


Elucidating historical fisheries' networks in the Iberian Peninsula using stable isotopes

Laura Llorente-Rodríguez^{1,2,3}  | Oliver E. Craig² | André Carlo Colonese^{2,4} | Matthew von Tersch² | Eufrasia Roselló-Izquierdo³ | Eduardo González Gómez de Agüero⁵ | Carlos Fernández-Rodríguez⁵ | Juan Antonio Quirós-Castillo⁶ | Begoña López-Arias³ | Ricard Marlasca-Martín⁷ | James Nottingham² | Arturo Morales Muñoz³

¹Laboratory for Archaeozoological Studies, Faculty of Archaeology, Leiden University, Leiden, The Netherlands

²BioArCh-Department of Archaeology, University of York, York, UK

³Laboratorio de Arqueozoología LAZ-UAM, Universidad Autónoma de Madrid, Madrid, Spain

⁴Department of Prehistory and Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona, Bellaterra, Spain

⁵Departamento de Historia, Universidad de León, León, Spain

⁶Departamento de Geografía, Prehistoria y Arqueología, Universidad del País Vasco / Euskal Herriko Unibertsitatea, Vitoria-Gasteiz, Spain

⁷Posidonia s.l. Avd. Sant Jordi, Eivissa, Spain

Correspondence

Laura Llorente-Rodríguez, Laboratory for Archaeozoological Studies-Faculty of Archaeology, Leiden University, Einsteinweg 2 2333 CC, Leiden, The Netherlands.
Email: l.lorente.rodriguez@arch.leidenuniv.nl

Oliver E. Craig, BioArCh-Department of Archaeology, University of York, YO10 5DD York, UK.
Email: oliver.craig@york.ac.uk

André Carlo Colonese, Department of Prehistory and Institute of Environmental Science and Technology (ICTA), Universitat Autònoma de Barcelona, Bellaterra 08193, Spain.
Email: andrecarlo.colonese@uab.cat

Arturo Morales Muñoz, Laboratorio de Arqueozoología LAZ-UAM, Universidad Autónoma de Madrid, C/ Darwin 2 28049 Madrid, Spain.
Email: arturo.morales@uam.es

Funding information

European Commission, Grant/Award Number: FISHARC-IF 658022; Spanish Ministry of Economy and Competitiveness, Grant/Award Number: HAR 2014-55722-P and HAR 2017-88325-P; European Molecular Biology Organization, Grant/Award Number: ASTF 354-2016

Abstract

Processed fish is known to have been systematically traded in Europe since the Early Middle Ages to meet increasing demand of incipient markets and religious precepts, yet specific details regarding the supply of different fish in Southern Europe is often missing. Here, we address this gap through an integrated approach involving bone metrics and stable isotopic analysis of archaeological European hake (*Merluccius merluccius*, Merluccidae) from the Iberian Peninsula. The results offer new insights regarding historical fisheries production systems, including the regions exploited and commercial routes, whilst also revealing biological differences between archaeological and present-day hake populations in the North-east Atlantic and the Mediterranean Sea. This research highlights the fruitful result of combining ichthyoarchaeological and historical data for tracking down the origin and development of historical fisheries in south-western Europe and their bearing on modern fisheries.

KEYWORDS

bone metrics, European hake, historical fisheries, Iberian peninsula, ichthyoarchaeology, stable isotopes

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1 | INTRODUCTION

European hake (*Merluccius merluccius*, Merluccidae) is one of the most commercially important species fished in Europe today, but little archaeological evidence exists regarding the origins of commercial hake exploitation. Archaeological and historical evidence suggest the start of large-scale offshore commercial fisheries with a focus on gadoids in the North and Baltic Seas during the so-called 'Fish Event Horizon' ca. CE 1000 (Locker, 2000, Barrett et al., 2004a, 2004b, 2008, 2011, Enghoff, 1999, 2000). However, this narrative is only part of the overall story regarding European fisheries and post-classical trade networks. After ca. 1,000 years of intense marine fishing in the Iberian Peninsula, fish seemed to fade from the archaeological record, whilst the once-thriving trade networks became minimal.

Written sources refer to a burgeoning fishing industry in the Northern Christian kingdoms but mostly in the late half of the Middle Ages (i.e., from 11th CE) (Azevedo Pereira, 2012; Hoffmann, 2004; Morales-Muñiz et al., 2009, 2011, 2018; Oueslati, 2019, Riera Melis, 2009) resulting in ca. 600–800 years of documentary gap between Late Antiquity and the Late Middle Ages. Non-documentary evidence also testifies to the socio-economic importance of fishing at that time, with the emergence of logistic infrastructures for mass capture and processing of fish (e.g., harbours and salting factories; Malpica Cuello, 2009) and of guilds of fishers by the 11th CE (Malpica Cuello, 2009, Riera Melis, 2009). These developments were likely to have differed between regions under Islamic and Christian control. The Muslim coastal cities of the Southern Iberian Peninsula were known for their salt factories and Bluefin tuna (*Thunnus thynnus*, Scombridae) fishing, and had major commercial connections to the Maghreb and the Mediterranean (Boutchich, 2005, Barrionuevo, 2005, Ferreira Fernandes, 2005, Malpica Cuello, 2009, Picard, 2005, Rossenberger, 2005, Torremocha Silva, 2005). In contrast, fish production in Northwest Iberia most likely targeted the Iberian Christian markets, at least since the 13th century. These fisheries centred upon dried fish (the so-called *cecial* fish), of which the European Hake, Conger eel (*Conger conger*, Congridae) and sardine (*Sardina pilchardus*, Clupeidae) were the most common catch (Ferreira Priegue, 1982, 1988).

The analysis of fish remains from archaeological sites provides a direct way to test these historical narratives, whilst providing additional information that is often missing from accounts restricted to the upper echelons of society. Traditionally, this approach has been used to examine relative changes in exploitation through time. From this source, it is evident that the exploitation of the European hake began in the Iberian Peninsula during the Late Iron Age (4th - 3rd BCE) (Roselló Izquierdo and Morales Muñiz, 1991, Morales-Muñiz et al., 1991, 2009, 2011, 2018, 2019). The evidence shows that large-scale exploitation of hake in Northwest Iberia started as early as the 8th century (i.e., Curiel Castle, Gijón) when hake is first recorded on an inland site. Although fish bone assemblages prove the trade of fish products after the dismantling of the Roman networks, they

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have been less useful for assessing the extent and nature of the trade.

