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Specific gravity and migratory patterns of amphidromous gobioid fish from Okinawa Island, Japan

Midori Iida [a,b,c,d,*], Masashi Kondo [a,e], Hélène Tabouret [c,f], Ken Maeda [g], Christophe Pécheyran [f], Atsushi Hagiwara [h], Philippe Keith [c], Katsunori Tachihara [a]

[a] Faculty of Science, University of the Ryukyus, 1 Senbaru, Nishihara, Okinawa 903-0213, Japan
[b] Tropical Biosphere Research Center, University of the Ryukyus, 1 Senbaru, Nishihara, Okinawa 903-0213, Japan
[c] Muséum national d'Histoire naturelle, UMR BOREA 7208 (MNHN-CNRS-UPMC-IRD), DMPA, CP026, 43 rue Cuvier, 75231 Paris cedex 05, France
[d] Sado Marine Biological Station, Faculty of Science, Niigata University, 87 Tassha, Sado, Niigata 952-2135, Japan
[e] Shimada Shosei Highschool, Shimada, Shizuoka 427-0034, Japan
[f] Laboratoire de Chimie Analytique Bio-Inorganique et Environnement, Institut des Sciences Analytiques et de Physico-Chimie pour l'Environnement et les Matériaux, UMR 5254 CNRS, Université de Pau et des Pays de l'Adour, Pau, France
[g] Marine Genomics Unit, Okinawa Institute of Science and Technology Graduate University (OIST), 1919-1 Tancha, Onna, Okinawa 904-0495, Japan
[h] Graduate School of Fisheries and Environmental Sciences, Nagasaki University, 1-14 Bunkyo, Nagasaki 852-8521, Japan

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ABSTRACT

Amphidromy is a diadromous life history pattern where fish spawn in freshwater, and their larvae drift downstream to the sea; the larvae develop in marine environments then migrate back in rivers to grow and reproduce. Two amphidromous types with different life history characteristics, such as egg and larval sizes, exist. To understand the ecology and early life history of amphidromous gobioid fish, six species from Okinawa Island were selected—two large egg-type species (*Rhinogobius similis* and *Tridentiger kuroiwae*) and four small egg-type species (*Stiphodon percnopterygionus*, *Stenogobius* sp., *Sicyopterus lagocephalus*, and *Eleotris acanthopoma*). The migratory pattern of four of these species was confirmed using otolith Sr:Ca and Ba:Ca ratios combined with water chemistry analysis. Although these species showed amphidromous migratory patterns, the timing of migration from estuarine to freshwater habitats was species-specific. The large egg-type, *R. similis*, showed three different migratory patterns: a long marine larval phase with a relatively fast migration from estuarine to freshwater habitats, a short marine larval phase with a relatively fast migration, and a gradual migration. Similar patterns of a long and fast migration or a gradual migration were seen in *T. kuroiwae*; however, the two small egg-type species, *Sti. percnopterygionus* and *Stenogobius* sp., showed rapid migration to freshwater after entering the river. To estimate larval ecology in the sea, ontogenetic changes in specific gravity (SG) were examined in all species. The SG was measured day and night for 1–5 days until settlement in *R. similis* and *T. kuroiwae*, and until 10 days after hatching in the other species. The SG of all species ranged from 1.0138 to 1.0488, and varied among ontogenetic stages and between day and night and species. Larval SG was relatively similar between *R. similis* and *T. kuroiwae*, with low SG in the early stages and high SG after yolk absorption. During the late larval stages and until settlement, *T. kuroiwae* showed diel changes in SG, with higher SG during the day, whereas *R. similis* had a relatively constant pattern. The diel changes of *T. kuroiwae* larvae suggest different activity during the day and at night (e.g. diel vertical migration). In the four small egg-type species, SG was high at hatching and decreased thereafter, not showing large diel changes. The results suggest that sympatric amphidromous gobioid species have various early life histories that may be influenced by several larval traits, including SG.

1. Introduction

Migration is the collective movement of individuals resulting in a change to their ecological status; migration and associated life cycles are complex systems emerging through multiple processes that operate at individual, population, food web, and ecosystem levels (Dingle, 1996; Secor, 2015). Diadromy is the migration of fish between marine and freshwater environments as a routine phase of their life cycle for the majority of the population (Myers, 1949; McDowall, 1988). Anadromy is a form of diadromy where fish migrate into freshwater environments for reproduction, e.g. salmon, whereas catadromy is the migration of fish into marine environments for reproduction, e.g. freshwater eels

* Corresponding author at: Sado Marine Biological Station, Faculty of Science, Niigata University, 87 Tassha, Sado, Niigata 952-2135, Japan.
E-mail address: mdr.iida@cc.niigata-u.ac.jp (M. Iida).

