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Can otolith elemental chemistry retrospectively track migrations in fully marine fishes?

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Otolith microchemistry can provide valuable information about stock structure and mixing patterns when the magnitude of environmental differences among areas is greater than the cumulative influence of any vital effects. Here, the current understanding of the underlying mechanisms governing element incorporation into the otolith is reviewed. Hard and soft acid and base (HSAB) theory is employed to explore the differences in chemical behaviours, distributions and affinities between elements. Hard acid cations (*e.g.* Mg^{2+}, Li^{+} and Ba^{2+}) tend to be less physiologically influenced and accepted more readily into the otolith crystal lattice but are relatively homogeneous in seawater. Soft acid cations (*e.g.* Zn^{2+} and Cu^{2+}) on the other hand, exhibit more varied distributions in seawater, but are more likely to be bound to blood proteins and less available for uptake into the otolith. The factors influencing the geographical distribution of elements in the sea, and their incorporation into the otoliths of marine fishes are reviewed. Particular emphasis is placed on examining physiological processes, including gonad development, on the uptake of elements commonly used in population studies, notably Sr. Finally, case studies are presented that either directly or indirectly compare population structuring or movements inferred by otolith elemental fingerprints with the patterns indicated by additional, alternative proxies. The main obstacle currently limiting the application of otolith elemental microchemistry to infer movements of marine fishes appears to lie in the largely homogeneous distribution of those elements most reliably measured in the otolith. Evolving technologies will improve the discriminatory power of otolith chemistry by allowing measurement of spatially explicit, low level elements; however, for the time being, the combination of otolith minor and trace element fingerprints with alternative proxies and stable isotopic ratios can greatly extend the scope of migration studies. Among the otolith elements that routinely occur above instrument detection limits, Ba, Mn and Li were deemed the most likely to prove reliable geographic markers in marine species.

Key words: chemical fingerprint; geolocation; microchemistry; movement; natural tag; trace metals.

INTRODUCTION

An understanding of the spatial structure of fish stocks and the connectivity within and between them is increasingly considered an important pre-requisite for sustainable fisheries management (Pulliam, 1988; Botsford *et al.*, 2009). The concept

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of open marine fish populations with individuals evenly distributed about a homogeneous environment is now largely redundant. Rather, marine habitats and their inhabitants are known to exhibit patchy distributions as a result of spatial and temporal shifts in physical (*e.g.* hydrodynamics, temperature and salinity) and biological (*e.g.* productivity and predator abundance) characteristics (Hixon *et al.*, 2002). Identifying such patches is particularly challenging in the open ocean, given its vast, three-dimensional structure and scarcity of geographically and temporally stable boundaries. Advances in satellite telemetry and remote sensing, however, have greatly increased the sophistication with which water masses and their inhabitants can be linked (Sims *et al.*, 2006) and improved the understanding of the migratory behaviour of individual fishes (Righton *et al.*, 2010; Block *et al.*, 2011).

Historically, catch data and mark–recapture experiments have formed the foundation of the broad understanding of marine fish distributions. The resolution of such data, however, tends to be relatively coarse, with patterns inextricably linked to the distribution of the fishing fleets (Bolle *et al.*, 2005; Righton *et al.*, 2010). The use of pop-up satellite archival tags (PSAT) and electronic data storage tags (DST) has increased dramatically over the past decade, with improved miniaturization and recording capacity allowing sometimes multi-year recordings of the ambient experience of individual fishes (Metcalfe & Arnold, 1997; Hunter *et al.*, 2003; Metcalfe *et al.*, 2006; Block *et al.*, 2011). These new technologies have provided exciting new insights into the migratory behaviours and mechanisms that underpin population structuring. Their use, however, is often precluded by cost, battery life, low rates of return and size constraints, with observations largely restricted to the adult phase in top predators.

In order to obtain a full picture of ontogenetic fish movements, a toolbox approach is required, where a range of independent techniques providing information at specific spatial and temporal scales can be used to understand connectivity across life-history stages (Begg & Waldman, 1999; Fromentin *et al.*, 2009; Kaplan *et al.*, 2010). A number of natural tags are employed for this purpose, including stable isotopes in soft tissues (Rodgers & Wing, 2008), amino-acid signatures (Riveiro *et al.*, 2011), molecular genetics (Cook *et al.*, 2007), parasite loadings (Sequeira *et al.*, 2010), phenotypic markers such as morphometrics (Lawton *et al.*, 2010), colour (Arnegard *et al.*, 1999) and otolith shape (Ferguson *et al.*, 2011), as well as the chemical composition of calcified structures such as otoliths and scales (Campana, 1999). Each method has shown potential for determining population structure and discriminating among resident and migrant fishes, however, otolith chemistry has shown the greatest promise for reconstructing lifetime movements. The technique relies on the basic assumption that as the otolith grows, chemical markers from the ambient environment are incorporated into its microstructure, resulting in a fingerprint that reflects, at least in part, the physicochemical properties of the environment in which it was formed (Bath *et al.*, 2000; Elsdon & Gillanders, 2003*a*).

Otoliths are paired crystalline structures located in the inner ear of all bony fishes, used for sound reception, maintaining equilibrium and processing directional cues (Popper & Fay, 2011). They display a number of key properties that have resulted in their chemical composition being increasingly exploited in the field of fish spatial dynamics. First, they exhibit unrivalled time-keeping properties. Otoliths develop very early in the fish's life, usually during the embryonic stages, and grow continuously through daily accretions of calcium carbonate ($CaCO_3$) aragonitic crystals

onto a fibroprotein organic matrix (Campana & Neilson, 1985; Tohse & Mugiya, 2002; Payan *et al*., 2004). Diurnal and seasonal rhythms result in growth bands that have been used in the field of sclerochronology for over a century and provide a baseline for carrying out time-resolved chemical analyses (Campana & Thorrold, 2001). Second, as otoliths are acellular and metabolically inert, they are not reworked or resorbed, even during times of starvation (Campana & Neilson, 1985). Chemical fingerprints are thus retained permanently within the microstructure. Third, while the precise relationships are not always clear, there is no question that otolith composition is affected by environmental conditions. This has been exploited by studies using otolith shape and whole otolith chemistry to infer stock structure, and chemical patterns across growth bands to provide information across life history stages (Elsdon *et al*., 2008). Fourth, otoliths are common to all teleost species, which is particularly appealing for investigating habitat use in inaccessible fishes (*e.g.* from deep or remote environments), where external tags cannot be applied or are unlikely to be recovered. Finally, while otolith processing and chemical analyses are not inexpensive, sample acquisition is equivalent to all individuals being tagged and the technique is often significantly cheaper than an equivalent tagging study (Fairclough *et al*., 2011).

While the last two properties are common to most natural tags, the capacity of otoliths to record (and retain) time-resolved lifetime environmental histories provides unique opportunity for geolocating individual fishes in time and space. Accordingly, otolith microchemistry represents a hugely valuable resource: a means to infer past conditions, stock structure, connectivity patterns and individual migrations. Indeed, otolith microchemistry has appeared in almost 700 peer-reviewed papers to date (Web of Science search on 26 September 2011, Topic = otolith chemistry OR otolith microchemistry) and growth within the field shows no sign of slowing (Fig. 1). The precise mechanisms governing elemental incorporation into the otolith, however, are still not fully understood (Campana, 1999) and inconsistent patterns of element incorporation among species and studies undermine its routine application to movement reconstruction (Elsdon *et al*., 2008). Here, the use of otolith microchemistry, specifically minor and trace element concentrations is examined, as a tool for describing the movements of fully marine fishes. The current understanding of the mechanisms underpinning otolith microchemistry is reviewed and its application specifically within the marine environment is discussed. Finally, case studies that have used otolith microchemistry to infer spatial distributions of marine fishes and attempts made to validate their interpretations using alternative proxies are presented.

HOW DOES OTOLITH MICROCHEMISTRY SERVE AS AN ENVIRONMENTAL TAG?

CHEMISTRY OF RELEVANT ELEMENTS AND MECHANISMS GOVERNING THEIR INCORPORATION INTO THE OTOLITH

The mechanisms governing otolith formation are quite different to those controlling bone, shell and coral growth, as the otolith crystallizes within the endolymph fluid and is not in direct contact with epithelial tissue or the surrounding water (Payan

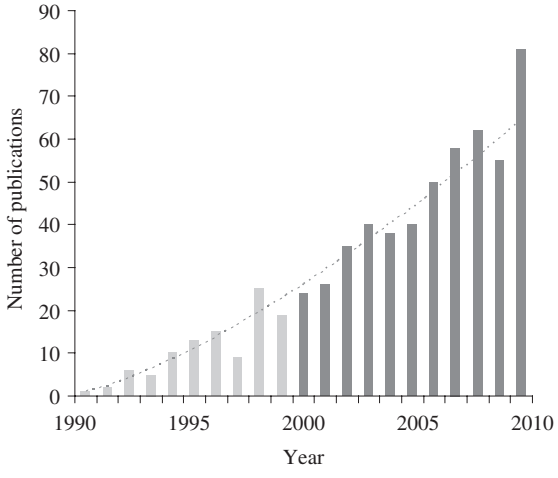

FIG. 1. Yearly numbers of publications featuring otolith chemistry over the past two decades (Web of Science search on 26 September 2011, Topic = otolith chemistry OR otolith microchemistry). , years overlapping with Campana & Thorrold (2001). A power curve closely fits the data ($y = 0.91\ x^{1.40}$; $r^2 = 0.97$), although the sharp rise in 2010 can be attributed, in part, by two special issues of Environmental Biology of Fishes dedicated to Proceedings of the 4th International Otolith Symposium (Miller *et al*., 2010).

et al., 2004). Moreover, the mechanism of otolith crystal growth is biologically controlled, and thus likely to differ considerably to inorganic crystal precipitation from a saturated solution (Weiner, 2008). Element incorporation into otolith aragonite is a complex, multistage process, involving the movement of ions from the ambient water into the blood plasma *via* branchial or intestinal uptake, across inner ear membranes into the endolymph fluid, and finally into the growing surface of the otolith (Payan *et al*., 2004). As such, elemental discrimination can occur at any of four major interfaces: environment–blood, blood–blood binding proteins, blood–endolymph and endolymph–otolith (Campana, 1999). Changes in element concentrations across these four interfaces provide a tangible means to examine their relative control on elemental fractionation. Here, it is useful to consider the similarities and differences in chemical affinities and behaviours between elements. In the 1960s, chemists developed a concept known as hard and soft acid and base (HSAB) theory (Pearson, 1963). HSAB theory categorizes reactants as acids or bases, depending on whether they donate or accept electrons within a reaction, and as hard, soft or intermediate, depending on their polarizability, oxidation state and electronegativity (Fig. 2). Hard acids and bases are typically small ions or molecules with relatively high charge density that are weakly polarizable. Soft acids and bases tend to be large and strongly polarizable. The value of this concept is that acids and bases form strong bonds when binding with similar counterparts (*i.e.* hard acids form stronger bonds with hard bases and soft acids with soft bases). In a dynamic medium like seawater, and particularly blood plasma, where the number of available ligands outweighs the number of metal ions, strong bonds will tend to dominate the speciation of any elemental ion, and the behaviour of elements can be loosely predicted (Williams, 1971).

Hard soft acid base (HSAB)	Element	Type of distribution†	Ocean residence time (years)	Ion radius	Charge	Electronegativity
Hard	Li	c	10^8	0·76	1+	0·98
	Mg	c	10^8	0·72	2+	1·31
	Ca	almost c	10^8	1·00	2+	1·00
	Sr	almost c	10^8	1·18	2+	0·95
	Ba	n	10^4	1·35	2+	0·89
Intermediate	Mn	s	10^4	0·67	2+	1·55
	Zn	n	10^4	0·74	2+	1·65
Soft	Cu	s + n	10^4	0·77	2+	1·90

†c, conservative; s, scavenged; n, nutrient-like (after Steele *et al.*, 2009).