Here, we developed a combined stable isotopic and traditional ichthyoarchaeological methodological approach to assess hake trade across the Atlantic and Mediterranean in the Iberian Peninsula, and to determine whether commercial connections between the Muslim and Christian kingdoms existed at the level of fish products. Carbon and nitrogen stable isotope analyses have previously proved successful in differentiating past fish stocks on biogeographical grounds, and to shed light on the emergence of the North Atlantic fish trade (Barrett et al., 2008, 2011). Here, we follow a similar approach to analyse carbon and nitrogen stable isotopes in collagen extracted from European hake from 27 Iberian archaeological sites spanning from the Iron Age to the early 20th century.

2 | MATERIALS AND METHODS

2.1 | Samples

Forty-nine modern bones of hake were selected for isotope analysis from specimens commercially acquired and scientific fishing operations of the Institute of Marine Research (Vigo, Spain: field campaigns of the Instituto Español de Oceanografía, Lance 86 and Lance CL179-GL17-MZ) in the North-eastern Atlantic and Western Mediterranean, including Food and Agriculture Organization (FAO)'s fishing areas 27 (sub-area 8, division c; sub-area 9, division a and sub-area 4, division a), 34 (sub-area 3.1) and 37 (sub-area 1, division

1) (FAO, 1990–2021). Samples from areas 27 (Iberian Atlantic) and 37 (Iberian Mediterranean) were chosen as references for comparative analyses because our null hypothesis is that ancient hake were primarily caught in these waters. The remaining modern samples were included in the discriminant function analysis (see below). In addition, 269 cranial bones and vertebrae of hake were selected from 27 coastal and inland Iberian archaeological sites dated from the Iron Age to the early 20th century that include both processing and consumption sites (Figure 1, Table S1). All coastal sites were totally, substantially, or partially sieved, and 40% of inland sites substantially, partially, or minimally sieved (following categorization of Barrett et al., 1999). Archaeological specimens were selected according to bone preservation and an attempt was made to incorporate as much size variability as possible from each site.

The total length (TL) of archaeological specimens was estimated through direct comparison with modern specimens of known size as well as with regression equation methods (Armitage, 2012; Smith, 1995). Because of restricted sample size, a time sequence analysis of TL could only be performed on specimens from the North-east Atlantic (FAO zones 27–8c and 27–9a). These specimens were categorized according to three size groups, namely (a) non-mature fishes, below 330 mm, (b) mature, sex-mixed, fishes according to Atlantic standards (i.e., specimens between 330 and 940 mm; TL at first maturity is set at *ca.* 35 cm for males and *ca.* 45–50 for females; Korta et al., 2015) and (c) specimens of 950 mm or above.

TL of Mediterranean samples was also estimated following the same categorization as length at first maturity is set at *ca.* 350 mm for males and 450 mm for females (Korta et al., 2015; Recasens et al., 2008).

2.2 | Collagen extraction

Whenever possible, bone surfaces were cleaned with a sterilized scalpel blade to remove contaminating material. After cleaning, 200–300 mg (archaeological) or 100 mg (modern) of bone were selected for collagen extraction. Samples were demineralized in 8 ml of 0.6 M HCl in a roller rocker at 4°C during 24–48 h, then rinsed with ultrapure water (milli-Q®) and gelatinized with pH3 HCl at 80°C for 48 h. Gelatinized samples were filtered using Polyethylene Ezee filters (Elkay Laboratories Ltd., 9 ml, pore size 60–90 µm) and afterwards filtered using 30 kDa Amicon® Ultra-4 centrifugal filter units (Millipore), frozen for 24–48 h at –20°C, lyophilized and weighed into tin capsules (1 mg) for stable isotopic analysis. Atlantic samples of modern (*n* = 11) and archaeological (*n* = 9) specimens over 395 mm were defatted prior to collagen extraction (Table S2). Cleaned bones were soaked in a 2:1 dichloromethane:methanol solution (x 3), sonicated for 15 minutes and dried at room temperature for 24 h. Collagen was then extracted following the procedures described above.

