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Local isotopic ecologies matter in the Pacific: an example from Waya Island, Fiji

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Abstract

The use of stable isotope analysis (SIA) has contributed significantly to our understanding of the diets of people who lived in Oceania in the past. While this work has relied extensively on Pacific-wide baselines, in this study, we demonstrate the importance of understanding local isotopic ecologies for the application of SIA to the interpretation of past human diets across the Pacific Islands. We expand on previous isotopic analysis from Waya Island, Fiji, by analysing additional human (n = 3) and faunal (n = 15) remains using δ^{13}C and δ^{15}N data from bone collagen. The analysed samples come from human and faunal individuals excavated from two different sites, Y2-25 "Olo" (2800-2400BP) and Y2-39 "Qaranicagi" (760-660 BP). We used a multispecies approach to SIA to capture aspects of the local isotope ecology of Waya Island, informing our interpretation of the human isotopic data. Through a re-analysis of previously published data alongside these new contributions, we demonstrate how intra-regional isotopic variation in marine environments may complicate the use of Pacific-wide baselines for understanding past human diets.

Keywords: Fijian archaeology; stable isotope analysis; isotope ecology; multispecies

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1. Introduction

In Oceania, the Pacific islands settled by related human groups beginning 50kya in New Guinea and then to the east (Cochrane and Hunt 2018), A general shift from marine-based to terrestrial-based diets was first proposed by Groube (1971). This hypothesis has been largely supported with isotopic analyses from sites on larger islands like Viti Levu (e.g., Phaff *et al.* 2016) and Efate (e.g., Bentley *et al.* 2007; Kinaston *et al.* 2014; Valentin *et al.* 2014). When people first arrived in these islands, they subsisted, in part, on abundant natural resources, including fish. Over time this changed as agricultural practices intensified, until diets included more terrestrial resources, in particular domesticated plants and animals. On smaller islands where there is less space to modify the environment to suit agriculture, this transition is not always clear. Dietary data from small islands in Fiji (e.g., Field *et al.* 2009; Jones & Quinn 2009a) have mixed results, and temporal changes in dietary practices can vary significantly.

One example is Waya Island, a small 22km^2 island in western Fiji (Figure 1). Previous isotopic analysis of human and faunal remains from Waya was undertaken by Field *et al.* (2009) at two different sites, Y2-25 “Olo” (2800-2400BP) and Y2-39 “Qaranicagi” (760-660 BP), Based on this analysis the authors argued for a change from a marine-based to more terrestrial diet over time. The current study increases the sample size of isotopic results from these two sites and includes more faunal material, including fish remains identified to a family level. By building on the work of Field *et al.* (2009), a picture can be formed of the isotopic ecology of Waya Island, which can be compared to other studies in Fiji and across Oceania to understand the isotopic variation present in these small-island land- and marine-scapes.

Establishing faunal or flora isotopic data for comparison to human data, sometimes called baselines, is an important part of SIA analysis aimed at understanding past human diets. These data help to contextualise human carbon and nitrogen isotope values and there have been a number of studies across Oceania contributing data to or using a ‘Pacific-wide baseline’ (e.g., Commendador *et al.* 2013; Kinaston *et al.* 2013). Many of these studies have also recognised the value in local (site-specific if possible) sampling of faunal material to understand local ‘baselines’ (e.g., Allen and Craig 2009; Kinaston *et al.* 2013) and acknowledged the potential for inter-island variation (Commendador *et al.* 2013). Recent work across the entire Pacific basin has identified issues with non-specific baselines due to geographical and ecological variation in carbon and nitrogen isotopes in marine environments (Boulanger *et al.* 2025). This paper aims to show the value of multi-species and context-appropriate stable isotope analyses in the Pacific to understand the histories of settlement on small islands. We investigate the relationships between people and the faunal species they exploited in one small Pacific Island, Waya Island, and demonstrate the need to critically evaluate the applicability of ‘Pacific-wide’ baseline data across all island environments for the purpose of exploring human diet and subsistence change.