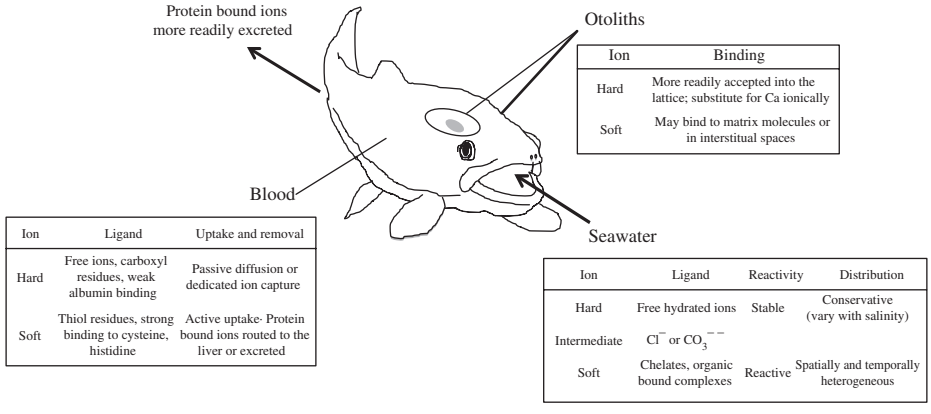

FIG. 2. Schematic summarizing the chemical behaviour of key elements used in otolith research. Hard acid elements such as Mg, Sr, Ca and Ba are typically held as hydrated ion complexes in both seawater and blood and their relative concentrations will be passed to otoliths with less influence from blood protein chemistry. By contrast, soft acid elements such as Cu (and Pb) are strongly bound to organic ligands and have a greater affinity for protein-binding in blood. The practical outcome is that while soft ions hold greater promise for geolocating in marine settings, they are also the ions most susceptible to physiological fractionation in the body. Figure is based on hard and soft acid and base (HSAB) theory and data in Williams (1971), Henderson (1984) and Kaim & Schwederski (1994).

So far, 50 elements have been detected in otoliths, at major (Ca, C, O and N), minor (>100 ppm: Cl, S, Mg, Na, P, Sr and K) and trace levels (<100 mg kg^{-1}: Ag, Al, As, B, Ba, Bi, Br, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Fe, Gd, Hg, Ho, La, Li, Lu, Mn, Nd, Ni, Pb, Pr, Rb, Sc, Se, Si, Sm, Tb, Tm, U, V, Y, Yb and Zn) (Campana, 1999; Chen & Jones, 2006). Only seven elements, however, are routinely used to infer past location in fishes (Li, Mg, Mn, Cu, Zn, Sr and Ba; Fig. 2), due to their environmental heterogeneity and otolith concentrations often above detection limits. In seawater, hard acid ions such as Li^+, Mg^{2+}, Ca^{2+}, Sr^{2+} and Ba^{2+} form strong bonds with $^{\bullet}OH$ radicals and are mainly found as hydrated free ions (Fig. 2). These ions typically have a residence time longer than the mixing time of the ocean and consequently their concentrations tend to vary with salinity. By contrast, soft and intermediate acid ions such as Cu^{++}, Zn^{++} and (to a lesser extent) Mn^{++}, bind to softer bases in seawater such as Cl^- and CO_3^{--}. These bonds are relatively weak, making soft elements reactive and readily removed from seawater (Henderson, 1984).

Little is known about the relative bioavailability of different elements to being taken up in marine fishes, but it is likely that they will be fractionated from one

another during transport across the gut, gills and skin. Osmoregulation is largely effected across gut membranes in marine species (Smith, 1930), and maintains relatively constant concentrations of blood Ca, Na, K, Mg and Cl in marine and freshwater fishes despite considerable differences in ambient concentrations (Campana, 1999). Once within the circulatory system, the transport, availability and ultimate fate of elements will depend on their chemical characteristics and requirement in metabolic reactions, as well as the composition of the blood fluid. Elements that are constituent parts of functioning enzymes or structural tissues are likely to have relatively long mean residence times in the body due to the continued recycling of enzymes and tissues. By comparison, elements with no major structural or physiological role may be removed rapidly, resulting in low residence times. Exceptions include the quintessentially toxic metals (Cd, Pb and Hg), which have very long residence times due to comparatively ineffective excretion mechanisms (Williams, 1971). The relative timing of elemental changes across an otolith may therefore reflect differences in turnover times and the number of body pools for those particular elements. Elements with short turnover times (*e.g.* Mn and Ba) may be better suited to studying detailed temporal changes than elements with potentially longer turnover times (*e.g.* Sr and Pb).

In the blood plasma, soft acid cations such as Cu^{++} and Zn^{++} and possibly Mn^{++} are actively bound to the histidine, methionine and cysteine residues of plasma proteins and used in metabolic reactions or actively transported to the liver where they are excreted (Watanabe *et al*., 1997). Less than 10% of total blood Cu (Williams, 1971) and $<1\%$ of Zn (Fletcher & Fletcher, 1980) are estimated to be present as free ions. Hard acid cations (*e.g.* Li^{+}, Mg^{++}, Ca^{++}, Sr^{++} and Ba^{++}) on the other hand, are largely transported as free ions or weakly bound to small molecular complexes, albumins or globulins (Williams, 1971). Calcium (and Ca homologues) may also be strongly bound to carboxyl residues in Ca-binding proteins, allowing plasma Ca to be divided into protein bound (30–40%) and ultrafiltrable fractions (60–70%). The ultrafiltrable fraction is dominated by ionized Ca, meaning that $>50\%$ of total Ca (and thus probably Sr) is estimated to be present in plasma as the free ion (Mugiya, 1966; Andreasen, 1985; Hanssen *et al*., 1989). Therefore, hard and soft acid ions are very likely to be fractionated from one another within the blood plasma. Mg may behave somewhat differently to other Group II elements due to an ionic radius that is very small unless hydrated, when it becomes extremely large (Kaim & Schwederski, 1994). Moreover, it has been implicated in stabilizing amorphous mineral phases during otolith biomineralization and, due to its participation in a number of biological processes, is tightly regulated in the body (Weiner, 2008).

Because the speciation of metal ions within blood plasma is dynamic, it is likely that blood chemistry, particularly the composition and relative abundances of blood proteins, will influence the proportion of free ions, and thus affect their ability to cross the plasma–endolymph membrane barrier (Kalish, 1991). Physiological variation in the composition of blood plasma proteins is more likely to influence the soft acid ions, as they are more strongly associated with blood proteins. Depletion of all major elements in the endolymph except K (Kalish, 1991), however, indicates active discrimination against most ion types by the saccular epithelium (Payan *et al*., 2004).

Finally, incorporation of an element into the otolith depends on its compatibility to bind directly into the crystal lattice, within interstitial spaces or to the organic matrix (Campana, 1999). Based on HSAB theory, the strong protein binding affinities of

soft metals will probably favour their incorporation into the otolith bound to the organic matrix. This is corroborated by spatial heterogeneity in otolith Cu (Milton *et al.*, 2000; Milton & Chenery, 2001*a*) and an estimated 70–100% of otolith Cu and 40–60% of otolith Zn associated with the protein matrix (Miller *et al.*, 2006). Inclusion within the otolith mineral phase occurs (1) *via* substitution for Ca, where partitioning will be controlled by ion charge, radius and crystal elasticity influences, (2) within dislocation sites on the growing crystal surface, where partitioning may be controlled by kinetic influences such as precipitation rate (Reeder & Rakovan, 1999), or (3) possibly through inclusion in amorphous precursor mineral phases (Weiner, 2008). Fractionation of elements during their incorporation into the otolith is further complicated by additional effects of temperature. It is debatable whether any such temperature effects are direct or indirect, with many studies attributing them to physiological processes, such as growth rate, which are in turn controlled by ambient temperature. Walther *et al.* (2010) discuss possible mechanisms underpinning 'growth rate effects' on otolith microchemistry, grouping them into two broad types: kinetic and physiological. Kinetic hypotheses include greater entrapment of trace element impurities into the growing crystal at higher temperatures, due to faster growth and increased numbers of crystal defects (Gaetani & Cohen, 2006). Another 'kinetic hypothesis' relates faster calcification rates with greater supply of Ca^{++} ions to the endolymph, effectively diluting the other elements within the precipitating fluid (Sinclair, 2005). While crystal growth rate has been shown to influence elemental partitioning during abiotic $CaCO_3$ formation, biogenic $CaCO_3$ forms *via* a transient amorphous phase associated with the organic matrix (Weiner, 2008), thus extrapolating patterns directly from inorganic crystal theory is potentially misleading. Finally, the physiological hypothesis is based on the coupling of somatic growth rates with protein synthesis, with significant changes in the protein composition of biological fluids affecting the availability of ions for uptake into the otolith (Kalish, 1991).

INFLUENCES ON OTOLITH MICROCHEMISTRY

In the early days of otolith microchemistry, it was assumed that trace elements would be incorporated into the otolith in proportion to their availability in the surrounding water. For most elements, this is now known not to be the case (Table I). Positive relationships, however, have been observed between ambient and otolith concentrations for a number of elements, particularly the hard acid elements, Sr and Ba. It is estimated that marine fishes derive 83 and 98% of their otolith Sr and Ba from the surrounding water, respectively (Walther & Thorrold, 2006). Occasionally, freshwater systems exhibit Sr concentrations higher than marine systems (Elsdon & Gillanders, 2005*a*), but generally water Sr follows a quasiconservative distribution, allowing otolith Sr:Ca ratios to act as a powerful marker of movement across extreme salinity gradients. As such, otolith Sr:Ca ratios are fairly routinely applied to reconstructing migrations of diadromous species (Kalish, 1990; Babaluk *et al.*, 1997; Secor *et al.*, 2001; Thorrold *et al.*, 2001; Gillanders, 2005; Milton & Chenery, 2005; Walther & Thorrold, 2010; Panfili *et al.*, 2012). Interpretation of the Sr:Ca signal still requires some caution, however, given considerable interspecific variation in Sr uptake rates (Swearer *et al.*, 2003; Rooker *et al.*, 2004), potential for vateritic inclusions to be misidentified as freshwater excursions (Tzeng *et al.*, 2007) and possibly confounding effects of temperature and

physiology (Kalish, 1991; Elsdon & Gillanders, 2004; Brown & Severin, 2009; Miller, 2011).

Occasionally, elements other than Sr and Ba have exhibited positive correlations between otolith and ambient concentrations (Geffen *et al*., 1998; Milton & Chenery, 2001*a*; Ranaldi & Gagnon, 2008*b*), but more often than not, no relationship is found or there are contradictions among species and studies (Table I). Some of these contradictions are probably due to species-specific elemental processing, but some may be artefacts of reporting method, with studies expressing water chemistry in terms of absolute water concentrations, water element:Ca ratios and salinity. It is not always clear which of these three measures have the greatest influence on otolith chemistry (Bath *et al*., 2000; Milton & Chenery, 2001*a*; Elsdon & Gillanders, 2004; Hicks *et al*., 2010) but is clearly an area requiring further research. Another important consideration is the true bioavailability of the element in question. Reported concentrations tend to represent total dissolved metals, which may be dominated by ligand-bound complexes that cannot cross biological membranes (Campana, 1999). Also, alternative sources of metals, such as sediment and diet, are rarely discussed but may prove significant for certain elements, such as Cd (Ranaldi & Gagnon, 2009).

As shown by the sheer volume of studies (and contradictions) summarized in Table I, temperature, diet and vital effects such as age, growth rate and gonad maturation, can all influence element incorporation into the otolith, often in multiplicative, complex ways (Kalish, 1991). Given the substantial variation in physiology, biochemistry and otolith morphology among fish species (Söllner *et al*., 2003; Popper & Fay, 2011), it is perhaps not surprising that interspecific differences in otolith elemental incorporation have been observed. Within-species differences in elemental processing may also be important, with recent experiments indicating different temperature effects on otolith Mg, Mn and Ba incorporation according to the population from which the fishes were sourced (Clarke *et al*., 2011). Such intrinsic effects on otolith microchemistry have not been previously demonstrated, but have important implications for understanding the underlying mechanisms and theoretically enhance its application for stock discrimination.