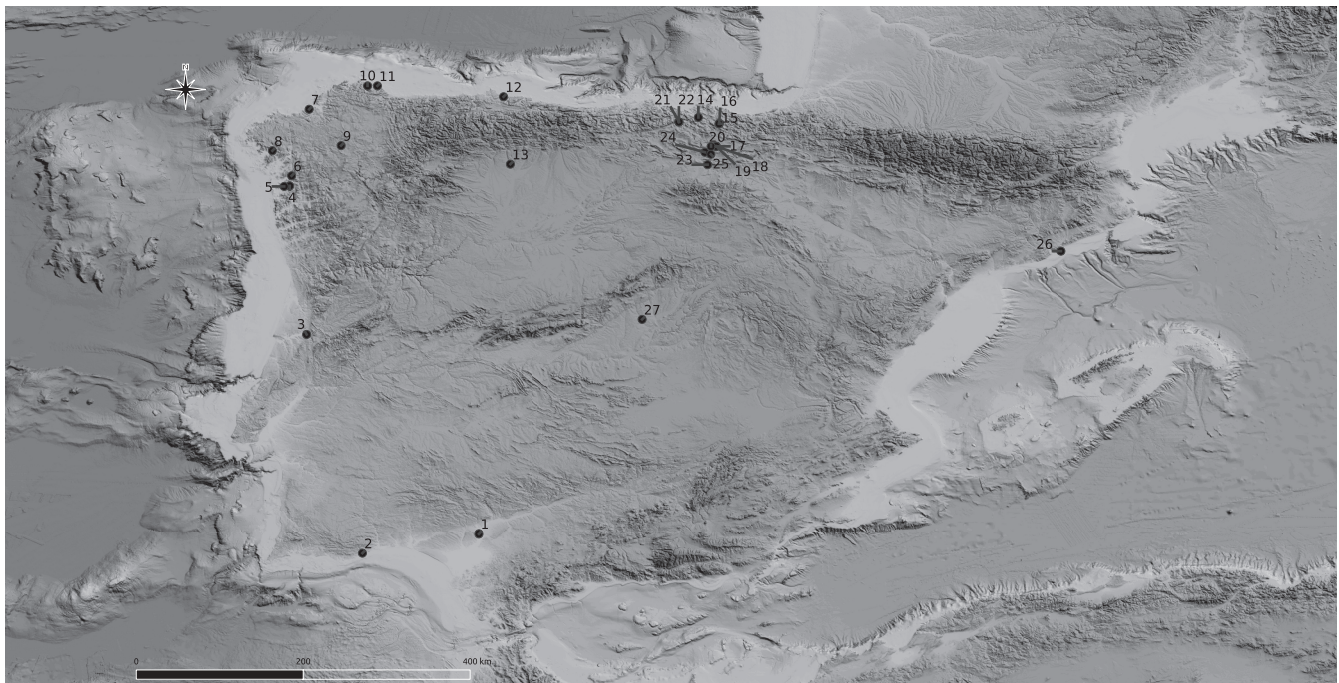


FIGURE 1 Location of archaeological sites where hake samples were analysed. Site codes: 1 La Cartuja, 2 Bnu, 3 Santa Clara-a-Velha, 4 Montealegre, 5 San Martin, 6 Arxobispo Malvar-Ponte do Burgo, 7 Rego de Auga, 8 Taramancos, 9 Castelo de Pambre, 10 Area, 11 Punta Atalaia, 12 Tabacalera, 13 Seminario de Leon, 14 Somera, 15 Artekale 22, 16 Artekale 39, 17 Correria 108, 18 Escuelas 2–4, 19 Catedral, 20 Arra 37, 21 Cubo 3–5–7, 22 Horcasitas-Martín Mendía, 23 Castillo de Labastida, 24 Castillo Arganzón, 25 Castillo de Treviño, 26 Barcelona, 27 Plaza de Oriente. We considered the 5–10 km threshold that is conventionally taken to set apart coastal from inland sites (Erlanson, 2001). Map created with QGIS 3.16 Geographical information system using the IGN raster cartography of the Iberian Peninsula as base map (CC BY 4.0 ign.es). Scale: 1:3445091. WMS source: <http://www.ign.es/wms-inspire/mdt?>

2.3 | Isotope Ratio Mass Spectrometry (IRMS) analysis

Stable carbon and nitrogen isotopic compositions were determined using a Sercon 20–22 continuous flow isotope ratio mass spectrometer coupled to a Sercon GSL elemental analyzer at the University of York. Accuracy was determined by measurements of international standard reference materials within each analytical run. These were IAEA 600 $\delta^{13}\text{C}$ raw = -27.71 ± 0.1 ‰, $\delta^{13}\text{C}_{\text{true}} = -27.77 \pm 0.043$ ‰, $\delta^{15}\text{N}_{\text{raw}} = 0.95 \pm 0.08$ ‰, $\delta^{15}\text{N}_{\text{true}} = 1 \pm 0.2$ ‰; IAEA N2 $\delta^{15}\text{N}_{\text{raw}} = 20.5 \pm 0.08$ ‰, $\delta^{15}\text{N}_{\text{true}} = 20.3 \pm 0.2$ ‰; IA Cane, $\delta^{13}\text{C}_{\text{raw}} = -11.8 \pm 0.09$ ‰; $\delta^{13}\text{C}_{\text{true}} = -11.64 \pm 0.03$ ‰. The overall uncertainties on the measurements of each sample were calculated based on the method of Kragten (1994) by combining uncertainties in the values of the international reference materials and those determined from repeated measurements of samples and reference materials. These are expressed as one standard deviation. The maximum uncertainty for all samples across all runs was <0.2 ‰ for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$.

In addition, a homogenized bovine bone extracted and analysed within the same batch as the samples produced the following average values; $\delta^{13}\text{C} = -22.85 \pm 0.13$; $\delta^{15}\text{N} = 7.01 \pm 0.26$. This was within the overall mean value from 50 separate extracts of this bone sample, which produced values of $\delta^{13}\text{C} = -23.04 \pm 0.66$ and $\delta^{15}\text{N} = 6.66 \pm 0.43$. Collagen control criteria follow those described in Ambrose (1990) and Van Klinken (1999) with modifications for fish (Szpak, 2011). Modern collagen $\delta^{13}\text{C}$ values were corrected for the Suess effect (Keeling, 1979) using a $\delta^{13}\text{C}$ correction factor of $+1.4$ ‰ observed in the North Atlantic between 200 and 400 m depth (Eide et al., 2017). This same correction factor was used on modern specimens from the Western Mediterranean following similarities in surface water circulation between these regions.

2.4 | Statistical analysis

Statistical analyses were performed using R version 3.4.4 (2018-03-15) (R Development Core Team 2013). Normality tests were performed with Shapiro–Wilk (populations <50 cases) and Lilliefors corrected Kolmogórov–Smirnov tests (populations >50 cases). Homoscedasticity was tested with either the Fisher test (2 populations tested) or the Bartlett test (more than 2 populations tested). Normally distributed populations were analysed using t-student or Welch when only two populations were contrasted and with ANOVA or Welch tests when three or more populations were tested. The non-parametric Kruskal–Wallis and Wilcoxon–Mann–Whitney tests were used when samples were not normally distributed. A p -value of .05 ($p \leq .05$) was used as the cut-off for significance in all tests.

We used linear discriminant analysis (DFA) based on our modern samples to attribute provenance of archaeological specimens providing probability of membership to control catch areas. The analysis was carried out including and excluding control specimens from the

region where no trade was expected (i.e. FAO area 34.3.1; Canary Islands) to confirm results.

3 | RESULTS

3.1 | Skeletal profiles and size of specimens

Archaeological hake bones from both inland and coastal sites alike include cranial bones, along with abdominal and caudal vertebrae (Figure 2 & Table S2). This suggests that hake, whether transported fresh, dried or salted, were traded as whole fishes.

Archaeological specimens ranged from 440 to 1140 mm (TL) and the size distributions do not exhibit statistical differences through time (Kruskal–Wallis chi-squared = 5.4134, $df = 3$, p -value = .1439) (Table 1; Table S2 and Table S3.1). Most of these specimens (75%) ranged between 730 and 800 mm (TL), with outliers representing large specimens for the most part. By contrast, the TL of modern specimens ranged from 285 to 1145 mm, with mean and median values being smaller than the archaeological samples (Table 1; Table S2 and Table S3.1, (Kruskal–Wallis chi-squared = 31.396, $df = 4$, p -value = 2.542e-06). In fact, 75% of this modern sample ranged between 340 and 650 mm (Table 2).

