 ± 1,244 g and 1,120–5,690 g, respectively. All specimens were female, and only the gonads of specimen No. 0803 caught in the autumn were mature; those of other specimens caught in the spring were all immature.

The mean (±SD) Sr:Ca ratio of all 10 specimens from Lake Akkeshi was $2.02 \times 10^{-3} \pm 0.46 \times 10^{-3}$ (range: 1.48×10^{-3} to 2.97×10^{-3}, the rest "$\times 10^{-3}$" is omitted). This value was close to the mean value of the freshwater-reared control specimens. The transition point between freshwater and saltwater (including brackish water for specimens caught from Lake Akkeshi) phases of some specimens such as Nos. 0802 and 0905 was clear, meanwhile the point of some specimens such as No. 0801 and 0903 was unclear (Fig. 2). Moreover, the ratios of Nos. 0902 and 0904 fluctuated at higher level (around 2.0–4.0) from their early life stages (<1000 μm) compared to other specimens (Fig. 2). The mean (±SD) Sr:Ca ratio of No. 0902 (2.97 ± 0.86) was the highest of all specimens. The ratio of No. 0904 transitioned to saltwater phase in the early life stage; the ratio remained high (2.64 ± 0.84, from 530 μm to the edge).

Discussion

Generally, it is known that females of iteroparous salmonids tend to migrate to the sea than males (Maekawa 1987; Yamamoto et al. 1999). From the past studies of anadromous *Hucho perryi*, females were found more than males (Kawamula et al. 1983; Komiyama 2003; Arai et al. 2004; Edo et al. 2005) and all females sampled from Lake Akkeshi in spring had immature gonads (Kawamula et al. 1983). In this study, the 10 *H. perryi* caught from Lake Akkeshi were all female. All specimens, except No. 0901, were mature in size but gonadally immature. These findings indicate the existence of anadromous females that did not spawn every year and instead migrated downstream during the spawning season and also indicate that the occurrence ratio of females is higher than males.

Our results demonstrated that the first sea-run timing of *H. perryi* at our study site was probably not constant; we observed specimens (Nos. 0902 and 0904) that migrated to brackish water as juveniles as well as those that migrated after maturing. Therefore, individuals of *H. perryi* at our study site varied in the timing of first sea run, the determining factor for which was neither a certain age nor a certain body size but other internal or external factors. As reported for many salmonid species, the age at first smolt is likely determined by the growth rate during the early life stage (reviewed by Jonsson and Jonsson 1993; Tamate and Yamamoto 2004). Titus and Mosegaard (1992) studied brown trout inhabiting in a small river in Sweden and reported that habitat density potentially affected the age at first smolt.

The Sr:Ca ratio at saltwater phase of specimens caught from Lake Akkeshi hardly exceeded 6.0, which was much less than that observed for anadromous specimens in Lake Aynskoye, Sakhalin Island (see Arai et al. 2004). Moreover, the mean Sr:Ca ratio at saltwater phase of the seawater- and freshwater-reared specimens (ESM Fig. S1, C5) was also much higher than specimens caught from Lake Akkeshi. Furthermore, Arai (2010) studied the change of Sr:Ca ratio in otoliths of *H. perryi* experienced salinity change in its lifetime and revealed the relationship between its Sr:Ca ratio and salinity environment. The Sr:Ca ratios of specimens in the study were ca. 5.0, 3.8 and 3.1 as the ratio of experienced seawater to freshwater in their lifetime increased as 0, 1/3, and 2/3, respectively. Thus, specimens from Lake Akkeshi very likely had not migrated to the ocean, or if they had, did not stay there for a long time. If the pattern of theses ten specimens caught from Lake Akkeshi represents the population in the Bekanbeushi River system, it may relate to the existence of the large brackish lake at the Bekanbeushi River mouth. Regarding this hypothesis, Honda et al. (unpublished) used an acoustic receiver at the border between Lake Akkeshi and Akkeshi Bay to trace 15 acoustically tagged adult *H. perryi* from spring to autumn 2008, and although some tagged fish that had migrated to Lake Akkeshi were observed, no fish remained in Akkeshi Bay for more than one day. Furthermore, *H. perryi* has rarely been caught by set-net fisheries in Akkeshi Bay (T. Sato, personal communication).

Considering the *H. perryi* migration speculated from our finding, brackish Lake Akkeshi plays an important role for the life history of its population within the Bekanbeushi River system as their part of habitats. In future, their detailed migration patterns including lake and estuary will help to reveal the unknown part of its life history and provide useful information to understand and protect the other populations.