Temperature has frequently been cited as a major control on otolith chemistry. Reports of negative relationships between temperature and otolith Sr:Ca ratios, akin to responses of inorganic aragonite and corals, have generally arisen from studies working with larvae of marine, temperate species (Radtke, 1989; Townsend *et al*., 1992; DiMaria *et al*., 2010). Otherwise, where significant temperature effects have been observed, the majority of studies have reported positive relationships between temperature and otolith Sr (Bath *et al*., 2000; Elsdon & Gillanders, 2002; Martin *et al*., 2004) and Ba (Miller, 2009). While separating the effects of temperature and growth remains a challenge, a number of studies have reported negative relationships between growth rate and otolith Sr:Ca (Sadovy & Severin, 1994; Walther & Thorrold, 2010), and more recently, Ba:Ca (Miller, 2009, 2011). Experiments examining temperature or vital effects on otolith elements other than Sr and Ba are scarce, but a negative temperature effect was reported for otolith Mn:Ca ratios (Miller, 2009) and a positive growth rate effect reported for otolith Mg:Ca ratios (Martin & Thorrold, 2005). Recently, increasing numbers of studies have reported interactions between otolith Sr:Ca, Mg:Ca and Ba:Ca ratios, water concentrations and temperature (Elsdon & Gillanders, 2004; Miller, 2011). Such findings have serious implications,

TABLE I. Review of significant and non-significant (NS) effects of different influences (water chemistry, temperature, diet, vital and intrinsic effects) on otolith element concentrations and their partition coefficients, focusing on fishes that spend at least part of their life in seawater; the few fully freshwater studies are indicated (FW). Elements have been loosely ordered into hard and soft acids, with Mn and Zn ions behaving as something of intermediaries

Element *v.*	Water chemistry (including element:Ca, absolute concentrations and salinity)	Temperature	Other (including diet, vital and intrinsic effects)
Sr	Positive: in the laboratory (Gallahar & Kingsford, 1996; Tzeng, 1996; Bath *et al.*, 2000; Milton & Chenery, 2001*a*; Elsdon & Gillanders, 2003*b*; Martin *et al.*, 2004; Elsdon & Gillanders, 2005*a*; Zimmerman, 2005; Walther & Thorrold, 2006; Hicks *et al.*, 2010; Macdonald & Crook, 2010; Miller, 2011)	Positive (Kalish, 1989; Fowler *et al.*, 1995*b*; Hoff & Fuiman, 1995; Bath *et al.*, 2000; Elsdon & Gillanders, 2002; Elsdon & Gillanders, 2004; Martin *et al.*, 2004; Martin & Wuenschel, 2006)	Somatic growth rate: negative (Sadovy & Severin, 1992, 1994; de Pontual *et al.*, 2003) Otolith precipitation and somatic growth rate: NS or weakly negative (Bath *et al.*, 2000; Martin *et al.*, 2004; DiMaria *et al.*, 2010)) Reproduction: significant (Kalish, 1989, 1991; Fuiman & Hoff, 1995; Friedland *et al.*, 1998; Clarke & Friedland, 2004)
	Positive: in the field (often inferred rather than measured) (Thorrold *et al.*, 1997; Babaluk *et al.*, 1997; Secor & Rooker, 2000; Milton & Chenery, 2005; Tzeng *et al.*, 2005)	Negative (Radtke *et al.*, 1990; Townsend *et al.*, 1992; DiMaria *et al.* 2010)	Stress: positive (Kalish, 1992; Townsend *et al.*, 1992). In the latter it was proposed that stress caused by low temperature reduces ability to discriminate against Sr
		NS (Gallahar & Kingsford, 1996)	Age and size: positive (Kalish, 1989; Fowler *et al.*, 1995*b*; Fuiman & Hoff, 1995; Proctor *et al.*, 1995; Fowler *et al.*, 2005; Steer *et al.*, 2009); NS (Elsdon & Gillanders, 2005*a*)
		Interaction with water chemistry (Elsdon & Gillanders, 2002, 2004; Martin & Wuenschel, 2006; Miller, 2011)	Ontogeny: significant (Toole *et al.*, 1993; Fowler *et al.*, 1995*a*; Tzeng, 1996; de Pontual *et al.*, 2003); NS (Elsdon & Gillanders, 2005*a*)

TABLE I. Continued.

Element *v*.	Water chemistry (including element:Ca, absolute concentrations and salinity)	Temperature	Other (including diet, vital and intrinsic effects)
Sr (cont.)			Intrinsic (among species): (Kalish, 1989; Swearer *et al*., 2003; Rooker *et al*., 2004; Martin & Wuenschel, 2006; Hamer & Jenkins, 2007)
	See also Secor & Rooker review (2000)		Diet: positive (Limburg, 1995; Gallahar & Kingsford, 1996; Buckel *et al*., 2004); NS (Hoff & Fuiman, 1995; Farrell & Campana, 1996; Sanchez-Jerez *et al*., 2002; Walther & Thorrold, 2006)
Ba	Positive *v* water Ba:Ca and negative vs. salinity (Bath *et al*., 2000; Elsdon & Gillanders, 2002, 2003*a*, *b*, 2004; de Vries *et al*., 2005; Elsdon & Gillanders, 2005*a*, *b*; Martin & Thorrold, 2005; Martin & Wuenschel, 2006; Walther & Thorrold, 2006; Miller, 2009; Hicks *et al*., 2010)	Positive (Elsdon & Gillanders, 2002, 2004; Miller, 2009)	Somatic growth rate: negative (Miller, 2011), NS (DiMaria *et al*., 2010)
		Negative (DiMaria *et al*., 2010)	Ontogeny: NS (Elsdon & Gillanders, 2005*a*; Hamer *et al*., 2006)
		NS (Bath *et al*., 2000; Martin & Thorrold, 2005; Martin & Wuenschel, 2006)	Diet: positive (Sanchez-Jerez *et al*., 2002; Buckel *et al*., 2004); NS (Walther & Thorrold, 2006)
	Positive: in field studies (Thorrold *et al*., 1997; Elsdon & Gillanders, 2005*a*, *b*; Dorval *et al*., 2007)	Interaction with water chemistry (Elsdon & Gillanders, 2002, 2004; Miller, 2011)	Intrinsic (within species): significant (Clarke *et al*., 2011)
	Interaction with Sr (de Vries *et al*., 2005)	Intrinsic (among species): significant (Hicks *et al*., 2010)	
	NS - in field (Forrester, 2005)		

TABLE I. Continued.

Element *v.*	Water chemistry (including element:Ca, absolute concentrations and salinity)	Temperature	Other (including diet, vital and intrinsic effects)
Mg	NS (Elsdon & Gillanders, 2002; Martin & Thorrold, 2005; Hamer *et al.*, 2006; Hicks *et al.*, 2010; Miller, 2011)	NS (DiMaria *et al.*, 2010)	Somatic and otolith growth rate: negative (Martin & Thorrold, 2005), NS (DiMaria *et al.*, 2010) Diet: NS (Hoff & Fuiman, 1995) Intrinsic (within species): significant (Clarke *et al.*, 2011)
Li	Negative *v.* water Li:Ca, but positive vs. salinity (Milton & Chenery, 2001*a*) Positive (Hicks *et al.*, 2010)		
Rb	Negative (Hicks *et al.*, 2010)		
K and Na		Negative (Hoff & Fuiman, 1995)	Reproduction: significant (Fuiman & Hoff, 1995) Diet: NS (Hoff & Fuiman, 1995)
Mn	NS or negative, particularly in the core (Hanson & Zdanowicz, 1999; Brophy *et al.*, 2003, 2004; Elsdon & Gillanders, 2003*b*; Miller, 2009)	Negative (Miller, 2009)	Diet: positive (Sanchez-Jerez *et al.*, 2002); NS (Buckel *et al.*, 2004) Intrinsic (within species): significant (Clarke *et al.*, 2011)
	Positive: in field (Dorval *et al.*, 2007), Positive but NS: in field (Hamer *et al.*, 2006) NS (cf. sediment concentrations) (Hanson & Zdanowicz, 1999)		

TABLE I. Continued.

Element *v.*	Water chemistry (including element:Ca, absolute concentrations and salinity)	Temperature	Other (including diet, vital and intrinsic effects)
Zn	Positive (Arai *et al.*, 2007) positive (FW)? (Halden *et al.*, 2000)		Reproduction?† positive (FW)? (Halden *et al.*, 2000)
	NS (Thorrold *et al.*, 1997; Hanson & Zdanowicz, 1999; Ranaldi & Gagnon, 2008*b*)		Diet: positive (Ranaldi & Gagnon, 2008*b*)
Cu	NS (*cf.* sediment concentrations) (Hanson & Zdanowicz, 1999)		Reproduction?†
	Positive (Milton & Chenery, 2001*a*)		Diet: NS (Milton & Chenery, 2001*a*)
Pb	Positive (Ranaldi & Gagnon, 2008*a*; Milton & Chenery, 2001*a*); positive for two species; NS for *Pleuronectes platessa* (Geffen *et al.*, 1998)		Diet: NS (Milton & Chenery, 2001*a*).
Hg	Positive for two species; NS for *P. platessa* (Geffen *et al.*, 1998)		
Se	Positive (Lochet *et al.*, 2010); positive (FW): in field (Limburg *et al.*, 2010)		Reproduction?†
Fe	Positive (Ranaldi & Gagnon, 2008*a*)		Age: negative (Papadopoulou *et al.*, 1980)
Cd	Positive (Ranaldi & Gagnon, 2009)		Diet: positive (Ranaldi & Gagnon, 2009);
Al	Positive: (Mugiya *et al.*, 1991)		
Others	Cr, Ni: NS (*cf.* sediment concentrations) (Hanson & Zdanowicz, 1999)		Age: negative for Cs, Co and Ag (Papadopoulou *et al.*, 1980)

†Crucial in vertebrate reproductive processes (Versieck & Cornelis, 1989; Bedwal & Bahuguna, 1994; Watanabe *et al.*, 1997); possible effects on otolith chemistry unknown.

particularly for studies using otolith Sr:Ca ratios to reconstruct migrations among salinity regimes (Martin & Wuenschel, 2006).

APPLICATION OF OTOLITH MICROCHEMISTRY TO RECONSTRUCT FISH MIGRATIONS IN THE MARINE ENVIRONMENT

THE MARINE SYSTEM

The marine system is a dynamic environment with elements constantly added, removed and recycled through biological, physical and chemical processes (Hunter & Boyd, 1999). Yet global averages for seawater element concentrations have remained remarkably conserved, particularly when compared with estuarine and freshwater systems (Turekian, 1968). As such, many marine fishes, particularly open ocean pelagics, experience a relatively uniform physicochemical environment with limited potential for spatial discrimination using inorganic chemical proxies (Proctor *et al*., 1995), although there are some exceptions (Ashford *et al*., 2008). Coastal areas generally offer greater chemical heterogeneity due to upwelling, fluvial and anthropogenic inputs, but often the pollutants that would contribute to such geographic variation (*e.g.* Ni and Zn) are soft acid metals that are physiologically discriminated against and typically below detection levels in the otoliths (Hanson & Zdanowicz, 1999). Importantly, unlike estuarine systems (Elsdon & Gillanders, 2005*b*), Sr:Ca and Ba:Ca ratios are not inversely related in seawater (Ashford *et al*., 2005). Both Ca and Sr exhibit quasiconservative distributions (Steele *et al*., 2009), resulting in near constant Sr:Ca ratios (and other conservative element:Ca ratios) at salinities above *c*. 8 (Secor *et al*., 1995; Babaluk *et al*., 1997; Zimmerman, 2005; Hicks *et al*., 2010). Ba is readily removed from surface waters as barite adsorbed to settling particles (Bruland & Lohan, 2003). Primary productivity is correlated with barite accumulation, resulting in a nutrient-type distribution in seawater (Dehairs *et al*., 1997). At mesopelagic depths, bacterial activity releases the barite, allowing it to accumulate and dissolve, enriching Ba with depth and producing a useful open-ocean otolith marker (Ashford *et al*., 2005). Manganese on the other hand, is a scavenged element and concentrations thus tend to decrease with depth and distance from coastlines and point sources such as hydrothermal vents (Bruland & Lohan, 2003).

While greater environmental heterogeneity in coastal areas generally increases the discriminatory power of associated otolith signatures, it is, unfortunately, usually at the expense of temporal stability. Indeed inter and intra-annual differences in water chemistry (Elsdon *et al*., 2008) and otolith chemical fingerprints (Gillanders, 2002; Swearer *et al*., 2003; Chittaro *et al*., 2004; Bergenius *et al*., 2005; Elsdon & Gillanders, 2006; Walther & Thorrold, 2009) are more the norm than the exception. For this reason, reference collections of otolith elemental fingerprints for relevant year classes and locations are recommended to elucidate site-specific information from unknown otolith chemistries, particularly for more variable habitats, such as lagoons (Gillanders, 2002; Walther & Thorrold, 2009; Mercier *et al*., 2012).

MARINE SPECIES

Although the physiology of marine, euryhaline and freshwater fishes differs significantly, particularly with regards to osmoregulation (Evans, 1993), there is little

to suggest inherent differences in otolith element incorporation mechanisms from laboratory studies (Farrell & Campana, 1996; Walther & Thorrold, 2006). When considering different life history stages, however, ontogenetic effects on otolith Sr:Ca ratios are often observed in species spending at least part of their lifecycle in salt water (Fowler *et al*., 1995*a*; Walther *et al*., 2010), particularly during significant metabolic events such as metamorphosis (Arai *et al*., 2000; de Pontual *et al*., 2003). Despite little variation in seawater Sr:Ca (Zimmerman, 2005), Sr:Ca ratios in otoliths of marine fishes often exhibit considerable interspecific differences (Kalish, 1989; Hamer & Jenkins, 2007), general increases with age (Kalish, 1989; Walther *et al*., 2010) and intra-annual fluctuations often larger than those exhibited by diadromous species (Brown & Severin, 2009). Explanations for these patterns have been sought, but to date, no single causal factor has been found, although temperature, age, somatic and otolith growth rate, stress and gonad maturation have all been implicated (Table I).

