Journal of Archaeological Science: Reports 8 (2016) 486–491

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Stable isotope evidence supports pelagic fishing by hunter-gatherers in southern South America during the Late Holocene

Atilio Francisco Zangrando [a],*, Luciana Riccialdelli [a], Sayuri Kochi [b], Jonathan W. Nye [c], Augusto Tessone [b]

[a] *Centro Austral de Investigaciones Científicas, Consejo Nacional de Investigaciones Científicas y Técnicas (CADIC — CONICET). Bernardo Houssay 200, 9410 Ushuaia, Tierra del Fuego, Argentina*
[b] *Instituto de Geocronología y Geología Isotópica (INGEIS-CONICET/UBA), Pabellón INGEIS — Ciudad Universitaria, C1428EHA CABA, Argentina*
[c] *University of California Merced, 5200 Lake Rd., Merced, CA 95343, USA*

ARTICLE INFO

Article history:
Received 21 October 2015
Received in revised form 5 May 2016
Accepted 10 May 2016
Available online 18 May 2016

Keywords:
Ichthyoarchaeology
δ^{13}C and δ^{15}N
Beagle Channel
Pelagic fishing practices
Middle–Late Holocene

ABSTRACT

Fishing intensification development during the Late Holocene in the Beagle Channel is recognized in zooarchaeological studies, especially in a diversification to pelagic fish, implying an expansion of fishing practices to pelagic zones. In this paper, we undertake a paleoecological framework based on stable isotope analysis (δ^{13}C and δ^{15}N) of modern and archaeological fish collagen bones. In this analysis we intend to provide an independent record to investigate possible variations in the patch use in marine fishing activities by hunter-gatherer societies in southern South America.

Archaeological bones of *Macruronus magellanicus*, *Merluccius* sp. and *Thyrsites atun* were recovered from three stratified shellmiddens located in the coast of the Beagle Channel. In addition, modern samples of *Macruronus magellanicus*, *Merluccius hubbsi* and *Merluccius australis* were obtained at three different locations of the Patagonian continental shelf.

Macruronus magellanicus results highlight the relative nearshore character of the archaeological specimens. No differences were found between archaeological and modern values for *Merluccius* sp., which indicate the offshore character of the archaeological specimens of this species. Results also show that the archaeological samples of *Thyrsites atun* are related to offshore ecosystems. In sum, stable isotope values of archaeological specimens agree with previous interpretations from zooarchaeological analyses of deep-water fishing during the Late Holocene in the Beagle Channel.

1. Introduction

Fishing intensification development during the Late Holocene in the Beagle Channel is recognized in zooarchaeological studies, South America (Tivoli and Zangrando, 2011; Zangrando, 2009a, 2009b). These previous studies have identified two related strategies: an increase in the littoral exploitation of fish (mainly species of the Nototheniidae family), and a diversification to predator fish implying an expansion of fishing practices to pelagic zones.

The numbers of bone remains of both small foraging fish (*Sprattus fuegensis*) and larger predator fish (*Macruronus magellanicus*, *Merluccius australis*, *Merluccius hubbsi* and *Thyrsites atun*) considered typical of pelagic zones vary along the archaeological sequence of the Beagle Channel. While Patagonian sprat (*Sprattus fuegensis*) and Patagonian grenadier (*Macruronus magellanicus*) dominate the bone assemblages dated between 6200 and 4000 BP, remains of hake (*Merluccius* sp.) and snoek (*Thyrsites atun*) are highly represented between 3000 and 100 BP. In the current marine ecosystem of the archipelago of Tierra del Fuego, we observe variations in the distribution of these pelagic fish species. In the Beagle channel, the Patagonian sprat (*Sprattus fuegensis*) and the Patagonian grenadier (*Macruronus magellanicus*) may come closer to the coasts, and appear in massive strandings during summers (Lloris and Rucabado, 1991). Conversely, adult individuals of snoek (*Thyrsites atun*) and hakes (*Merluccius australis*, *Merluccius hubbsi*) are only observed in epipelagic waters (Fenucci et al., 1974; López et al., 1996; Lloris and Rucabado, 1991). Assuming that the habitat preferences of prehistoric fish populations were broadly similar to those of modern species, *Merluccius* sp. and *Thyrsites atun* can be considered archaeological proxies; an indicator of pelagic fishing during the intensification process (Tivoli and Zangrando, 2011; Zangrando, 2009a).

However, archaeological interpretations based on modern fish ecology can lead to inaccurate interpretations of the past. It is well known that fish species distributions are likely to have fluctuated during the Holocene as a consequence of sea surface temperature and marine productivity, among other factors (Finney et al., 2002; Jackson et al., 2001; Misarti et al., 2009). It is also widely recognized that modern commercial fisheries had significant impacts on fish communities (Jackson

---

* Corresponding author.
E-mail addresses: panchozan@yahoo.com.ar (A.F. Zangrando), lriccialdelli@gmail.com (L. Riccialdelli), kochisayuri@gmail.com (S. Kochi), jnye@ucmerced.edu (J.W. Nye), atessone@ingeis.uba.ar (A. Tessone).

http://dx.doi.org/10.1016/j.jasrep.2016.05.015
2352-409X/© 2016 Elsevier Ltd. All rights reserved.

et al., 2001; Maschner et al., 2008). This is certainly the situation of *Merluccius* species, whose overexploitation is considered one of the most dramatic problems in the SW Atlantic Ocean (Esteves et al., 2000).