3.2 | Stable carbon and nitrogen isotope analysis

Collagen was successfully extracted from the 49 modern specimens with yields ranging from 23% to 9.5% (Table 2, Table S2). Values of their $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ ranged between -11.4 ‰ and -14.7 ‰ and $+8.8$ ‰ and $+13.8$ ‰ respectively. Collagen extraction was attempted in 184 archaeological specimens of which 137 (74.4%) met the quality criteria for preserved collagen and will be discussed hereafter. The success rate in collagen extraction per site is above 70% except in four cases (Table S1). Overall, the %C and %N values ranged from 31.1% to 45.7% and 9.9% to 16.8%, respectively, whereas their C:N ratio ranged from 3.05 to 3.7. Samples with collagen yields $<1\%$ exhibited C:N ratios >3.5 and large uncertainties in isotope values of duplicate samples ($>0.25\%$). All remaining samples had $\delta^{13}\text{C}$ values ranging between -13.3 ‰ and -11.4 ‰ and $\delta^{15}\text{N}$ values between $+12.4$ ‰ and $+14.2$ ‰ (Table S2). Defatted and non-defatted bones from modern and archaeological specimens produced statistically indistinguishable C:N ratios and C% and $\delta^{13}\text{C}$ values (Table S3.2), allowing to rule out effect of lipids in our samples (Guiry et al., 2016).

Modern hake above 330 mm TL exhibited significantly higher $\delta^{15}\text{N}$ values when compared to smaller individuals in both the North-east Atlantic (Kruskal–Wallis test chi-squared = 8.84870, p -value = .01435) and Mediterranean samples (t -Student test $t = -2.722$, $df = 13$, p -value = .01745) (Table S3.3). This can be accounted for both in terms of slightly different foraging niches and by ontogenetic change in the diet, the large adults incorporating more prey from higher trophic levels (Korta et al., 2015). In addition, North-east Atlantic specimens consistently had higher $\delta^{15}\text{N}$ values

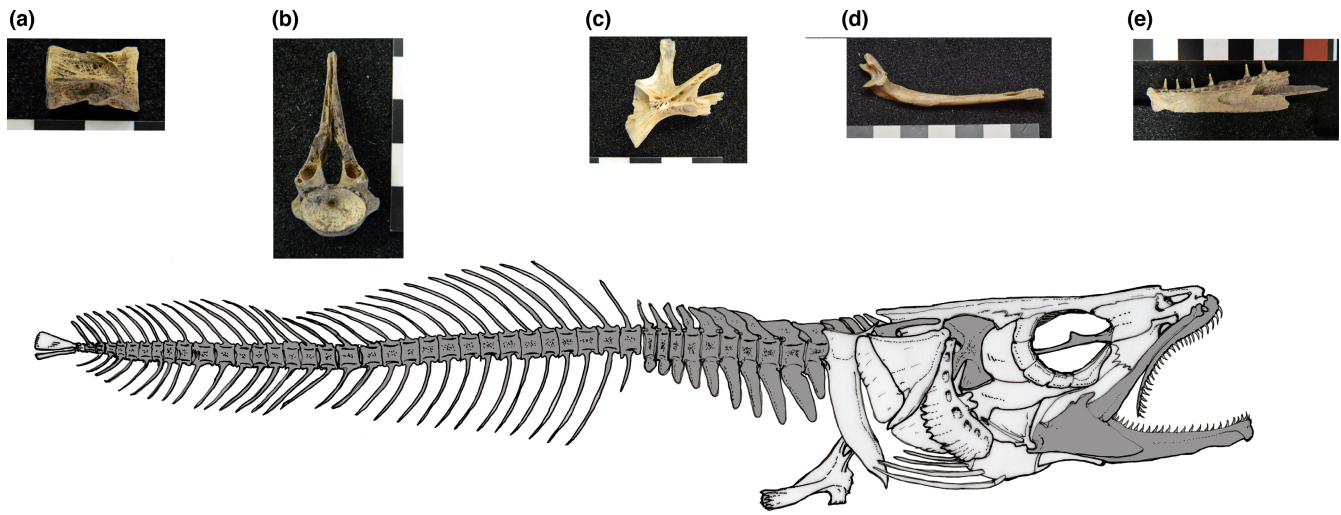


FIGURE 2 Presence of bones retrieved at inland sites (shaded bones in the skeleton) and examples from the sites of Catedral de Vitoria, Plaza de Oriente and Artekale 39 (2, 6 and 23 in Figure 1). (a) caudal vertebra (lateral view), (b) atlas (=1st abdominal vertebra, cranial view); (c) Hyoideum (ventral view), (d) maxilla (medial view), (e) dentary (lateral view). Composition by L. LL.R & A. M.M

TABLE 1 Atlantic hake descriptive statistics of size (mm) according to period

Period	Mean	SD	Median	Min	25%	50%	75%	Max	n
Before 8th CE	761.7	79.2	750	600	730	750	800	950	18
8th–12th CE	783.2	41	760	750	750	760	800	870	22
13th–15th CE	793.9	121.5	750	600	720	750	850	1140	53
16th–19th CE	736.6	54.8	750	630	710	750	768	830	19
20th–21th CE	492.2	293.5	376.5	93	297	376.5	730	1145	32
Total Atlantic samples									144

Abbreviations: Max, maximum length; Min, minimum length; n, number of samples; SD, standard deviation.