Unfortunately, no experimental work has systematically tested the relationship between ambient temperature and otolith Sr:Ca in adult marine fishes across a full reproductive cycle. In adult blue grenadier *Macruronus novaezelandiae* (Hector 1871), Australian salmon *Arripis trutta* (Forster 1801) and bearded rock cod *Pseudophycis barbatus* Günther 1863, growth rate and reproductive investment appear to have a greater effect on otolith Sr:Ca ratios than temperature (Kalish, 1989, 1991). Otolith Sr:Ca ratios in female *P. barbatus* correlated significantly with the gonadosomatic index and plasma protein concentrations, particularly the relative proportions of albumins and globulins (Kalish, 1991). It was therefore suggested that plasma and endolymph proteins vary in type and prevalence during gonad development, and differences in their metal-binding capacity alter the proportion of free Sr^{++} ions, thus altering availability and uptake of Sr into the otolith. Similarly, otolith Na, K and Sr concentrations were linked to spawning activity in wild red drum *Sciaenops ocellatus* (L. 1766) (Fuiman & Hoff, 1995) and seasonal fluctuations in otolith Sr:Ca ratios were observed in adult Atlantic salmon *Salmo salar* L. 1758 held for >2 years in sea cages, where salinity was almost constant (32–33) (Clarke & Friedland, 2004). Because the changes in otolith Sr:Ca ratios of the caged *S. salar* appeared to lag behind the changes in water temperature, they were attributed to gonad maturation. Gonad development, however, is often accompanied by reduced feeding, slower growth rates and seasonal changes in ambient conditions, so there are a number of plausible explanations for the observed otolith Sr:Ca fluctuations. Whatever the explanation, such physiological influences on otolith element ratios have the potential to complicate any element-based interpretations of movement patterns and stock discrimination. It remains to be seen whether purely physiological influences on the trace element composition of otoliths could prove useful. Marked variations in otolith Sr:Ca ratios within fully marine fishes might, for example, indicate onset of sexual maturity or provide a quantitative measure of reproductive investment.

PRACTICAL CONSIDERATIONS

In addition to the variety of exogenous and endogenous factors that can affect otolith chemical patterns, analytical artefacts can also play a role. Instrument performance can significantly affect accuracy and precision (Campana *et al*., 1997), while otolith treatment can contaminate or remove elements from the microstructure

(Gauldie *et al*., 1998; Proctor & Thresher, 1998; Thresher, 1999; Swan *et al*., 2006). Instruments are, however, constantly evolving, with the development of improved technologies such as high resolution or sector field inductively coupled plasma mass spectrometry (HR-ICPMS or SF-ICPMS) (Thorrold & Shuttleworth, 2000), and increasing numbers of studies are focusing their attentions on improving decontamination methods (Campana *et al*., 2000; Davies *et al*., 2011).

A significant practical obstacle encountered when attempting to identify movement-related information in otoliths, is the desire to obtain time-resolved chemical data. Current approaches generally achieve this through microsampling or probe-based techniques such as laser ablation ICPMS (LA-ICPMS). Solution analyses can address certain movement-related questions, for example, using whole otolith signatures as natural tags during brief mixing periods (Campana *et al*., 2000), however, probe-based techniques take advantage of the otolith chronology and offer the attractive option of targeting specific growth increments and life history stages. The downside to probe-based analyses is that the volume of ablated material is relatively small, reducing detection capabilities and the number of available elements (Campana, 1999). Given the ever-increasing desire for longer element lists and improved discriminatory capabilities, beam diameter and power might be increased to improve detection limits, but this results in wider, deeper pits and averaging over longer time periods. Thus probe-based techniques face a constant struggle between optimizing temporal resolution and instrument performance. Pit depth is rarely reported in the literature, but given the three-dimensional structure of otoliths, could have a significant averaging effect, and artificially inflate apparent time lags between environmental changes and responses within the otolith (Jones & Chen, 2003).

Attempting to use otolith chemistry to infer intra-annual movements of adult fishes is particularly difficult, as age-related decreases in growth rate (Fowler *et al*., 2005) result in the progressive narrowing of growth increments, often to widths well under 30 μm. This clearly limits the spatial and temporal resolution attainable for multi-elemental otolith analyses. It also means that few validation studies have focused their attentions on adult fishes, with most information inferred from wild-caught adults for which environmental histories are not explicitly known (Kalish, 1989; Fuiman & Hoff, 1995). The vast majority of empirical studies have employed larval or juvenile fishes due to easier and cheaper maintenance, faster growth rates and wider otolith increments. Given age-related changes in physiology and elemental processing, however, interpretation of otolith signals in adult fishes based on observations from young life-history stages should be treated with caution.

Finally, there are also practical considerations regarding the choice of statistical methods used to analyse the complex, often skewed, multivariate data produced by most otolith elemental analyses (Elsdon *et al*., 2008). Analyses within chemical profiles from individual fishes suffer from issues of non-independence, but this can be overcome by using repeated measures of analysis of variance (RM-ANOVA) (Clarke *et al*., 2010) or mixed model analyses (Hamilton & Warner, 2009). Habitat discrimination based on multivariate elemental fingerprints is a common aim among otolith studies. Recent work comparing the classification accuracy of different statistical methods indicated that machine learning methods such as random forest exhibited greater classification efficiency with fewer assumptions than equivalent discriminant function analyses (Mercier *et al*., 2011).

CASE STUDIES

To date, though many studies have used otolith chemistry to examine population structure and movements of marine or partially marine fishes, few have attempted to corroborate their results with additional, alternative proxies. As discussed by Begg & Waldman (1999), a more holistic approach to stock identification instils greater confidence in the results, but also provides support for (or challenges to) the spatial distributions implied by each marker. Here, examples of studies that have used otolith microchemistry to infer population structure or movements of adult marine (or partially marine) fishes are presented and attempts made to corroborate their results, either directly or indirectly, with additional, alternative proxies.

OTOLITH CHEMISTRY *v*. GENETIC TAGS

Very few studies have directly compared chemical and molecular tags for describing spatial distributions of fish populations. One such study found that both microsatellite DNA and trace element concentrations at the otolith margin (Mg, Mn, Zn, Sr and Ba) inferred *c*. 65% site fidelity for adult black rockfish *Sebastes melanops* Girard 1856, a value independently suggested by mark–recapture studies (Miller *et al*., 2005). This study provides rare quantitative support for the use of probe-based techniques such as LA-ICPMS to elucidate population structuring in an exclusively marine fish. Possible movement patterns were not explored in this work, but otolith chemical profiles may have indicated temporally resolved differences between the resident fish and recent immigrants. Microsatellite and otolith elemental markers were also integrated in an attempt to determine dispersal patterns of the anadromous rainbow smelt *Osmerus mordax* (Mitchill 1814) (Bradbury *et al*., 2008). While the two techniques were not formally compared, they produced corroborative results, with molecular markers indicating high local recruitment and otolith Sr and Ba profiles implying limited dispersal among estuaries.

A number of stock discrimination studies have anecdotally compared results from otolith chemistry and molecular studies. While none have reported contradictory results, nearly all have observed higher spatial complexity using otolith microchemistry than their genetic equivalent. For example, otolith margin microchemistry (Li, Mg, Mn, Sr and Ba) of the southern garfish *Hyporhamphus melanochir* (Valenciennes 1847), an estuarine and nearshore species, inferred six ‘semi-discrete, population components’, contrasting with the two management units suggested by molecular markers (Steer *et al*., 2009). The difference was attributed to a stepping-stone model of exchange among neighbouring subpopulations, as misclassified fish were generally assigned to adjacent or proximal sites. Similarly, whole otolith fingerprints (Ba, Cd, Cu, K, Pb, Sr, Zn, Mg, Na and S) of orange roughy *Hoplostethus atlanticus* Collett 1889, a marine species, implied stock separations that corroborated those indicated by genetic markers and parasite loads, but inferred an additional grouping within an area previously classified as a single stock (Edmonds *et al*., 1991). These examples raise an important point, while otolith microchemistry may resolve groups of fishes with shared environmental histories and thus reveal spatial structuring undetectable by other methods, these groups may mix on spawning grounds and still be best managed as a single unit. Thus, terming such works stock discrimination can be somewhat misleading, for the point at which groups of fishes with shared environmental histories should be considered and managed as separate stocks

is difficult to define and depends on a number of factors specific to the system, species and subunits in question (Campana, 2005). Otolith core chemistry has also been used to infer shared (Fowler *et al*., 2005) or multiple (Tanner *et al*., 2012*a*) spawning grounds in marine species. A significant challenge remains, however, to demonstrate that shared core chemistries reflect common origin, rather than similar water chemistries or physiological overprinting (maternal or intrinsic). Encouragingly, element concentrations in the otolith nuclei of two marine species, Scotia Sea icefish *Chaenocephalus aceratus* (Lönnberg 1906) and Patagonian toothfish *Dissostichus eleginoides* Smitt 1898 corroborated population boundaries inferred by a number of additional markers, including growth rates, morphometrics, parasite loadings and genetics, but again, suggested finer scale population structuring than the other methods (Ashford *et al*., 2006, 2010).

OTOLITH CHEMISTRY *v*. OTOLITH SHAPE

While otolith shape has a predominantly genetic basis, it is susceptible to local conditions and, after significant time in contrasting environments, can differ significantly among regions and stocks (Campana & Casselman, 1993). In an estuarine and nearshore species, the mulloway *Argyrosomus japonicus* (Temminck & Schlegel 1843), otolith margin Na, Mg, Sr and Ba concentrations classified fish to capture region with high success (94%), while otolith morphometrics produced slightly lower classification scores (83%) but supported the subdivisions suggested by the elemental fingerprints (Ferguson *et al*., 2011). The relative time periods represented by each marker is important to consider, with otolith margin chemistry representing the most recent material and implying short-term geographic separation, while differences in otolith shape imply limited mixing over longer time periods. Similar methods were used to examine spatial distributions of the roundnose grenadier *Coryphaenoides rupestris* Gunnerus 1765, a deep-sea macrourid (Longmore *et al*., 2010). Here, classification scores were considerably lower using shape descriptors (43%) *cf*. otolith microchemistry (92%), implying possible mixing events prior to the most recent otolith growth. Ontogenetic patterns in otolith Li, Mn, Cu, Zn and Ba concentrations and stable isotopic ratios (δ^{18}O and δ^{13}C) suggested a shallower larval phase for this deep sea species, which may facilitate regional genetic drift, but provided little evidence for recent mixing events, implying relatively static population units (Longmore *et al*., 2011).

OTOLITH CHEMISTRY *v*. MORPHOMETRICS

Similar to otolith shape, variations in fish morphometrics can be genetically and environmentally induced (Silva, 2003). In a study of adult sea perch *Helicolenus percoides* (Richardson & Solander 1842) in Fiordland, New Zealand, differences in whole otolith microchemistry (Li, Mg, Sr and Ba), morphometric characters, length at age and muscle δ^{15}N and δ^{13}C composition implied limited movement between the four fjords under study (Lawton *et al*., 2010). In the same region, consistent differences in otolith marginal chemistry (Beer *et al*., 2011) and tissue isotopes (Rodgers & Wing, 2008) of blue cod *Parapercis colias* (Forster 1801) implied even finer-scale population structuring, with limited movement between inner and outer fjord habitats; results that were also corroborated by mark–recapture studies (Carbines & McKenzie, 2004). In contrast, morphometric variations in the shad hilsa *Tenualosa ilisha*

(Hamilton 1822), an anadromous species, were not corroborated by patterns in otolith core chemistries (Li, Na, Mg, Al, Mn, Zn, Sr and Ba) or allozyme markers (Milton & Chenery, 2001*b*; Salini *et al*., 2004). Rather, the variability in morphometrics was attributed to susceptibility to local conditions, while the widespread variability in chemical and molecular markers was attributed to extensive genetic exchange. While it has been suggested that a lack of detectable differences in otolith microchemistry provides little information (Campana *et al*., 2000), the authors argued that the areas in question were characterized by significant differences in water chemistry and the manner in which the otolith and molecular markers covaried indicated highly mobile individuals and a well-mixed population.

OTOLITH CHEMISTRY *v*. APPLIED TAGS

Mark–recapture studies provide the most irrefutable evidence of individual movement patterns but, to the best of our knowledge no study has directly compared tag-derived geolocations in a marine species with otolith material deposited during the same period. In Australia, age-related changes in otolith Sr:Ca and Ba:Ca profiles for snapper *Pagrus auratus* (Forster 1801), a fully marine species, were related to emigration from a common spawning ground (Fowler *et al*., 2005). As water Sr and Ba concentrations were not formally examined, there was the possibility that such shared otolith chemistries reflected intrinsic ontogenetic effects, rather than common origin (Fowler *et al*., 1995*a*; de Pontual *et al*., 2003; Tanner *et al*., 2012*b*). Substantial differences in oceanographic conditions and terrestrial inputs, however, were predicted among the water masses in question, and the interpretations were supported by behavioural inferences from mark–recapture studies. Meanwhile, in a different part of Australia, the same species was shown to persist in a far more complex set of population units; findings inferred by whole otolith microchemistry, mark–recapture studies, morphometrics and genetics (Edmonds *et al*., 1989, 1995). Such intra-specific plasticity in population structuring emphasizes the benefits of using a toolbox approach, while highlighting the potential hazards of extrapolating observed species distributions to adjacent areas.