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Figure legends

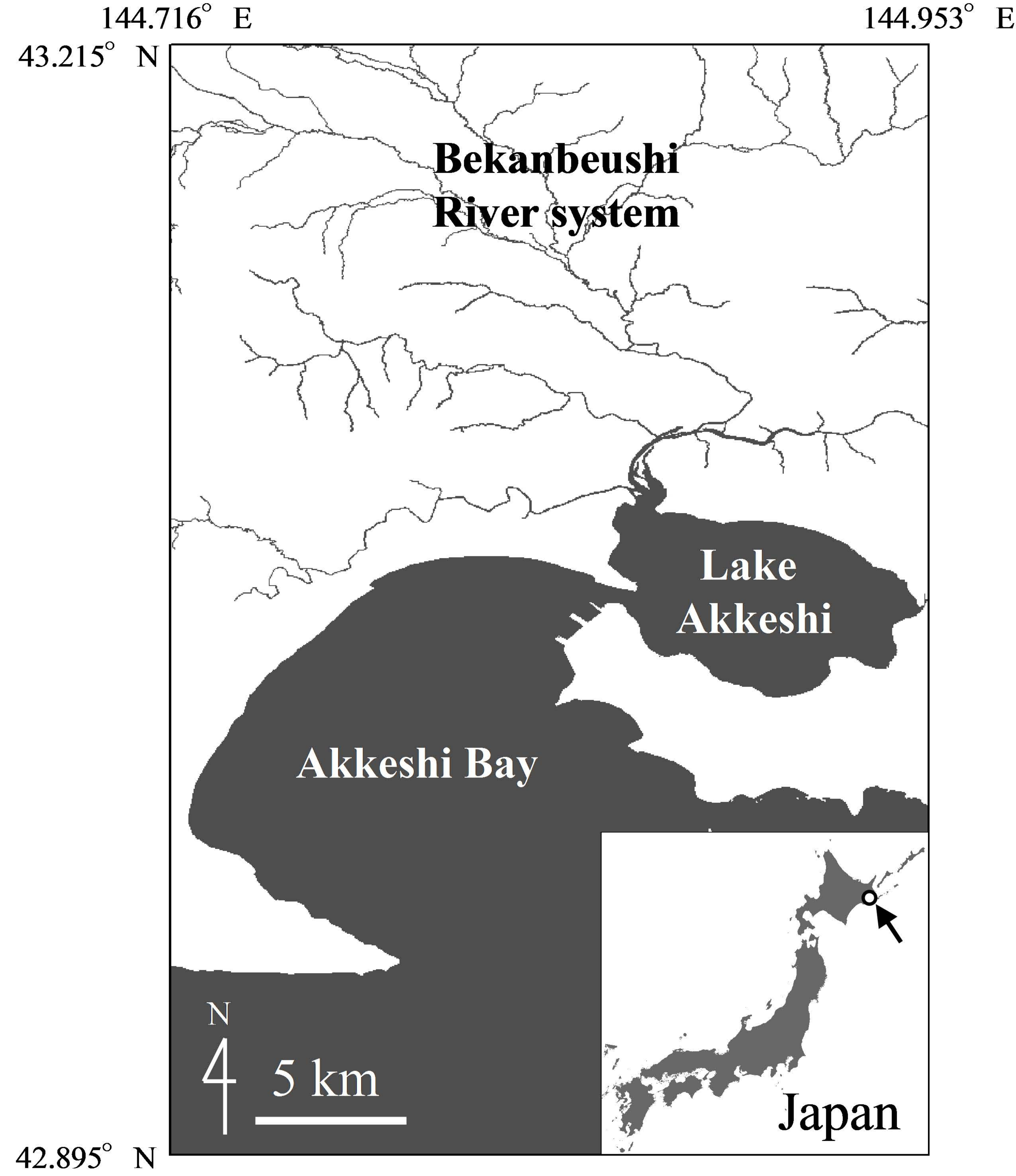
Fig. 1 Study site: the Bekanbeushi River system, Lake Akkeshi and Akkeshi Bay in eastern Hokkaido Island, Japan

