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– ARTICLE –

Otolith Stable Isotopes and Māori Archaeology: Marine Paleoclimate Data for Northern Aotearoa New Zealand

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Abstract

Marine paleoclimate records for the last 1,000 years are scarce in the southwest Pacific, limiting our understanding of complex environmental changes that may have affected Māori seascapes and fisheries. We seek to begin filling this knowledge gap by studying stable oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes in archaeological and modern otoliths from tāmure (Australasian snapper, *Chrysophrys auratus*), which provide information about water temperature, salinity, and fish diet and metabolism. Our results show that fourteenth and fifteenth century tāmure otoliths recorded environmental conditions that are comparable to twentieth century temperatures, with some evidence for anomalously warmer seas and/or higher precipitation during the fifteenth century. These findings are concordant with previous reconstructions of terrestrial climatic conditions in northern Aotearoa and of central west Pacific Ocean sea surface temperatures, providing additional evidence that Māori experienced a warm climatic period during their first centuries of habitation and fishing in the North Island.

Keywords: otoliths, stable isotopes, paleoclimate, Aotearoa New Zealand, snapper / tāmure

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1. Introduction

Understanding the complex relationships between humans and the dynamic landscapes they inhabit is one of archaeology's primary concerns (Allen 1992). Unfortunately, marine paleoclimatic records for the late Holocene are scarce relative to terrestrial counterparts in the southwest Pacific Ocean, especially during the period of Māori settlement and habitation in Aotearoa New Zealand (hereafter, Aotearoa). Analysis of speleothem isotopes (Lorrey et al. 2020), tree ring growth patterns (Cook et al. 2002, 2006; D'Arrigo et al. 1996; Fowler and Boswijk 2007), glacial moraine chronologies (Winkler 2014; Winkler and Lambiel 2018), and palynology and charcoal (McGlone and Wilmshurst 2005; McWethy et al. 2009, 2014; Perry et al. 2014; Wilmshurst et al. 1999) have enabled high resolution reconstructions of atmospheric climate conditions and Māori terrestrial landscapes, both singly and in synthesis (Ahmed et al. 2013; Lorrey et al. 2014, 2008, 2011). In contrast, there are virtually no nearshore climate reconstructions for Māori seascapes, and researchers continue to rely on terrestrial climate signals or distant sea surface temperature reconstructions as proxies for local marine conditions over the last 1,000 years.

The need for direct, marine proxy data is highlighted by recent studies indicating that the southwest Pacific may have experienced abrupt changes in surface circulation that are not represented in terrestrial proxy data. Komugabe-Dixson et al. (2016) observed substantial increases in the local marine radiocarbon reservoir offset (ΔR) of deep water black coral (*Leiopathes* sp.) samples between 1600-1860 cal CE in the southwest Tasman Sea. The authors suggest these fluctuations in reservoir ages were caused by (1) increased transport of older, ^{14}C-depleted (more positive ΔR) surface water to the Southwest Pacific via the East Australia Current, and (2) increased advection of older (more positive ΔR), subantarctic water along the Subtropical Front into the south Tasman Sea. These changes to surface circulation are, in turn, hypothesized to be the consequences of the Little Ice Age (Komugabe-Dixson et al. 2016) – a global, semi-synchronous period of continental- and ocean-scale cooling that was first observed as late as 1500 CE in Australasia (Ahmed et al. 2013; Lorrey et al. 2008, 2011; McGregor et al. 2015). Subsequently, Petchey and Schmid (2020) observed similar ΔR increases between 1600-1950 cal CE in paired marine and terrestrial radiocarbon samples from Māori archaeological sites in Aotearoa, indicating that surface circulation changes likely affected marine environments on both sides of the Tasman Sea. In addition, extremely negative ΔR perturbations have now been documented in paired archaeological samples from Aotearoa between 1350-1400 cal CE (Petchey and Schmid 2020), in black coral samples from Cape Howe, Australia before 1550 cal CE (Komugabe-Dixson et al. 2016), and paired archaeological samples from Tongatapu, Tonga around 1300-1400 cal CE (Petchey et al. 2023). Petchey and Schmid (2020) suggest these earlier, negative shifts in marine radiocarbon reservoirs could be related to complex changes in South Pacific marine conditions during the period between the Medieval Climatic Anomaly and the Little Ice Age, though no specific explanations for the ^{14}C-enrichment (more negative ΔR) of South Pacific surface waters during this period have been advanced.

Any such changes in southwest Pacific circulation that influenced sea surface temperatures could have affected Māori seascapes through potential climate effects on important marine food species. Climate has been cited as the single most important factor driving species distributions and demography in marine systems, as it affects growth, reproduction, and survival rates (O'Brien et al.

2013). Observations of species responses to a warming Tasman Sea over the last 100 years indicate that climate shifts rapidly affect the latitudinal distributions of fishes (Last et al. 2011). One review of potential Little Ice Age impacts on 14 species of sharks, skates, and rays and 17 marine fish species that are common in northern Māori archaeological fish catches confirms that several important food species were likely vulnerable to decreases in sea surface temperature, and that colder-water fishes might have expanded further north if colder conditions prevailed (Nims 2022a). For example, the reproduction and growth rates of tāmure (snapper, *Chrysophrys auratus*), a keystone fish, is particularly vulnerable to cold summer temperatures (Parsons et al. 2014; Sim-Smith et al. 2013). A summary of all extant archaeological fishbone data from the northern North Island indicates the relative abundances of snapper in archaeological deposits did decrease dramatically after 1500 cal CE (Nims 2022a). However, the causal role that marine climate change may have played in any such fisheries or other marine resource dynamics cannot be definitively established in the absence of reliable reconstructions for local marine conditions over this time span.

To fill this significant knowledge gap, we seek to obtain new information about the paleoclimatic conditions of Māori seascapes through stable isotopic analysis of archaeological tāmure otoliths. Otoliths are carbonate structures of a fish's inner ear that grow continuously, recording daily environmental and somatic conditions that were experienced by the fish over the entire course of its life (Campana 1999). Oxygen isotope values (δ^{18}O) from archaeological otoliths have been studied from numerous contexts globally to reconstruct long-term changes in the temperature and salinity of marine (e.g., Ainis et al. 2021; Andrus et al. 2002; Bryant 2019; Dias et al. 2019; Ólafsdóttir et al. 2017; Samor Lopes et al. 2022; Surge and Walker 2005; Wang et al. 2013; West et al. 2012; Young-Boyle 2015) and freshwater habitats (e.g., Dufour et al. 2018; Long et al. 2021). Carbon stable isotope values (δ^{13}C) in archaeological otoliths, meanwhile, can provide additional environmental information about fish diets, growth, and habitat use (e.g., Samor Lopes et al. 2022; Young-Boyle 2015). In Aotearoa, one unpublished report analysed oxygen and carbon stable isotopes for tāmure otoliths from one North Island archaeological site, and hoka (red cod, *Pseudophychis bachus*) otoliths from one South Island archaeological site (Neil et al. 2011). Subsequently, there has been a concerted effort to learn about changes in tāmure habitat use from trace element analysis (Campbell et al. 2021, 2025a; Lilkendey et al. 2025; Sabetian et al. 2021), but otoliths are otherwise locally unutilized as a source of paleoclimatic information. In this paper, we report new stable isotope data from fourteenth century tāmure otoliths recovered from Tauranga Bay (P04/639), Whangaroa, Northland (Figure 1) to begin addressing this knowledge gap and increase our understanding of Aotearoa's marine climate history.