To examine movement-related questions, there is a basic need for time-resolved information. Most studies address this using probe-based otolith analyses, but Campana *et al*. (2000) used averaged whole otolith fingerprints (Mg, Sr, Ba, Mn and Li) to track spawning stock aggregations of cod *Gadus morhua* L. 1758 during brief mixing periods. A maximum-likelihood based stock-mixture analysis estimated the relative contribution of reference stocks to summer feeding and over wintering fish, based on the assumption that source signatures would remain identifiable so long as the mixing period was shorter than the time taken for new otolith growth to overprint reference signatures. By repeated sampling over time, it was possible to test this assumption and elemental fingerprints were found to be stable over a 2–3 year period and some elements even over a decade. The results of this study were supported by previous tagging work but were unambiguous in their own right, taking advantage of substantial sample sizes (*c*. 2500 fish) sampled across a large geographic area over a number of years (Campana, 2005). It should be noted that despite efforts to sample similar size ranges, significant relationships between element concentrations and otolith mass were still observed (positive for Sr; negative for Mn and Mg) and

needed detrending, again stressing the importance of size and age in otolith studies (Campana *et al*., 2000).

DISCUSSION

It is encouraging that of most of the studies published so far have reported congruence between the spatial distributions implied by otolith trace element fingerprints and by alternative tags, both natural and artificial (Miller *et al*., 2005). By taking advantage of the superior detection capabilities associated with whole otolith solution analyses (Campana *et al*., 2000), stock discrimination and mixed stock analyses can be carried out with relative confidence (Campana & Gagne, 1995; Ferguson *et al*., 2011). In addition, otolith trace elemental profiles and fingerprints have shown good potential to infer ontogenetic and inter-annual changes in the distribution of marine fish stocks and source-sink connectivity patterns (Fowler *et al*., 2005; Clarke *et al*., 2010). With regards using otolith microchemistry to track the seasonal migration patterns of individual, fully marine fishes (Hunter *et al*., 2004), further validation is required. Only very few studies to date have attempted to use intra-annual otolith chemistries to obtain geolocations of individual fishes across time and space (Mercier *et al*., 2012). As discussed by Elsdon *et al*. (2008), the number of assumptions increases markedly with the spatial complexity of the question being asked. In the marine realm, the low spatial variability among the hard acid cations most likely to be incorporated into the otolith as a function their availability would certainly appear to hinder the widespread application of otolith microchemistry for finescale geolocation. For example, for *D. eleginoides* captured in the open ocean, otolith element concentrations typically varied by just 1–3 s.d. (Ashford *et al*., 2007). Once the inherent error and skew found in most trace elemental data has been accounted for, the likelihood for otolith chemical profiles to reveal individual migrations with great precision or accuracy is slim. Other factors too appear discouraging, such as the relatively poor detection capabilities of probe-based analyses and possible confounding effects of temperature, ontogeny and physiology.

Otolith-derived positional information can be further improved by adding stable isotopes (*e.g*. δ^{13}C and δ^{18}O) to the chemical fingerprint (Thorrold *et al*., 2001; Ashford & Jones, 2007; Tanner *et al*., 2012*b*). It is still essential that the physicochemical characteristics of the area in question are well described, however, as subtle differences in salinity can significantly alter water (Harwood *et al*., 2008) and otolith (Surge & Walker, 2005) δ^{18}O and δ^{13}C signatures. The geographical and temporal scales of migration are clearly of great importance. Geographic differences in otolith chemistries are often observed among groups within the same species of marine fish, implying that even if there is insufficient information to couple element concentrations with specific locations, there may be potential for separating groups of fish with shared migration histories [known as contingents (Secor, 1999; Secor *et al*., 2001; Elsdon *et al*., 2008)]. *In situ* validation studies coupling migration pathways and environmental conditions derived from DST records with concomitant otolith chemistries will further help to elucidate whether otolith trace-element concentrations can successfully reconstruct or infer individual movements in exclusively marine species (Hunter & Darnaude, 2004).

Interpretation of signals in physiologically influenced otolith elements, such as Mg and most importantly, Sr, has been identified as an area urgently requiring further investigation. As discussed, otolith composition is influenced by the ambient environment as well as by a suite of physiological processes that may alter the relative abundances of elements between water and their eventual incorporation into the otolith. To better understand these trends, validation experiments examining elemental uptake across realistic temperature regimes and maturity states would be hugely beneficial (Walther *et al*., 2010), as would quantifying the time taken for environmental changes to be reflected in the growing otolith (Miller, 2011). Stock discrimination studies, however, often include phenotypic traits, such as size and growth rate, to discriminate among groups of fishes. If such traits also generate distinctive, reproducible otolith chemistries, their use as population markers can be considered legitimate (Campana *et al*., 2000). While this assumption may well hold for averaged whole otolith chemical fingerprints, determining the causal effect of intra-annual signals within individual otoliths is particularly complex, and interpretations could easily be confounded by interactions between environment and physiology. When attempting to obtain spatial information from any form of otolith microchemistry, it must be emphasized that the influence of physiology should be minimized by controlling for sex, size and age when selecting individuals for analysis.

CONCLUSIONS

In order to track individual fish migrations using otolith microchemistry, knowledge of the distributions of elements in the region of interest must be balanced with an understanding of the physiological influences on otolith chemistry over the time period of interest. Limited contemporary understanding of the mechanisms controlling elemental incorporation into the otolith restricts the application of elemental data for positioning fishes in time and space (Elsdon *et al*., 2008), while limited environmental variability in the elements most reliably measured in otoliths presents an additional significant challenge for geolocating exclusively marine species. The otolith elements most likely to act as useful spatial indicators within the open ocean will vary among species, systems and scales, and as detection capabilities of probe-based analyses improves, will be augmented by spatially explicit, low-level elements such as rare earths (Arslan & Paulson, 2003). Based on their behaviour as hard or intermediate acid cations, their potential for environmental heterogeneity and their positive relationships with ambient concentrations, it seems likely that Ba, and perhaps Mn and Li, will prove to be the most useful and reliable otolith elements in studies of marine fish movements in the coming years. Nevertheless, the importance of complementing laboratory experiments with *in situ* validation studies cannot be underestimated. Combining otolith trace element profiles with other geolocation tools such as archival-tag data and genetics (Begg & Waldman, 1999; Fromentin *et al*., 2009) will support and greatly extend the overall utility of otolith chemistry for retrospectively describing migrations and mixing patterns of fully marine fish.

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References

Andreasen, P. (1985). Free and total calcium concentrations in the blood of rainbow trout, *Salmo Gairdneri*, during "stress" conditions. *Journal of Experimental Biology* **118,** 111–120.

Arai, T., Otake, T. & Tsukamoto, K. (2000). Timing of metamorphosis and larval segregation of the Atlantic eels *Anguilla rostrata* and *A. anguilla*, as revealed by otolith microstructure and microchemistry. *Marine Biology* **137,** 39–45.

Arai, T., Ohji, M. & Hirata, T. (2007). Trace metal deposition in teleost fish otolith as an environmental indicator. *Water, Air, and Soil Pollution* **179,** 255–263.

Arnegard, M. E., Markert, J. A., Danley, P. D., Stauffer, J. R., Ambali, A. J. & Kocher, T. D. (1999). Population structure and colour variation of the cichlid fishes *Labeotropheus fuelleborni* Ahl along a recently formed archipelago of rocky habitat patches in southern Lake Malawi. *Proceedings of the Royal Society B* **266,** 119–130.

Arslan, Z. & Paulson, A. J. (2003). Solid phase extraction for analysis of biogenic carbonates by electrothermal vaporization inductively coupled plasma mass spectrometry (ETV-ICP-MS): an investigation of rare earth element signatures in otolith microchemistry. *Analytica Chimica Acta* **476,** 1–13.

Ashford, J. & Jones, C. M. (2007). Oxygen and carbon stable isotopes in otoliths record spatial isolation of Patagonian toothfish (*Dissostichus eleginoides*). *Geochimica et Cosmochimica Acta* **71,** 87–94.

Ashford, J., Jones, C., Hofmann, E., Everson, I., Moreno, C., Duhamel, G. & Williams, R. (2005). Can otolith elemental signatures record the capture site of Patagonian toothfish (*Dissostichus eleginoides*), a fully marine fish in the Southern Ocean? *Canadian Journal of Fisheries and Aquatic Sciences* **62,** 2832–2840.

Ashford, J., Arkhipkin, A. I. & Jones, C. (2007). Otolith chemistry reflects frontal systems in the Antarctic circumpolar current. *Marine Ecology Progress Series* **351,** 249–260.

Ashford, J. R., Arkhipkin, A. I. & Jones, C. M. (2006). Can the chemistry of otolith nuclei determine population structure of Patagonian toothfish *Dissostichus eleginoides*? *Journal of Fish Biology* **69,** 708–721.

Ashford, J. R., Jones, C. M., Hofmann, E. E., Everson, I., Moreno, C. A., Duhamel, G. & Williams, R. (2008). Otolith chemistry indicates population structuring by the Antarctic circumpolar current. *Canadian Journal of Fisheries and Aquatic Sciences* **65,** 135–146.

Ashford, J., La Mesa, M., Fach, B. A., Jones, C. & Everson, I. (2010). Testing early life connectivity using otolith chemistry and particle-tracking simulations. *Canadian Journal of Fisheries and Aquatic Sciences* **67,** 1303–1315.

Babaluk, J. A., Halden, N. M., Reist, J. D., Kristofferson, A. H., Campbell, J. L. & Teesdale, W. J. (1997). Evidence for non-nadromous behaviour of Arctic charr (*Salvelinus alpinus*) from Lake Hazen, Ellesmere Island, Northwest Territories, Canada, based on scanning proton microprobe analysis of otolith strontium distribution. *Arctic* **50,** 224–233.

Bath, G. E., Thorrold, S. R., Jones, C. M., Campana, S. E., McLaren, J. W. & Lam, J. W. H. (2000). Strontium and barium uptake in aragonitic otoliths of marine fish. *Geochimica et Cosmochimica Acta* **64,** 1705–1714.

Bedwal, R. S. & Bahuguna, A. (1994). Zinc, copper and selenium in reproduction. *Cellular and Molecular Life Sciences* **50,** 626–640.

Beer, N. A., Wing, S. R. & Swearer, S. E. (2011). Otolith elemental evidence for spatial structuring in a temperate reef fish population. *Marine Ecology Progress Series* **442,** 217–227.

Begg, G. & Waldman, J. (1999). An holistic approach to fish stock identification. *Fisheries Research* **43,** 34–44.

Bergenius, M. A. J., Mapstone, B. D., Begg, G. A. & Murchie, C. D. (2005). The use of otolith chemistry to determine stock structure of three epinepheline serranid coral reef fishes on the Great Barrier Reef, Australia. *Fisheries Research* **72,** 253–270.