TABLE 2 Descriptive statistics of carbon and nitrogen isotopes of the modern samples by size group

Size group	Sample	Mean	Variance	SD	Median	Min	Max	n
$\delta^{13}\text{C}\text{‰}$								
<330 mm	Atlantic	-13.27	0.4298	0.66	-13.14	-14.15	-12.40	6
	Mediterranean	-13.35	0.5837	0.76	-13.24	-14.68	-12.40	8
330–940 mm	Atlantic	-12.83	0.3032	0.56	-12.81	-14.12	-11.89	12
	Mediterranean	-12.99	0.6337	0.80	-13.10	-13.98	-11.96	7
>950 mm	Atlantic	-12.43	0.2362	0.49	-12.43	-12.77	-12.08	2
	Mediterranean	-	-	-	-	-	-	0
$\delta^{15}\text{N}\text{‰}$								
<330 mm	Atlantic	11.71	0.4342	0.66	11.89	10.63	12.38	6
	Mediterranean	9.67	0.3663	0.61	9.69	8.76	10.62	8
330–940 mm	Atlantic	12.49	0.3747	0.62	12.67	11.06	13.30	12
	Mediterranean	10.48	0.2997	0.55	10.55	9.52	11.38	7
>950 mm	Atlantic	13.27	0.5526	0.74	13.27	12.74	13.79	2
	Mediterranean	-	-	-	-	-	-	0

than Mediterranean fish of equivalent size (TL < 330 mm group size $t = 5.8193$, $df = 11$, p -value = .000116, TL between 330–940 mm $W = 190$, p -value = $7.606e-07$).

Archaeological specimens from Atlantic coastal sites and, to a lesser degree, Mediterranean sites, had $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values within the range of modern specimens from these regions respectively (Figure 3, Tables 2 and 3). The discriminant analyses used to assign probable source of provenance of archaeological specimens had success rate of 67 % independently if region 34.3.1 was included or not (Table S3.5 and Table S4). All analyses attributed an Atlantic provenance to most coastal (archaeological) Atlantic samples, with probability of membership higher than 0.9 in most cases except for three unresolved samples (AR9, TB6, BNU2), and a fourth that was attributed to the Mediterranean (TB3). Specimens from inland sites produced $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values comparable with values from the Atlantic (Figure 3; Tables 2 and 3; Table S4). Within this Atlantic group, one sample had a 0.9 probability of membership to the North Sea (SA3; inland site), three North Sea probabilities between 0.7 and 0.8 (AT30, AT31, AT17, AT18; coastal site) and a further two (AT43; coastal, ESC3; inland) probabilities around 0.6 (Table S4). These data should, nevertheless, be taken with caution given the small number of North Sea reference specimens with similar TL (ca. 360 mm).

Another interesting result is the differences in the $\delta^{15}\text{N}$ between the Atlantic specimens from different periods (Kruskal-Wallis chi-squared = 18.169, $df = 3$, p -value = .000406; excluding modern specimens; Kruskal-Wallis chi-squared = 29.38, $df = 4$, p -value = $6.543e-06$ including modern specimens; see S3.4). These differences are partly explained by the high $\delta^{15}\text{N}$ variability

of post-mediaeval samples dated to 16th–19th CE ($\delta^{15}\text{N}$ 12.85–14.33‰; Table 3) when compared to other periods.

Similarly, archaeological specimens from the Mediterranean site of Barcelona had higher variability in $\delta^{15}\text{N}$ values when compared to modern specimens, independently of size (Tables 2 and 3). Only two (BCN1 and BCN4) out of six specimens sampled from Barcelona could be assigned to the Mediterranean (membership probability above 0.9). Another specimen, with a 0.77 probability, could also be considered local (BCN2) (Figure 3: black points, Table S4) (Figure 3: black points). The provenance of the remaining samples from Barcelona is clearly Atlantic (probabilities above 0.8 and 0.9; Table S4), suggesting that local hake was a secondary catch.

4 | DISCUSSION

This study demonstrated that bone collagen $\delta^{15}\text{N}$ values can successfully discriminate between specimens of European hake from the North-east Atlantic and the Mediterranean Sea, offering a tool to track geographical provenance and trade networks in past and present-day hake stocks in the Iberian Peninsula (Figure 3). The analyses allowed us to detect geographical differences independently of size. This is the first time that such carbon and nitrogen isotopic differences are reported between populations of European hake as opposed to the signature previously reported among hake species (Carrera & Gallardo, 2017).

Whereas bone collagen $\delta^{13}\text{C}$ values remained comparable between our two regions, the consistently lower $\delta^{15}\text{N}$ values of the Mediterranean specimens may reflect the oligotrophy and the

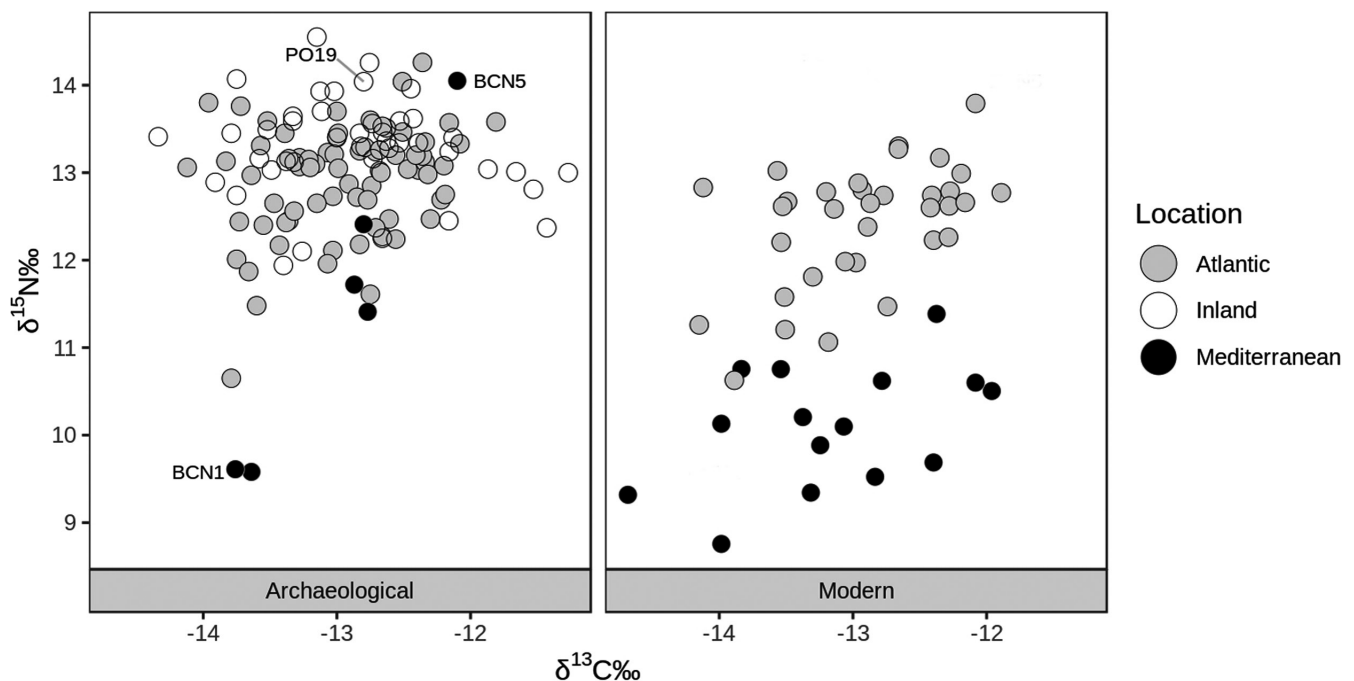


FIGURE 3 Scatter plot of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of modern and archaeological samples showing differences according to geographical location. Sample codes refer to PO19: Plaza de Oriente; BCN1 & BCN 5: Barcelona