2. Background

2.1. Otoliths and Stable Isotope Analysis

Otoliths are organic carbonate structures in the inner ears of all vertebrates that play a role in balance and/or hearing. Teleost fishes have three pairs of otoliths, two of which (the sagittae and lapilli) are composed of the aragonite polymorph of calcium carbonate and the third pair (asterisci) is of vaterite (Campana 1999). Sagittae are the most common otolith studied from archaeological samples as they are larger and more taxonomically diagnostic than the other two pairs. Otoliths grow continuously through the precipitation of calcium carbonate, but variations in the rate of precipitation create daily, seasonal, and/or annular bands that can be observed in cross-section as alternating opaque and translucent growth rings.

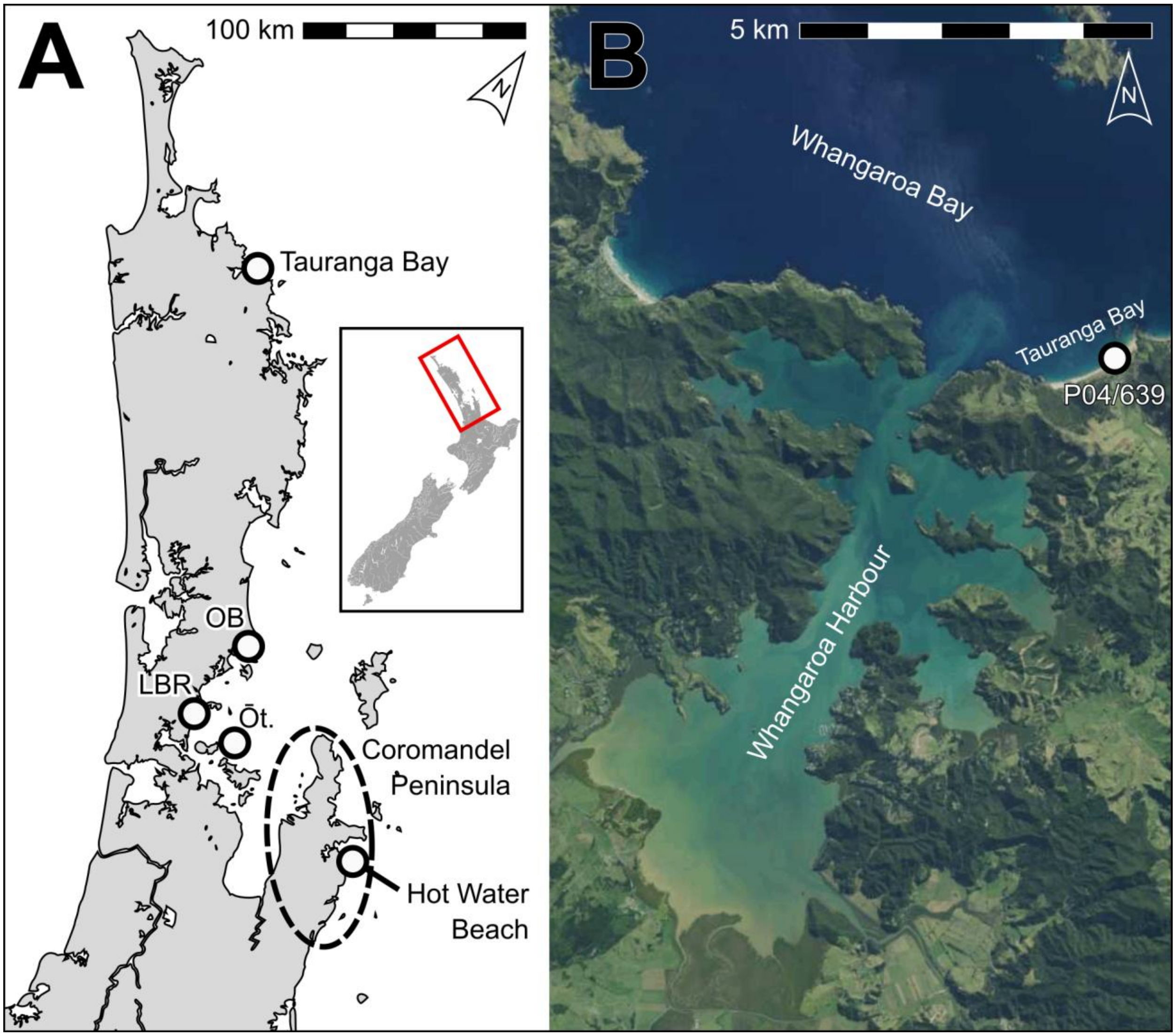

Figure 1. Map of locations mentioned in the text. A) Sites with tāmure otolith samples analysed from Northern Aotearoa ("LBR" = Long Bay Restaurant; "OB" = Omaha Beach; "Ōt." = Ōtata). B) Whangaroa Harbour and Tauranga Bay (satellite images sourced from the LINZ Data Service and licensed for reuse under CC BY 4.0).

The relative abundances of stable isotopes (naturally occurring, non-radioactive variants of chemical elements) that are deposited within the carbonate of otolith growth rings are affected by both environmental processes and biological processes. Analysing the stable isotopes within carbonate samples cored from individual growth rings allows researchers to study season- or annual-scale changes in a fish's environmental and somatic conditions over the course of its entire life history. Of the three constituent elements within the calcium carbonate ($CaCO_3$) structure of otoliths, the processes that influence oxygen and carbon stable isotope fractionation are wellunderstood (Campana 1999), while the ecological information potential of calcium stable isotopes has yet to be fully realized (Tacail et al. 2020).

Oxygen isotope ($\delta^{18}O$) values of otolith aragonite primarily reflect the isotopic composition of the ambient water and the temperature of that water. During carbonate precipitation, the temperature of the water affects isotope fractionation, resulting in lower (more negative) $\delta^{18}O_{otolith}$ values in warmer water and higher (more positive) $\delta^{18}O_{otolith}$ values in cooler water (Høie et al. 2004; Patterson et al. 2013; Thorrold et al. 1997). Oceanographic processes, like evaporation, can also impact $\delta^{18}O_{otolith}$ values, and are also responsible for the covariation between salinity and oxygen isotopes (LeGrande and Schmidt 2006). Freshwater inputs reduce salinity and often have isotopically negative $\delta^{18}O_{water}$ values; therefore, $\delta^{18}O_{otolith}$ values can be used to understand fish movement or habitat shifts between estuarine and open sea environments (e.g., Hsieh et al. 2019).