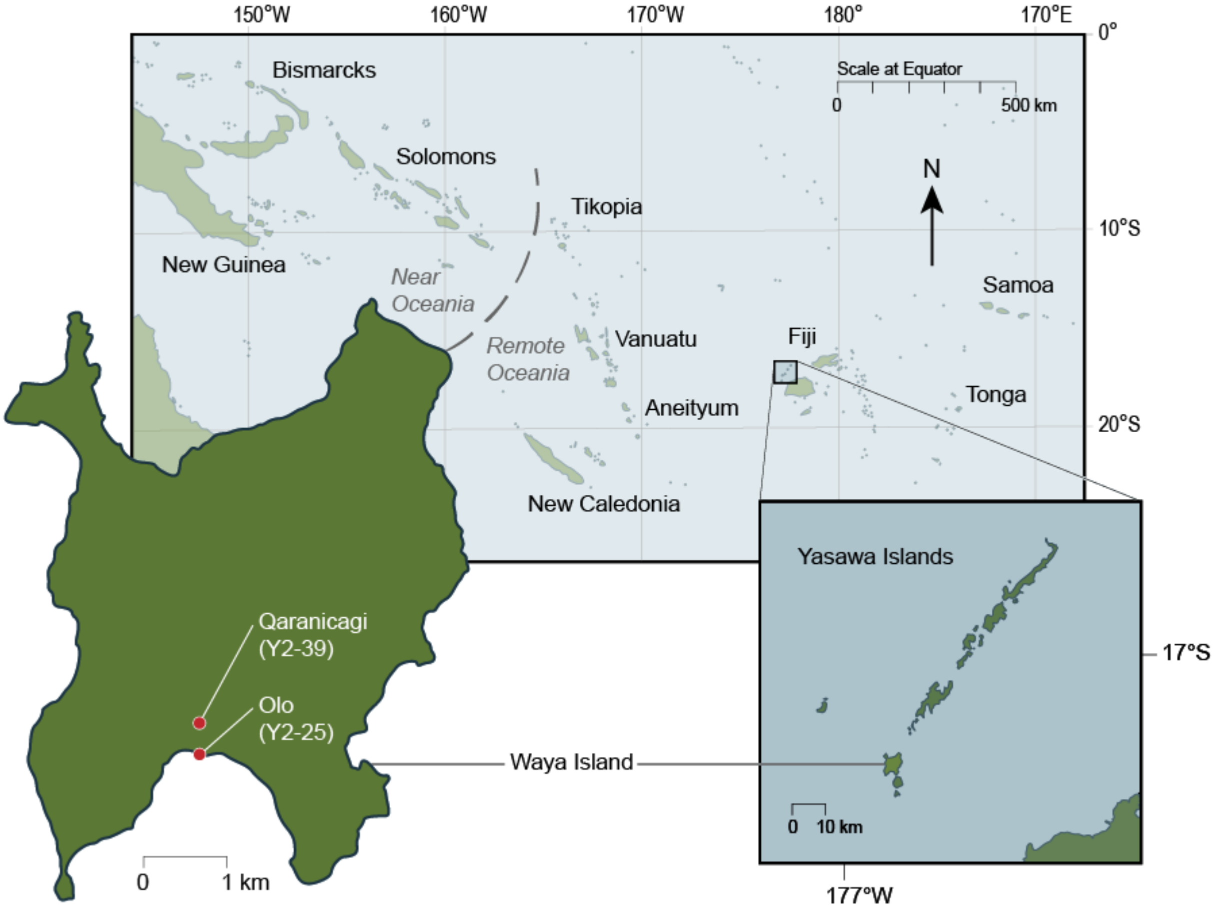

Figure 1: Waya Island map showing sites mentioned in text, and Waya Island in relation to the rest of Fiji/Pacific Islands

2. Stable isotope analysis (SIA) in island and marine environments

Carbon and nitrogen isotopes are a commonly used tool in archaeology to reconstruct human diets and are becoming more common in multi-species archaeology to characterise ecological and human-mediated relationships between different species. Particularly in the island environments of the Pacific, where people were able to exploit a range of terrestrial and marine species, it is important to consider both land- and sea-scapes when using SIA in dietary studies since their isotopic ecologies are distinct. In the following section, we briefly summarise relevant information on isotopic systems in the Pacific.

2.1. Carbon

The main source of carbon in terrestrial environments is CO_2. Different methods of photosynthesis results in varying discrimination of carbon isotopes between plants, introducing variation into the $\delta^{13}C$ values of the plants and animals that consume them (Boutton *et al.* 1991; van der Merwe 1982). C_3 photosynthesis is the most common method used by plants in temperate environments. The $\delta^{13}C$ values in C_3 plants range between -20‰ to -35‰ (van der Merwe 1982). In the Pacific, most of the plants consumed by Lapita and other ancient peoples, like taro and yams, are C_3 (Yoshinaga *et al.* 1991). C_4 photosynthesis occurs in plants growing in arid environments (van der Merwe 1982). The $\delta^{13}C$ values in C_4 plants typically range from -9‰ to -16‰ (van der Merwe 1982). There are not many C_4 plants in the Pacific that people consumed, except for domesticated sugar cane and some seaweeds (Ambrose *et al.* 1997).

