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A Review of the Application of Otolith Microchemistry Toward the Study of Latin American Fishes

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ABSTRACT

In developed countries, otolith microchemistry has been used for more than three decades for studies of life history, migration, and environmental ecology of fish stock of commercial importance. Although Latin America produces 16% of the annual fish capture, most of their fishery resources have not been well studied and handled. Modern methodologies related to microchemistry have not been applied to the underdeveloped countries of Latin America due to its high cost. In the last decade, there have been several studies on Latin American resources, carried out mainly by first world countries. Currently, some regional economies are strong and stable enough to ensure the training of specialized human resources and to generate opportunities for the exchange of projects and acquisition of state-of-the-art technology. In this work, all available literature associated to Latin American resources in relation to the use of otolith microchemistry has been reviewed. The use of different methodologies in the region in relation to global trends has been discussed. In addition to that, the extent of collaboration between underdeveloped and developed countries has been evaluated. This review shows a promising future in the application of otolith microchemistry to study biology of fishes, which will impact on the medium and long term to ensure the sustainability of certain resources and, therefore, the strengthening of regional economies.

KEYWORDS

Otolith microchemistry; Latin America; fish stock; fishery resources

Introduction

Latin America in the world

Latin America has 13.5% of the planet's land surface (22,222,000 km^2). It is composed of 20 countries; most of them are underdeveloped countries. This region presents a wide variety of climates and environments housing a large geographical and biological diversity. This is the region with the most biodiversity in the world and one of which with the largest number of endemic species.

Latin America has approximately 4231 inland fish species, 4035 of which are from fresh waters, and 196 from estuaries (Lévêque et al., 2008). The number of marine species is even higher. In the different coastal areas of the South and Atlantic Ocean alone there are approximately 5101 species of fish (Miloslavich et al., 2011).

Because of the large number of species bearing commercial importance, it is one of the regions of the world where higher volumes of fish are captured (15 million tons per year; FAO, 2012). Latin America registers one of the lowest figures for fish consumption per capita in the world, far below the global average consumption, and its production is mostly exported to countries in Europe, Asia, and North America (FAO, 2012). Latin American countries responsible for 90% of regional production, in descending order with respect to the captured volume, are as follows: Peru, Chile, Mexico, Argentina, and Brazil (FAO, 2012).

As is the case worldwide, extractive fishery catch has increased in Latin America toward the end of the twentieth century and has remained at a relatively constant level in the last FAO decade (2012). It is estimated that since 1950, 25% of the world's fisheries have collapsed (Hilborn et al., 2005; Mullon et al., 2005), some of which are Latin American fish species of great commercial interest such as the anadromous catfish *Genidens barbus* (Velasco et al., 2007; Avigliano et al., 2015d) or large freshwater fish like the arapaima (*Arapaima gigas*) and the pacú (*Colossoma macropomum*) from the Amazon River (Chapman, 1989) or the pacú from the Río de la Plata basin (*Piaractus mesopotamicus*).

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Because of the large volume of annual catch that occurs in the region, it is necessary to develop and implement efficient methodologies designed to study the biology and ecology of the species in order to ensure the sustainability of fisheries. In many cases, the current socioeconomic reality of the region hampers development and incorporation of modern monitoring and evaluation methodologies.

General methods of study of environmental biology of fishes

Oriented strategies to ensure an efficient management and sustainable organization of fisheries are based on stocks identification, nursery areas, and regulation of fishing efforts, among other factors. To this end, the intention is to avoid an irreversible decrease of fishery reserves that may jeopardize the continuity of fishery or lead the fishing productive sector to a difficult socioeconomic framework.

The methodologies that have been historically used to study population structure, migration, and fish stocks identification are generally costly and difficult to implement, especially in under-resourced countries as it is the case in Latin America. In addition, some techniques are not comprehensive and are used to study only one aspect of the fish. For instance, size structure methodology or meristic analyses identify fish stocks but they do not allow to directly relate the stocks with different environmental variables, and thus determine migration routes. Moreover, this methodology requires a large number of specimens of all possible sizes. The study of abundance and diversity of parasites has identified populations and evaluated connectivity (Timi et al., 2005; Braicovich and Timi, 2008); however, it does not provide information on migration and identification of natal nurseries. Disadvantages include the need for considerable biological information on the parasites, and intra-stock variation due to adoption of different life history modes within a fish stock (not to mention the assumption that parasitic fauna are stable over time, and the difficulties in doing quantitative parasitology; Begg and Waldman, 1999). Genetic methods (protein variation, mitochondrial DNA, nuclear DNA) could provide information on the connectivity of different populations; however, it is not possible to obtain detailed information on the life history of the fish. Variation in proteins or enzymes is an indirect expression of nucleotide base differences between groups. The usefulness of this approach is undermined by the fact that the same protein may be coded by multiple nucleotide sequences. Interpretation of nDNA data may be complicated by polyploidy, as it is common in sturgeons and salmonids (Begg and Waldman, 1999).

Furthermore, the capture-re/capture method is one of the few methods that can unveil information related to different aspects such as migration, connectivity, abundance estimate, homing behavior, growth, etc. (Raabe and Gardner, 2013; Letcher et al., 2014). The success of mark-recapture for stock identification purposes is dependent on representative tagging and recapture efforts (a condition rarely met; Begg and Waldman, 1999). Such studies are generally costly and time consuming. Another method to study various aspects of fish life is satellite tagging and tracking system (Sims et al., 2009; Hoolihan et al., 2011). Tagging devices are often very expensive and studies are usually carried out with low sample sizes, some of which are often little representative. Another limitation of this methodology is that the fish must be of large size to support the tagging device without affecting behavior.

The study of calcified structures like fish scales has identified fish stocks (Poulet et al., 2005; Staszny et al., 2012) and displacement (Pouilly et al., 2014a); however, as the presence of rings or chemical composition of this structure is not necessarily continuous, it could lead to interpretation mistakes.

Application of otolith microchemistry toward the study of environmental biology of fishes

In recent years, the use of chemical composition of otoliths has allowed stocks identification, nursery areas and description of life histories of different commercial species (Avigliano and Volpedo 2013; Kerr and Campana 2013; Reis-Santos et al. 2015a,b; Tanner et al. 2015). Otoliths of teleost fish are complex polycrystalline bodies composed mainly of calcium carbonate in the form of aragonite and trace and ultra-trace elements embedded within an organic matrix (Campana, 1999) and housed in the vestibular apparatus.