In this paper, a paleoecological framework based on stable isotope analysis ($\delta^{13}C$ and $\delta^{15}N$) in collagen from fish bones preserved in archaeological middens intend to provide an independent record that can be use as a methodological tool for investigating possible variations in patch use in marine fishing activities by hunter-gatherer societies in southern South America. A number of studies have suggested that variations in carbon isotope composition among marine animals can be explained, in part, by differences in the isotope composition of marine primary producers (e.g. phytoplankton, macroalgae) between nearshore and offshore ecosystems (e.g., Clementz and Koch, 2001; France, 1995; Peterson, 1999). Variations in $\delta^{15}N$ values allow us to identify changes related to the trophic levels of these resources (Minagawa and Wada, 1984; Vander Zanden et al., 1999). Stable isotope analyses are used as paleoecological markers for assessing the distribution of fish resources in the past through the comparison of stable isotope signatures of modern and archaeological samples of pelagic predatory fish. This procedure allows us to know the foraging areas of those prey in the past, and consequently to identify the marine patch use for fishing activities by hunter-gatherer societies.

2. Materials and methods

2.1. Modern samples and reference values

Larger individuals of hakes (*Merluccius hubbsi* and *Merluccius australis*) feed mainly on anchovies, sprats, nototheniids and squids. The Patagonian grenadier (*M. magellanicus*) is a more general predator and feeds on a diversity of prey, including fish (sprats, anchovies, etc.), mysids, cephalopods, euphausiids and amphipods. Modern $\delta^{15}N$ values of muscle have shown that the Argentine hake (*Merluccius hubbsi*) and Southern hake (*Merluccius australis*) have a higher trophic level position than the Patagonian grenadier (Ciancio et al., 2008), as the former species characterized as consumers of intermediate size fish and squid and the latter as a macrozooplankton feeder. Cannibalism identified in the Argentina hake (Ocampo Reinaldo et al., 2011) could also explain the difference in trophic levels. No significant difference in $\delta^{13}C$ values of muscle was observed between those species (Ciancio et al., 2008). A study of the diet of Argentine hake stomach contents has also revealed ontogenetic dietary variations associated with size, changing from zooplankton in small individuals to fish and cephalopods in larger ones (Belleggia et al., 2014). There are no studies of feeding ecology in modern populations of southwestern Atlantic Ocean snoeks (*Thyrsites atun*). According to reports from New Zealand (Hurst and Bagley, 1989) and South Africa (Griffiths, 2002), snoeks are a major predator of anchovies and sardines, and have a high trophic level (Freón et al., 2005).

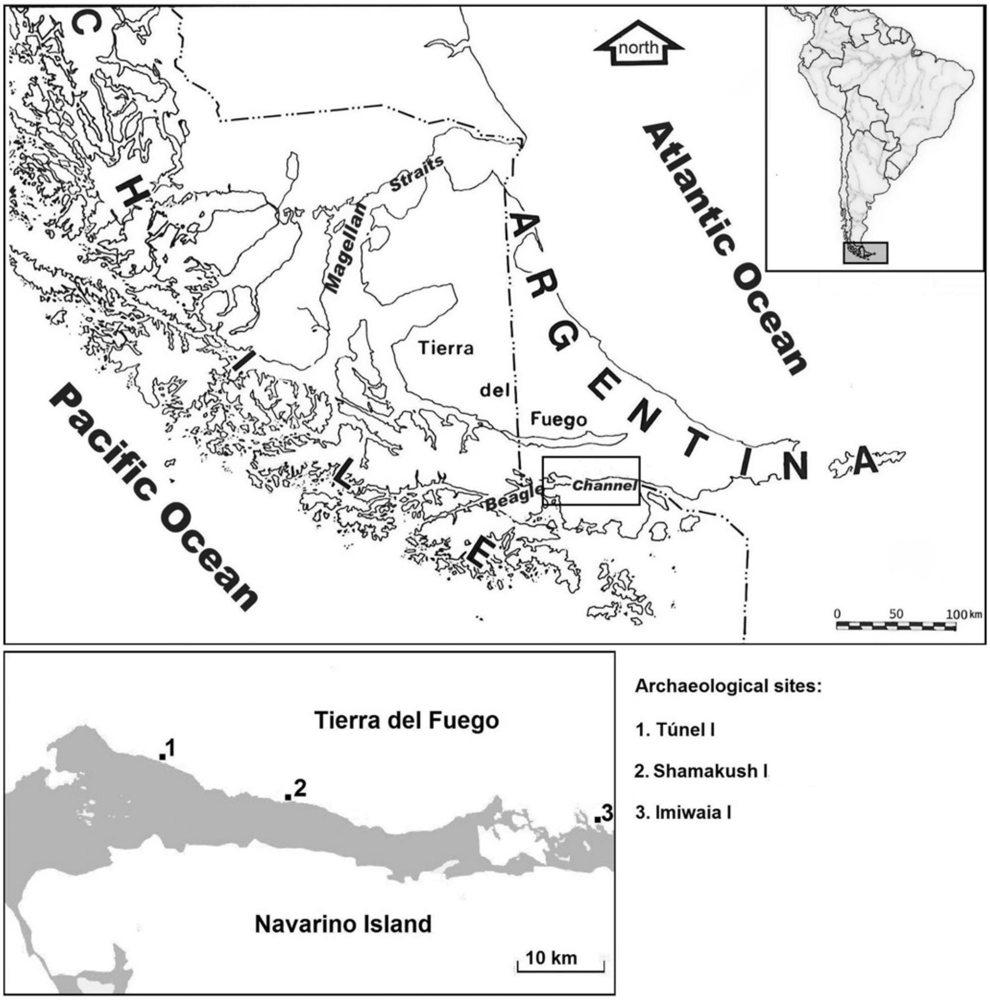

Fig. 1. Map of the archipelago of Tierra del Fuego and locations of archaeological sites.