In contrast, $\delta^{13}C$ in otoliths reflects a mixture of environmental dissolved inorganic carbon in the water ($\delta^{13}C_{water}$) and metabolic carbon from food, with the majority coming from dissolved inorganic carbonate (Kalish 1991; Martino et al. 2020; Thorrold et al. 1997). A higher metabolic rate or a greater reliance on respiratory metabolic carbon results in more negative values for $\delta^{13}C_{otolith}$, which means $\delta^{13}C_{otolith}$ provides a proxy for both metabolism and dietary carbon sources (Campana 1999; Chung et al. 2019; Kalish 1991). Conversely, increases in a fish's trophic level are correlated with increases in $\delta^{13}C_{otolith}$ (Grønkjær et al. 2013; Trueman et al. 2013). A multi-isotopic approach, using both $\delta^{18}O$ and $\delta^{13}C$ profiles across otolith growth increments, can be analysed to reconstruct an individual's environment, including temperature, habitat, and shifts in metabolic or dietary experiences over their life course (Campana 1999; Grønkjær 2016).

2.2. Study Species

Tāmure, or Australasian snapper, is an iconic fish species found throughout the Indo-Pacific region south of latitude 18°S, and it is one of the most abundant coastal fishes of the northern North Island (Parsons et al. 2014; Trnski and Roberts 2015). Adults are associated with a wide range of coastal habitats, including estuaries, harbours, reefs, mud, and sand, largely between 20-60 m depth but also up to 300 m (Francis 2012). Spawning timing varies regionally, and in Aotearoa, large spawning aggregations form in open water over an extended period during summer, beginning around September and ending around March (Parsons et al. 2014; Scott and Pankhurst 1992; Sim-Smith et al. 2013). Larvae settle in large concentrations in sheltered estuaries with structured habitats like seagrass, horse mussel beds, and sponge gardens. Juveniles measuring up to 6 cm FL (fork length: a standard measurement from the rostrum to the centre fork of the caudal fin) are common in estuaries, harbours and bays from December to April (Parsons et al. 2014; Sim-Smith et al. 2013; Trnski and Roberts 2015). Juveniles may spend up to two years in nurseries, but when they grow to 5-10 cm FL they usually undergo an ontogenetic shift and migrate out to coastal environments and deeper harbour waters, 5-20 m deep (Hamer and Jenkins 2004; Parsons et al. 2014, 2016). Growth in the first 6 months is largely correlated with sea surface temperature, but growth over the remaining life span is thought to be affected by access to food, which may in turn be limited in areas with high densities of tāmure (Parsons et al. 2014). Maturity is reached at 20-30 cm FL, or 2-5 years (Francis 2012; Hamer and Jenkins 2004; Parsons et al. 2014; Trnski and Roberts 2015), and they can live to a maximum age of 65 years in Aotearoa (Francis 2012). Most tāmure observed today are between 25-50 cm FL and they can grow to an estimated maximum length of 70 cm, though fish as large as 130 cm FL have been observed in Australia (Randall et al. 1997) and at least one individual recovered from the Tauranga Bay archaeological site in Northland, New Zealand was estimated to be nearly 120 cm FL in size (Nims 2022a).

Given their abundance, moderately large body-size, and habit of seasonal aggregation, it is not surprising that tāmure are the most ubiquitous and abundant fish represented in Māori archaeological fish catches from the northern North Island (Anderson 1997; Leach 2006; Leach and Boocock 1993; Nims 2022a; Smith 2013). Māori oral traditions and ethnohistorical observations indicate that Māori captured tāmure with hook and line, with nets, from shore, and from boats (Best 1929; Leach 2006; Poata 1929; Te Rangi Hiroa 1926). Mathematical fisheries models derived from five northern North Island archaeological tāmure catches suggest Māori fishing had minimal impacts on tāmure populations in most cases and used gear that preferentially selected for fish between 30-60 cm FL (Plank et al. 2018). Tāmure post-cranial elements (pectoral bones, pelvic bones, and vertebrae) are consistently underrepresented in Māori archaeological assemblages relative to the frequencies of identified cranial elements (Campbell 2016; Campbell et al. 2025b; Nims 2022a). Campbell et al. (2025b) noted these patterns are highly consistent with ethnohistoric observations that Māori preferentially targeted tāmure in late summer, discarded the heads, dried their catch, and removed the bodies for storage and consumption later at a separate location (Best 1929; Leach 2006; Paulin 2007).

A limited number of archaeological tāmure otoliths have been analysed using two distinct spectrometry techniques – trace element analysis and stable isotope analysis – that yield different kinds of information about tāmure ecology and environmental conditions in the past. A series of studies on the trace elements found in tāmure otoliths from four archaeological sites (see Figure 1A: Tauranga Bay, Omaha Beach, Long Bay Restaurant, and Ōtata) and modern fish catches examined changes in tāmure developmental biology, from the earliest Māori settlements through to the modern, industrial period. Using laser ablation inductively coupled plasma mass spectrometry to reconstruct patterns of tāmure habitat use over the life histories of individual fish, these authors demonstrated that tāmure were not affected by Māori transformations of terrestrial landscapes, even though deforestation had measurable impacts on nearshore water quality (Campbell et al. 2025a). They also showed that juvenile tāmure historically used nearshore and estuarine nursery habitats that have since become inhospitable for juveniles following recent siltation associated with European land-use practices (Campbell et al. 2021; Lilkendey et al. 2025; Sabetian et al. 2021).

Separately, Neil et al. (2011) analysed stable oxygen and carbon isotopes in six archaeological tāmure otoliths recovered from Layer 5 of the 1969 excavations at the Hot Water Beach site on the Coromandel Peninsula, and 16 modern tāmure that were collected during routine fisheries research off the peninsula between 1970-2007 (see Figure 1A). Both the δ^{18}O and δ^{13}C patterns in the archaeological tāmure otoliths were indistinguishable from those of the modern tāmure, suggesting the temperature, salinity, habitat use, and metabolic experiences of these fish from two different time periods were also the same. While the Layer 5 deposits from Hot Water Beach were not directly dated (Neil et al. 2011; Smith and James-Lee 2009), it is very likely that these tāmure were captured sometime between ca. 1330-1560 cal CE (95% confidence interval) based on Bayesian modelling of radiocarbon dates from Layers 4 and 6 (Nims 2022b). In this article, we compare Neil et al.'s (2011: Appendix Table A3) stable isotope results for Hot Water Beach and modern Coromandel tāmure otoliths to our results from Tauranga Bay as points of reference, and to begin building a sequence of marine climate history for northern Aotearoa.