The addition of calcium is an extracellular process that would be hormonally regulated and influenced by environmental variations such as temperature (Morales-Nin, 1998, 2000). Besides, the concentration of the trace elements deposited in otoliths is regulated by the physiological activity of the fish and environmental factors (Radtke and Shafer 1992; Campana 1999; Martin et al. 2004; Martin and Wuenschel 2006; Ranaldi and Gagnon 2008; Miller 2011; Sturrock et al. 2012; Bouchard et al. 2015). Temperature and salinity are among the most relevant environmental factors regarding the incorporation of elements in the otolith (Campana 1999; Secor and Rooker 2000; Elsdon and Gillanders 2002; Martin et al. 2004; Sturrock et al. 2012; Bouchard et al. 2015). The predominant source of most elements and isotopes to otoliths is the surrounding water. Elements are incorporated from the water to the fish's blood plasma via the gills or intestines, then into the endolymph, and finally into the crystallizing otolith (Sturrock et al., 2012; Kerr and Campana, 2013; Bouchard et al., 2015). The diet of the fish can contribute to the chemical composition of the otolith; however, the relative contribution varies for different elements (Walther and Thorrold, 2006; Sturrock et al., 2012; Kerr and Campana, 2013; Bouchard et al., 2015).

In summary, chemical composition of otoliths is conservative because the material in their makeup is not reabsorbed or altered (Campana and Neilson, 1985; Casselman, 1990; Campana and Thorrold, 2001; Elsdon et al., 2008). Trace elements in combination with growth rings result in an important file that records environment information frequented by fish, environmental changes and exposure to pollutants throughout ontogeny (Halden and Friedrich, 2008). For these reasons, otolith microchemistry has been widely used to study environmental biology of fish and identification of fish stocks. Microchemistry analysis can provide data on the environmental history of each fish (Campana and Thorrold, 2001; Wells et al., 2003; Whitledge et al., 2006; Dufour et al., 2008; Sturrock et al., 2012; Kerr and Campana, 2013; Avigliano et al., 2015c; Bouchard et al., 2015; Izzo et al., 2015; Tanner et al., 2015). In this sense and in comparison with other techniques, fish migration is the only process where otolith science has provided unique insights (Secor, 2010). In general, the different studies with trace elements that can be currently carried out in otoliths allow us to deal with several issues (connectivity, migration, life story, nursery areas, stocks, population structure, homing behavior) at a low or moderate cost of analysis, without the use of expensive methodologies. There are good examples of how microchemistry of otoliths has enabled detailed study of the biology of commercial fish, thus improving the management of different resources. As emblematic examples we can mention the case of eels (*Anguilla anguilla, Anguilla japonicus, Anguilla rostrata*; Lin et al., 2007; Tabouret et al., 2010), Atlantic bluefin tuna and Pacific salmon (Rooker et al., 2008; Schloesser et al., 2010; Secor, 2010).

Most of the works will be focused on commercial fish species in the northern hemisphere, mainly the USA, Canada, western and northwestern Europe, Japan, and China, in contrast with countries of the Southern Hemisphere with the exception of Australia, where this methodology is underdeveloped. The major reason for a lack of applicability of these methodologies in Latin America is a shortage of specialists in the subject and a general underinvestment in the Science and Technology area, in comparison with developed countries. Furthermore, the absence of global long-term fisheries policies prevents the development of cutting-edge methodologies. Nevertheless, by generating cooperation with specialists from different nations and promoting international projects (funding, postgraduate training and research), efficient and relative low-cost techniques with respect to microchemistry of otoliths (relative to the ones previously discussed) could be implemented in the region.

Therefore, the aim of this study is to review the history and current status of the use of the otolith microchemistry as a tool for studying the biology and the ecology of fish in Latin America and to project prospects in comparison to the development of this methodology worldwide. Our purpose is to encourage the implementation and development of current technologies that contribute to scientific knowledge and to stimulate the strengthening of the fishing industry in Latin America. Finally, this paper aims to encourage researchers from Latin America to collaborate with experts from other continents to generate high-quality results and thus improve the management of fishery resources.

Methods of bibliographic survey

The works associated with a certain aspect of otolith microchemistry of species with distribution in Latin America made by researchers, both regional and from abroad, have been reviewed. In addition, the worldwide scientific literature was reviewed in order to compare the current status with the progress and local perspectives. A literature survey was conducted for the 20 countries making up Latin America.

Journals indexed in SCIMAGO and/or Thompson & Reuter and different platforms related to them, such as ScienceDirect, SCIELO, Google Scholar, Wiley, Springer, SCIRO publishing, Cambridge University Press, and so on, have been considered.

Different aspects of each work have been identified and organized in a table (Table 1), considering: (1) the tested species; (2) thematic subject area (general chemistry composition, determination of fish stocks, determination of nurseries areas, population structure, migration, life history, paleoclimate, natural tag, pollution, and methodology), habitat of species (freshwater, estuarine, marine, anadromous/catadromous); (3) country of origin of the sample or resource; (4) origin of authors (Latin American or non-Latin American authors); (5) type of collaboration (Latin American authors, non-Latin American authors and authors from Latin America and other continents); (6) methodology applied in the study (e.g. ICP-OES, ICP-MS, LA-ICPMS, SIRMS); (7) certain analytes (major and trace elements and isotopes). In the event of joint works, the same paper for all countries that have been declared to be the authors' workplaces has

Table 1. List of scientific works published in Latin America.