TABLE 3 Descriptive statistics of carbon and nitrogen isotopes of the archaeological samples by catch location or inland origin

Period	Sample	Mean	Variance	SD	Median	Min	Max	n
$\delta^{13}\text{C}\text{‰}$								
Before 8th CE	Atlantic	-12.97	0.31	0.56	-12.92	-13.75	-12.39	6
8th–12th CE	Atlantic	-12.95	0.3	0.55	-12.88	-13.37	-12.08	22
	Inland	-12.83	-	-	-	-	-	1
13th–15th CE	Atlantic	-12.94	0.26	0.51	-12.99	-13.96	-11.81	45
	Inland	-13.08	0.22	0.47	-13.13	-13.91	-12.39	27
16th–19th CE	Atlantic	-13.22	0.26	0.53	-13.18	-14.40	-12.91	13
	Inland	-12.37	0.73	0.86	-12.16	-14.34	-11.27	14
	Mediterranean	-12.99	0.38	0.62	-12.84	-13.76	-12.10	6
$\delta^{15}\text{N}\text{‰}$								
Before 8th CE	Atlantic	12.89	0.3	0.55	13.1	12.01	13.47	6
8th–12th CE	Atlantic	12.81	0.17	0.41	12.86	11.87	13.51	22
	Inland	13.45	-	-	-	-	-	1
13th–15th CE	Atlantic	12.99	0.49	0.70	13.16	10.65	14.26	45
	Inland	13.37	0.39	0.62	13.36	11.94	14.55	27
16th–19th CE	Atlantic	13.61	0.14	0.37	13.64	12.85	14.33	13
	Inland	13.15	0.13	0.41	13.19	13.00	13.41	14
	Mediterranean	11.46	2.9275	1.71	11.57	9.58	12.24	6

relatively shorter food webs in this basin when compared to the North-east Atlantic (Coll & Libralato, 2012). Relatively low $\delta^{15}\text{N}$ values have also been reported for Mediterranean species with similar trophic level and habitat preferences as hake (García-Guixé et al., 2010; Vika & Theodoropoulou, 2012). Nevertheless, such differences may also arise due to the different pools of nitrogen that support primary producers in each basin, the $\delta^{15}\text{N}$ values then propagating through the respective food webs (Owens, 1988).

Our time-series analyses showed a significant increase in $\delta^{15}\text{N}$ values of the Atlantic specimens from the 16th century CE to the present day, irrespective of size. Nitrogen loading derived from anthropogenic activities (such as fertilizers and deforestation) might be argued to lie behind such trend. However, the region where most of our historical coastal sites are located (Galicia, Northwest Iberian Peninsula), and where the bulk of the present-day Iberian hake fisheries are located, has a relatively small catchment, as well as low urban population and industrialization levels to this day, limiting anthropogenic nutrient input into the ocean. In addition, nutrient loading effects are minimized by the upwelling that prevails in the *rías* (Bode et al., 2011, 2014; Viana & Bode, 2013; Viana et al., 2011).

An alternative explanation is the stronger Atlantic Meridional Overturning Circulation (AMOC) produced by the Medieval Climatic Anomaly (MCA: ca. CE 950–1200) that turned weaker during the Little Ice Age (LIA, ca. 1,500–1,840) (Wanamaker et al., 2012). This latter change to the Gulf Stream and the North Atlantic Current (NAC) might have contributed to more powerful upwelling during the 16th–19th centuries, leading to a lengthening of food webs that ultimately reflected an increase of the $\delta^{15}\text{N}\text{‰}$ and changes to the trophic position of hake. In the case of the differences with present-day samples, the surface component of the North Atlantic system

exhibits similar patterns to that of the MCA event produced, in theory, by global warming (Wanamaker et al., 2012). Ideally, in addition to a larger sample, $\delta^{15}\text{N}$ of different sources and trophic amino acids (Choi et al., 2020) in collagen would be needed to confirm this hypothesis.

4.1 | The onset and development of the Iberian hake fisheries

Our data confirm that European hake began to be widely traded with inland settlements around the 10th CE, if not earlier. Interestingly, the earliest records of long-distance hake trade in Iberia appear in the Islamic levels (10th–11th CE) from Plaza de Oriente, in the centre of the Iberian Peninsula (Madrid). Our isotopic data show that these samples were most likely transported from the Atlantic (e.g., Figure 3: PO19). Although most written sources focus on Islamic commercial networks in the Mediterranean (Curta, 2011, Malpica Cuello, 2009), Atlantic Muslim towns such as Saltés are also known to have supplied fish to inland localities such as the city of Seville, although hake is never mentioned (al Idrīsī, 1866). Archaeological remains from inland cities such as Mértola (Estremadura, Portugal) and Calatrava La Vieja (Ciudad Real, Spain), also testify to such fish trade though, again no hake remains have been thus far reported (Morales et al., 1994). This fish trade might have reached Plaza de Oriente but hake in this case could also reflect trade with the Christian kingdoms' flourishing Atlantic fisheries (Ferreira Priegue, 1982, 1988; Hinojosa Montalvo, 1982, 1995; Salicrú i Lluçh, 2009; Morales-Muñiz et al., 2019). Indeed, although hake has visible scales, these are not of the prominent kind deemed desirable by the Qur'anic

precepts (Foltz, 2006). Also, the population of Madrid in the 10th century was a mix of Muslims, Christians and Jews, thus the traders and consumers responsible for that hake might not have been restricted to the Islamic faith. More archaeological evidence is thus required to confirm this case.