3. Materials and methods

3.1. Tauranga Bay (P04/639), Northland

The Tauranga Bay site includes several areas of stratified shell, bone, and charcoal deposits that were exposed in eroding dune sands along the foreshore of Tauranga Bay Beach, Whangaroa (Campbell et al. ND) (see Figure 1B). Campbell et al.'s 2003 investigations focused on two areas of the site following consultation with hapū associated with Karangahape Marae: the "Southern Area" (Areas B, C, and D; total area 4 m x 1 m) and Area E (total area 0.5 m x 0.5 m). All excavated material was wet sieved on site with 2 mm mesh, producing large samples of vertebrate and molluscan remains that were retained for analysis.

The Southern Area was centred on a 12-m-long exposure of cultural material (Layer 3) under a mixed layer of sand and Māori cultural materials (Layer 2) that were potentially redeposited from Layer 3. These deposits contained numerous fish, bird, and pinniped remains, adzes, obsidian and chert flakes, and a variety of fishing gear made from moa bone, shell, and ivory.

In Excavation Area E, about 100 m west of the Southern Area, excavators identified three successive Māori cultural deposits separated by windblown sand lenses with smaller amounts of loose cultural material. Shell deposits in Area E varied in density and contained high concentrations of charcoal, and fire cracked rock, a possible cooking feature, and sparse artefactual material.

Radiocarbon dates from Tauranga Bay (Table 1) indicate cultural material in the Southern Area was most likely deposited in the fourteenth century, and the material at Area E was deposited up to 200-400 years later. One charcoal sample (Wk-17332) from Layer 3 of Area B was calibrated with the Southern Hemisphere atmospheric calibration curve ShCal20 (Hogg et al. 2020) to about 1290-1395 cal CE (Figure 2). Five other Southern Area radiocarbon dates from two marine shell samples and the unused portions of three tāmure otoliths that were sampled for stable isotope analysis show strong agreement with the charcoal date (Figure 2). Shell samples from Layer 6 and Layer 2 of Area E date to between the mid-1500s and about 1900 cal CE. These marine dates were all calibrated in OxCal (Ramsey 2021) using the marine calibration curve Marine20 (Heaton et al. 2020) with a local marine reservoir offset (ΔR) of -154 ± 38 (after Anderson and Petchey 2020). However, the substantial temporal variability in ΔR offsets observed across the South Pacific Ocean complicates the accuracy and precision of the Marine20 curve for this region (Petchey 2020; Petchey et al. 2023; Petchey and Schmid 2020). Fortunately, the single charcoal date from the Southern Area is sufficient to substantiate claims of early cultural deposition at Tauranga Bay during the 1300s CE (Figure 2).

3.2. Otolith isotope analysis

Nims identified numerous sagittal otoliths from tāmure, kahawai (*Arripis trutta*), maomao (*Scorpis* sp.), and hauture/kōheru (*Trachurus* sp./*Decapterus* sp.) in the Southern Area assemblages from Tauranga Bay, but only a very small number of tāmure, kahawai, and hauture/kōheru otoliths were recovered in the Area E assemblages. Because only one tāmure otolith was identified for Area E, our analysis focuses on the Southern Area assemblages only.

Table 1. Conventional radiocarbon ages (CRA) and calibrated age ranges for dated samples from Tauranga Bay.

Sample Number	Context	Material	CRA (BP)	$\delta^{13}C$ (‰)	Source	Calibrated 2σ Range (cal CE)
Wk-16912	Area E, Layer 2	shell (tuangi)	614 ± 31	1.4 ± 0.2	Campbell et al. nd	1541–1947
Wk-16914	Area E, Layer 6	shell (tuangi)	624 ± 32	1.3 ± 0.2	Campbell et al. nd	1531–1896
Wk-53181; CAT3-6	Area C, Layer 3	otolith (tāmure)	1073 ± 21	-1.0 ± 0.5	*this paper*	1196–1448
Wk-53180; CAT2-2	Area B, Layer 3	otolith (tāmure)	985 ± 19	-2.2 ± 0.5	*this paper*	1276–1510
Wk-53179; CAT2-1	Area B, Layer 3	otolith (tāmure)	966 ± 20	n/a**	*this paper*	1285–1525
Wk-16911	Area B, Layer 3	shell (tuangi)	1057 ± 32	0.6 ± 0.2	Campbell et al. nd	1204–1464
Wk-13977	Area B, Layer 3	shell (mussel)	1028 ± 36	0.6 ± 0.2	Campbell et al. nd	1227–1485
Wk-17332	Area B, Layer 3	charcoal *	683 ± 33	-24.9 ± 0.2	Campbell et al. nd	1290–1395

** Mixed sample of* Coprosma *sp., mapou, pōhutukawa, puriri*

*** The $\delta^{13}C$ value for this sample was measured on prepared graphite using the AMS spectrometer. The AMS-measured $\delta^{13}C$ value can differ from the $\delta^{13}C$ of the original material and it was not reported by the radiocarbon dating laboratory.*

Ten of the largest whole, left-sided, archaeological tāmure otoliths from Layer 3 of the Southern Area were selected for stable isotope analysis by the Taihoro Nukurangi / National Institute of Water and Atmospheric Research (NIWA) Atmospheric Isotope Laboratory in Wellington, New Zealand. Large otoliths were prioritised because we expected they represent older fishes with longer time-series of isotope values, and because the unused portions of larger otoliths would provide more material for subsequent radiocarbon analysis. More suitable otoliths were available for analysis, but we only had sufficient resources to analyse the whole life history of approximately 10 fish in detail.

NIWA technicians Josette Delgado and Rahul Peethambaran embedded otoliths in resin, sliced them, and cut 1.4 mm transverse thin sections that were mounted to glass slides. They then used a micromill to collect a sequence of 35 µg carbonate samples from each otolith to create a life history of stable isotope values for individual tāmure. Delgado and Peethambaran carefully milled one or more samples from the central, summer growth of each annual growth ring. However, smaller annuli from growth later in life (median age of year 4+) were more compact than the size of the micromill auger, such that carbonate from multiple growth rings was necessarily collected together as mixed samples.