Reference	Species	Environment	Issue	Sampling site (Country)	Country of research	Methodology	Analytes
Albuquerque et al., 2010	*Micropogonias furnieri*	Marine	Life-history	Brazil	Brazil	LA-ICPMS	Sr:Ca, Ba:Ca
Albuquerque et al., 2012	*Micropogonias furnieri*	Estuarine/marine	Life-history	Brazil, Uruguay, Argentina	Brazil, USA	LA-ICPMS	Sr:Ca,
Andrus et al., 2002a	*Galeichthys peruvianus*	Marine	Paleoclimate	Perú	USA	IRMS	δ^{18}O
Andrus et al., 2002b	*Galeichthys peruvianus*	Marine	Paleoclimate	Perú	USA	IRMS	δ^{18}O, δ^{13}C
Araya et al., 2014	*Oncorhynchus tshawytscha*	Freshwater/estuarine/ marine (anadromous)	Life-history	Chile	Chile, USA	WDS	Sr:Ca
Arkhipkin et al., 2009	*Micromesistius australis*	Marine	Population structure	Chile, Argentina, Antartic	UK, Australia	LA-ICPMS	Li:Ca, Mg:Ca, Sr:Ca, Ba:Ca
Ashford and Jones, 2007	*Dissostichus eleginoides*	Marine	Stock identification	Chile, Argentina, Antartic	USA	SIRMS	δ^{18}O, δ^{13}C
Ashford et al., 2005	*Dissostichus eleginoides*	Marine	Stock identification	Chile, Argentina, Antartic	Chile, USA, UK, Fance, Australia	LA-ICPMS	Mg:Ca, Mn:Ca, Sr:Ca, Ba:Ca
Ashford et al., 2006	*Dissostichus eleginoides*	Marine	Stock identification	Chile, Argentina, Antartic	UK	LA-ICPMS	Mn:Ca, Sr:Ca, Ba:Ca
Ashford et al., 2007	*Dissostichus eleginoides*	Marine	Natural tag	Chile, Argentina, Antartic	USA, UK	LA-ICPMS	Mg:Ca, Mn:Ca, Sr:Ca, Ba:Ca
Ashford et al., 2008	*Dissostichus eleginoides*	Marine	Natural tag	Chile, Argentina, Antartic	Chile, USA, UK, Fance, Australia	LA-ICPMS	Mg:Ca, Mn:Ca, Sr:Ca, Ba:Ca
Ashford et al., 2011	*Trachurus murphyi*	Marine	Population structure	Chile	Chile, USA	LA-ICPMS	Sr:Ca,Ba:Ca, Mg:Ca, Mn:Ca
Avigliano and Volpedo, 2013	*Odontesthes bonariensis*	Freshwater/estuarine	Life-history	Argentina	Argentina	ICP-OES	Sr:Ca
Avigliano et al., 2014	*Odontesthes bonariensis*	Freshwater/estuarine	Stock identification	Argentina	Argentina, Colombia	ICP-OES	Sr:Ca; Ba:Ca
Avigliano et al., 2015b	*Percophis brasiliensis*	Marine	Natural tag	Argentina	Argentina	ICP-OES	Sr:Ca, Zn:Ca
Avigliano et al., 2015d	*Genidens barbus*	Freshwater/estuarine/ marine (anadromous)	Life-history	Argentina, Brazil	Argentina, Brazil, USA[a]	LA-ICPMS	Sr:Ca, Ba:Ca
Avigliano et al., 2015c	*Genidens barbus*	Freshwater/estuarine/ marine (nadromous)	Population structure/ methodology	Argentina, Brazil	Argentina, Brazil	Micromilling/ICP-OES	Sr:Ca, Ba:Ca, Mg:Ca
Avigliano et al., 2015e	*Odontesthes bonariensis*	Freshwater/estuarine	Natural tag	Argentina	Argentina	ICP-OES	Sr:Ca
Avigliano et al., 2015a	*Mugil curema*	Estuarine/marine	Stock identification	Venezuela	Venezuela, Argentina	ICP-OES	Sr:Ca, Ba:Ca
Avigliano et al., 2016a	*Genidens barbus*	Freshwater/estuarine/ marine (anadromous)	Nursery	Argentina, Brazil	Argentina, Brazil	Micromilling/ICP-Ms	Sr:Ca, Ba:Ca, Li:Ca, Mg:Ca, Mn:Ca, Zn:Ca
Avigliano et al., 2016b	*Prochilodus lineatus*	Freshwater	Nursery	Argentina	Argentina	ICP/OES	Sr:Ca, Ba:Ca, Zn:Ca
Chittaro et al., 2004	*Haemulon flavolineatum*	Marine	Population structure	Belize	Canadá	LA-ICPMS	Sr:Ca, Ba:Ca, Pb:Ca, Sn:Ca, Li:Ca, Mg:Ca, Cu:Ca, Rb:Ca
Chittaro et al., 2005	*Haemulon flavolineatum*	Marine	Natural tag	Belize	Canadá	LA-ICPMS	Li:Ca, Mg:Ca, Cu:Ca, Zn:Ca, Rb:Ca, Sr:Ca, Sn:Ca, Ba:Ca, Pb:Ca
Chittaro et al., 2006a	*Stegastes partitus*	Marine	Life-history	Mexico	USA, Canada	LA-ICPMS	Mn:Ca, Zn:Ca, Sr:Ca, Sn:Ca, Ba:Ca, Ce:Ca, Pb:Ca
Chittaro et al., 2006b	*Lutjanus podus*	Marine	Natural tag	Belize	Canadá	LA-ICPMS	Li:Ca, Mg:Ca, Cu:Ca, Zn:Ca, Rb:Ca, Sr:Ca, Sn:Ca, Ba:Ca, Pb:Ca
Collins et al., 2013	*Prochilodus mariae*	Freshwater	Population structure	Venezuela	Venezuela, USA, Austria, France	LA-ICPMS	Sr:Ca, Ba:Ca, Mg:Ca, ^{87}Sr:^{86}Sr
Condini et al., 2015	*Epinephelus marginatus*	Estuarine/marine	Life-history	Brazil	Brazil, Portugal	LA-ICPMS	Sr:Ca, Ba:Ca
Fodrie and Herzka, 2008	*Paralichthys californicus*	Marine	Nursery	Mexico	Mexico, USA	LA-ICPMS	Mg:Ca, Mn:Ca, Cu:Ca, Sr:Ca, Ba:Ca, Pb:Ca, U:Ca
Garcez et al., 2014	*Cichla temensis*	Freshwater	Natal origin	Brazil	Brazil, USA	LA-ICPMS	Sr:Ca, Ba:Ca, ^{87}Sr:^{86}Sr
Hegg et al., 2015	*Brachyplatystoma rousseauxii, B. vaillantii, B. filamentosum*	Freshwater	Life-history	Brazil	Brazil, USA	LA-CM-ICPMS	^{87}Sr:^{86}Sr
Herrera-Reveles, 2013	*Abudefduf saxatilis*	Marine	Contamination	Venezuela	Venezuela	WDS	Cd:Ca, Cu:Ca, Hg:Ca, Pb:Ca, Zn:Ca
Ibáñez et al., 2012	*Mugil cephalus, M. curema*	Marine	Life-history	México	México, Taiwan,	LA-ICPMS	Sr:Ca