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(Myers, 1949; McDowall, 1988). A third form of diadromy, amphidromy, involves fish migration into freshwater environments, after which newly hatched larvae migrate downstream into marine environments where they spend their larval period before juveniles migrate back into rivers to grow and reproduce (McDowall, 1988). Anadromy and catadromy are forms of reproductive migration, whereas amphidromy is trophic (McDowall, 2007). Amphidromy has also been observed in some crustaceans and molluscs (Ford and Kinzie, 1982; Hodges and Allendorf, 1998; Fièvet and Eppe, 2002; March et al., 2002; Crandall et al., 2009; Cook et al., 2012; Castelin et al., 2013). Amphidromous species are predominantly found in temperate regions and tropical oceanic islands, which were possibly historically colonised after their marine larval phase (McDowall, 2007). Possible advantages of amphidromy include dispersal to vacant habitats, predator avoidance, and maintenance of high fecundity (McDowall, 2007; Closs et al., 2013). It has been proposed that high fecundity is beneficial when amphidromous species live close to suitable pelagic habitat for larval life, and is possibly advantageous over their non-migratory relatives (Closs et al., 2013).

Previous studies, including those on gobioid fish, suggest the existence of two types of amphidromy with different life history characteristics, such as egg and larval sizes (Iida et al., 2009; Watanabe et al., 2014). The 'large egg' type includes fish with relatively large egg sizes (approximately 1.0–2.8 mm in major axis, after egg sizes described in Kondo, 2013), pigmented eyes, and opened mouths at hatching, and the larvae start to feed soon after hatching; whereas the 'small egg' type includes fish with small eggs (approximately 0.4–1.0 mm) and newly hatched larvae of about 1–1.5 mm total length, without pigmented eyes, or opened mouths at hatching. Although egg size variation occurs among species and genera of plecoglossid, and galaxiid fish, e.g. *Plecoglossus* (from Asia) and *Galaxias* (from the southern hemisphere), some fish from the suborder Gobioidei are examples of large egg-type fish; however, the Gobioidei subfamily Sicydiinae and genus *Eleotris*, which mainly inhabit oceanic tropical islands, are considered small egg-type fish (Iida et al., 2009; Watanabe et al., 2014). The larvae of small egg-type fish resemble newly hatched larvae of marine fish, which produce pelagic eggs (Shiogaki and Dotsu, 2014). In contrast to larvae from large egg-type fish, larvae from small egg-type fish are not fully developed at hatching, suggesting that egg and larval sizes are related to early life history characteristics such as dispersal, retention, and recruitment (Maeda et al., 2008; Iida et al., 2010; Maeda and Tachihara, 2010).

Okinawa Island is the largest island in the Ryukyu Archipelago, southern Japan, and has more than 200 small rivers inhabited by various diadromous and estuarine fish and aquatic organisms (Tachihara, 2003). Many amphidromous fish belonging to the suborder Gobioidei are sympatrically distributed in the rivers of Okinawa Island and the life history of some of these species has been previously described (Maeda and Tachihara, 2004; Yamasaki et al., 2007; Kondo et al., 2013). Amphidromous gobies from these rivers can be categorised into one of the egg-size types: large egg-type fish include species from the genera *Rhinogobius* and *Tridentiger*, whereas small egg-type fish belong to the genera *Awaous* and *Eleotris*, and to the subfamily Sicydiinae (see Miller, 1984, and Shiogaki and Dotsu, 2014 for egg size of gobioids). Nevertheless, the ecology of marine early life stages in amphidromous gobies is not well known because of the difficulty in collecting larvae during oceanic field surveys.