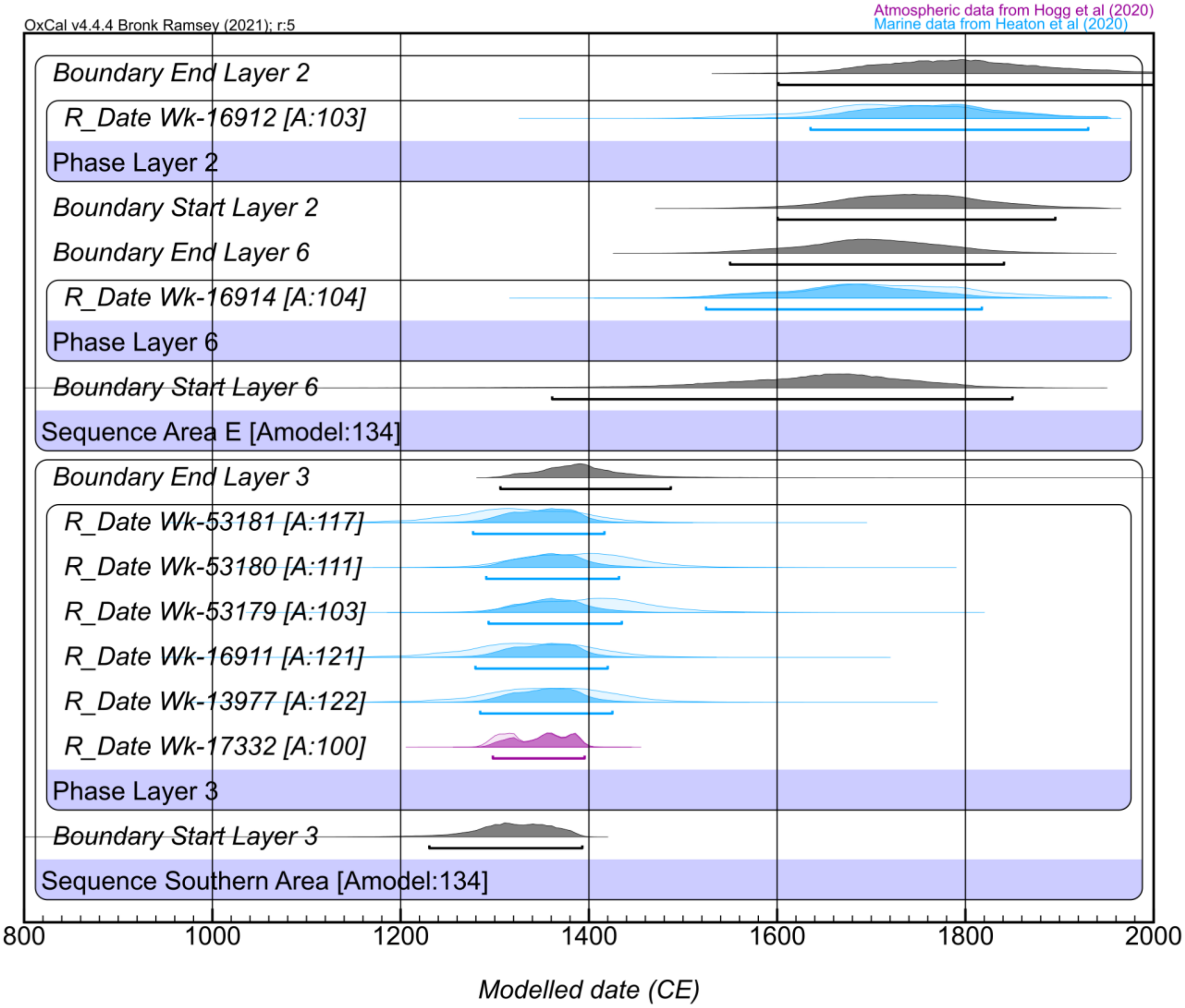

Figure 2. Sequence models of calibrated radiocarbon dates from Area E and the Southern Area of Tauranga Bay. Bars under probability distributions show 95% confidence ranges of modelled radiocarbon dates.

Otolith carbonate samples were analysed by NIWA staff with a MAT252 isotope ratio mass spectrometer coupled with a Kiel III carbonate device at the NIWA Stable Isotope Analytical Facility. Sample ^{13}C/^{12}C and ^{18}O/^{16}O isotope ratio measurements were normalized to the Vienna PeeDee belemnite scale (VPDB δ^{13}C and VPDB δ^{18}O) using single-point corrections from daily analysis of the international standard reference material, NBS-19. Measurement precision was determined to be ±0.03‰ for δ13C and ±0.06‰ for δ18O on the basis of repeated measurements of calibration standards. Accuracy or systematic error was not determined as no check samples were run.

4. Results

Annual growth rings show the 10 left tāmure otoliths analysed from the Tauranga Bay archaeological site are from fish that lived to a median age of 33 years old (range: 15 to 52 years old) before they were captured by Māori fishers about 600-700 years ago (Figure 3). NIWA staff milled a total of 152 carbonate samples from these otoliths, but three samples were not analysed and results for 10 samples were not reliable due to measurement errors. Stable isotope values for the remaining 139 samples document changing environmental conditions over the life histories of 10 tāmure, with a median number of 15 analysed samples per otolith (range: 6 to 17 samples; Figure 3). Nearly half of the carbonate samples represent one or fewer years of growth in the first six years of life, but samples collected from year 4+ represent growth across increasingly large numbers of annuli (range = <1 to 7 annuli/sample, median = 2 annuli/sample).

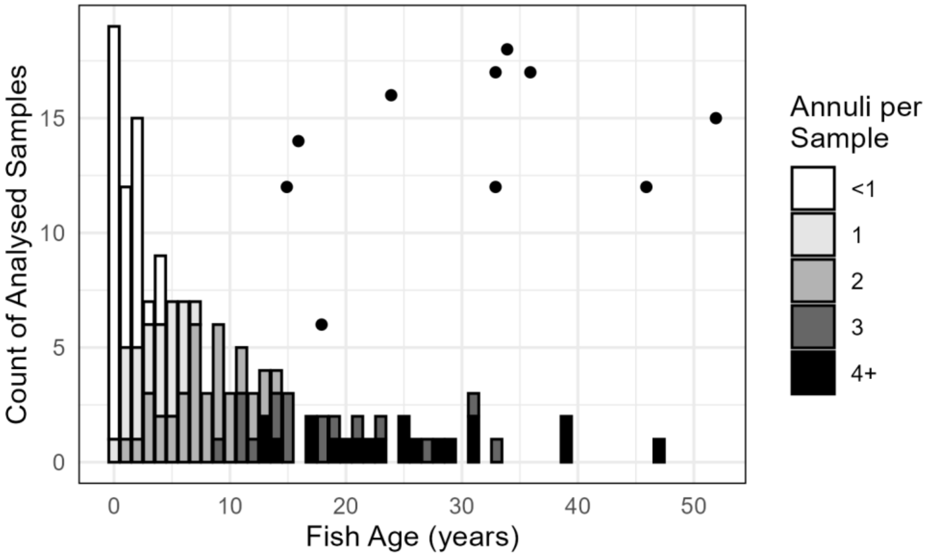

Figure 3. Number of analysed carbonate samples for individual otoliths by maximum fish age (black dots) and for all otoliths by the youngest annulus in each sample (histogram bars) and the number of annuli milled per sample (colour scale).