In this paper, modern bone samples of *Macruronus magellanicus* ($n = 8$), *Merluccius hubbsi* and *Merluccius australis* ($n = 17$ including both) are isotopically analyzed in an attempt to obtain a reference for a more direct comparison with archaeological sample values. Modern samples were obtained at three different locations of the Patagonian continental shelf (51°39′S, 64°45′W; 53°01′S, 64°19′W; 53°09′S, 62°48′W). Total length of these fish specimens ranges from 490 to 685 mm. It was not possible to capture specimens of snoek during the sampling activities. Nowadays, captures of hake are very rare in the Beagle Channel and the snoek is almost an unknown species for the region. Conversely, the Patagonian grenadier is among the most common species.

2.2. Archaeological samples and size-based control

Archaeological bones were recovered from three stratified shellmiddens located in the north coast of the Beagle Channel (Tierra del Fuego, Argentina; Fig. 1). Samples were selected from assemblages with different chronologies within Túnel I, Imiwaia I and Shamakush I archaeological sites (Orquera and Piana, 1999, 2009). Imiwaia I is located at Cambaceres Bay (54°52′21.51″S–67°17′44.81″W), and includes archaeofaunal samples from two stratigraphic components: layers K, L and M — 6000 BP-, layer D — 3000 BP-, and layer B — 1500 BP. Túnel I is situated at the Estancia Túnel (54°49′12.55″S–68°9′3.30″W), and fish bone assemblages are from the Second Component and Layer C, with chronologies between 6400–4300 BP and 4300–2660 BP respectively. Shamakush I is located at Estancia Remolino (54°51′30.41″S–67°51′10.05″W), and bone assemblages date from 1000 BP. There are no significant differences concerning excavation methods and bone preservation between sites.

Bone samples include specimens of *Macruronus magellanicus* ($n = 14$), *Merluccius* sp. ($n = 17$) and *Thyrsites atun* ($n = 12$). Dentaries differentiated by laterality were considered for *Merluccius* sp. and *Thyrsites atun*, and premaxillae for *Macruronus magellanicus* following the same criteria. Considering that larger and older fish could result in elevated δ^{13}C and δ^{15}N values due to their higher trophic positions (DeNiro and Epstein, 1978; Jennings et al., 2002; Minagawa and Wada, 1984), the archaeological samples were limited to individuals with estimated total lengths in the 500–800 mm range based on allometric regressions, bone measurements and comparison with reference specimens of known size.

2.3. Laboratory methods

For modern samples, collagen was extracted from each bone sample by demineralization in 0.2 N HCl for ~72 h at room temperature with

Table 1
Isotopic values for bone collagen of archaeological fish samples.

Site	Layer	Species	δ^{13}C	δ^{15}N	Amt %N	Amt %C	C/N
Imiwaia I	K240	*Macruronus magellanicus*	−12	17.1	15.8	44.2	3.3
Túnel I	CR	*Macruronus magellanicus*	−12	15.6	13.4	37	3.2
Túnel I	4D	*Macruronus magellanicus*	−11.6	15.2	16.4	44.4	3.2
Túnel I	5D	*Macruronus magellanicus*	−12.2	16.2	15.2	41.9	3.2
Túnel I	Cbasal	*Macruronus magellanicus*	−11.5	15.1	16.8	46	3.2
Túnel I	10D	*Macruronus magellanicus*	−11.3	15.6	16.6	45.8	3.2
Túnel I	12D	*Macruronus magellanicus*	−11.8	14.7	16.4	44.4	3.2
Túnel I	D15	*Macruronus magellanicus*	−12	14.8	15.2	41.5	3.2
Túnel I	D6	*Macruronus magellanicus*	−11.6	15.5	16.1	43.9	3.2
Túnel I	D30	*Macruronus magellanicus*	−11.5	16.1	16.1	44.3	3.2
Túnel I	12D	*Macruronus magellanicus*	−10.8	18.3	14.5	39.8	3.2
Túnel I	E1	*Macruronus magellanicus*	−11.3	15.7	16.8	46.1	3.2
Túnel I	3D	*Macruronus magellanicus*	−11.6	15.4	15.6	42.8	3.2
Túnel I	12D	*Macruronus magellanicus*	−11.5	15.6	16.2	45	3.2
Imiwaia I	D100/105	*Merluccius* sp.	−13	18.3	17	47.2	3.2
Imiwaia I	D100	*Merluccius* sp.	−13.4	17	15.4	43.6	3.3
Imiwaia I	D100	*Merluccius* sp.	−11.7	17.9	16.4	45.1	3.2
Imiwaia I	D100	*Merluccius* sp.	−12.6	17.5	15.5	42.8	3.2
Imiwaia I	D100	*Merluccius* sp.	−12.5	16.6	17.3	47.2	3.2
Imiwaia I	D115	*Merluccius* sp.	−13.5	16.7	16.4	45.3	3.2
Imiwaia I	D115	*Merluccius* sp.	−13	16.4	17.2	47.1	3.2
Imiwaia I	D100/110	*Merluccius* sp.	−12.9	17.9	15.9	44.8	3.3
Imiwaia I	D100	*Merluccius* sp.	−13.2	16.6	15.7	44.9	3.3
Imiwaia I	D100/110	*Merluccius* sp.	−13	17	16	45.2	3.3
Imiwaia I	D115	*Merluccius* sp.	−11	16.5	16.5	46.5	3.3
Imiwaia I	D	*Merluccius* sp.	−12.1	14.8	16.4	45.3	3.2
Imiwaia I	D115	*Merluccius* sp.	−13.7	17.5	16	45.2	3.3
Imiwaia I	D100	*Merluccius* sp.	−12.9	16.9	15.6	43.8	3.3
Imiwaia I	D	*Merluccius* sp.	−13.1	16.2	15.3	43.7	3.3
Túnel I	D20	*Merluccius* sp.	−12.5	18.2	16.1	43.3	3.1
Túnel I	D20	*Merluccius* sp.	−12.7	17.3	15.3	42.7	3.2
Imiwaia I	B	*Thyrsites atun*	−13.2	14.5	15.3	42.6	3.3
Imiwaia I	B	*Thyrsites atun*	−12.1	15.8	16.3	44.2	3.2
Imiwaia I	B	*Thyrsites atun*	−13	14.6	16.8	46.8	3.2
Imiwaia I	B	*Thyrsites atun*	−12.3	15.5	17.3	46.9	3.2
Imiwaia I	B	*Thyrsites atun*	−12.2	15.2	15.5	43	3.2
Imiwaia I	B	*Thyrsites atun*	−13.1	14.8	14.7	40.6	3.2
Imiwaia I	B	*Thyrsites atun*	−12.7	14.9	15.4	42.8	3.2
Imiwaia I	B	*Thyrsites atun*	−12.4	15.8	15.3	42.4	3.2
Imiwaia I	B	*Thyrsites atun*	−13	14.8	15	42.2	3.3
Shamakush I	D210	*Thyrsites atun*	−11.6	17.7	15.2	42.3	3.2
Shamakush I	sondeo 6	*Thyrsites atun*	−12.3	16	16.7	46.6	3.3
Imiwaia I	K290	*Thyrsites atun*	−11.7	15.5	15.6	42.7	3.2
Imiwaia I	L10	*Thyrsites atun*	−13.5	14.4	17.3	49.2	3.3
Imiwaia I	K70	*Thyrsites atun*	−12.6	14	16.6	45.6	3.2