Mai et al., 2014	*Lycengraulis grossidens*	Freshwater/estuarine/ marine (Anadromous)	Life-history	Brazil, Uruguay, Argentina	Brazil	LA-ICPMS	Sr:Ca, Ba:Ca
Markwitz et al., 2000	*Trachurus murphyi*	Marine	Metodology	Perú	Perú, New Zealand, Germany, USA	micro-PIXE	Sr:Ca
Mateo et al., 2010	*Haemulon flavolineatum, Lutjanus apodus*	Marine	Nursery	Puerto Rico	USA	Micromilling/IRMS/ MC-LA-ICPMS	Sr:Ca, Ba:Ca, Cu:Ca, Mg:Ca, Co:Ca, Na:Ca, δ^{18}O, δ^{13}C,
Meekan et al., 1999	*Stegastes acapulcoensis, S. arcifrons, S. leucorus*	Marine	Natal origin	Ecuador	USA	LA-ICPMS	Mg:Ca, Mn:Ca, Sr:Ca, Ba:Ca, Pb:Ca
Niklitschek et al., 2010	*Micromesistius australis*	Marine	Stock identification/ nursery	Chile, Argentina, Antartic	Chile, USA	Micromilling/ ICPMS/IRMS	Sr:Ca, Ba:Ca, Mg:Ca, Mn:Ca, δ^{13}C, δ^{18}O
Niklitschek et al., 2014	*Macruronus magellanicus*	Marine	Nursery	Chile	Chile, USA	IRMS	δ^{13}C, δ^{18}O
Oliveira and Farina, 1996	*Serrasalmus spilopleura, S. rhombeus, Pygocentrus nattereri*	Freshwater	Otolith composition	Brazil	Brazil, USA	Electron diffraction	Vaterite, Calcite, Aragonite
Patterson et al., 1999	*Epinephelus striatus*	Marine	Natural tag	Belize	USA	ICPMS	Zn:Ca, Sr:Ca, Ba:Ca, Pb:Ca
Pouilly et al., 2014	*Hoplias malabaricus, Schizodon fasciatus*	Freshwater	Natal origin	Brazil	France, Brazil	TIMS	^{87}Sr:^{86}Sr
Riva Rossi et al., 2007	*Oncorhynchus mykiss*	Freshwater/estuarine/ marine (anadromous)	Life-history	Argentina	Argentina, Canadá	EPMA	Sr:Ca
Ruttenberg and Warner, 2006	*Stegastes beebei*	Marine	Natal origin	Ecuador	USA	LA-ICPMS	Mg:Ca, Mn:Ca, Sr:Ca, Ba:Ca, Pb:Ca
Schuchert et al., 2010	*Macruronus magellanicus*	Marine	Population structure	Argentina, Chile	UK, USA	LA-ICPMS	Mn:Ca, Mg:Ca, Sr:Ca, Fe:Ca, Ba:Ca, P:Ca
Valle and Herzka, 2008	*Sardinops sagax*	Marine	Population structure	México	México, USA	CF-IRMS	δ^{18}O
Volpedo and Fernandez Cirelli, 2006	*Micropogonias furnieri*	Freshwater/estuarine	Stock identification	Argentina	Argentina	ICP-OES	Cd:Ca, Cu:Ca, Mg:Ca, Mn:Ca, Sr:Ca, Zn:Ca

[a] Determinations made in USA as a service to third.

been recorded in order to evaluate the researchers' origin.

The analysis of the works generated different graphs depicting the history and trends in the application of microchemistry in Latin America. Based on these analyses, the use and progress of different technologies have been compared taking into account each regional socioeconomic situation in relation to the global development of these issues. Finally, trends and perspectives in the implementation of the otolith microchemistry are being discussed in the study and management of fishery resources in Latin America.

Result and discussion

Application of the otolith microchemistry worldwide

History

Scientific interest in fish otoliths emerged four decades ago with the discovery of daily increments (Panella, 1971), resulting now in thousands of scientific papers on otolith.

According to Secor (2010), there was a nearly twofold expansion of otolith science during the period 1981–1995, followed by a stable period where otolith applications comprised 0.6% of the literature base. During the entire period (1981–2008), the literature base recorded more 3600 primary contributions in otolith science showed a growth followed by stability suggests maturation of otolith applications (Secor, 2010) with annual rates approaching 200 papers per year (Campana 2005). Campana (2005) estimated that by the middle of the last decade, about 17% of the publications on otoliths in peer-review journals included some chemical aspect (trace elements, isotopes, etc.). Moreover, Tanner et al. (2015) conducted a review of work on stocks identification using the otolith microchemistry that revealed an exponential growth of publications by 2010, with a slight decrease until early 2015.

To date, five symposiums have taken place (International Symposium on Fish Otolith Research and Application) engaged to the study of different aspects of the otoliths. In the second symposium (Bergen, Norway, 1998), 862 otolith-oriented papers published (Campana 2005) were present. Although close to 40% of the papers could be classified as "annual age and growth" studies, the remaining papers were roughly equally divided between studies of otolith microstructure, otolith chemistry and non-aging applications (Campana 2005). The third symposium, among the five themes developed (age and growth; chemistry; life history and management; physiology and morphology; and sclerochronology and the environment), the application of microchemistry represented 27% of the works submitted, exceeded only by age and growth (29%; Begg et al., 2005). In the following symposia, this topic grew significantly. In the fourth and fifth symposium, microchemistry (or topics that included some aspect of chemistry) was the issue on which more works were presented, featuring in over 40% of the total works submitted (Miller et al., 2010; Morales-Nin and Geffen, 2015). The number of works from Latin America has increased especially in the 5th Symposium (Morales-Nin and Geffen, 2015), which represented approximately 20% of the works presented.