A few coastal and inland cases suggest an Atlantic provenance of hake beyond Iberian fishing grounds, suggesting that fish products may have been traded with northern Europe alongside other luxury items documented by written sources (Ferreira Priegue, 1982,1988, Fernández Fernández, 2014; McCormick, 2002; Wickham, 2005).

Our isotopic data also show that although hake found in Mediterranean sites were caught in the Atlantic (e.g. Figure 3: BCN5), some were derived from the local fisheries (e.g. Figure 3: BCN1). This is the first evidence that Mediterranean hake were fished locally to supplement imported fish and refutes written sources that only refer to the import of Atlantic dried fish to Mediterranean cities (Ferreira Priegue, 1988, 1994).

Through these interchange networks, it seems that fishes were transported whole (Figure 2) as confirmed by the skeletal representation, supporting the documentary evidence that describes the ways in which *cecial* fish (i.e., dried fish) was preserved in the Iberian Christian Kingdoms (Ferreira Priegue, 1988). This method of fish preservation contrasts with that of North Atlantic Europe, where large gadoids were generally beheaded prior to export to maximize the amount of meat being transported (Locker, 2000; Perdikaris, 1996). In Iberia, a far wider array of similar-looking fish with different meat quality were traded (e.g., pollock, saithe, hake, whiting and conger eel), and the head was the only means for inspectors and customers alike to recognize the product. For such

reason, *cecial* fish were beheaded by fishmongers at the market (Guerrero-Navarrete, 2009).

In terms of size, a reduction of ca. 10–15 cm in the mean TL in the hake specimens from the Atlantic, and ca. 25 cm in the Mediterranean specimens was identified (Gurbet et al., 2013). (Figure 4 and Table 1). This difference could be attributed to different fishing methods used before the 18th century (i.e., longlines and gillnets) compared with today (i.e., trawling) or to the recovery method of archaeological fish remains. However, the specimens used in our analyses derive from totally or substantially sieved ≤ 1 mm mesh/floated samples (Table S1) and the fish size differences attending to fishing gears used nowadays appears to be minimal despite the purported 'increase' in fish mean length reported by ICES from 2006 (33 cm) to 2007–2010 (35–36 cm) (ICES, 2011, p. 137) (Figure 4). This difference may reflect the intensity of the exploitation caused by the fish tackle that was used to capture these hakes. In the 18th century, hake was preferentially fished with longlines in the Iberian Peninsula, whereas today bottom trawling prevails (MAPAMA, 2016; Sañez Reguart, 1791). Longlines are known to catch, on average, substantially larger specimens than bottom trawling (Korta et al., 2015). However, bottom trawling was already widely used by the 18th century when both large hakes and their offspring were the most frequent catches (Sañez Reguart, 1791). Indeed, Sañez Reguart was the first to warn on the damage that bottom trawling was causing in the Iberian coasts, stressing how this technique '...*aniquila las crias...*' (lit. annihilates the offspring), and '...*descasta los mares...*' (lit. empties the sea), to the extent that fishermen had to seek for new fishing grounds (Sañez Reguart, 1791: 321).

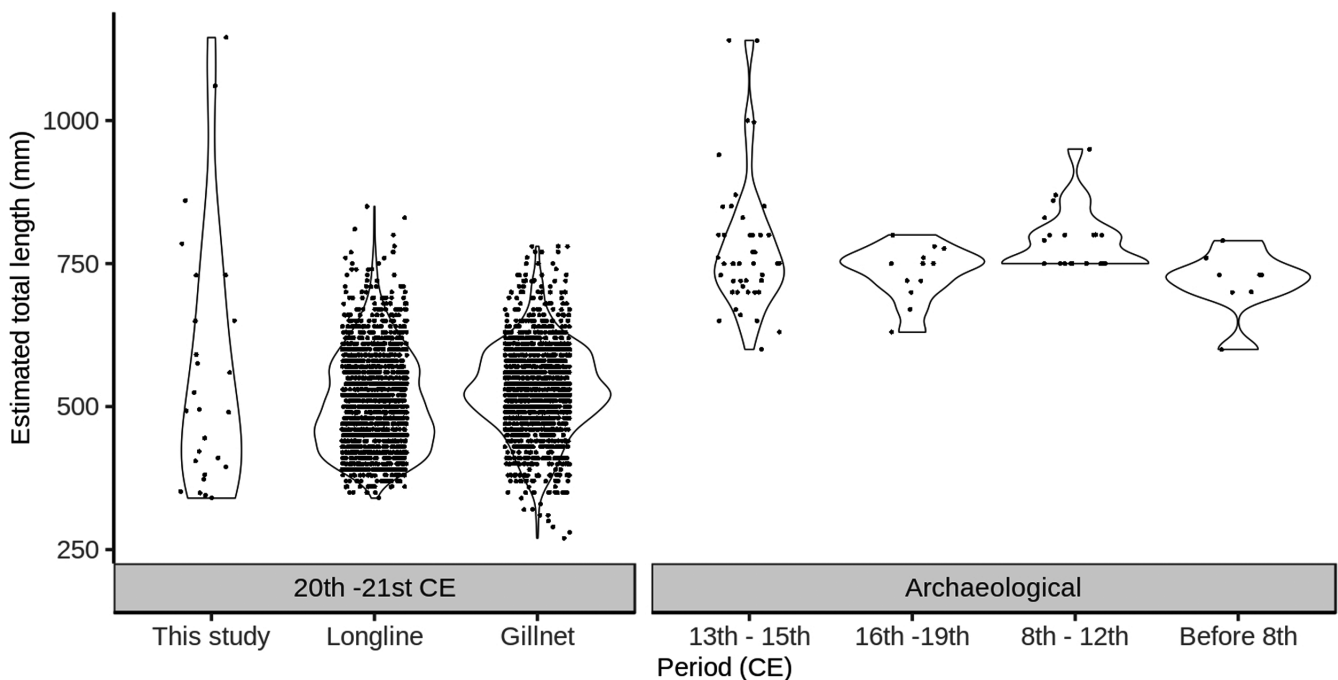


FIGURE 4 Pooled total length data of Atlantic hake throughout time and by gear. Sample size for period before 8th CE $n = 9$, 8th–12th CE $n = 25$; 13th–15th CE $n = 84$; 16th–19th CE $n = 27$; Modern sample (this study) $n = 53$; modern longline $n = 15,096$ and gillnet $n = 1479$ gears in Spain analysed from ICES (2011: Table 7.2)

In the case of certain key taxa such as the European hake, the productivity decrease of fisheries is thought to be induced by the collapse of the populations. Growth rate, age and size at maturation, lie behind most decreasing yields of fisheries nowadays due to the induced selection of smaller mature sizes that overfishing triggers (Domínguez-Petit et al., 2008, Olsen et al., 2004, 2005, Trippel, 1995). The long practice of bottom trawling in the Iberian coast may have produced a progressive decrease in the size of the hake and the disappearance of the largest specimens, especially when bottom trawlers gradually displaced longlines as the main fishing method.

