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Short communication

Insights into mixing and movement of South Pacific albacore *Thunnus alalunga* derived from trace elements in otoliths

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ABSTRACT

Information on the movement and stock structure of commercially important tunas underpins the effective management of exploited populations. In the case of the South Pacific albacore (*Thunnus alalunga*) stock, longstanding questions remain regarding the degree of connectivity among larval pools, the migration routes of juveniles and adults and the biophysical factors influencing these processes. We measured trace elements (Li, Mg, Mn, Cu, Sr, Ba, Pb, Ca) in albacore otoliths collected across a broad geographical range in the South Pacific Ocean to address these knowledge gaps. Capture locations in French Polynesia, New Caledonia and New Zealand were discriminated with high accuracy (overall 85% of individuals correctly classified) based on analyses at the otolith edge (reflecting the final <1 month of life) using LA-ICPMS. Spatial comparisons of otolith core chemistry (reflecting the first ~2 weeks of life post-hatch) from the 2005/06 cohort suggest some mixing of larval pools for fish sampled from New Caledonia and New Zealand, whereas French Polynesian fish may have originated from a chemically and/or geographically distinct larval source. Annual and/or sub-annual cycles in Sr:Ca and Ba:Ca were evident along ablation transects encompassing the full life history of individuals. These patterns may reflect seasonal north-south movements across ocean fronts; however, the vertical behaviours of albacore and the lack of opportunities for controlled experiments on temperature effects and time-lags in elemental incorporation complicates environmental reconstructions based on trace element data alone. Expanding the present analysis across multiple years and regions, and integrating data from several sources (e.g. commercial catch data, tag returns, otolith $\delta^{13}C$ and $\delta^{18}O$, ocean circulation models) could help clarify the linkages between environmental factors and mixing and movement patterns in albacore.

1. Introduction

Tunas are highly mobile fishes that often undertake long-range movements to track prey resources, both horizontally and vertically, and to reproduce at distant spawning grounds (Patterson et al., 2008; Rooker et al., 2008; Block et al., 2011). Mark-recapture experiments using conventional tags, and data from satellite, acoustic and archival tagging programmes have provided important insights into the movements of tunas (Dagorn et al., 2000; Block et al., 2001; Sibert and Hampton, 2003; Patterson et al., 2008), including albacore *Thunnus alalunga* (Ichinokawa et al., 2008; Childers et al., 2011). However, unlike the North Pacific and North Atlantic Oceans and the Mediterranean Sea where such tagging methods have been successfully applied to albacore (e.g. Otsu and Uchida, 1963; Bertignac et al., 1999; Arrizabalaga et al., 2002; Ichinokawa et al., 2008; Childers et al., 2011), similar results have not been observed in the South Pacific, with only small numbers of tags recovered (Labelle, 1993; Bertignac et al., 1996; Williams et al., 2010). This in part has been due to the difficulties in tagging sufficient numbers of juveniles in the surface fisheries and, until quite recently, low exploitation rates in the longline fisheries (Williams et al., 2010). Moreover, the poor condition of many adult fish captured via longline methods has often prevented tagging, or resulted in high tagging-induced mortality (Williams et al., 2010).

Associating long-term catch per unit effort (CPUE) datasets with trends in oceanographic parameters has proved useful in showing how climatic variability (Kimura et al., 1997; Lu et al., 1998; Briand et al., 2011), localised environmental forces (Laurs et al., 1977; Zainuddin et al., 2008; Domokos, 2009; Lan et al., 2012), prey distribution (Domokos et al., 2007) or combinations of these factors (Briand et al., 2011) can influence the horizontal and vertical distribution, movement and recruitment dynamics of

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albacore. However, fundamental questions remain regarding the number and/or location of spawning areas, connectivity and mixing between larval sources and adult populations and the biophysical forces that structure these connections. This situation has limited the spatial resolution of the population model used to assess the status of the stock (Kolody et al., 2010; Hoyle, 2011).

Analysis of the chemical constituents of otoliths may provide an alternative method for elucidating mixing and movement patterns in albacore. Otoliths can be considered as natural tags that grow continuously throughout the fish's life. They form daily and annual growth bands, and are composed of a calcium carbonate lattice that is not re-metabolised once deposited (Campana and Nielson, 1985; Campana, 1999). These properties, combined with strong evidence that certain trace elements and isotopes are incorporated into otoliths in response to changes in environmental, dietary, physiological and/or ontogenetic parameters (e.g. Elsdon and Gillanders, 2003; Macdonald and Crook, 2010; Walther et al., 2010), have allowed scientists to trace movements and explore connections between larval and adult populations of marine fishes, including several tuna species, at a range of spatial and temporal scales (e.g. Swearer et al., 1999; Rooker et al., 2001, 2008; Wang et al., 2009; Schloesser et al., 2010; Shiao et al., 2010; Wells et al., 2012).

Here we examine variation in trace elements in albacore otoliths across a large spatial scale spanning ~19° latitude and 49° longitude in the South Pacific Ocean to test the utility of otolith chemistry analysis as a tool for defining movements and stock structure in albacore. Specifically, we address the following questions: (1) Can capture locations be delineated based on the trace element concentrations at the otolith edge? (2) Is there evidence for larval mixing following spawning, or for the existence of non-mixing populations in the South Pacific? Additionally, we present examples of trace element transects measured across the entire lifetimes of eight albacore, and discuss the potential of combining such information with tagging efforts and other isotopic, genetic and catch data to increase inference in tracing movement patterns for the species.