The source of origin of the chemical elements (environment, diet) and the description of life history of marine or euryhaline species are among the most developed themes in recent times. Marine and euryhaline species are valuable models to evaluate different aspects of ecology and biology of fish, such as meta-population dynamics at different temporary and spatial scales, and to estimate interconnectivity between geographically segregated subpopulations and describe ontogenetic displacements (Thorrold et al., 2001; Gillanders, 2005; Vasconcelos et al., 2008; Chittaro et al., 2009; Scartascini and Volpedo, 2013; Bouchard et al., 2015). The study of different fragments of the otolith as the nucleus, pertaining to the time of the birth of fish, has been widely used to identify areas of birth and rearing of different species around the world (Brown, 2006; Rooker et al., 2008; Schuchert et al., 2010; Geffen et al., 2011; Bailey et al., 2015).

Besides trace elements, isotopes such Sr, O, and C (^{87}Sr:^{86}Sr, ^{18}O:^{16}O, and ^{13}C:^{12}C) have been applied in recent decades, being useful for identifying rates of natal homing dispersal, thermal histories, and movements across salinity gradients (Walther and Thorrold, 2009; Newman et al., 2010; Schloesser et al., 2010; Garcez et al., 2014). ^{87}Sr:^{86}S and ^{18}O:^{16}O isotopes in otolith directly reflect disolved ambient ratios, which in freshwater habitats depends on the geological composition of the drainage basin, whereas stable ^{13}C:^{12}C isotopes are affected by the metabolism of individual fish (i.e., relative trophic level and changes in metabolic rate over the life) and dietary change (Newman et al. 2010). The δ13C and δ18O values in fish otoliths usually increase with salinity and decrease with increasing temperture (Elsdon and Gillanders, 2002; Stanley et al., 2015).

Analysis methodology

The trace elements in otoliths have been traditionally analyzed by the following methods: (a) total acid digestion of the otoliths followed by inductively coupled plasma-optical emission spectrometry (ICP-OES; e.g., Edmonds et al. 1989; Avigliano et al. 2014) or inductively coupled plasma-mass spectrometry (ICP-MS; e.g., Swan et al. 2003; Patterson et al. 2004); and (b) spot and line scan analysis of the otolith element:Ca ratios by electron probe micro-analysis (EPMA) and microproton-induced X-ray emission (micro-PIXE; e.g. Lin et al. 2007; Hedger et al. 2008), and more recently by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS; e.g., Arai and Hirata 2006; Tabouret et al. 2010; Morales-Nin et al. 2014).

The methods based on total otolith solution and microchemistry analysis by ICP are easy to implement and have high resolution, but lead to a loss of information on fish life history. Micro milling different techniques by which it is possible to isolate fragments of the otolith such as the nucleus, allows to reduce the loss of information compared to determinations on otoliths solutions (Brown, 2006; Arslan and Secor, 2008; Schloesser et al., 2010, Avigliano et al., 2015d). However, although LA-ICP-MS is a powerful method due to the combination of spot ablation feature of laser and high sensitivity of ICP-MS (Campana et al., 1997; Arai and Hirata, 2006; Arai et al., 2007; Boehler et al., 2012). Electron probe micro-analysis and micro-PIXE lack the sensitivity required for accurate detection of trace elements, such as Cd, Cu, Pb, and Zn (Thresher, 1999; Arai and Hirata, 2006; Arslan and Secor, 2008).

Current status and prospects

The global trend for the study of populations structure or identification of nursery areas and fish stocks is toward the use of different methodologies simultaneously (Kerr and Campana 2013; Reis-Santos et al. 2015a,b; Tanner et al. 2015). One of the most appealing combinations is linking stock structure information obtained from otolith chemistry with genetic markers (Longmore et al., 2014; Tanner et al., 2014, 2015). Although genetic differentiation in some marine species may be too low to differentiate populations efficiently, new bioinformatic tools in relation to DNA tests look very promising (Tanner et al., 2015). Single nucleotide polymorphisms (SNPs) have shown great promise and albeit the associated costs of this application, it is reasonable to believe that it will become the marker of choice in the near future (Mariani and Bekkevold, 2013).

Other recently used techniques in conjunction with otolith microchemistry involve mathematical models and new statistical methodologies such as the Lagrangian particle tracking models (Tanner et al., 2015). The use of artificial markers has shown to have potential to predict dispersion and to assess connectivity between populations (Brickman et al., 2010).

Moreover, the global trend shows a strong articulation of different statistical techniques such as more specific and in-depth analysis of discrimination. For example, statistical methods for the evaluation of mixed stocks as maximum likelihood estimation or mixed Bayesian analysis could provide a high-level classification to the detriment of the discriminant analysis, which is not recommended in these cases (Rooker et al., 2014).

The application of the otolith microchemistry in Latin America

History and topics studied

In Latin America, the first works were published in the late 1990s (Table 1 and Figure 1). Our literature search showed that 45 scientific papers have been published involving

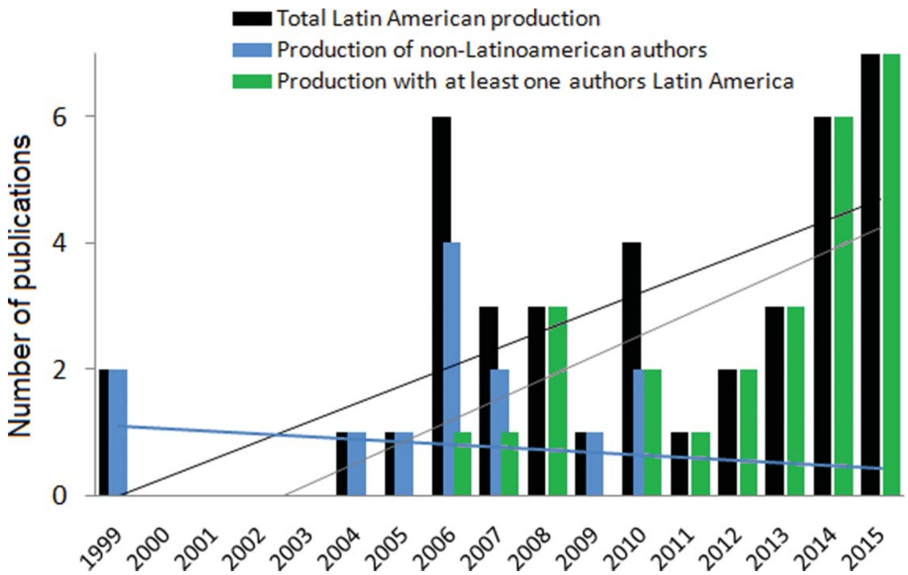

Figure 1. Historical Scientific production related to fisheries resources in Latin America according to researchers' country of origin. Lines indicate trends.