Analysis of stable oxygen and carbon isotopes from these samples indicates that most tāmure deposited at Tauranga Bay experienced similar environmental conditions over their lives. The $\delta^{18}O$ values ranged between –1.16‰ to +1.42‰, with one outlier of –2.18‰ recorded in one sample from otolith CAT3-8 that might represent measurement error or a major, short-term habitat change between years 1-2 of age (Figure 4). Most individuals exhibited a predictable trend of more negative $\delta^{18}O$ values at the beginning of their life, followed by a shift to more stable, higher $\delta^{18}O$ values after 2-5 years of age. These patterns are consistent with modern tāmure development, with juveniles inhabiting shallow, warmer waters, potentially in estuaries or embayments with freshwater input (depleted in ^{18}O), such as Whangaroa Harbour (Figure 1B), and adults inhabiting deeper, cooler waters that are likely more saline (enriched in ^{18}O), such as Tauranga Bay. Notably,

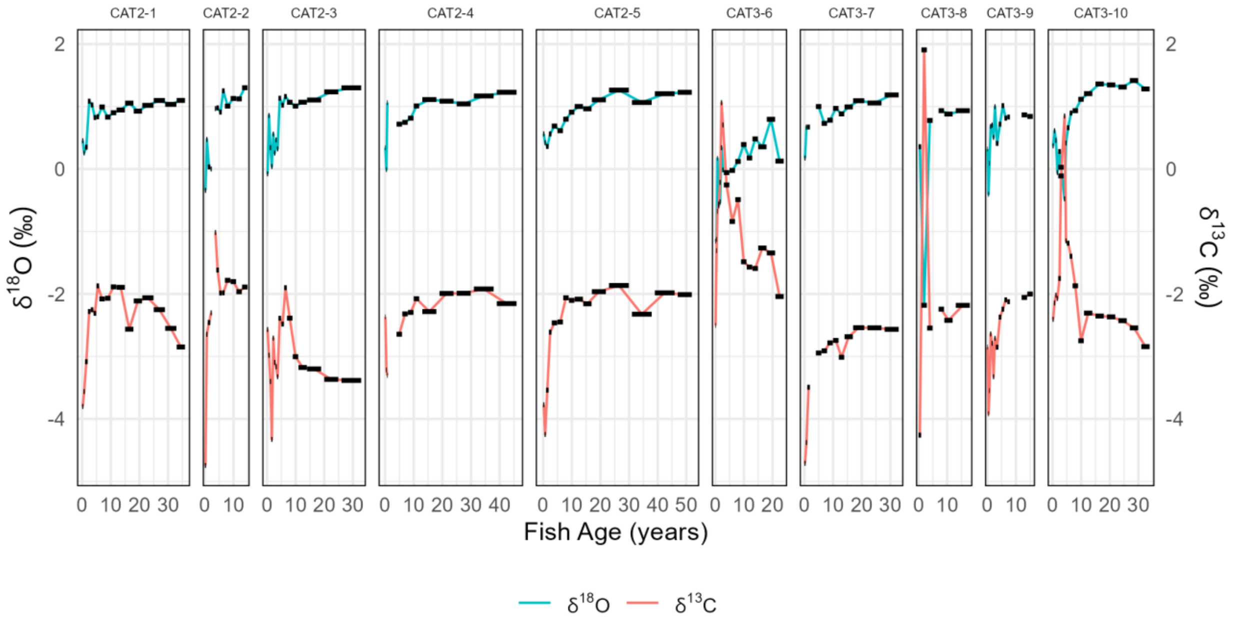

Figure 4. Stable oxygen ($\delta^{18}O$ – blue lines) and carbon ($\delta^{13}C$ – red lines) values by fish age in years for 10 tāmure otoliths from Layer 3, Southern Area, Tauranga Bay. Width of black bars indicates the number of growth rings per sample. Line breaks show gaps where samples were not analysed or were omitted due to measurement error.

one tāmure (otolith CAT3-6) recorded consistently lower $\delta^{18}O$ values than other fishes across much of its life history (Figure 4), indicating this fish may have resided in a more protected habitat.

The $\delta^{13}C$ values of tāmure otoliths from Tauranga Bay ranged between –4.75‰ and +1.06‰, with an outlier of +1.91‰ recorded in the same sample from otolith CAT3-8 that produced an outlying oxygen isotope measurement (Figure 4). The lifetime trends for these tāmure showed a rapid increase in $\delta^{13}C$ values over the first 2-5 years of age, followed by a plateau or gradual decrease in $\delta^{13}C$ values over the span of their adult life. These patterns are consistent with expectations from the life history of teleost fishes, which often see an increase in trophic level (increasing $\delta^{13}C$) and decreasing metabolism (decreasing $\delta^{13}C$) over time, causing $\delta^{13}C$ to peak at the age of maturity (Campana 1999). However, half of the tāmure (otoliths CAT2-2, CAT2-3, CAT3-6, CAT3-8, and CAT3-10) had particularly extreme peaks in $\delta^{13}C$ at the expected onset of sexual maturity that rapidly declined to relatively moderate adult average values (Figure 4). For two fish (otoliths CAT3-8 and CAT3-10), these peaks have an inverse correlation with $\delta^{18}O$ values, which may indicate that these tāmure briefly entered an estuarine habitat with very different $\delta^{18}O_{water}$ and $\delta^{13}C_{water}$ profiles. It is also notable that one fish with more negative $\delta^{18}O$ values (CAT3-6) also had more positive $\delta^{13}C$ values over its lifetime relative to the other fish in this study.

Pooling our oxygen and carbon isotope results with the values for archaeological tāmure from Hot Water Beach and modern Coromandel Peninsula tāmure reported by Neil et al. (2011) indicates that most of the tāmure from these two studies experienced largely similar ranges of environmental and somatic conditions over their lifetimes. Across 683 carbonate samples from a total of 35 northern North Island tāmure otoliths, nearly all $\delta^{18}O$ results are tightly clustered between about –0.3‰ and +1.8‰, and nearly all δ^{13}C results are between –4.2‰ and –0.5‰ (Figure 5). While many tāmure have individual otolith samples that are outliers, there is one fish – CAT3-6 from Tauranga Bay – that lies well outside of this cluster, and likely experienced a very different set of environmental conditions than the other sampled tāmure.