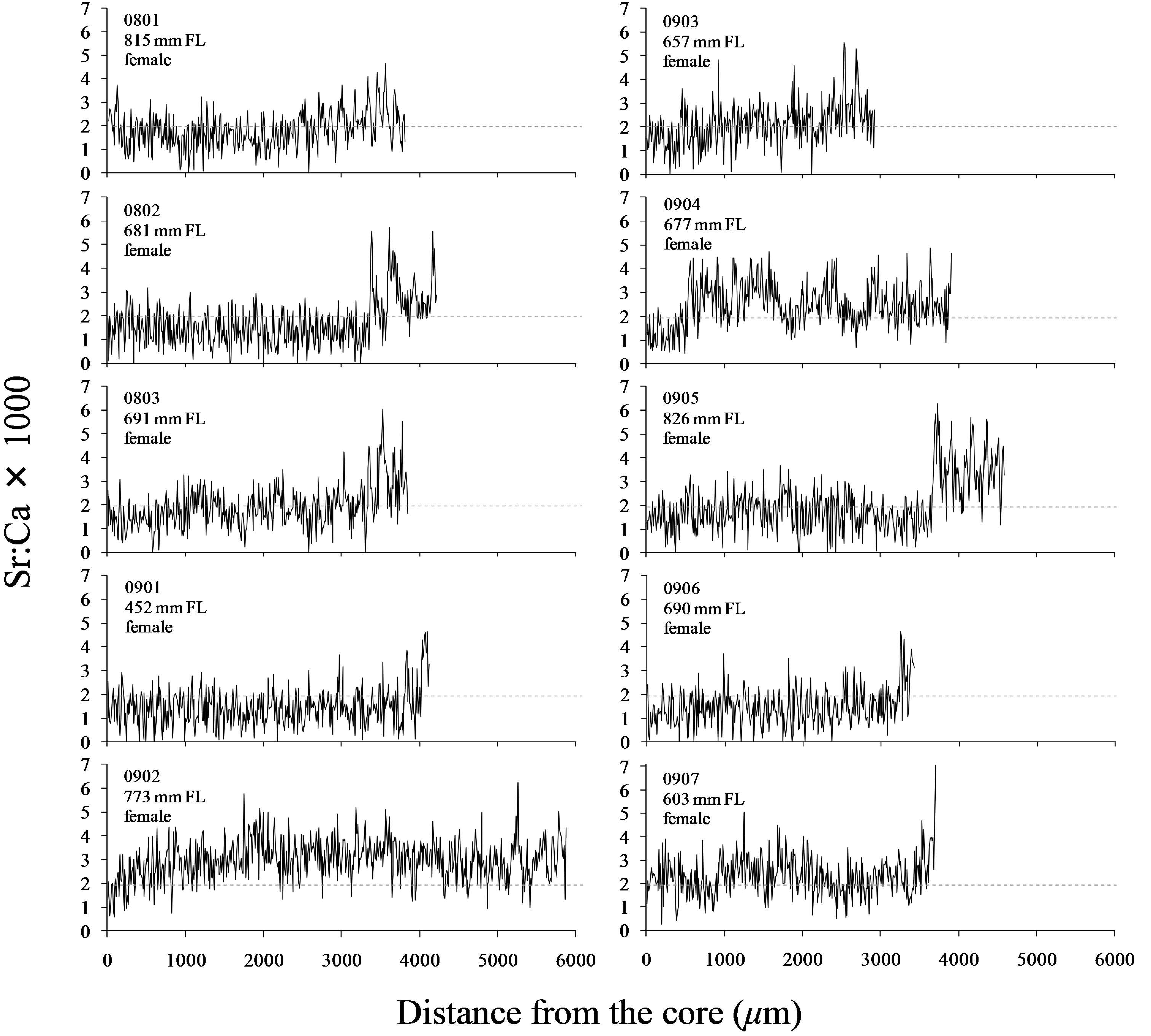
Fig. 2 Transects of otolith Sr:Ca ratios measured with a wavelength dispersive electron microprobe from the core to the edge in specimens of *Hucho perryi* collected at Lake Akkeshi, Hokkaido Island, Japan. *Each point* represents all data for the respective 10-µm intervals. *A dot line* shows the mean Sr:Ca ratios of four freshwater-reared control specimens. *Four-digit number at left* indicates fish number. *FL* fork length

Table 1 Fish number, date captured, body size, sex and maturational status of *Hucho perryi* caught from Lake Akkeshi, Hokkaido, Japan

Fish No.	Date captured	Fork length	Body weight (g)	Sex	Maturational status
0801	29 Apr 2008	815	5690	Female	Immature
0802	9 May 2008	681	3770	Female	Immature
0803	27 Oct 2008	691	3670	Female	Mature
0901	25 Apr 2009	452	1120	Female	Immature
0902	18–22 May 2009	773	4570	Female	Immature
0903	18–22 May 2009	657	3640	Female	Immature
0904	18–22 May 2009	677	3610	Female	Immature
0905	15–31 May 2009	826	5150	Female	Immature
0906	18–22 May 2009	690	3790	Female	Immature
0907	15–31 May 2009	603	2290	Female	Immature

Accurate dates captured of 0902–0907 were not recorded; these specimens were landed on a day in the duration written


144.716° E
144.953° E
43.215° N
Bekanbeushi
River system
Lake
Akkeshi
Akkeshi Bay
N
5 km
Japan
42.895° N


0801
815 mm FL
female
0802
681 mm FL
female
0803
691 mm FL
female
0901
452 mm FL
female
0902
773 mm FL
female
0903
657 mm FL
female
0904
677 mm FL
female
0905
826 mm FL
female
0906
690 mm FL
female
0907
603 mm FL
female
Sr:Ca × 1000
Distance from the core (μm)