Block, B. A., Jonsen, I. D., Jorgensen, S. J., Winship, A. J., Shaffer, S. A., Bograd, S. J., Hazen, E. L., Foley, D. G., Breed, G. A., Harrison, A. L., Ganong, J. E., Swithenbank, A., Castleton, M., Dewar, H., Mate, B. R., Shillinger, G. L., Schaefer, K. M.,

Benson, S. R., Weise, M. J., Henry, R. W. & Costa, D. P. (2011). Tracking apex marine predator movements in a dynamic ocean. *Nature* **475,** 86–90.
Bolle, L., Hunter, E., Rijnsdorp, A., Pastoors, M., Metcalfe, J. & Reynolds, J. (2005). Do tagging experiments tell the truth? Using electronic tags to evaluate conventional tagging data. *ICES Journal of Marine Science* **62,** 236–246.
Botsford, L., Brumbaugh, D., Grimes, C., Kellner, J., Largier, J., O'Farrell, M., Ralston, S., Soulanille, E. & Wespestad, V. (2009). Connectivity, sustainability, and yield: bridging the gap between conventional fisheries management and marine protected areas. *Reviews in Fish Biology and Fisheries* **19,** 69–95.
Bradbury, I. R., Campana, S. E. & Bentzen, P. (2008). Estimating contemporary early life-history dispersal in an estuarine fish: integrating molecular and otolith elemental approaches. *Molecular Ecology* **17,** 1438–1450.
Brophy, D., Danilowicz, B. & Jeffries, T. (2003). The detection of elements in larval otoliths from Atlantic herring using laser ablation ICP-MS. *Journal of Fish Biology* **63,** 990–1007.
Brophy, D., Jeffries, T. E. & Danilowicz, B. S. (2004). Elevated manganese concentrations at the cores of clupeid otoliths: possible environmental, physiological, or structural origins. *Marine Biology* **144,** 779–786.
Brown, R. J. & Severin, K. P. (2009). Otolith chemistry analyses indicate that water Sr:Ca is the primary factor influencing otolith Sr:Ca for freshwater and diadromous fish but not for marine fish. *Canadian Journal of Fisheries and Aquatic Sciences* **66,** 1790–1808.
Bruland, K. W. & Lohan, M. C. (2003). Controls of trace metals in seawater. In *Treatise on Geochemistry*. 6: *The Oceans and Marine Geochemistry* (Holland, H. D. & Turekian, K. K., eds), pp. 23–47. Amsterdam: Elsevier.
Buckel, J. A., Sharack, B. L. & Zdanowicz, V. S. (2004). Effect of diet on otolith composition in *Pomatomus saltatrix*, an estuarine piscivore. *Journal of Fish Biology* **64,** 1469–1484.
Campana, S. E. (1999). Chemistry and composition of fish otoliths: pathways, mechanisms and applications. *Marine Ecology Progress Series* **188,** 263–297.
Campana, S. E. (2005). Otolith elemental composition as a natural marker of fish stocks. In *Stock Identification Methods: Applications in Fishery Science* (Cadrin, S. X., Friedland, K. D. & Waldman, J. R., eds.), pp. 227–245: Elsevier.
Campana, S. E. & Casselman, J. M. (1993). Stock discrimination using otolith shape analysis. *Canadian Journal of Fisheries and Aquatic Sciences* **50,** 1062–1083.
Campana, S. E. & Gagne, J. (1995). Cod stock discrimination using ICPMS elemental assays of otoliths. In *Recent Developments in Fish Otolith Research* (Secor, D., Dean, J. & Campana, S. E., eds). Columbia, SC: University of South Carolina Press.
Campana, S. E. & Neilson, J. D. (1985). Microstructure of fish otoliths. *Canadian Journal of Fisheries and Aquatic Sciences* **42,** 1014–1032.
Campana, S. E. & Thorrold, S. R. (2001). Otoliths, increments, and elements: keys to a comprehensive understanding of fish populations? *Canadian Journal of Fisheries and Aquatic Sciences* **58,** 30–38.
Campana, S. E., Thorrold, S. R., Jones, C. M., Günther, D., Tubrett, M., Longerich, H., Jackson, S., Halden, N., Kalish, J., Piccoli, P., Pontual, H. d., Troadec, H., Panfili, J., Secor, D., Severin, K., Sie, S., Thresher, R., Teesdale, W. & Campbell, J. (1997). Comparison of accuracy, precision, and sensitivity in elemental assays of fish otoliths using the electron microprobe, proton-induced X-ray emission, and laser ablation inductively coupled plasma mass spectrometry. *Canadian Journal of Fisheries and Aquatic Sciences* **54,** 2068–2079.
Campana, S. E., Chouinard, G. A., Hanson, J. M., Frechet, A. & Brattey, J. (2000). Otolith elemental fingerprints as biological tracers of fish stocks. *Fisheries Research* **46,** 343–357.
Carbines, G. & McKenzie, J. (2004). Movement patterns and stock mixing of blue cod in Dusky Sound in 2002. *New Zealand Fisheries Assessment Report 2004.* Wellington: Ministry of Fisheries.
Chittaro, P. M., Fryer, B. J. & Sale, P. F. (2004). Discrimination of French grunts (*Haemulon flavolineatum*, Desmarest, 1823) from mangrove and coral reef habitats using otolith microchemistry. *Journal of Experimental Marine Biology and Ecology* **308,** 169–183.

Clarke, L. M. & Friedland, K. D. (2004). Influence of growth and temperature on strontium deposition in the otoliths of Atlantic salmon. *Journal of Fish Biology* **65,** 744–759.

Clarke, L. M., Munch, S. B., Thorrold, S. R. & Conover, D. O. (2010). High connectivity among locally adapted populations of a marine fish (*Menidia menidia*). *Ecology* **91,** 3526–3537.

Clarke, L. M., Thorrold, S. R. & Conover, D. O. (2011). Population differences in otolith chemistry have a genetic basis in *Menidia menidia*. *Canadian Journal of Fisheries and Aquatic Sciences* **68,** 105–114.

Cook, B. D., Bunn, S. E. & Hughes, J. M. (2007). Molecular genetic and stable isotope signatures reveal complementary patterns of population connectivity in the regionally vulnerable southern pygmy perch (*Nannoperca australis*). *Biological Conservation* **138,** 60–72.

Davies, C. A., Brophy, D., Jeffries, T. & Gosling, E. (2011). Trace elements in the otoliths and dorsal spines of albacore tuna (*Thunnus alalunga*, Bonnaterre, 1788): an assessment of the effectiveness of cleaning procedures at removing postmortem contamination. *Journal of Experimental Marine Biology and Ecology* **396,** 162–170.

Dehairs, F., Shopova, D., Ober, S., Veth, C. & Goeyens, L. (1997). Particulate barium stocks and oxygen consumption in the Southern Ocean mesopelagic water column during spring and early summer: relationship with export production. *Deep Sea Research II* **44,** 497–516.

DiMaria, R., Miller, J. & Hurst, T. (2010). Temperature and growth effects on otolith elemental chemistry of larval Pacific cod, *Gadus macrocephalus*. *Environmental Biology of Fishes* **89,** 453–462.

Dorval, E., Jones, C. M., Hannigan, R. & Montfrans, J. v. (2007). Relating otolith chemistry to surface water chemistry in a coastal plain estuary. *Canadian Journal of Fisheries and Aquatic Sciences* **64,** 411–424.

Edmonds, J. S., Moran, M. J., Caputi, N. & Morita, M. (1989). Trace element analysis of fish sagittae as an aid to stock identifications: pink snapper (*Chrysophrys auratus*) in Western Australian waters. *Canadian Journal of Fisheries and Aquatic Sciences* **46,** 50–54.

Edmonds, J., Caputi, N. & Morita, M. (1991). Stock discrimination by trace-element analysis of otoliths of orange roughy (*Hoplostethus atlanticus*), a deep-water marine teleost. *Marine and Freshwater Research* **42,** 383–389.

Edmonds, J. S., Caputi, N., Moran, M., Fletcher, W. & Morita, M. (1995). Population discrimination by variation in concentrations of minor and trace elements in sagittae of two Western Australian teleosts. In *Recent Developments in Fish Otolith Research* (Secor, D., Dean, J. & Campana, S. E., eds). Columbia SC: University of South Carolina Press.

Elsdon, T. S. & Gillanders, B. (2002). Interactive effects of temperature and salinity on otolith chemistry: challenges for determining environmental histories of fish. *Canadian Journal of Fisheries and Aquatic Sciences* **59,** 1796–1808.

Elsdon, T. S. & Gillanders, B. M. (2003*a*). Reconstructing migratory patterns of fish based on environmental influences on otolith chemistry. *Reviews in Fish Biology and Fisheries* **13,** 217–235.

Elsdon, T. S. & Gillanders, B. M. (2003*b*). Relationship between water and otolith elemental concentrations in juvenile black bream *Acanthopagrus butcheri*. *Marine Ecology Progress Series* **260,** 263–272.

Elsdon, T. S. & Gillanders, B. M. (2004). Fish otolith chemistry influenced by exposure to multiple environmental variables. *Journal of Experimental Marine Biology and Ecology* **313,** 269–284.

Elsdon, T. & Gillanders, B. (2005*a*). Consistency of patterns between laboratory experiments and field collected fish in otolith chemistry: an example and applications for salinity reconstructions. *Marine and Freshwater Research* **56,** 609–617.

Elsdon, T. S. & Gillanders, B. M. (2005*b*). Alternative life-history patterns of estuarine fish: barium in otoliths elucidates freshwater residency. *Canadian Journal of Fisheries and Aquatic Sciences* **62,** 1143–1152.

Elsdon, T. S. & Gillanders, B. M. (2006). Temporal variability in strontium, calcium, barium, and manganese in estuaries: implications for reconstructing environmental histories of

fish from chemicals in calcified structures. *Estuarine, Coastal and Shelf Science* **66,** 147–156.

Elsdon, T. S., Wells, B. K., Campana, S. E., Gillanders, B. M., Jones, C. M., Limburg, K. E., Secor, D. H., Thorrold, S. R. & Walther, B. D. (2008). Otolith chemistry to describe movements and life-history parameters of fishes: hypotheses, assumptions, limitations, and inferences. *Oceanography and Marine Biology: An Annual Review* **46,** 297–330.

Evans, D. H. (1993). *The Physiology of Fishes.* Boca Raton, FL: CRC Press, Inc.

Fairclough, D. V., Edmonds, J. S., Lenanton, R. C. J., Jackson, G., Keay, I. S., Crisafulli, B. M. & Newman, S. J. (2011). Rapid and cost-effective assessment of connectivity among assemblages of *Choerodon rubescens* (Labridae), using laser ablation ICP-MS of sagittal otoliths. *Journal of Experimental Marine Biology and Ecology* **403,** 46–53.

Farrell, J. & Campana, S. E. (1996). Regulation of calcium and strontium deposition on the otoliths of juvenile tilapia, *Oreochromis niloticus*. *Comparative Biochemistry and Physiology A* **115,** 103–109.

Ferguson, G. J., Ward, T. M. & Gillanders, B. M. (2011). Otolith shape and elemental composition: complementary tools for stock discrimination of mulloway (*Argyrosomus japonicus*) in southern Australia. *Fisheries Research* **110,** 75–83.

Fletcher, P. E. & Fletcher, G. L. (1980). Zinc- and copper-binding proteins in the plasma of winter flounder (*Pseudopleuronectes americanus*). *Canadian Journal of Zoology* **58,** 609–613.

Forrester, G. (2005). A field experiment testing for correspondence between trace elements in otoliths and the environment and for evidence of adaptation to prior habitats. *Estuaries and Coasts* **28,** 974–981.

Fowler, A., Campana, S. E., Jones, C. M. & Thorrold, S. R. (1995*a*). Experimental assessment of the effect of temperature and salinity on elemental composition of otoliths using laser ablation ICPMS. *Canadian Journal of Fisheries and Aquatic Sciences* **52,** 1431–1441.

Fowler, A., Campana, S. E., Jones, C. M. & Thorrold, S. R. (1995*b*). Experimental assessment of the effect of temperature and salinity on elemental composition of otoliths using solution-based ICPMS. *Canadian Journal of Fisheries and Aquatic Sciences* **52,** 1421–1430.

Fowler, A. J., Gillanders, B. M. & Hall, K. C. (2005). Relationship between elemental concentration and age from otoliths of adult snapper (*Pagrus auratus*, Sparidae): implications for movement and stock structure. *Marine and Freshwater Research* **56,** 661–676.

Friedland, K. D., Reddin, D. G., Shimizu, N., Haas, R. E. & Youngson, A. F. (1998). Strontium:calcium ratios in Atlantic salmon (*Salmo salar*) otoliths and observations on growth and maturation. *Canadian Journal of Fisheries and Aquatic Sciences* **55,** 1158–1168.

Fromentin, J.-M., Ernande, B., Fablet, R. & de Pontual, H. (2009). Importance and future of individual markers for the ecosystem approach to fisheries. *Aquatic Living Resources* **22,** 395–408.

Fuiman, L. A. & Hoff, G. R. (1995). Natural variation in elemental composition of sagittae from red drum. *Journal of Fish Biology* **47,** 940–955.

Gaetani, G. A. & Cohen, A. L. (2006). Element partitioning during precipitation of aragonite from seawater: A framework for understanding paleoproxies. *Geochimica et Cosmochimica Acta* **70,** 4617–4634.

Gallahar, N. K. & Kingsford, M. J. (1996). Factors influencing Sr/Ca ratios in otoliths of *Girella elevata*: an experimental investigation. *Journal of Fish Biology* **48,** 174–186.

Gauldie, R. W., Thacker, C. E., West, I. F. & Wang, L. (1998). Movement of water in fish otoliths. *Comparative Biochemistry and Physiology A* **120,** 551–556.

Geffen, A., Pearce, N. & Perkins, W. (1998). Metal concentrations in fish otoliths in relation to body composition after laboratory exposure to mercury and lead. *Marine Ecology Progress Series* **165,** 235–245.

Gillanders, B. (2002). Temporal and spatial variability in elemental composition of otoliths: implications for determining stock identity and connectivity of populations. *Canadian Journal of Fisheries and Aquatic Sciences* **59,** 669–679.

Gillanders, B. M. (2005). Otolith chemistry to determine movements of diadromous and freshwater fish. *Aquatic Living Resources* **18,** 291–300.

Halden, N. M., Mejia, S. R., Babaluk, J. A., Reist, J. D., Kristofferson, A. H., Campbell, J. L. & Teesdale, W. J. (2000). Oscillatory zinc distribution in Arctic char (*Salvelinus alpinus*) otoliths: the result of biology or environment? *Fisheries Research* **46,** 289–298.