Many aquatic organisms, including amphidromous fish, have planktonic larval phases. Undeveloped larvae are possibly passively dispersed by ocean currents (Caley et al., 1996); however, studies on reef fish showed that these larvae move actively in the water and have a high self-recruitment to natal areas (Sponaugle et al., 2002; Swearer et al., 2002; Leis, 2006). Stable isotope analysis indicates that some amphidromous gobies may also self-recruit (Sorensen and Hobson, 2005), but several genetic studies have indicated a dispersal tendency in these species (Lord et al., 2012; Taillebois et al., 2013). In estuarine, nearshore, coral reef, and continental shelf habitats, fish larval transport is largely affected by vertical distribution of larvae (Hare et al., 1999, 2006; Forward and Tankersley, 2001; Paris and Cowen, 2004). Vertical and horizontal larval distributions are related to larval specific gravity (SG) (equivalent to buoyancy) (Sclafani et al., 1997; Ådlandsvik et al., 2001), which is affected by swim bladder inflation (Hunter and Sanchez, 1976; Kitajima et al., 1993), as well as growth and mortality (Fiksen et al., 2007). The larval SG of amphidromous fish, however, is not well known.

Otoliths are calcified structures in the inner ears of fish that are widely used to estimate age, growth, and fish movement (Campana and Neilson, 1985; Secor and Dean, 1992; Campana, 1999). Since otoliths are often the first calcified structures formed during early development, and grow throughout the lifetime of a fish and do not show evidence of resorption (Campana and Neilson, 1985), they are useful proxies for reconstructing fish movement (Campana, 1999). Previous studies on elemental fingerprints of otoliths have provided information on fish migratory histories and stocks (Campana, 1999; Bath et al., 2000; Gillanders, 2001; Elsdon and Gillanders, 2004). Strontium (Sr) and barium (Ba) concentrations in otoliths are influenced by environmental variables such as temperature, salinity, and elemental concentrations, and these are commonly used as natural tags for fish movement (Bath et al., 2000; Elsdon and Gillanders, 2005; Tabouret et al., 2010; Iida et al., 2015).

The objective of this study was to understand the early life history of amphidromous gobies in terms of dispersal and retention from hatching through marine larval to recruitment to freshwater stages. To understand the recruitment process from marine to freshwater environments, the migratory history of gobioid species inhabiting Okinawa Island was assessed by otolith microchemistry analysis. In addition, to understand the early life history ecology in the marine larval stage, larval SG was measured in large and small egg-type gobioids.

2. Materials and methods

2.1. Study species

Two large egg-type species (*Rhinogobius similis* Gill, 1859 and *Tridentiger kuroiwae* Jordan & Tanaka, 1927) and four small egg-type species (*Stiphodon percnopterygionus* Watson & Chen, 1998, *Stenogobius* sp., *Sicyopterus lagocephalus* (Pallas, 1770), and *Eleotris acanthopoma* Bleeker, 1853) of amphidromous gobioid fish were selected for this study. Larval SG was measured for all species. Otolith microchemistry analysis was performed for four species (*R. similis, T. kuroiwae*, *Sti. percnopterygionus* and *Stenogobius* sp.) to confirm their migratory patterns, and otolith microstructure analysis was performed. The distribution ranges of most of the selected species are not well known. The genus *Rhinogobius* is distributed from East Asia to Indochina and the Philippines, *Tridentiger* is mainly found in East Asia, and *Stiphodon*, *Sicyopterus*, *Stenogobius,* and *Eleotris* are widely distributed in the Indo-Pacific area. The large egg-type, *T. kuroiwae*, is an endemic to the Ryukyu Archipelago. The small egg-type, *Stenogobius* sp., is commonly known as 'Tanekawa-haze' in Japan; however, its species name could not be determined because the taxonomy of this genus has not been well studied. Moreover, *R. similis,* previously known as *R. giurinus*, is commonly known as 'Gokuraku-haze' in Japan (Suzuki et al., 2016). Egg sizes of each species are as follows: *R. similis*: 2.4 mm long in clavate (Dôtu, 1961); *T. kuroiwae*: 1.4 mm long in elliptical (Kondo, 2013); *Sti. percnopterygionus*: 0.5–0.6 mm in almost spherical (Yamasaki and Tachihara, 2006); *Stenogobius* sp.: 1.0 mm long in elliptical (Yamasaki et al., 2011); *Sic. lagocephalus*: 0.5–0.7 mm in almost spherical (Valade et al., 2009); *E. acanthopoma*: 0.4 mm in almost spherical (Maeda et al., 2008). Some life history characteristics of *Sti. percnopterygionus*, *Stenogobius* sp., and *E. acanthopoma* from Okinawa Island have previously been described (Maeda and Tachihara, 2004, 2005; Yamasaki