Latin American fishery resources. The first work was done by Oliveira et al. (1996) using electron and X-ray diffraction (Table 1) and describes the presence of vaterite, aragonite, and calcite in three species of Amazonian piranhas.

Microchemistry works directly related to the study of fish biology (stock, life history, nursery, etc.) were published in 1999 (Meekan et al. 1999; Patterson et al. 1999). These studies have been conducted by researchers from the USA on species distributed in Latin American waters. For example, Meekan et al. (1999) studied the birth origin of *Stegastes acapulcoensis, Stegastes arcifrons, Stegastes leucorus* in Galapagos Island (Ecuador) by using LA-ICPMS to determine Mg, Mn, Sr, Ba, and Pb in the nucleus of the otolith (Table 1).

In the same year, Patterson et al. (1999) published a work on identification of fish stocks of *Epinephelus striatus* in Belize, where the ratios of Zn:Ca, Sr:Ca, Ba:Ca, and Pb:Ca were analyzed by using solution-based ICP-MS. After these works, there is a gap until 2004, moment in which a sustained increase in scientific production (Figure 1) is observed. In 2002, two works on paleoclimate have been published, in which two stable isotopes of oxygen (δ18O) were determined by infrared laser microprobe in the Peruvian species *Galeichthys peruvianus* (Andrus et al., 2002a,b). These works were not included in the analysis of Figure 1 because they do not deal with aspects related to the biology of the species as identification of stocks, migration, nurseries aspects, etc.

In Figure 2 it is shown that different topics studied have been expanded over the last years. Although the classification of articles by different topics can be somewhat ambiguous, because some articles may infer in more than one issue, it is observed that the largest scientific production is related to the life history of the fish, followed by identification of nursery areas, natural tags, stocks identification, and population structure. In recent years, other issues such as pollution and methodological work have emerged. In contrast, publications on paleoclimate or otolith composition have not been recorded over the last 14–20 years (Figure 2).

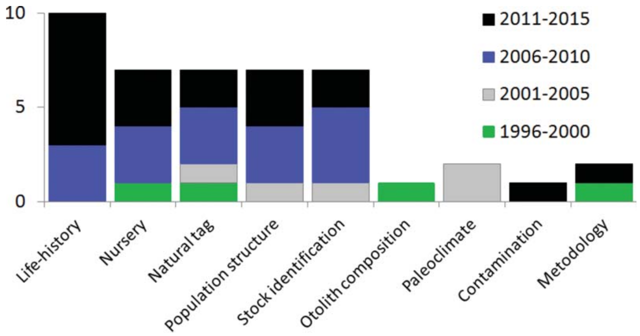

Figure 2. Thematic works on otolith microchemistry in Latin America classified by year of publication.

Biological characteristics of the species under study

The vast majority of the species studied by applying the otolith microchemistry in Latin America are of marine habits (Table 1). Nevertheless, there are studies on strictly freshwater species as *Prochilodus lineatus* (Avigliano et al., 2016b), *Prochilodus mariae* (Collins et al., 2013), *Cichla temensis* (Garcez et al., 2014), *Hoplias malabaricus, Schizodon fasciatus* (Pouilly et al., 2014a,b), and *Brachyplatystoma rousseauxii, Brachyplatystoma vaillantii, Brachyplatystoma filamentosum* (Hegg et al., 2015). These are all commercially important species and are associated with large river basins such as the Amazon, the Plata, and Orinoco basins. Works on estuarine or euryhalin species, such as *Mugil curema* (Avigliano et al., 2015a), *Epinephelus marginatus* (Condini et al., 2016), *Micropogonias furnieri* (Volpedo and Cirelli, 2006; Albuquerque et al., 2010, 2012), *Lycengraulis grossidens* (Mai et al., 2014), and *Odontesthes bonariensis* (Avigliano and Volpedo, 2013; Avigliano et al., 2014, 2015e), have also been carried out over the last years. These last three species are associated with estuaries of the South West Atlantic Ocean (e.g., Río de la Plata and Laguna dos Patos). They are commercially important species and are generally exported to different countries such as Italy, the Netherlands and Ukraine, Russia, and the United States of America (Minagro, 2016). Moreover, they are trans boundary species, managed and shared jointly by different countries.

Works where otolith microchemistry is being used for the study of anadromous species are less abundant in Latin America. Among the anadromous species, we can find: *Oncorhynchus mykiss* (Riva-Rossi et al., 2007), *Oncorhynchus tshawytscha* (Araya et al., 2014), *Genidens barbus* (Avigliano et al., 2015c,d), and some populations of *Lycengraulis grossidens* (Mai et al., 2014). The latter has high plasticity and some of its populations strictly exist in fresh, estuarine, or marine waters (Mai et al., 2014).

Methodologies used in the study of microchemistry and examples of cases

The analytical methods most used in reviewed studies are ICP-OES, ICP-MS, laser ablation, infra-red microprobe analysis (IRMA), and isotope-ratio mass spectrometry (IRMS; Table 1).

The determination of isotopes requires specific techniques and equipment such as IRMA, IRMS, or multicollector ICP-MS. Because of the high cost of this equipment for the economies of underdeveloped countries, these are extremely rare in Latin America and are dedicated almost exclusively to geochemical analyses related to mining or oil industry. This explains why works' analyses where isotopes in otoliths were determined have been developed in non-Latin American countries with or without collaboration of the region's authors (Table 1).

Some papers describe the population structure of marine species such as *Sardinops sagax* with stable isotopes of oxygen (δ18O; Valle and Herzka, 2008), whereas the simultaneous use of oxygen and carbon isotopes (δ13C, δ18O) has identified fishing stocks of *Dissostichus eleginoides* (Ashford and Jones, 2007) and nursery areas of *Haemulon flavolineatu* and *Lutjanus apodus* (Mateo et al., 2010), *Micromesistius australis* (Niklitschek et al., 2010), *Macruronus magellanicus* (Niklitschek et al., 2014). Furthermore, isotopic ratios of Sr (^{87}Sr/^{86}Sr) allowed the identification of the birth origin or nursery areas in species of the Amazon as *H. malabaricus, S. fasciatus* (Pouilly et al. 2014a,b), *C. temensis* (Garcez et al., 2014), *B. rousseauxii, B. vaillantii, B. filamentosum* (Hegg et al., 2015). Hegg et al. (2015) has not only managed to identify the birth origin of some of the largest silurids species of the Amazon but also describe ontogenetic migration patterns by associating the ^{87}Sr:^{86}Sr ratio between water and the otolith.