Table 2
Isotopic values for bone collagen of modern fish samples.

Site	Species	$\delta^{13}C$	$\delta^{13}C_{corrected}$	$\delta^{15}N$	Amt %N	Amt %C	C/N
53°09′S–62°48′W	*Macruronus magellanicus*	−14.2	−13.2	13.5	17.4	46.7	3.1
53°09′S–62°48′W	*Macruronus magellanicus*	−13.6	−12.6	15	17.4	46.8	3.1
53°09′S–62°48′W	*Macruronus magellanicus*	−13.4	−12.4	15.3	17.4	47.7	3.2
53°09′S–62°48′W	*Macruronus magellanicus*	−14.2	−13.2	13.8	17.3	47.3	3.2
BBS	*Macruronus magellanicus*	−15.2	−14.2	14.1	18.3	48.9	3.1
Cholgas	*Macruronus magellanicus*	−13.6	−12.6	15.1	17.2	46.7	3.2
Cholgas	*Macruronus magellanicus*	−13.2	−12.2	16.8	16.2	45.5	3.3
Cholgas	*Macruronus magellanicus*	−13.1	−12.1	16.2	16.4	44.2	3.1
51°39′S–64°45′W	*Merluccius hubbsi*	−14.1	−13.1	16.4	17.3	47.1	3.2
51°39′S–64°45′W	*Merluccius hubbsi*	−14.0	−13.0	15.8	17	47.5	3.3
51°39′S–64°45′W	*Merluccius hubbsi*	−15.7	−14.7	18.3	15.7	48.2	3.6
51°39′S–64°45′W	*Merluccius australis*	−13.3	−12.3	15.6	17.3	46.2	3.1
51°39′S–64°45′W	*Merluccius australis*	−14.5	−13.5	15.2	16.7	46.9	3.3
51°39′S–64°45′W	*Merluccius australis*	−14.9	−13.9	17.7	21.6	59.1	3.2
51°39′S–64°45′W	*Merluccius australis*	−14.1	−13.1	17.6	16.8	48.1	3.3
51°39′S–64°45′W	*Merluccius australis*	−12.8	−11.8	17.7	17.5	48.2	3.2
51°39′S–64°45′W	*Merluccius australis*	−15.1	−14.1	17.7	15.8	46.3	3.4
51°39′S–64°45′W	*Merluccius australis*	−13.4	−12.4	16.7	17.3	47.8	3.2
51°39′S–64°45′W	*Merluccius australis*	−14.0	−13.0	17.1	16.3	46.7	3.3
51°39′S–64°45′W	*Merluccius australis*	−14.1	−13.1	15	16.9	47.6	3.3
51°39′S–64°45′W	*Merluccius australis*	−13.3	−12.3	17.2	16.8	47.4	3.3
51°39′S–64°45′W	*Merluccius australis*	−14.8	−13.8	16.4	16.6	46.5	3.3
51°39′S–64°45′W	*Merluccius australis*	−14.4	−13.4	18	15.3	45.6	3.5
51°39′S–64°45′W	*Merluccius australis*	−13.2	−12.2	16.8	15	43.5	3.4
51°39′S–64°45′W	*Merluccius australis*	−13.4	−12.4	16.6	17.4	48.7	3.3
51°39′S–64°45′W	*Merluccius australis*	−12.5	−11.5	17.6	15.9	43.7	3.2

regular changes to fresh HCl solution during this period. Samples were then rinsed in distilled water to achieve a more neutral pH. Lipids were removed by repeated rinsing of the samples with a 2:1 solution of chloroform:methanol. The resulting collagen preparations were then rinsed several times with distilled water and dried in an oven at 60 °C for ~24 h.

Dry modern samples (~0.5–0.6 mg) were weighed into tin capsules (3 × 5 mm) and analyzed by using a Carlo Erba Elemental Analyzer (EA) interfaced with a DELTA plus XL-Thermo Finnigan isotope ratio mass spectrometer at the Geophysical Laboratory, Carnegie Institution of Washington, Washington D.C.

