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The sex-ratio reversal of the Japanese eel *Anguilla japonica* in the Kaoping River of Taiwan: The effect of cultured eels and its implication

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Abstract

The sex ratio of wild Japanese eels in the Kaoping River of southwestern Taiwan has been extremely skewed towards females in the recent years. However, the sex ratio skewed towards males after Typhoon Mindulle, July 2, 2004 then recovered to the previous female-dominated status in the following year. To determine why the sex ratio drastically changed, eels captured in the river were examined by both morphologic characteristics and otolith elemental signatures by solution-based inductively coupled plasma mass spectrometry (SB-ICPMS) and laser-ablation ICPMS (LA-ICPMS). Most of the eels collected in the river after the typhoon had a blue-gray colored back, with morphology and sex ratio similar to that of cultured eels, which differed from wild yellow eels which had a green colored back. The chemical signature in otoliths of eels with a blue-gray colored back was similar to that of cultured eels, with significantly lower Sr/Ca ratios but slightly higher Mn/Ca ratios than for wild eels. This confirmed that the reversal in eel sex ratio in the Kaoping River estuary resulted from cultured eels that had escaped from eel farms. Eel farmers estimated that about 30,000 eels escaped during the typhoon, sufficient to reverse the sex ratio of the eels in the river. Furthermore, silver eels caught in the estuary in the winter 2004 were also mostly males. The chemical signature in otoliths of these silver eels was similar to that of escaped cultured eels. Their morphology and mean GSIs, however, were comparable to wild silver eels. Thus, cultured eels that have escaped from eel farms can silver normally in the wild. Consequently, cultured eels may help to balance the sex ratio of the wild eel population and may contribute to the spawning stock of Japanese eel.

Keywords: Elemental signature; Japanese eel; Otolith; Sex ratio; Typhoon Mindulle

1. Introduction

The Japanese eel, *Anguilla japonica* Temminck and Schlegel, is a catadromous fish (Ege, 1939). At maturity, the eel migrates from its diverse habitats to a marine spawning site around seamounts west of the Mariana Islands (Tsukamoto, 1992, 2006; Tsukamoto et al., 1998).

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The eel larvae (leptocephali) are transported by the North Equatorial Current and Kuroshio Current from the spawning ground to the continental shelf of East Asian countries (Tesch, 1977; Tsukamoto, 1992; Cheng and Tzeng, 1996, 2003), then metamorphose into glass eels and become elvers in estuaries. The elvers grow as yellow eels for 4–10 yr then metamorphose into silver eels (Tzeng et al., 2000; Han et al., 2003). After metamorphosis, silver eels migrate back to their birthplace to spawn and die.

The eel before the elver stage is considered to be intersexual. Sexually undifferentiated elvers can be feminized by treatment with estrogen (Degani and Kushnirov, 1992; Satoh et al., 1992; Chiba et al., 1993), indicating that the sex of the eel is labile. The sexual differentiation of the eel is thought to be phenotype-dependent and to occur at the yellow eel stage (Colombo and Grandi, 1996; Han and Tzeng, 2006). The habitat in which eels grow might affect their sex differentiation. Individual growth rate (Helfman et al., 1987; Holmgren and Mosegaard, 1996), temperature (Holmgren, 1996), latitude (Vladykov, 1966; Helfman et al., 1987) and river types (Sinha and Jones, 1967; Oliveira et al., 2001) have been proposed to be the possible extrinsic cues (for review, please see Davey and Jellyman, 2005). However, a lot of studies indicate that the population density play an important role on eel sex determination, i.e., at high population densities, males dominate and at low population densities females dominate (Parsons et al., 1977; Degani and Kushnirov, 1992; Roncarati et al., 1997; Krueger and Oliveira, 1999; Oliveira et al., 2001; Tzeng et al., 2002a; Han and Tzeng, 2006). In the wild, eel sex ratios vary widely, ranging from almost all males to predominantly females (Matsui, 1972; Parsons et al., 1977; Tesch, 1977; Jessop, 1987; Tzeng et al., 1995, 2002a; Oliveira, 1997, 1999; Oliveira and McCleave, 2000; Oliveira et al., 2001; Han et al., 2003; McCleave and Jellyman, 2004; Han and Tzeng, 2006). The sex skewness of the eel is probably an adaptive strategy for achieving maximum fitness. Although the mean age at maturation of the eel is negatively correlated to the mean growth rate in both sexes (Svedäng et al., 1996; Tzeng et al., 2000, 2002a), male eels might prefer a time-minimizing growth strategy by maturing as soon as possible while females prefer a size-maximizing growth strategy to attain higher fecundity (Vøllestad and Jonsson, 1986; Helfman et al., 1987; Larsson et al., 1990; Vøllestad, 1992; Tzeng et al., 2002a; Han and Tzeng, 2006). In high-density eel habitats with limited food resources, eels preferentially differentiate into males and mature at a young age so that an earlier spawning migration reduces conspecific competition. In contrast, in low-density eel habitats with plentiful food, eels differentiate into females to fully utilize their habitat, and grow and mature at a larger size so as to achieve higher fecundity and increased reproductive success (Helfman et al., 1987; Tzeng et al., 2000, 2002a,b; Han and Tzeng, 2006). However, the abundance of wild Japanese, American and European eel populations have recently declined to approximately 1–10% of those 20 years ago (Dekker, 2003; Tatsukawa, 2003). Severely low eel abundance might result in a widespread sex ratio bias and accelerate population collapse. Thus, in addition to passive habitat protection and over-fishing prevention, an active strategy like restocking young eels should be considered.

The fish otolith is an aragonite crystal mainly composed of calcium carbonate in an organic matrix together with trace elements incorporated from the ambient water that is a natural tag useful as a tool to study the migratory environmental history of fish (Campana, 1999; Campana and Thorrold, 2001; Tzeng et al., 2002b; Tzeng, 2004). The elemental compositions of different water masses in which fish live usually differ. Thus, fish collected from different geographic areas can be distinguished based on the trace elements of their otoliths (Gillanders and Kingsford, 2000; Rooker et al., 2001, 2003). Accordingly, otolith trace elements may be used to discriminate eel groups of different life history.

In East Asia, the Japanese eel is a commercially important cultured species. For cultivation purposes, elvers in the estuary have been overexploited for many years, which is one of the important reasons for the severe decline of eel populations (Tzeng, 1984, 1985, 2004; Tzeng et al., 1995; Liao, 2001; Tatsukawa, 2003). The population densities of eel in the rivers of Taiwan have been low with sex ratios skewed towards females for many years (Tzeng et al., 2002a; Han and Tzeng, 2006). Interestingly, the eel sex ratio suddenly skewed towards males in the Kaoping River after Typhoon Mindulle, July 2, 2004 for a half year and then recovered to the previous female-dominant status in the following year. The sex ratio of Japanese eels collected in the Kaoping River from 1998 to 2005 together with their morphological characteristics and otolith trace elements were analysed to investigate this novel phenomenon. Our results strongly suggest that the eel sex-ratio reversal in the Kaoping River was due to the escape of cultured eels. The ecological and conservation implications of these escaped cultured eels are also discussed.

2. Materials and methods

2.1. Sample collection

Wild Japanese eels were collected by eel traps in the estuary of the Kaoping River in southwestern Taiwan