This situation is repeated for the determination of trace elements by LA-ICPMS, where the acquisition of equipment is not possible for some developing countries of Latin America. The LA-ICPMS equipment is limited and is also placed in governmental or private institutions associated with the mining industry. Currently, these devices are deployed in Mexico (there is at least one), Brazil (there are at least two), and Chile (two). According to the literature search, the only determination of trace elements in otoliths by LA-ICPMS done in Latin America was developed in Brazil (Albuquerque et al., 2010). The use of LA-ICPMS in works done on Latin American resources by foreign and local researchers are not scarce in relation to the total of published articles (Meekan et al., 1999; Patterson et al., 1999; Chittaro et al., 2004, 2005, 2006a,b; Ashford et al., 2005, 2006, 2008, 2011; Ruttenberg and Warner, 2006; Ashford and Jones, 2007; Fodrie and Herzka, 2008; Arkhipkin et al., 2009; de Albuquerque et al., 2010; Mateo et al., 2010; Schuchert et al., 2010; Ibáñez et al. 2012; Garcez et al., 2014; Mai et al., 2014; Avigliano et al., 2015c).

Besides, the micromilling technique has been recently applied as an alternative in the otolith microchemistry determination by LA-ICPMS, in order to identify trace elements in different fragments of otoliths (Niklitschek et al., 2010; Avigliano et al., 2015d). This methodology has been widely used in developed countries (Brown, 2006; Arslan and Secor, 2008; Schloesser et al., 2010), but its use is rather new in Latin America. Niklitschek et al. (2010) isolated nucleus of *M. australis* and determined the ratios Sr:Ca, Ba:Ca, Mg:Ca, Mn:Ca, and the isotopes (δ13C and δ18O) in order to study fish stocks and nursery areas in southern Patagonia and Antarctic regions. However, Mateo et al. (2010) used the micromilling technique in order to isolate the otolith nucleus to identify nursery areas in Belize through the following ratios Sr:Ca, Ba:Ca, Cu:Ca, Mg:Ca, Co:Ca, Na:Ca, and isotopes (δ18O, δ13C). Avigliano et al. (2015b, 2016a) compared the ratios Sr:Ca, Ba:Ca, and Mg:Ca in different groups of otolith rings of anadromous catfish *Genidens garbus*, allowing to describe the population structure of this species in the Southwest Atlantic Ocean. This work has described a micromilling methodology for the first time, which permits to separate the rings or group of rings from an otolith section and to isolate not only the nucleus or the edge but also other elements.

Scientific production by country and origin of the authors

The first studies that applied the otolith microchemistry to study different aspects of the fish have been exclusively developed with Latin American species by researchers from non-Latin American countries, mainly the United States (Figure 1 and Table 1). Such collaborations were kept until 2011 (Figure 1 and Table 1). Gradually, Latin American authors began to contribute as partners and later as principal authors of the work. This has been occurring since 2006, when a steady growth in scientific production is observed, mainly with works joining Latin American and non-Latin American developed countries.

Fifty-six percent of the total scientific productions on fishery resources in Latin America are works done in collaboration with various countries around the world. As regards to the total number of publications, 18% are among Latin American countries and 24% are among non-Latin American countries.

It is important to highlight that 72% of collaborative works have been performed between Latin and non-Latin countries, 16% corresponds exclusively to collaborative works done between Latin countries, whereas 12% of the works are carried out by researchers from non-Latin American countries on local resources.

Over the last four years (2012–2015), 100% of production has included at least one Latin American researcher or works that have been exclusively developed in Latin countries. Collaborative production exclusively between Latin American countries is recent and shows a slow but sustained growth, in terms of interest, equipment, and scientific development of some countries in the region. This has recently allowed the development of international quality works (Avigliano and Volpedo, 2013; Avigliano et al., 2014, 2015a,b,c,d).

The scientific production by country in this area (Figure 3) coincides with the major fish exporting

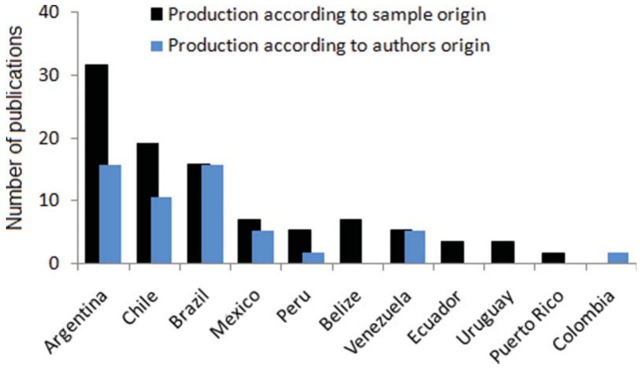

Figure 3. Scientific production related to fisheries resources in Latin America according to researchers' country of origin and samples.

countries of the region (Peru, Chile, Mexico, Argentina, and Brazil; FAO, 2012). This shows an effort made by these countries to generate scientific knowledge that contributes to the sustainability of their resources. In Figure 3, we can see that the number of works per country is greater when the origin of the sample is considered regardless the origin of the authors. This shows the interest of the research groups of non-Latin American countries on local fish resources and aims to pushing forward collaborative works with groups of the region.

Future prospects in Latin America

Studies on otolith microchemistry have been mainly applied to marine species in the Atlantic and the Pacific Oceans in Latin America. In line with the global trend, works on freshwater fish are rather limited. Nonetheless, several papers on freshwater species of the Amazon and the Plata Basin (Collins et al., 2013; Garcez et al., 2014; Mai et al., 2014; Pouilly et al., 2014a,b; Avigliano et al., 2014b; Hegg et al., 2015) have been recently published. These works have strengthened the development of human resources and the utilization of specific equipment, and this has led to mapping strontium isotopes throughout the Amazon Basin (Queiroz et al., 2009; Reis-Santos et al., 2015a,b). This gave the chance to produce high-quality works on migrations of Amazonian fish by linking the ratio ^{87}Sr:^{86}Sr between otolith and water (Garcez et al., 2014; Pouilly et al., 2014a,b; Hegg et al., 2015) and it will likely be a starting point for further research in different Amazonian species. The aforementioned background in the region could also boost joint activities in order to map isotopes in other large basins such as the Plata and the Orinoco, and to describe in detail the migration route of commercial species thereafter.