For collagen extraction from archaeological bone, fragments were cleaned with abrasive elements and ultrasonic baths. Each sample between 0.1 and 0.9 g was demineralized in weak hydrochloric acid (HCl 0.5%), which was replaced every 24–48 h. Then they were rinsed with distilled water and treated with sodium hydroxide (NaOH 0.125%) for 20 h. Finally, the collagen extracted was dried in an oven at 40 °C for 24 h. The protocol with low concentration reagents was used to minimize protein loss, which is suitable for small or less well preserved samples (Waters-Rist et al., 2011, Sealy et al., 2014). This is the case of fish bones that have a different composition than mammals and birds (Szpak, 2011, see discussion in Sealy et al., 2014).

The measurements of isotopic ratios of bone archaeological samples were performed in the Instituto de Geocronología y Geología Isotópica (INGEIS, CONICET-UBA) laboratories (Buenos Aires, Argentina) with a Carlo Erba EA1108 Elemental Analyzer (CHN), connected to a continuous flow Thermo Scientific Delta V Advantage mass spectrometer through a Thermo Scientific ConFlo IV interface.

Stable isotope results are expressed as the ratio of the heavier isotope to the lighter isotope ($^{13}C/^{12}C$ or $^{15}N/^{14}N$), and reported as δ values in parts per thousand (‰) relative to internationally defined standards: VPDB for carbon and AIR for nitrogen. Finally, the modern samples were corrected by adding 1‰ due to the Suess effect (Burton et al., 2001).

3. Results and discussion

Tables 1 and 2 respectively shows $\delta^{13}C$ and $\delta^{15}N$ values, atomic C/N, species and provenance of archaeological and modern samples analyzed. In relation to the archaeological samples, collagen yields were between 2% and 20% and C/N ratios range from 3.1 to 3.3 with an average of 3.2 ± 0.04. Modern samples, meanwhile, recorded a range of C/N ratios between 3.1 and 3.6 with a mean of 3.3 ± 0.1. All samples were within the accepted range for collagen quality parameters, which assures primary isotopic signals (DeNiro, 1985; van Klinken, 1999). Mean isotope values for archaeological and modern samples are respectively presented in Tables 3 and 4.

Concerning archaeological samples, *Macruronus magellanicus* has the most enriched $\delta^{13}C$ mean among the three archaeological fish species analyzed, with a mean of −11.6‰ ± 0.3‰ and ranges from −12.2‰ to −10.8‰ (Fig. 2). Both *Merluccius* sp. and *Thyrsites atun* have similar $\delta^{13}C$ values and are lower than *Macruronus magellanicus*. *Merluccius* sp. shows an average value of −12.7‰ ± 0.6‰ with a distribution between −13.7‰ and −11.0‰ and *Thyrsites atun* has a mean of −12.5‰ ± 0.5‰, and ranges from −13.5‰ to −11.6‰. *Macruronus magellanicus* has a mean of about 1‰ higher than the other two species.

Table 3
$\delta^{13}C$ and $\delta^{15}N$ mean values of archaeological bone collagen from fish samples.

Samples	*Macruronus magellanicus*		*Merluccius* sp.		*Thyrsites atun*	
	$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{15}N$
N	14	14	17	17	14	14
Mean (‰)	−11.6	15.8	−12.8	17.0	−12.6	15.3
SD (‰)	0.4	0.9	0.7	0.9	0.6	0.9
Min (‰)	−12.2	14.7	−13.7	14.8	−13.5	14.0
Max (‰)	−10.8	18.3	−11.0	18.3	−11.6	17.7

Table 4
$\delta^{13}C$ and $\delta^{15}N$ mean values of modern bone collagen from fish samples.

Samples	*Macruronus magellanicus*		*Merluccius* sp.	
	$\delta^{13}C$	$\delta^{15}N$	$\delta^{13}C$	$\delta^{15}N$
N	9	9	18	18
Mean (‰)	−12.7	15.0	−13.0	16.9
SD (‰)	0.7	1.1	0.8	1.0
Min (‰)	−14.2	13.5	−14.7	15.0
Max (‰)	−12.0	16.8	−11.5	18.3

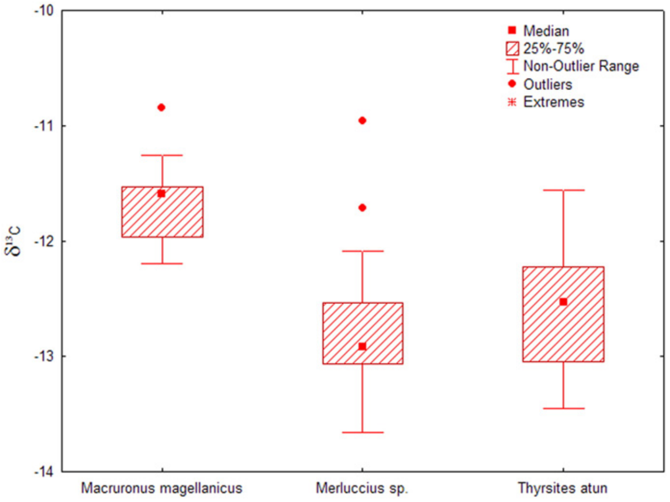

Fig. 2. Box-plots of archaeological bone collagen δ^{13}C by taxa.