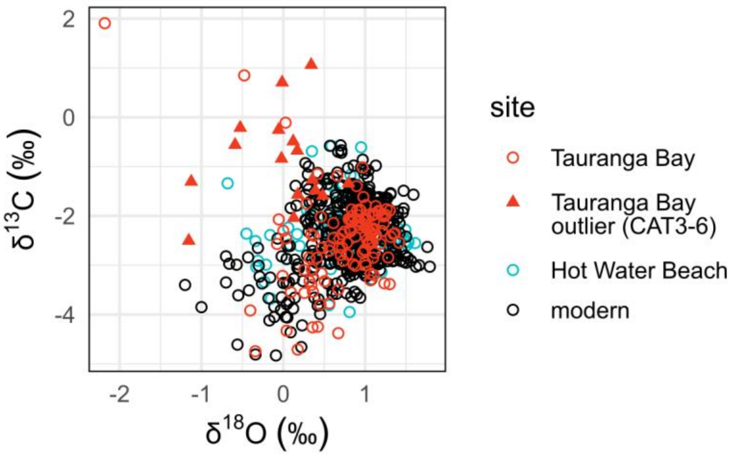

Figure 5. Scatterplot of stable oxygen (δ^{18}O) and carbon (δ^{13}C) isotope values from northern North Island tāmure otoliths. Filled red triangles indicate single outlier otolith (CAT3-6) from Tauranga Bay (Layer 3, Southern Area - red circles) samples. Layer 5, 1969 excavations, Hot Water Beach (Layer 5, 1969 excavations - blue circles) and modern Coromandel Peninsula (black circles) tāmure data from Neil et al. (2011: Appendix Table A3).

Comparing stable oxygen isotopes in tāmure otoliths from each site shows that nearshore climate conditions were virtually identical in the fourteenth centuries and/or fifteenth centuries in northern Aotearoa, and nearshore waters were warmer than during the late twentieth century. For this analysis, we considered variation across three separate types of otolith samples: (1) core samples, (2) a lifetime average of all samples, and (3) the last, outermost sample of each otolith. Samples taken from (1) the core of otoliths reflect conditions at the very beginning of larval development during summer or early fall, providing a fixed, seasonal point of comparison. Tauranga Bay otoliths had moderately more positive δ^{18}O values in core samples relative to archaeological Hot Water Beach or modern Coromandel Peninsula otoliths (Figure 6), but a Kruskal-Wallis rank sum test shows this difference was not statistically significant (Table 2). In contrast, both archaeological sets of otoliths had more negative δ^{18}O values relative to modern tāmure for both (2) the lifetime averages of otolith samples, and (3) the last samples of each otolith (Figure 6). Notably, Neil et al. (2011) only collected samples from the full isotopic life history for five of the 19 modern tāmure in their study. The differences between the last carbonate samples of each otolith are not statistically significant, but there are statistically significant differences in the lifetime averages of otoliths from each site (Table 2). A post hoc test shows the modern otoliths have significantly more positive δ^{18}O values compared to Hot Water Beach otoliths, but they are not significantly different from Tauranga Bay otoliths (Table 3). Overall, these results suggest water temperature and salinity on the east Northland coast between 1280-1440 cal CE were comparable to modern Coromandel Peninsula conditions, but the tāmure captured at Hot Water Beach between

1330-1560 cal CE experienced warmer waters or more freshwater input than Coromandel tāmure from the twentieth century.

Meanwhile, comparing carbon isotopes in tāmure otoliths across the same three types of samples shows tāmure from these sites experienced no statistically or practically significant differences in diet or metabolism. If tāmure diets, trophic levels, or metabolism had changed, or if there were differences in the dissolved inorganic carbonate levels of coastal waters, we would expect these to be reflected in δ^{13}C values. However, δ^{13}C in (1) core samples, (2) lifetime averages, and (3) the last samples of Tauranga Bay and Hot Water Beach otoliths are all statistically indistinguishable from each other and from modern Coromandel Peninsula otoliths (Figure 6; Table 2).

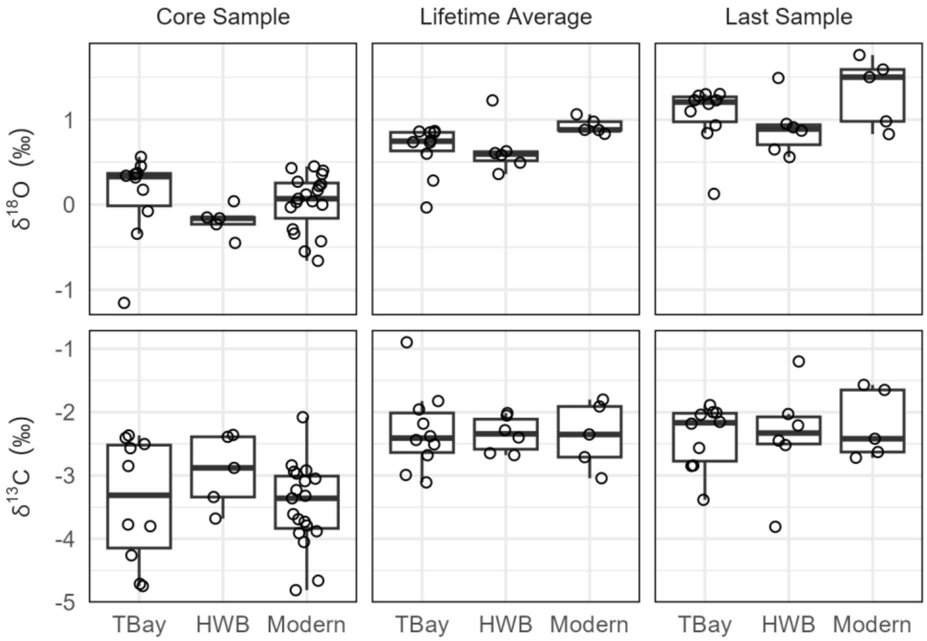

Figure 6. Boxplots of stable oxygen (δ^{18}O) and carbon (δ^{13}C) isotopes in tāmure otoliths from archaeological deposits at Tauranga Bay (Layer 3, Southern Area - "TBay") and Hot Water Beach (Layer 5, 1969 excavations - "HWB") and from modern Coromandel Peninsula fish catches ("Modern"). "Core Sample" = comparison of the samples from each otolith core; "Lifetime Average" = comparison of mean isotope values from all samples for individual otoliths; "Last Sample" = comparison of the outermost sample collected from each otolith.

Table 2. Results of Kruskal-Wallis test comparing rank sums of stable oxygen and carbon isotope values in archaeological ("TBay" = Tauranga Bay, "HWB" = Hot Water Beach) and modern tāmure otoliths. "Core Sample" = comparison of the samples from each otolith core; "Lifetime Average" = comparison of mean isotope values from all samples for individual otoliths; "Last Sample" = comparison of the outermost sample collected from each otolith.