According to the global trend, Latin America is also prone to the integration of different methodologies in order to make correct stocks identifications or assessments of population structures. Avigliano et al. (2014) have applied the simultaneous use of otolith microchemistry and morphometry as a tool to identify stocks of silversides, whereas Collins et al. (2013) have simultaneously used the otolith microchemistry with genetic markers in *Prochilodus mariae* of Venezuela. Niklitschek et al. (2010) have used analysis of parasites together with trace elements and isotopes of otoliths in order to identify mixed stocks of *M. australis*. Pouilly et al. (2014a,b) have used isotope ratios in scales and otoliths to identify the origin of the fish of the Amazon as *H. malabaricus* and *S. fasciatus*. Currently, some research groups are working on the identification of nursery areas of the allisshad *Prochilodus lineatus* through the study of the microchemistry, scale geometric morphometry, and morphometric indexes of otoliths of juvenile fish throughout the Plata Basin (unpublished data).

Unlike the global trend, the application of statistical analysis or complex models that allow, for example, the identification of the origin of unknown samples or predict the dispersal of larvae by using chemical variables of otolith as input data is a pending issue in Latin America (Tanner et al., 2015). Brickman et al. (2010) conducted a pioneering work in this regard as they evaluated the dispersion and connectivity of icefish (*Chaenocephalus aceratus*) in the Arctic polar circle by using otolith chemistry and particle-tracking simulations. Besides, Niklitschek et al. (2010) used a maximum likelihood procedure to evaluate the existence of different stocks integrating evidence from otolith microchemistry and parasite assemblage in *M. australis* from Argentina and Chile.

The works mentioned in this review are mostly collaborations among different countries. There is a clear upward trend in scientific production through a joint work done between authors from different Latin American countries with authors from developed countries. Since 2012, all published works include at least one researcher from Latin America, whereas the scientific production that includes only foreign researchers has disappeared. This shows a clear trend toward an increase in joint collaboration between local researchers with other non-Latin American and intraregional teams. Joint publications between authors of Latin American research teams, in addition to the contribution to this matter, will enable to strengthen the links of the scientific and technological systems which are the solid foundations of public policies.

This collaboration will be hopefully further strengthened in the coming years with the acquisition of new equipment of LA-ICPMS, development and access to new technologies, and development of specialized human resources in the fish industry.

A significant increase in studies in the most productive regions as in cold water masses of the South Pacific in Chile and Peru (Humboldt Current), Antarctic, and Patagonia waters is projected. These areas are the most productive in terms of commercial marine species, which explains the current domain in relation to research efforts. Particularly, in the Humboldt current, over 20% of regional species are fished (FAO, 2012).

In addition, Latin America has three of the largest river basins in the world: the Amazon, Plata, and Orinoco Basins. Different commercial species are caught in the different environments in which they move across, such as plains, deltas, and estuaries. Salinity gradients presented by these sites enable the application of the otolith microchemistry (Sr:Ca and Ba:Ca ratios) to determine life history, fish stocks, and migratory population structure of different species. However, natal origin of different commercial species that inhabit the large estuaries could be determined by comparing the otolith signature or using isotopes. For example, among the largest estuaries (north to south) are: the Amazon (Brazil), Todos los Santos (Bahia, Brazil), Guanabara (Rio de Janeiro, Brazil), Paranaguá (Paraná, Brazil), Lagoa dos Patos (Rio Grande, Brazil), Río de la Plata (Argentina-Uruguay), Bahia Blanca (Buenos Aires, Argentina), where species of commercial importance inhabit, some of them are possibly cross border species. Mullets as *M. curema* and *Mugil liza* are spread not only in these estuaries but also to Canada on the Atlantic and from the United States to Chile on the Pacific. These are among the most coveted species in the region and little information is known about their life history, natal origin, and population connectivity between estuaries. Here, LA-ICPMS analysis could provide important information about life history, as well as the fact that the analysis of the chemical form of the nucleus would enable to possibly identify native areas. Other species that use the estuaries or different areas of offshore platforms are in a similar situation, such as *Micropogonias fournieri* (from Argentina to the Caribbean), *Menticirrhus americanus* (from Argentina to Canada) and (from Argentina to Canada). The life history and natal origin of anadromous salmonids in Argentinian Patagonia could be studied as was done in the Chilean Patagonia (Araya et al., 2014).

This growth could be slow but steady, due to the fact that existing equipment is generally being used intensively and exclusively for geological purposes and is not adapted or calibrated for analyzing otoliths. In this sense, a short-term increase of collaborations is likely to be observed between regional and developed countries, seeking the support of researchers who are experienced in calibration of ablation equipment to determine traces in otoliths. At this point, the encouragement and support of scientific organizations in Latin America is recommended to give rise to projects of international cooperation in order to develop human resources in this area.

Finally, with the development of new studies and the application of new technologies, monitoring projects of main fishery resources in the region are expected to be performed in the medium and long term. However, the growing aquaculture industry in some Latin American countries could help to reduce captures of wild species, facilitating the implementation process of management plans and recovery of compromised resources. In the long term, this scenario together with the new technologies discussed herein will contribute to the sustainability of marine and inland resources.

Conclusion

The otolith microchemistry is a good alternative for the study of fisheries due to the relative ease of application and moderate cost compared to other methodologies, all of which are main requirements for developing countries. In addition, different analyses of the microchemistry of otoliths (LA-ICPMS, isotopes, etc.) could provide information on different aspects of the biology of the fish, avoiding sometimes the use of different highly priced techniques. The full development of this issue would contribute to give rise to good conservation practices and fisheries management and to add value to the growth of the countries in this region. In the long term, this will have a direct impact on the development of local economies by improving life quality for residents and securing part of the fish supply consumed worldwide nowadays.

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