2. Materials and methods

2.1. Otolith selection and preparation

Sagittal otoliths were sourced from albacore captured by longline vessels operating in waters off French Polynesia (20°13′ S–20°38′ S, 146°40′ W–146°52′ W), New Caledonia (21°43′ S–23°16′ S, 164°10′E–165°19′ E) and New Zealand (39°25′ S–39°44′ S, 178°24′ E–178°27′ E) between September 2009 and May 2010. Fork length (FL) for each fish was measured to the nearest cm and otoliths were removed immediately following capture. Otoliths were cleaned of adhering tissue, washed in an ultrasonic bath with deionised water then dried at 30 °C for at least 24 h before being archived in polyethylene capsules. Otoliths from a subsample of 29 fish (New Caledonia, *n* = 12; New Zealand, *n* = 8; French Polynesia, *n* = 9) with similar FL and capture date were selected for analysis to maximise the likelihood that individuals would belong to the same cohort (Table 1).

One otolith from each fish was embedded in epoxy resin (Epofix®, Struers) and sectioned transversely through the core using a modified high-speed diamond cutting saw (Gemasta™) fitted with a 100-μm wide diamond impregnated blade. Transverse sections (~1-mm thick) were mounted on a circular glass disc using araldite and polished to expose (assumed[1]) daily growth increments near the primordium using 1000× wet and dry sandpaper and 3-μm lapping film. Sections were then turned over and the procedure repeated on the opposite side. Prepared sections were triple-rinsed in deionised water, air dried overnight in a class-100 laminar flow cabinet, and arranged in rows on microscope slides using double-sided tape.

Table 1
Summary of capture locations, fish numbers (*n*), mean fork length (FL) and ranges (in parentheses), estimated ages from annual increment counts (from Farley et al., 2013a) and season spawned for albacore used in this study.

Capture location	*n*	FL (mm)	Age class	Season spawned
New Caledonia	1	84.0	2+	2007/08
	6	82.8 (81–85)	3+	2006/07
	5	83.4 (81–87)	3+	2005/06
New Zealand	6	81.9 (81–83)	3+	2006/07
	2	82.5 (80–85)	4+	2005/06
French Polynesia	4	91.3 (88–93)	3+	2005/06
	3	89.3 (86–91)	4+	2004/05
	1	90.0	5+	2003/04
	1	95.0	7+	2001/02

2.2. Trace element analysis

Otoliths were analysed using laser ablation-inductively coupled plasma mass spectrometry (LA-ICPMS). We used an Agilent 7700 ICPMS (Agilent Technologies), coupled to a HelEx laser system (Laurin Technic, Canberra, and the Australian National University) located at the School of Earth Sciences, The University of Melbourne, Australia. The HelEx system is constructed around a Compex 110 (Lambda Physik, Gottingen, Germany) ArF excimer laser (Eggins et al., 1998). Otolith mounts were placed in the sample cell and the primordium of each otolith was located visually with a 400× objective and a video imaging system. The intended ablation path on each sample was then digitally plotted using GeoStar v6.14 software (Resonetics, USA).

Each otolith was ablated along a transect running from the primordium along the antisulcul margin to the first inflection point (IP), then along the ventral arm, distal to the ventral groove, to the terminal edge. A pre-ablation step was implemented to minimise potential surface contamination (Proctor and Thresher, 1998; Davies et al., 2011), with the laser scanned at 12 μm s^{-1} across the sample at low energy using a 71 μm diameter spot. The resulting transect was 6-μm deep based on calculations incorporating the laser drilling rate, scan speed and power density on the sample for the HelEx system in addition to microscopic examination of ablation site geometry (Eggins et al., 1998;Woodhead et al., 2005). Data were then acquired from a second analysis along the same transect using a 32 μm spot, with the laser pulsed at 10 Hz and scanned at 6 μm s^{-1} with fluence of ~5 J cm^{-2}. This produced a 32-μm wide × 6-μm deep transect, which, when daily increment positions are considered for our samples, negates concerns regarding vertical versus horizontal growth integration errors (Hoover and Jones, 2013). Ablation occurred inside a sealed chamber in an atmosphere of pure He (flow rate, ~0.3 L min^{-1}) with the vaporised material transported to the ICP-MS in the Ar carrier gas (flow rate, ~1.23 L min^{-1}) via a signal smoothing manifold. Otoliths were analysed for a suite of elements including ^{7}Li, ^{25}Mg, ^{43}Ca, ^{55}Mn, ^{63}Cu, ^{88}Sr and ^{138}Ba, ^{207}Pb and Ca was used as an internal standard to correct for variation in ablation yield among samples.

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[1] Daily increment deposition has not been empirically validated for otoliths of early juvenile South Pacific albacore (Farley et al., 2013a). However, Laurs et al. (1985) did demonstrate daily increment formation in North Pacific albacore sagittae for fish between 50 and 100 cm FL, and suggested that increments are accreted daily from the time of yolk-sac absorption in the species.