Isotope	Comparison	median (‰)			n	H	p value	ε^2	Effect Size
		TBay	HWB	Modern					
δ^{18}O	core sample	+0.33	−0.16	+0.07	34	4.30	0.117	0.13	moderate
	lifetime average	+0.75	+0.60	+0.88	21	6.83	0.033*	0.34	large
	last sample	+1.21	+0.89	+1.50	21	3.79	0.150	0.19	large
δ^{13}C	core sample	−3.31	−2.88	−3.36	34	2.69	0.260	0.08	moderate
	lifetime average	−2.41	−2.34	−2.35	21	0.02	0.990	<0.01	small
	last sample	−2.17	−2.33	−2.42	21	0.18	0.916	0.01	small

*groups are significantly different ($p < 0.05$)

Table 3. Results of Dunn's pairwise rank sum test with Bonferroni adjustment ("adj. *p* value") comparing lifetime average stable oxygen values in tāmure otoliths from archaeological ("TBay" = Tauranga Bay, "HWB" = Hot Water Beach) and modern tāmure otoliths.

Isotope	Comparison	Group 1	n_1	Group 2	n_2	z	p value	adj. p value
δ^{18}O	lifetime average	TBay	10	HWB	6	-0.531	0.596	1.000
		TBay	10	Modern	5	2.207	0.027	0.082
		HWB	6	Modern	5	2.449	0.014	0.043*

*groups are significantly different (adjusted $p < 0.05$)

5. Discussion and Conclusion

Stable oxygen and carbon isotope analysis of tāmure otoliths from Tauranga Bay, Northland produced new information about Aotearoa's seascapes from a fish's perspective. Through larval development, maturation, and adulthood, these tāmure experienced relatively uniform marine conditions as they settled in nurseries with warm, potentially estuarine conditions, and then migrated into deeper colder waters as they aged, before they were ultimately captured by Māori fishers, ca. 1300s cal CE. These stable isotope patterns are consistent with the findings from trace element analysis of 10 additional tāmure otoliths from Tauranga Bay, as well as archaeological otoliths from the Hauraki Gulf, that show tāmure juveniles historically had prolonged residencies in estuarine nurseries, which are not used by tāmure today (Lilkendey et al. 2025).

The variance in δ^{13}C values from Tauranga Bay tāmure and the anomalous δ^{18}O values for one fish may indicate they had similarly diverse mobility patterns as modern tāmure stocks. Today, some tāmure are known to reside within their natal home-range for their whole lives, and others make large-scale movements over 100s of kilometres (Curley et al. 2013; Fowler 2023; Francis 2012; Parsons et al. 2014). The differences between tāmure with logarithmic δ^{13}C profiles and tāmure with extreme peaks in δ^{13}C suggest that these two groups of tāmure may have recruited to

Tauranga Bay from qualitatively different nursery habitats than others. While it is not possible to source fish to one nursery in particular from stable isotope analysis, it is reasonable to suspect that at least some of the studied tāmure settled in and subsequently migrated out from the enclosed waters of Whangaroa Harbour (see Figure 1B), or another Northland harbour. Many of these harbours are considered key nursery sites for modern tāmure stocks (Morrison et al. 2019). One fish (otolith CAT3-6) that had notably more negative δ^{18}O values relative to other tāmure likely resided in a warmer – and/or potentially less saline – habitat than any of its peers for much of its 24-year-long lifespan. Other tāmure may have originated from relatively exposed rocky reefs along the headlands of the east Northland coast and adjacent coastal islands.

Adding our results from Tauranga Bay to Neil et al.'s (2011) prior study of tāmure otoliths also advances our understanding of marine climate conditions during the initial period of Māori settlement in Aotearoa. These fish may have lived up to about 200 years apart in time (~1280-1440 cal CE at Tauranga Bay vs. ~1330-1560 cal CE at Hot Water Beach), they were captured 277 km apart from one another, and their otoliths had moderate differences in δ^{18}O values that were not statistically significant. However, these results provide some indication that the northern North Island's marine climate experienced some variability over the first two centuries of Māori habitation and fishing. The Hot Water Beach otoliths also had significantly more negative δ^{18}O values compared to modern Coromandel Peninsula tāmure, while oxygen isotope values from the Tauranga Bay otoliths were statistically indistinguishable from modern tāmure. From these observations, we can conclude that northern Aotearoa's fourteenth century marine climate was likely very similar to conditions observed over the course of the twentieth century. But coastal waters were warmer and/or less saline during the late-fourteenth or the fifteenth century than they were during the modern period.

Overall, these findings are consistent with existing reconstructions of terrestrial and Pacific Ocean conditions and provide additional evidence of a warm climatic period in the fourteenth and/or fifteenth centuries. Terrestrial climate models indicate that atmospheric temperatures oscillated between mild to warm conditions on a multi-decadal scale between 1200-1500 CE (Ahmed et al. 2013; Cook et al. 2006; Lorrey et al. 2020), with a dry weather regime from 1250-1350 CE followed by a high-rainfall regime between 1400-1500 CE (Lorrey et al. 2011). Therefore, the lower δ^{18}O signal in Hot Water Beach otoliths may reflect warmer than normal conditions, increased freshwater run-off due to higher-than-normal precipitation, or both. These patterns are also concordant with sea surface temperature reconstructions from Sr/Ca element ratios in coral cores from the last 627 years in Fiji (where seas were substantially warmer than twentieth century conditions from at least 1370 CE to 1553 CE), and with models that suggest sea surface temperatures are strongly correlated across the southwest Pacific from Fiji to Aotearoa (D'Olivo et al. 2024).

Unfortunately, our results do not yet provide any additional insight into hypothesized changes in southwest Pacific surface flows during the transition period from the Medieval Climatic Anomaly to the Little Ice Age (Petchey and Schmid 2020), or during the Little Ice Age itself (Komugabe-Dixson et al. 2016). Additional sea surface temperature reconstructions from archaeological samples may contribute new understanding of Aotearoa's complex environmental histories in the future. Critically, additional analysis of tāmure otoliths dating to between 1500-1920 cal CE and from other coasts of Aotearoa is needed to fill the existing gap in our stable isotope chronology and explore the effects of the Little Ice Age on marine ecosystems and Māori fisheries. While otoliths of other fishes are rarely represented in North Island archaeological assemblages, the scope of the current isotopic dataset could also be usefully broadened by including hoka otoliths from the South Island (Neil et al. 2011) or marine shellfish species (Butler et al. 2019) to improve our understanding of the complex relationships between Māori and their seascapes.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author, RN, upon reasonable request.

Partnerships

Excavations at Tauranga Bay were conducted in consultation with the Karangahape Marae, kaitiaki of Tauranga Bay.

Conflicts of Interest

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Author Contributions

Conceptualization, RN and CS; methodology, RN and CS; excavation, MC; resources, MC; writing—original draft preparation, RN and CS; writing—review and editing, RN, CS, and MC; visualization, RN; funding acquisition, RN and MC. All authors have read and agreed to the published version of the manuscript.

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