Hamer, P. A. & Jenkins, G. P. (2007). Comparison of spatial variation in otolith chemistry of two fish species and relationships with water chemistry and otolith growth. *Journal of Fish Biology* **71,** 1035–1055.

Hamer, P. A., Jenkins, G. P. & Coutin, P. (2006). Barium variation in *Pagrus auratus* (Sparidae) otoliths: a potential indicator of migration between an embayment and ocean waters in south-eastern Australia. *Estuarine, Coastal and Shelf Science* **68,** 686–702.

Hamilton, S. L. & Warner, R. R. (2009). Otolith barium profiles verify the timing of settlement in a coral reef fish. *Marine Ecology Progress Series* **385,** 237–244.

Hanson, P. J. & Zdanowicz, V. S. (1999). Elemental composition of otoliths from Atlantic croaker along an estuarine pollution gradient. *Journal of Fish Biology* **54,** 656–668.

Hanssen, R. G., Lafeber, F. P., Flik, G. & Wendelaar Bonga, S. E. (1989). Ionic and total calcium levels in the blood of the European eel (*Anguilla anguilla*): effects of stanniectomy and hypocalcin replacement therapy. *Journal of Experimental Biology* **141,** 177–186.

Harwood, A. J. P., Dennis, P. F., Marca, A. D., Pilling, G. M. & Millner, R. S. (2008). The oxygen isotope composition of water masses within the North Sea. *Estuarine, Coastal and Shelf Science* **78,** 353–359.

Henderson, P. (1984). *Inorganic Geochemistry.* Oxford: Pergamon Press.

Hicks, A. S., Closs, G. P. & Swearer, S. E. (2010). Otolith microchemistry of two amphidromous galaxiids across an experimental salinity gradient: a multi-element approach for tracking diadromous migrations. *Journal of Experimental Marine Biology and Ecology* **394,** 86–97.

Hixon, M., Pacala, S. & Sandin, S. (2002). Population regulation: historical context and contemporary challenges of open vs. closed systems. *Ecology* **83,** 1490–1508.

Hoff, G. R. & Fuiman, L. A. (1995). Environmentally induced variation in elemental composition of red drum (*Sciaenops Ocellatus*) otoliths. *Bulletin of Marine Science* **56,** 578–591.

Hunter, K. A. & Boyd, P. (1999). Biogeochemistry of trace metals in the ocean. *Marine and Freshwater Research* **50,** 739–753.

Hunter, E., Aldridge, J., Metcalfe, J. & Arnold, G. (2003). Geolocation of free-ranging fish on the European continental shelf as determined from environmental variables. I. Tidal location method. *Marine Biology* **142,** 601–609.

Hunter, E., Metcalfe, J., Arnold, G. & Reynolds, J. (2004). Impacts of migratory behaviour on population structure in North Sea plaice. *Journal of Animal Ecology* **73,** 377–385.

Jones, C. M. & Chen, Z. (2003). New techniques for sampling larval and juvenile fish otoliths for trace-element analysis with laser-ablation sector-field inductively-coupled plasma mass spectrometry (SF-ICP-MS). In *The Big Fish Bang. Proceedings of the 26th Annual Larval Fish Conference* (Browman, H. I. & Skiftesvik, A. B., eds), pp. 431–443. Bergen: Institute of Marine Research.

Kaim, W. & Schwederski, B. (1994). *Bioinorganic Chemistry: Inorganic Elements in the Chemistry of Life.* Chichester: John Wiley & Sons Ltd.

Kalish, J. M. (1989). Otolith microchemistry: validation of the effects of physiology, age and environment on otolith composition. *Journal of Experimental Marine Biology and Ecology* **132,** 151–178.

Kalish, J. (1990). Use of otolith microchemistry to distinguish the progeny of sympatric anadromous and non-anadromous salmonids. *Fishery Bulletin* **88,** 657–666.

Kalish, J. (1991). Determinants of otolith chemistry: seasonal variation in the composition of blood plasma, endolymph and otoliths of bearded rock cod *Pseudophysis barbatus*. *Marine Ecology Progress Series* **74,** 137–159.

Kalish, J. (1992). Formation of a stress-induced chemical check in fish otoliths *Journal of Experimental Marine Biology and Ecology* **162,** 265–277.

Kaplan, I. C., Levin, P. S., Burden, M. & Fulton, E. A. (2010). Fishing catch shares in the face of global change: a framework for integrating cumulative impacts and single species management. *Canadian Journal of Fisheries and Aquatic Sciences* **67,** 1968–1982.

Lawton, R. J., Wing, S. R. & Lewis, A. M. (2010). Evidence for discrete subpopulations of sea perch (*Helicolenus percoides*) across four fjords in Fiordland, New Zealand. *New Zealand Journal of Marine and Freshwater Research* **44,** 309–322.

Limburg, K., Lochet, A., Driscoll, D., Dale, D. & Huang, R. (2010). Selenium detected in fish otoliths: a novel tracer for a polluted lake? *Environmental Biology of Fishes* **89,** 433–440. doi: 10.1007/s10641-010-9671-4

Limburg, K. E. (1995). Otolith strontium traces environmental history of subyearling American shad *Alosa sapidissima*. *Marine Ecology Progress Series* **119,** 25–35.

Lochet, A., Limburg, K. E., Rudstam, L. & Montesdeoca, M. (2010). Selenium incorporation in fish otoliths: effects of selenium and mercury from the water. *Canadian Journal of Fisheries and Aquatic Sciences* **67,** 1388–1397.

Longmore, C., Fogarty, K., Neat, F., Brophy, D., Trueman, C., Milton, A. & Mariani, S. (2010). A comparison of otolith microchemistry and otolith shape analysis for the study of spatial variation in a deep-sea teleost, *Coryphaenoides rupestris*. *Environmental Biology of Fishes* **89,** 591–605.

Longmore, C., Trueman, C., Neat, F., O'Gorman, E., Milton, J. & Mariani, S. (2011). Otolith geochemistry indicates life-long spatial population structuring in a deep-sea fish, *Coryphaenoides rupestris*. *Marine Ecology Progress Series* **435,** 209–224.

Macdonald, J. I. & Crook, D. A. (2010). Variability in Sr:Ca and Ba:Ca ratios in water and fish otoliths across an estuarine salinity gradient. *Marine Ecology Progress Series* **413,** 147–161.

Martin, G. B. & Thorrold, S. R. (2005). Temperature and salinity effects on magnesium, manganese, and barium incorporation in otoliths of larval and early juvenile spot *Leiostomus xanthurus*. *Marine Ecology Progress Series* **293,** 223–232.

Martin, G. B., Thorrold, S. R. & Jones, C. M. (2004). Temperature and salinity effects on strontium incorporation in otoliths of larval spot (*Leiostomus xanthurus*). *Canadian Journal of Fisheries and Aquatic Sciences* **61,** 34–42.

Martin, G. B. & Wuenschel, M. J. (2006). Effect of temperature and salinity on otolith element incorporation in juvenile gray snapper *Lutjanus griseus*. *Marine Ecology Progress Series* **324,** 229–239.

Mercier, L., Darnaude, A. M., Bruguier, O., Vasconcelos, R. P., Cabral, H. N., Costa, M. J., Lara, M., Jones, D. L. & Mouillot, D. (2011). Selecting statistical models and variable combinations for optimal classification using otolith microchemistry. *Ecological Applications* **21,** 1352–1364.

Mercier, L., Mouillot, D., Bruguier, O., Vigliola, L. & Darnaude, A. M. (2012). Multi-element otolith fingerprints unravel sea-lagoon lifetime migrations of the gilthead sea bream (*Sparus aurata* L.) *Marine Ecology Progress Series* **444,** 175–194.

Metcalfe, J. & Arnold, G. (1997). Tracking fish with electronic tags. *Nature* **387,** 665–666.

Metcalfe, J., Hunter, E. & Buckley, A. (2006). The migratory behaviour of North Sea plaice: currents, clocks and clues. *Marine and Freshwater Behaviour and Physiology* **39,** 25–36.

Miller, J. A. (2009). The effects of temperature and water concentration on the otolith incorporation of barium and manganese in black rockfish *Sebastes melanops*. *Journal of Fish Biology* **75,** 39–60.

Miller, J. A. (2011). Effects of water temperature and barium concentration on otolith composition along a salinity gradient: Implications for migratory reconstructions. *Journal of Experimental Marine Biology and Ecology* **405,** 42–52.

Miller, J., Banks, M., Gomez-Uchida, D. & Shanks, A. (2005). A comparison of population structure in black rockfish (*Sebastes melanops*) as determined with otolith microchemistry and microsatellite DNA. *Canadian Journal of Fisheries and Aquatic Sciences* **62,** 2189–2198.

Miller, J. A., Wells, B. K., Sogard, S. M., Grimes, C. B. & Cailliet, G. M. (Eds) (2010). Proceedings of the 4th International Otolith Symposium. *Environmental Biology of Fishes* **89**.

Miller, M. B., Clough, A. M., Batson, J. N. & Vachet, R. W. (2006). Transition metal binding to cod otolith proteins. *Journal of Experimental Marine Biology and Ecology* **329,** 135–143.

Milton, D. A. & Chenery, S. R. (2001*a*). Sources and uptake of trace metals in otoliths of juvenile barramundi (*Lates calcarifer*). *Journal of Experimental Marine Biology and Ecology* **264,** 47–65.

Milton, D. A. & Chenery, S. R. (2001*b*). Can otolith chemistry detect the population structure of the shad hilsa *Tenualosa ilisha*? Comparison with the results of genetic and morphological studies. *Marine Ecology Progress Series* **222,** 239–251.

Milton, D. A. & Chenery, S. R. (2005). Movement patterns of barramundi *Lates calcarifer*, inferred from $^{87}Sr/^{86}Sr$ and Sr/Ca ratios in otoliths, indicate non-participation in spawning. *Marine Ecology Progress Series* **301,** 279–291.

Milton, D. A., Tenakanai, C. D. & Chenery, S. R. (2000). Can the movements of barramundi in the Fly River Region, Papua New Guinea be traced in their otoliths? *Estuarine, Coastal and Shelf Science* **50,** 855–868.

Mugiya, Y. (1966). Calcification in fish and shellfish. Seasonal change in calcium and magnesium concentration of the otolith fluid in some fish with special reference to the zone formation of their otolith. *Bulletin of the Japanese Society of Scientific Fisheries* **32,** 549–557.

Mugiya, Y., Hakomori, T. & Hatsutori, K. (1991). Trace metal incorporation into otoliths and scales in the goldfish, *Carassius auratus*. *Comparative Biochemistry and Physiology C.* **99,** 327–331.

Panfili, J., Darnaude, A., Lin, Y. C., Chevalley, M., Iizuka, Y., Tzeng, W. N. & Crivelli, A. J. (2012). Habitat residence during continental life of the European eel *Anguilla anguilla* investigated using linear discriminant analysis applied to otolith Sr:Ca ratios. *Aquatic Biology* **15**, 175–185.

Papadopoulou, C., Kanias, G. D. & Moraitopoulou-Kassimati, E. (1980). Trace element content in fish otoliths in relation to age and size. *Marine Pollution Bulletin* **11,** 68–72.

Payan, P., De Pontual, H., Boeuf, G. & Mayer-Gostan, N. (2004). Endolymph chemistry and otolith growth in fish. *Comptes Rendus del'Académie des Sciences-Palevol* **3,** 535–547.

Pearson, R. G. (1963). Hard and soft acids and bases. *Journal of the American Chemical Society* **85,** 3533–3539.

de Pontual, H., Lagardère, F., Amara, R., Bohn, M. & Ogor, A. (2003). Influence of ontogenetic and environmental changes in the otolith microchemistry of juvenile sole (*Solea solea*). *Journal of Sea Research* **50,** 199–211.

Popper, A. N. & Fay, R. R. (2011). Rethinking sound detection by fishes. *Hearing Research* **273,** 25–36.

Proctor, C. H. & Thresher, R. E. (1998). Effects of specimen handling and otolith preparation on concentration of elements in fish otoliths. *Marine Biology* **131,** 681–694.

Proctor, C. H., Thresher, R. E., Gunn, J. S., Mills, D. J., Harrowfield, I. R. & Sie, S. H. (1995). Stock structure of the southern bluefin tuna *Thunnus maccoyii*: an investigation based on probe microanalysis of otolith composition. *Marine Biology* **122,** 511–526.

Pulliam, H. (1988). Sources, sinks, and population regulation. *The American Naturalist* **132,** 652–661.

Radtke, R. L. (1989). Strontium–calcium concentration ratios in fish otoliths as environmental indicators. *Comparative Biochemistry and Physiology A* **92,** 189–193.