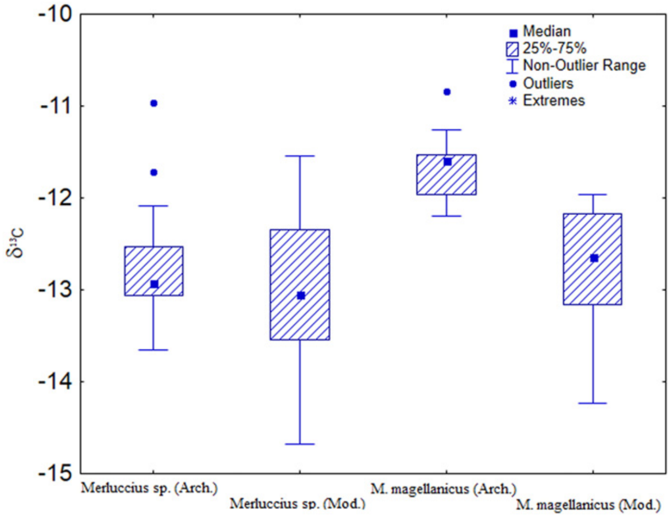

Fig. 4. Box-plots of archaeological and modern bone collagen δ^{13}C by taxa.

There is a statistical difference between *Macruronus magellanicus* and the remaining two species for δ^{13}C ($p \leq 0.01$, Mann–Whitney test).

Considering nitrogen isotope ratios, *Merluccius* sp. has the highest δ^{15}N mean which is 17.0‰ ± 0.8‰ and a distribution between 14.8‰ and 18.3‰ (Fig. 3). The other two species, *M. magellanicus* and *T. atun*, appear very similar in δ^{15}N. The latter has the lowest mean of 15.2‰ ± 0.9‰ and ranges from 14‰ to 17.7‰. *Macruronus magellanicus* has a slightly higher mean of 15.7‰ ± 0.9‰ and ranges from 14.7‰ to 18.3‰. Differences between these two species and *Merluccius* sp. were statistically significant ($p \leq 0.01$, Mann–Whitney test).

The corrected modern samples of *Merluccius* sp. show a mean value of 16.9‰ ± 1‰ and −13.0‰ ± 0.8‰ for δ^{15}N and δ^{13}C respectively. Meanwhile modern *M. magellanicus* had a mean value of 15.0‰ ± 1.1‰ for δ^{15}N and for δ^{13}C of −12.7‰ ± 0.7‰. *Merluccius* sp. had a mean nitrogen isotope ratio 1.9‰ higher than *M. magellanicus*.

There is a statistically significant difference in carbon isotopic ratios between archaeological and modern samples of *M. magellanicus* ($p \leq 0.01$, Mann–Whitney test) (Fig. 4). The similarities between body size ranges of both sets do not allow us to ascribe this difference to age variations. This interpretation concurs with a non-significant statistical difference between the δ^{15}N mean values ($p \geq 0.05$, Mann–Whitney test), suggesting that modern and archaeological samples are in a similar trophic level (Fig. 5). Taking into consideration that modern specimens come from sampling locations in the Southern Patagonian Shelf, the difference in δ^{13}C suggests the nearshore character of the archaeological specimens. On the contrary, no statistical differences were found between archaeological and modern mean values of δ^{13}C and δ^{15}N for *Merluccius* sp. ($p \geq 0.05$, Mann–Whitney test). This suggests that the feeding ecology of *Merluccius* sp. was similar to the present one, supporting the offshore character of the archaeological specimens. Although we do not provide modern reference values for *Thyrsites atun*, δ^{13}C results of archaeological samples indicate that they also have been linked to offshore ecosystems. The significant difference between the trophic level position of *Merluccius* sp. and the other two pelagic predator species (*Macruronus magellanicus* and *Thyrsites atun*) is also noteworthy. This observation fits well with modern observations in that *M. magellanicus* is a staple in the diet of *Merluccius* sp., as well as the cannibalistic habits identified in the latter species (Ocampo Reinaldo et al., 2011).

In relation to the expansion of fishing practices to pelagic zones in the Late Holocene, possible time-based variations in the feeding ecology of pelagic predatory fish should also be considered. Mean stable isotope values from Middle Holocene assemblages for *Macruronus magellanicus* and *Thyrsites atun* do not show significant differences with those corresponding to the same species from Late Holocene records (Table 5). Although sample sizes should be increased for each time period, this first exploration suggests that fishing strategies of hunter-gatherer societies

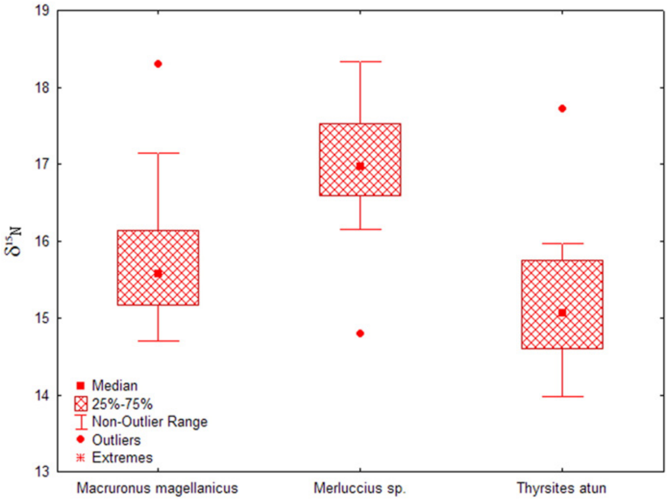

Fig. 3. Box-plots of archaeological bone collagen δ^{15}N by taxa.

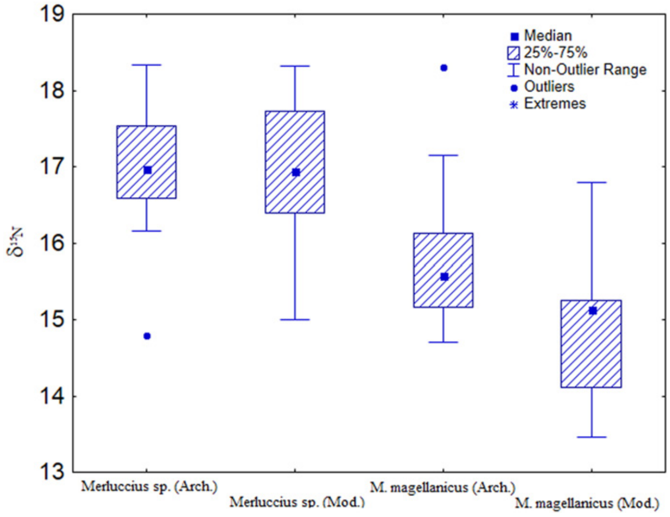

Fig. 5. Box-plots of archaeological and modern bone collagen δ^{15}N by taxa.