5 | CONCLUSIONS

Our isotopic data confirm that production sites in the Northwest Atlantic coast of the Iberian Peninsula existed following the collapse of the Roman fisheries. This suggests that Iberian fish trading networks may have been in operation at an earlier time than hitherto postulated. At the level of consumption sites and inland trade, the earliest archaeological evidence of these enterprises, whose distinctive stock-fish trademark was dried, non-beheaded fish (i.e. *cecial*), appear by CE 9th, pre-dating analogous developments in Northern Europe. Both the archaeological record and our isotopic data mostly document hake trade posts in this Northwest region ruled by Christian kingdoms. Some isotopic results, though, suggest that certain fish could have been caught at more northern grounds where fishing connections are known since the Late Middle Ages (e.g., Ferreira Priegue, 1982, 1988, 2009). A larger number of samples from the North Celtic-Biscay and North Sea areas are needed to more reliably assess the contribution of other Atlantic grounds to the Iberian hake market.

In the case of the Mediterranean, our isotopic data suggest that the earliest evidence of local hake fishing takes place at the end of the Middle Ages without evidence of an inland trade existing for these fishes.

In terms of fishing techniques, the documentary sources indicate that gillnets and longlines were the preferential gear used both in the Atlantic and the Mediterranean, during the Middle and Modern Ages. The implementation of these size-selective techniques for catching fish conforms to the results of our biometrical analysis, which show significantly larger hake in the mediaeval samples than is the case today. Our research suggests that preferential targeting on large specimens with gillnets and longlines for centuries did not impact the population structure of stocks in the way that bottom trawling does today.

This study highlights the importance of long-term baselines to understand the structure and variability of fish populations. Investigating past ecology and fish size in archaeological assemblages can help to fill the gap existing in the present-day fisheries time series, often based on data from the most recent decades. That is the case of the result on average and size distribution of hake in our research, which with better tools to analyse trophic ecology in ancient samples, such as CSIA in collagen amino acids, past structure

of populations through aDNA studies and long-term trends in fish landings starting with the help of all sorts of written records, can provide critical information to understand the long-term trends that have shaped modern-day fisheries.

ACKNOWLEDGEMENTS

We acknowledge Dr Fran Saborido-Rey, director of the Institute for Marine Research (IIM, Vigo, Spain) for supplying samples from scientific campaigns, his support to this research and his feedback. We are also grateful to Gerardo García-Castrillo Riesgo, director of the Maritime Museum of the Cantabrian Sea (Santander, Spain) for providing further samples to our research. Museo Arqueológico Nacional de Madrid (Madrid, Spain), Arabako Arkeologia Museoa (Araba, Spain) and Arkeologi Museoa (Bilbao, Spain) granted archaeological material for this study. This research was mainly supported by the European Commission through the FISHARC-IF 658022 Marie-Curie-Sklodowska-IF fellowship for Career development. Additional support was received by the Spanish Ministry of Economy and Competitiveness [HAR 2014-55722-P (Ictioarqueología de la Prehistoria cantábrica: Modelos para la caracterización de las primeras pesquerías europeas), HAR 2017-88325-P (Historical archaeobiology of the European hake (*Merluccius merluccius*, L.1758) in the NE Atlantic: The Iberian evidence (AD 10th–18th)), and the European Molecular Biology Organization (ASTF 354-2016). The research is also under the framework of the the Leidse Universiteit Fonds-Bakels 2021 fund, the PID-118662GB-100 (FISHCIIS - Fishing Isotopes) project from the Ministry of Science and Innovation, and the Research Group of Cultural Landscapes and Heritage of the University of the Basque Country. We finally want to thank two anonymous reviewers for their helpful suggestions that have improved the quality of this paper. This work contributes to the “María de Maeztu” Programme for Units of Excellence of the Spanish Ministry of Science and Innovation (CEX2019-000940-M).


AUTHOR CONTRIBUTIONS

L.L.L.R. A.C.C., A.M.M. and O.E.C. conceived and designed the research. L.L.L.R., A.M.M., E.R.I., B.L.A., C.F.R. and E.G.G-A. selected the samples and carried out the archaeozoological analyses. L.L.L.R. carried out the laboratory work with the assistance of M.V-T and B.L.A. Data and statistical analyses were carried out L.L.L.R. with the input of A.C.C., M.V-T. and O.E.C. Samples and archaeological context information were provided by A.M.M., E.R.I., C.F.R., E.G.G-A., R.M. and J.A.Q. Figures and tables were prepared by L.L.L.R., who led the writing of the manuscript with input from authors. L.L.L.R., O.E.C., and A.M.M. provided funding.

DATA AVAILABILITY STATEMENT

Isotopic raw data were generated at BioArCh, University of York. Total lengths were measured or estimated by L.L.L.R. A.M.M., E.R.I. and B.L.A., at LAZ-UAM and BioArCh, University of York. The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

ORCID

Laura Llorente-Rodríguez  <https://orcid.org/0000-0001-9329-5554>

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How to cite this article: Llorente-Rodríguez, L., Craig, O. E., Colonese, A. C., von Tersch, M., Roselló-Izquierdo, E., González Gómez de Agüero, E., Fernández-Rodríguez, C., Quirós-Castillo, J. A., López-Arias, B., Marlasca-Martín, R., Nottingham, J., & Morales Muñoz, A. (2022). Elucidating historical fisheries' networks in the Iberian Peninsula using stable isotopes. *Fish and Fisheries*, 23, 862–873. <https://doi.org/10.1111/faf.12655>