Radtke, R., Townsend, D., Folsom, S. & Morrison, M. (1990). Strontium:calcium concentration ratios in otoliths of herring larvae as indicators of environmental histories. *Environmental Biology of Fishes* **27,** 51–61.

Ranaldi, M. & Gagnon, M. (2008*a*). Trace metal incorporation in otoliths of black bream (*Acanthopagrus butcheri* Munro), an indicator of exposure to metal contamination. *Water, Air, and Soil Pollution* **194,** 31–43.

Ranaldi, M. M. & Gagnon, M. M. (2008*b*). Zinc incorporation in the otoliths of juvenile pink snapper (*Pagrus auratus* Forster): The influence of dietary versus waterborne sources. *Journal of Experimental Marine Biology and Ecology* **360,** 56–62.

Ranaldi, M. M. & Gagnon, M. M. (2009). Accumulation of cadmium in the otoliths and tissues of juvenile pink snapper (*Pagrus auratus* Forster) following dietary and waterborne exposure. *Comparative Biochemistry and Physiology C* **150,** 421–427.

Reeder, R. J. & Rakovan, J. (1999). Surface structural controls on trace element incorporation during crystal growth. In *Growth, Dissolution, and Pattern Formation in Geosystems*

(Jamtveit, B. & Meakin, P., eds), pp. 143–162. Dordrecht: Kluwer Academic Publishers.

Righton, D. A., Andersen, K. H., Neat, F., Thorsteinsson, V., Steingrund, P., Svedäng, H., Michalsen, K., Hinrichsen, H. H., Bendall, V., Neuenfeldt, S., Wright, P., Jonsson, P., Huse, G., van der Kooij, J., Mosegaard, H., Hüssy, K. & Metcalfe, J. (2010). Thermal niche of Atlantic cod *Gadus morhua*: limits, tolerance and optima. *Marine Ecology Progress Series* **420,** 1–13.

Riveiro, I., Guisande, C., Iglesias, P., Basilone, G., Cuttitta, A., Giraldez, A., Patti, B., Mazzola, S., Bonanno, A., Vergara, A.-R. & Maneiro, I. (2011). Identification of subpopulations in pelagic marine fish species using amino acid composition. *Hydrobiologia* **670,** 189–199.

Rodgers, K. & Wing, S. (2008). Spatial structure and movement of blue cod (*Parapercis colias*) in Doubtful Sound, New Zealand, inferred from δ^{13}C and δ^{15}N. *Marine Ecology Progress Series* **359,** 239–248.

Rooker, J., Kraus, R. & Secor, D. (2004). Dispersive behaviors of black drum and red drum: Is otolith Sr:Ca a reliable indicator of salinity history? *Estuaries and Coasts* **27,** 334–341.

Sadovy, Y. & Severin, K. P. (1992). Trace-elements in biogenic aragonite – correlation of body growth-rate and strontium levels in the otoliths of the white grunt, *Haemulon plumieri* (Pisces, Haemulidae). *Bulletin of Marine Science* **50,** 237–257.

Sadovy, Y. & Severin, K. P. (1994). Elemental patterns in red hind (*Epinephelus guttatus*) otoliths from Bermuda and Puerto-Rico reflect growth-rate, not temperature. *Canadian Journal of Fisheries and Aquatic Sciences* **51,** 133–141.

Salini, J. P., Milton, D. A., Rahman, M. J. & Hussain, M. G. (2004). Allozyme and morphological variation throughout the geographic range of the tropical shad, hilsa *Tenualosa ilisha*. *Fisheries Research* **66,** 53–69.

Sanchez-Jerez, P., Gillanders, B. & Kingsford, M. J. (2002). Spatial variability of trace elements in fish otoliths: comparison with dietary items and habitat constituents in seagrass meadows. *Journal of Fish Biology* **61,** 801–821.

Secor, D. (1999). Specifying divergent migrations in the concept of stock: the contingent hypothesis. *Fisheries Research* **43,** 13–34.

Secor, D. H. & Rooker, J. R. (2000). Is otolith strontium a useful scalar of life cycles in estuarine fishes? *Fisheries Research* **46,** 359–371.

Secor, D. H., Henderson-Arzapalo, A. & Piccoli, P. M. (1995). Can otolith microchemistry chart patterns of migration and habitat utilization in anadromous fishes? *Journal of Experimental Marine Biology and Ecology* **192,** 15–33.

Secor, D. H., Rooker, J. R., Zlokovitz, E. & Zdanowicz, V. S. (2001). Identification of riverine, estuarine, and coastal contingents of Hudson River striped bass based upon otolith elemental fingerprints. *Marine Ecology Progress Series* **211,** 245–253.

Sequeira, V., Gordo, L. S., Neves, A., Paiva, R. B., Cabral, H. N. & Marques, J. F. (2010). Macroparasites as biological tags for stock identification of the bluemouth, *Helicolenus dactylopterus* (Delaroche, 1809) in Portuguese waters. *Fisheries Research* **106,** 321–328.

Silva, A. (2003). Morphometric variation among sardine (*Sardina pilchardus*) populations from the northeastern Atlantic and the western Mediterranean. *ICES Journal of Marine Science* **60,** 1352–1360.

Sims, D. W., Witt, M. J., Richardson, A. J., Southall, E. J. & Metcalfe, J. D. (2006). Encounter success of free-ranging marine predator movements across a dynamic prey landscape. *Proceedings of the Royal Society B* **273,** 1195–1201.

Sinclair, D. J. (2005). Correlated trace element "vital effects" in tropical corals: A new geochemical tool for probing biomineralization. *Geochimica et Cosmochimica Acta* **69,** 3265–3284.

Smith, H. W. (1930). The absorption and excretion of water and salts by marine teleosts. *American Journal of Physiology – Legacy Content* **93,** 480–505.

Söllner, C., Burghammer, M., Busch-Nentwich, E., Berger, J., Schwarz, H., Riekel, C. & Nicolson, T. (2003). Control of crystal size and lattice formation by starmaker in otolith biomineralization. *Science* **302,** 282–286.

Steele, J. H., Turekian, K. K. & Thorpe, S. A. (2009). *Marine Chemistry & Geochemistry: A Derivative of the Encyclopedia of Ocean Sciences.* New York, NY: Academic Press.

Steer, M. A., Fowler, A. J. & Gillanders, B. M. (2009). Age-related movement patterns and population structuring in southern garfish, *Hyporhamphus melanochir*, inferred from otolith chemistry. *Fisheries Management and Ecology* **16,** 265–278.

Surge, D. & Walker, K. J. (2005). Oxygen isotope composition of modern and archaeological otoliths from the estuarine hardhead catfish (*Ariopsis felis*) and their potential to record low-latitude climate change. *Palaeogeography, Palaeoclimatology, Palaeoecology* **228,** 179–191.

Swan, S. C., Geffen, A. J., Gordon, J. D. M., Morales-Nin, B. & Shimmield, T. (2006). Effects of handling and storage methods on the concentrations of elements in deep-water fish otoliths. *Journal of Fish Biology* **68,** 891–904.

Swearer, S. E., Forrester, G. E., Steele, M. A., Brooks, A. J. & Lea, D. W. (2003). Spatio-temporal and interspecific variation in otolith trace-elemental fingerprints in a temperate estuarine fish assemblage. *Estuarine, Coastal and Shelf Science* **56,** 1111–1123.

Tanner, S. E., Vasconcelos, R. P., Cabral, H. N. & Thorrold, S. R. (2012*a*). Testing an otolith geochemistry approach to determine population structure and movements of European hake in the northeast Atlantic Ocean and Mediterranean Sea. *Fisheries Research* **125–126**, 198–205. doi: 10.1016/j.fishres.2012.02.013

Tanner, S. E., Vasconcelos, R. P., Reis-Santos, P., Cabral, H. N. & Thorrold, S. R. (2012*b*). Spatial and ontogenetic variability in the chemical composition of juvenile common sole (*Solea solea*) otoliths. *Estuarine, Coastal and Shelf Science* **91,** 150–157.

Thorrold, S. R. & Shuttleworth, S. (2000). In situ analysis of trace elements and isotope ratios in fish otoliths using laser ablation sector field inductively coupled plasma mass spectrometry. *Canadian Journal of Fisheries and Aquatic Sciences* **57,** 1232–1242.

Thorrold, S. R., Jones, C. M. & Campana, S. E. (1997). Response of otolith microchemistry to environmental variations experienced by larval and juvenile Atlantic croaker (*Micropogonias undulatus*). *Limnology and Oceanography* **42,** 102–111.

Thorrold, S. R., Latkoczy, C., Swart, P. K. & Jones, C. M. (2001). Natal homing in a marine fish metapopulation. *Science* **291,** 297–299.

Thresher, R. (1999). Elemental composition of otoliths as a stock delineator in fishes. *Fisheries Research* **43,** 165–204.

Tohse, H. & Mugiya, Y. (2002). Diel variations in carbonate incorporation into otoliths in goldfish. *Journal of Fish Biology* **61,** 199–206.

Toole, C., Markle, D. & Harris, P. (1993). Relationships between otolith microstructure, microchemistry, and early life history events in Dover sole, *Microstomus pacificus*. *Fishery Bulletin* **91,** 732–753.

Townsend, D. W., Radtke, R. L., Corwin, S. & Libby, D. A. (1992). Strontium:calcium ratios in juvenile Atlantic herring *Clupea harengus* L. otoliths as a function of water temperature. *Journal of Experimental Marine Biology and Ecology* **160,** 131–140.

Turekian, K. (1968). *Oceans.* Englewood Cliffs, NY: Prentice-Hall.

Tzeng, W. (1996). Effects of salinity and ontogenetic movements on strontium:calcium ratios in the otoliths of the Japanese eel, *Anguilla japonica* Temminck and Schlegel. *Journal of Experimental Marine Biology and Ecology* **199,** 111–122.

Tzeng, W. N., Severin, K. P., Wang, C. H. & Wickstrom, H. (2005). Elemental composition of otoliths as a discriminator of life stage and growth habitat of the European eel, *Anguilla anguilla*. *Marine and Freshwater Research* **56,** 629–635.

Tzeng, W., Chang, C., Wang, C., Shiao, J., Yoshiyuki, I., Yang, Y., You, C. & Lozys, L. (2007). Misidentification of the migratory history of anguillid eels by Sr/Ca ratios of vaterite otoliths. *Marine Ecology Progress Series* **348,** 285–295.

Versieck, J. & Cornelis, R. (1989). *Trace Elements in Human Plasma or Serum.* Boca Raton, FL: CRC Press Inc.

de Vries, M. C., Gillanders, B. M. & Elsdon, T. S. (2005). Facilitation of barium uptake into fish otoliths: Influence of strontium concentration and salinity. *Geochimica et Cosmochimica Acta* **69,** 4061–4072.

Walther, B. & Thorrold, S. R. (2006). Water, not food, contributes the majority of strontium and barium deposited in the otoliths of a marine fish. *Marine Ecology Progress Series* **311,** 125–130.

Walther, B. D. & Thorrold, S. R. (2009). Inter-annual variability in isotope and elemental ratios recorded in otoliths of an anadromous fish. *Journal of Geochemical Exploration* **102,** 181–186.
Walther, B. D. & Thorrold, S. R. (2010). Limited diversity in natal origins of immature anadromous fish during ocean residency. *Canadian Journal of Fisheries and Aquatic Sciences* **67,** 1699–1707.
Walther, B., Kingsford, M., O'Callaghan, M. & McCulloch, M. (2010). Interactive effects of ontogeny, food ration and temperature on elemental incorporation in otoliths of a coral reef fish. *Environmental Biology of Fishes* **89,** 441–451.
Watanabe, T., Kiron, V. & Satoh, S. (1997). Trace minerals in fish nutrition. *Aquaculture* **151,** 185–207.
Weiner, S. (2008). Biomineralization: a structural perspective. *Journal of Structural Biology* **163,** 229–234.
Williams, D. R. (1971). *The Metals of Life*. London: Van Nostrand Reinhold Company.
Zimmerman, C. (2005). Relationship of otolith strontium-to-calcium ratios and salinity: experimental validation for juvenile salmonids. *Canadian Journal of Fisheries and Aquatic Sciences* **62,** 88–97.

Electronic References

Hunter, E. & Darnaude, A. M. (2004). Determination of plaice lifetime movements in the North Sea by linking natural and electronic data records. ICES CM 2004/K: 05. Available at http://www.ices.dk/products/Cmdocs/2004/K/K0504.pdf/
Chen, Z. & Jones, C. M. (2006). *Simultaneous Determination of 33 Major, Minor, and Trace Elements in Juvenile and Larval Fish Otoliths by High Resolution Double Focusing Sector Field Inductively Coupled Plasma Mass Spectrometry*. Available at http://www.people.fas.harvard.edu/~zchen/Solution_Otolith_Fin.pdf/