Table 5
$\delta^{13}C$ and $\delta^{15}N$ mean values of archaeological bone collagen from fish samples by time periods.

	Macruronus magellanicus		*Thyrsites atun*	
$\delta^{13}C$				
Time period (BP)	6000–4300	4000–2600	6000–4300	1500–1000
Sample size (n)	13	2	3	11
Mean (±SD)	−11.6 ± 0.37	−11.8 ± 0.30	−12.6 ± 0.85	−12.5 ± 0.51
$\delta^{15}N$				
Time period (BP)	6000–4300	4000–2600	6000–4300	1500–1000
Sample size (n)	13	2	3	11
Mean (±SD)	15.9 ± 1.03	15.4 ± 0.35	14.6 ± 0.79	15.4 ± 0.92

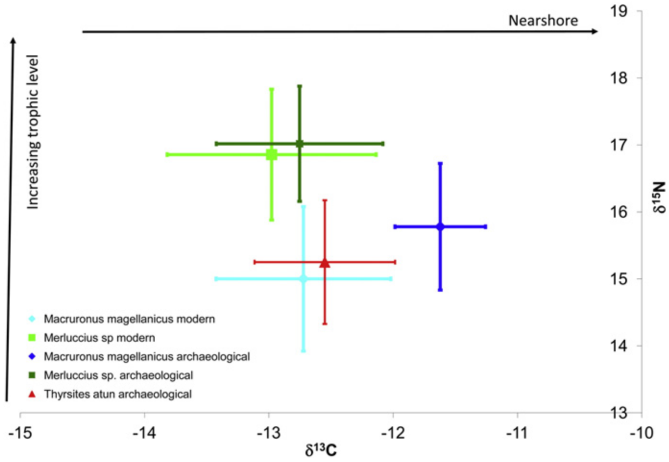

Fig. 6. $\delta^{13}C$ and $\delta^{15}N$ on bone collagen of archaeological and modern samples.

changed through the Holocene, while the feeding ecology of those species apparently remained stable. Moreover, the feeding ecology of pelagic fish does not indicate important variation between prehistoric and modern times; a surprising observation considering the overfishing occurring in recent years in the southwestern Atlantic.

In conclusion, $\delta^{13}C$ results highlight the relative nearshore character of the *Macruronus magellanicus* in comparison with other pelagic fish predator in prehistoric times, while $\delta^{15}N$ values suggest the consumption of fish species with higher trophic levels (e.g., *Merluccius* sp.) (Fig. 6). With this in mind, stable isotope information agrees with current ethological observations of pelagic fish predators from the southwestern Atlantic, and therefore supports previous interpretations from zooarchaeological analyses concerning deep-water fishing during the Late Holocene in the Beagle Channel, southern South America (Tivoli and Zangrando, 2011; Zangrando, 2009a, 2009b).

Acknowledgements

This research was supported by PICT-2013-1011 (FONCYT). Excavations and research in Túnel I, Shamakush I and Imiwaia I sites were conducted by Luis Orquera and Ernesto Piana (CONICET). The authors are responsible for the contents of this paper.

References

Belleggia, M., Figueroa, D., Irusta, G., Bremec, C., 2014. Spatio-temporal and ontogenetic changes in the diet of the Argentine hake Merluccius hubbsi. J. Mar. Biol. Assoc. U. K. 94, 1701–1710.

Burton, K., Snodgrass, J., Gifford-Gonzalez, D., Guilderson, T., Brown, T., Koch, P., 2001. Holocene changes in the ecology of northern fur seals: insights from stable isotopes and archaeofauna. Oecologia 128, 107–115.

Ciancio, J.E., Pascual, M.A., Botto, F., Frere, E., Iribarne, O., 2008. Trophic relationships of exotic anadromous salmonids in the southern Patagonian shelf as inferred from stable isotopes. Limnol. Oceanogr. 53, 788–798.

Clementz, M.T., Koch, P.L., 2001. Differentiating aquatic mammal habitat and foraging ecology with stable isotopes in tooth enamel. Oecologia 129, 461–472.

DeNiro, M.J., 1985. Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to paleodietary reconstruction. Nature 317, 806–809. http://dx.doi.org/10.1038/317806a0.

DeNiro, M.J., Epstein, S., 1978. Influence of diet on the distribution of carbon isotopes in animals. Geochim. Cosmochim. Acta 42, 495–506.

Esteves, J.L., Ciocco, N.F., Colombo, J.C., Freije, H., Harris, G., Iribarne, O., Isla, I., Pascual, M.S., Penchaszadeh, P.E., Rivas, A.L., Santinelli, N., 2000. The Argentine Sea: The Southeast south American Shelf Marine Ecosystem. In: Sheppard, C.R.C. (Ed.), Seas at the Millenium: An Environmental Evaluation. Pergamon, New York, pp. 749–771.

Fenucci, J., Virasoro, C., Cousseau, M.B., Boschi, E., 1974. Campaña Tierra del Fuego 74. Informe Preliminar (Investigación Pesquera). Contribuciones del Instituto de Biología Marina 261, pp. 1–37.

