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Seasonal and ontogenic migrations of meagre (*Argyrosomus regius*) determined by otolith geochemical signatures

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ABSTRACT

Argyrosomus regius uses different water masses during its life history, being associated with estuaries for reproduction. In order to study the life history and migration patterns, variations in otolith Na, Sr and Ba were measured by laser ablation-ICPMS along transects running from the first year of life to the otolith edge, comprising up to 12 years of age. Visual and statistical modelling approaches were used to analyse both individual- and population-level patterns. Ontogenetic trends in Sr:Ca and Ba:Ca followed a sigmoidal increase over the life span, with an inflection point in Sr:Ca occurring at 5 years of age in males and 6.6 in females, suggesting respective age at maturity. Using reared young-of-year (YOY) meagre for validation, the habitat use of wild fish was characterized and our data suggest that most fish spend the first 2–4 years in offshore waters, and begin moving between water masses after age 6. Population-level analyses indicated significant seasonal variations, with a larger proportion of fish with high otolith Sr:Ca in the spring and summer. Although Sr:Ca would normally be expected to be lower after movement into estuaries, in this case the increase could mark gonad maturation and spawning activity. Alternatively, since the Sr:Ca maxima correspond to higher otolith Ba:Ca in the summer, fish would have moved into the estuarine area, especially since the Guadalquivir river drains metal-rich areas with heavy mining activities leading to elevated Sr concentrations compared to adjacent coastal waters.

1. Introduction

Studying the movement of individuals in the wild has always been a challenge in ecology. However, estimating such movement is essential in life sciences as it is the baseline for evaluating connectivity, a major component in developing management and conservation plans. Moreover, the individual movements and the temporal and spatial scales of fish movement throughout the life-cycle are fundamental determinants of population dynamics and genetic structure, although there is a wide range of movement patterns along the life history, and movement is heterogeneous both within and among individuals (Morrissey and Ferguson, 2011 and cites therein). Fish otoliths are widely used in marine ecology and fish biology, particularly to understand age structure and growth patterns, to define population structure, identify natal sources and nursery areas and study migration patterns (Campana, 2005; Radtke, 1984). The use of the geochemical signatures in the fish otoliths as natural tags is based on the otolith encoding, spatially and chronologically, of the chemical environmental signals experienced by the fish from birth to death. Although, the incorporation of elements into the otolith aragonite and protein matrix is complex, they may reflect directly the surrounding environmental conditions (e.g. Sr, Ba and O isotopes), but other elements are physiologically regulated and may reflect more complex interactions (e.g. Na, K, Zn; Campana, 1999). A wide range of studies are contributing to the development of sound evidence of the utility of the natural tags on otolith fingerprinting for movement studies, particularly for fishes associated to habitats with different water chemistries like estuaries and rivers (see reviews by Elsdon et al., 2008; Elsdon and Gillanders, 2003). Studies of diadramous fish have often incorporated analysis of otolith microchemistry as a means to reconstruct the movements of individual fish along an environmental gradient (Elsdon et al., 2008). Otolith element ratios, especially Sr:Ca, often vary with salinity and provide temporal records of movement between riverine, estuarine, and open sea conditions.

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Variations in the elemental ratios analysed along transects or life history profiles have revealed unsuspected complexity in migration patterns with individual strategies evident (Elfman et al., 2000; Secor, 1999). Individual variations in migration patterns have been determined in diverse species such as eels (Arai et al., 2004, 2008; Elfman et al., 2000; Tsukamoto and Arai, 2001), striped bass (Morris et al., 2003; Secor et al., 2001; Zlokovitz et al., 2003), sticklebacks (Arai and Goto, 2005), as well as various shad and herring species (Limburg, 1998; Limburg et al., 2001), primarily based on the pattern of variation in otolith elemental ratios.

Meagre (*Argyrosomus regius* (Asso, 1801)) is distributed in coastal waters of the Northeast Atlantic, from the northern Gulf of Guinea to the Bay of Biscay including the Mediterranean, with total annual catches averaging 3900 tonnes in the last decade (2000–2009; FAO, 2010). Meagre is a large fish, and can reach to 200 cm total length (TL) and a maximum age of 42 years (González-Quirós et al., 2011; Quéro and Vayne, 1987). The presence of large-size meagres within, or nearby estuaries and salt-marshes along the species range of distribution is thought to be related with their reproduction (Champagnat and Domain, 1978; Lagardère and Mariani, 2006; Quéro, 1989). This hypothesis is consistent with the conceptual model of life history transitions recently proposed for this species in the Gulf of Cádiz (González-Quirós et al., 2011), based on growth, maturity and fisheries data, and previous information about distribution and abundance of the early-life stages in the area (Anonymous, 2005, 2008; Baldó and Drake, 2002; Catalán et al., 2006a,b). Namely, large-size adults (~>110 cm TL and >6 years of age) enter estuarine and salt-marshes from March to August to reproduce. Most catches of adults in the Gulf correspond to local artisanal ships near the Guadalquivir River mouth, whose estuary (the largest in the Gulf of Cádiz) is the main spawning, larval and early-juvenile habitat in the area. Thereafter, juveniles (*ca.* 7–25 cm TL) recruit in open waters nearby the Guadalquivir mouth and along the coast (5–10 m depth contour) throughout the year (Catalán et al., 2006b). Premature meagres (*ca.* 20–70 cm TL and 0^{+}–3 years) may progressively expand their habitat and are fished all year round by local fleets in coastal waters of the Gulf. Meagre above 3 years of age and at a size around 70 cm TL are underrepresented in the landings of local fleets, until they mature and then migrate back to estuaries and salt-marshes to reproduce every year from March to August. Out of the reproductive season adults are underrepresented in the catches of local fleets. It is unknown whether the underrepresentation of prematures and adults during the non-reproductive season in local catches is a consequence of migration off the Gulf of Cádiz or a change in behaviour that reduces catchability.