Finney, B.P., Gregory-Eaves, I., Douglas, M.S., Smol, J.P., 2002. Fisheries productivity in the northeastern Pacific Ocean over the past 2,200 years. Nature 416, 729–733.

France, R.L., 1995. Carbon-13 enrichment in benthic compared to planktonic algae: foodweb implications. Mar. Ecol. Prog. Ser. 124, 307–312.

Freón, P., Drapeau, L., David, J.H.M., Fernández Moreno, A., Leslie, R.W., Herman Oosthuizen, W., Shannon, L.J., van der Lingen, C.D., 2005. Spatialized ecosystem indicators in the southern Benguela. ICES J. Mar. Sci. 62, 459–468.

Griffiths, M.H., 2002. Life history of south African snoek, *Thyrsites atun* (Pisces: Gempylidae): a pelagic predator of the Benguela ecosystem. Fish. Bull. 100, 690–710.

Hurst, R.J., Bagley, N.W., 1989. Movements and possible stock relationships of the New Zealand barracouta, *Thrysites atun*, from tag returns. N. Z. J. Mar. Freshw. Res. 23, 105–111.

Jackson, J.B.C., Kirby, M.X., Berger, W.H., Bjorndal, K.A., Botsford, L.W., Bourque, B.J., Bradbury, R.H., Cooke, R., Erlandson, J., Estes, J.A., Hughes, T.P., Kidwell, S., Lange, C.B., Lenihan, H.S., Pandolfi, J.M., Peterson, C.H., Steneck, R.S., Tegner, M.J.J., Warner, R.R., 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293, 629–638.

Jennings, S., Greenstreet, S.P.R., Piet, G.J., Pinnegar, J.K., Warr, K.J., 2002. Long-term in the trophic structure of the north sea fish community: evidence from stable-isotopes analysis, size-spectra and community metrics. Mar. Biol. 141, 1085–1097.

Lloris, D., Rucabado, J., 1991. Ictiofauna del Canal Beagle (Tierra del Fuego): Aspectos ecológicos Y análisis biogeográfico. Instituto Español de Oceanografía (Publicación Especial 8), Madrid.

López, H.L., García, M., San Román, N., 1996. Lista Comentada de la Ictiofauna del Canal Beagle, Tierra del Fuego, Argentina. Contribución Científica (Publicación Especial). CADIC, Ushuaia.

Maschner, H.G., Betts, M., Reedy-Maschner, K., Trites, A., 2008. A 4500-year time series of Pacific cod (*Gadus macrocephalus*) size and abundance: archaeology, oceanic regime shifts, and sustainable fisheries. Fish. Bull. 106, 386–394.

Minagawa, M., Wada, E., 1984. Stepwise enrichment of ^{15}N along food chains: further evidence and the relation between $\delta^{15}N$ and animal age. Geochim. Cosmochim. Acta 48, 1135–1140.

Misarti, N., Finney, B., Maschner, H., Wooller, M.J., 2009. Changes in Northeast Pacific marine ecosystems over the last 4500 years: evidence from stable isotope analysis of bone collagen from archeological middens. The Holocene 19, 1139–1151.

Ocampo Reinaldo, M., González, R., Romero, M.A., 2011. Feeding strategy and cannibalism of the Argentine hake *Merluccius hubbsi*. J. Fish Biol. 79, 1795–1814.

Orquera, L., Piana, E., 1999. Arqueología de la región del Canal Beagle (Tierra del Fuego, República Argentina). Sociedad Argentina de Antropología, Buenos Aires.

Orquera, L., Piana, E., 2009. Sea nomads of the Beagle Channel in southernmost South America: over six thousand years of coastal adaptation and stability. J. Island Coast. Archaeol. 4, 61–81.

Peterson, B.J., 1999. Stable isotopes as tracers of organic matter input and transfer in benthic food webs: a review. Acta Oecol. 20, 479–487.

Sealy, J., Johnson, M., Richards, M., Nehlich, O., 2014. Comparison of two methods of extracting bone collagen for stable carbon and nitrogen isotope analysis : comparing whole bone demineralization with gelatinization and ultra filtration. J. Archaeol. Sci. 47, 64–69. http://dx.doi.org/10.1016/j.jas.2014.04.011.

Szpak, P., 2011. Fish bone chemistry and ultrastructure: implications for taphonomy and stable isotope analysis. J. Archaeol. Sci. 38, 3358–3372.

Tivoli, A.M., Zangrando, A.F., 2011. Subsistence variations and landscape use among maritime hunter-gatherers. A zooarcheological analysis from the Beagle Channel (Tierra del Fuego, Argentina). J. Archaeol. Sci. 38, 1148–1156.

van Klinken, G.J., 1999. Bone collagen quality indicators for paleodietary and radiocarbon measurements. J. Archaeol. Sci. 26, 687–695.

Vander Zanden, M.J., Casselman, J.M., Rasmussen, J.B., 1999. Stable isotope evidence for the food web consequences of species invasions in lakes. Nature 401, 464–467.

Waters-Rist, A.L., Bazaliiskii, V.I., Weber, A.W., Katzenberg, M.A., 2011. Infant and child diet in Neolithic Hunter-Fisher Gatherers from Cis-Baikal, Siberia: intra-long bone stable nitrogen and carbon isotope ratios. Am. J. Phys. Anthropol. 146, 225–241.

Zangrando, A.F., 2009a. Historia Evolutiva Y Subsistencia de Cazadores-Recolectores marítimos de Tierra del Fuego (Colección Tesis de Doctorado) Sociedad Argentina de Antropología, Buenos Aires.

Zangrando, A.F., 2009b. Is fishing intensification a direct route to hunter-gatherer complexity? A case study from the Beagle Channel region (Tierra del Fuego, southern South America). World Archaeol. 41, 589–608.