Analysis of variations in chemical composition of otoliths along transects representing the life history have provided valuable information about ontogenetic habitat changes and migratory behaviour in many fish species (Arai and Goto, 2005; Elfman et al., 2000; Limburg, 2001; Limburg et al., 2001; Zlokovitz et al., 2003) and to determine the spawning areas near salt marshes and estuaries (Brown, 2006; Vasconcelos et al., 2007). The large otoliths of meagre also offer the opportunity for sampling seasonal changes in otolith element composition to analyse inter- and intra-annual patterns, and responses to environmental variations. Annual increment formation has been validated by marginal increment analysis (González-Quirós et al., 2011) and opaque bands are formed in spring (March to May), when water temperature increases. The translucent zone starts to develop in early summer and lasts until late winter or early spring (from June to February), with quite a uniform seasonality to the transition between opaque and translucent zone formation. The wide annual increments and precision in assigning dates to sub-annual structures make these otoliths especially useful for investigating the life history transitions and behaviour of individuals.

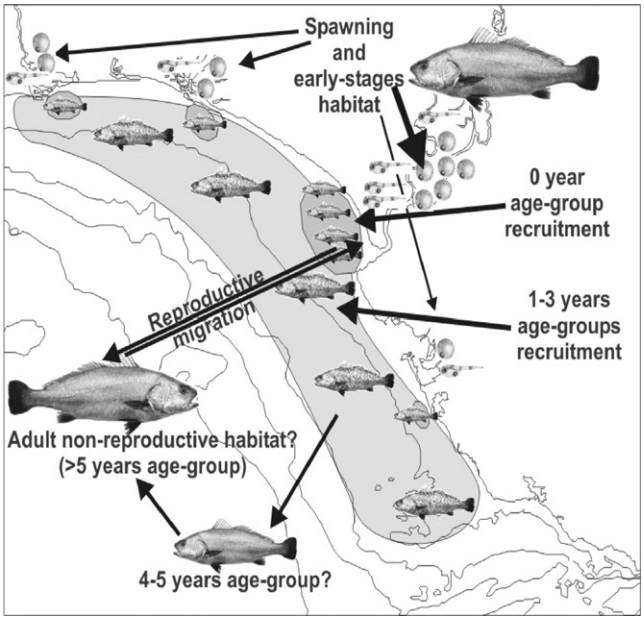

Fig. 1. Migratory meagre behaviour based on the fishing and biological data (González-Quirós et al., 2011).

The life cycle with complex migrations suggested for the meagre in the Gulf of Cádiz (González-Quirós et al., 2011) (Fig. 1) is partially based on indirect inferences from fisheries information and needs further support to be used in the management of the species. Several questions remain, including the individual timing of reproductive migrations and the relationship between environmental variables and migrations, which are particularly amenable to investigation through otolith analysis. The objectives of this study were to use the variation in otolith elemental composition to identify ontogenetic changes in life history which may be associated with habitat shifts, maturation, and spawning migrations. Individual variations in patterns of habitat use were quantified to evaluate the conceptual life history model and estuarine dependence of this species. Additionally, the individual variability observed in reared individuals was estimated to provide an insight into inherent variations under controlled conditions. Our results suggest a complex behaviour that requires consideration when management measures are provided for the species.

2. Materials and methods

2.1. Collection of fish

The otoliths used for this study were provided by IFAPA Centro del Toruño (Cádiz, Spain). *A. regius* were collected in the Gulf of Cádiz (SW Spain) from April to July 2007 by the small-size artisanal fishing vessels primarily within the 50 m depth contour in the area south of the Guadalquivir estuary (Fig. 2).

All fish were sampled at the fish market of Chipiona, where they were sexed, weighed (W; g), measured (TL; cm) and their heads removed for otolith extraction (Table 1). The otoliths of 29 meagre were analysed, from fish ranging in size 118–151 cm TL and 12.4–28.1 kg, and 8–13 years of age, with the exception of one individual of 19 years. Eighteen of the fish were male, nine were female, and sex was not determined for the remaining two individuals. The oldest fish were female, though there were no significant differences in size or age between the sexes. The fish were collected during 2007, and thus the environmental record from published information was compared for the years from 1987 to 2007 comprising the life span of the studied individuals.