The main carbon source in marine ecosystems is dissolved bicarbonates in the ocean, which have a $\delta^{13}C$ value of ~0‰ (Schwarcz & Schoeninger 1991). Other carbon sources include runoff (where $\delta^{13}C$ values will reflect those of local terrestrial plants) and dissolved CO_2 (which has the same $\delta^{13}C$ value as atmospheric CO_2) (Schoeninger & Moore 1992). When analysing isotopic data in marine systems, it is important to understand the factors that produce the isotopic values at the base of the food web (i.e., primary producers) (Kurle and Whorter 2017). Marine plants undergo C_3 photosynthesis but the various carbon sources in the ocean results in different $\delta^{13}C$ values, and they range between -31‰ to -7‰ (van der Merwe, 1982). While in reef and shallow water environments, benthic macrophytes and seagrasses tend to have more positive $\delta^{13}C$ values, pelagic food pathways are depleted in ^{13}C in comparison (Pinnegar and Poluonin 1999).

2.2. Nitrogen

The main nitrogen source in terrestrial environments is atmospheric N_2 (DeNiro 1987). N_2 becomes bioavailable for organisms through fixation, a process where microorganisms in soils convert N_2 into other compounds (like nitrates), allowing them to be taken up by plants (Chen *et al.* 2003). Some plants, such as legumes, have symbiotic relationships with these microorganisms, allowing them to directly fix atmospheric N_2 themselves (DeNiro 1987). The $\delta^{15}N$ values of these plants are similar to the $\delta^{15}N$ value of atmospheric N_2, ~0‰ (Schoeninger & Moore 1992). Other plants cannot access N_2 directly from the atmosphere, so they must access bioavailable nitrogen from decomposing organic matter in soils (DeNiro 1987). Variations in soils are reflected in the $\delta^{15}N$ values of these plants (Craine *et al.* 2015). These changes are reflected throughout the food chain. Additionally, due to isotopic discrimination in metabolic processes, consumer tissues are more enriched in ^{15}N than their diet (Wada *et al.* 1991). This enrichment results in incremental increases in $\delta^{15}N$ in food webs that increase with trophic level, however this amount of increase is variable and dependent on factors such as taxon, diet quality, and tissue type analysed (Stephens *et al.* 2023).

In marine environments, organisms access nitrogen through dissolved nitrate and ammonium ions synthesised from dissolved atmospheric N_2 (DeNiro 1987). This fixation mainly occurs through cyanobacteria, also known as blue-green algae (DeNiro 1987). After this fixation, nitrogen isotopes enter the food chain. The complexity of marine food webs means that marine organisms commonly have enriched $\delta^{15}N$ values compared to terrestrial animals (Hard & Katzenberg 2011). Marine environments have more trophic levels, as consumers eat from multiple trophic levels below them to gain their required energy. The dietary behaviour of marine species is therefore relevant to understanding the $\delta^{15}N$ values of the people consuming them. People with a marine-based diet will show enriched $\delta^{15}N$ values compared to those with terrestrial-based diets (Schwarcz & Schoeninger 2011).

2.3. Sources of isotopic variation in Oceania

Primary producers form the basis of food webs and plant $\delta^{13}C$ values are propagated through these systems into the tissues of consumers. $\delta^{13}C$ values will be affected by factors that influence photosynthesis, like temperature (Tieszen 1991). Air temperatures in the tropical Pacific are relatively stable, however, and unlikely to produce variation across plant species in terrestrial environments. On the other hand, dense tropical rainforests have a canopy effect, and plants in the canopy will have enriched $\delta^{13}C$ values compared to plants at the ground (van der Merwe & Medina 1991). This occurs due to CO_2 cycling, photosynthetic pathways in lower light, and other physiological factors (van der Merwe & Medina 1991).

It is also important to consider variation in marine carbon isotope values. The carbon isotope values of marine primary producers vary by geographic region in a broad sense and are impacted by several key variables: 1) the dissolved inorganic carbon (DIC) pool which can vary by temperature and location; 2) physiological and morphological traits of different phytoplankton species; 3) isotopic discrimination from differences in photosynthesis; and 4) species-specific growth rates of phytoplankton (Michener and Kaufman 2007). Gradients of $\delta^{13}C$ between shallow (inshore) and pelagic environments are important to characterise to understand potential fish values as consumed by humans, and can contribute to our understanding of where people were fishing in the past and what environments these fish were living in.

Anthropogenic effects on the environment have altered $\delta^{15}N$ values over time, and there can be differences in these values due to plant cultivation and animal husbandry that are not present in wild fauna (DeNiro & Epstein 1981). Fertilisers can enrich $\delta^{15}N$ values in plants by 2-6‰, and these changes can be propagated through the food chain (Bogaard *et al.* 2007; Szpak 2014). This makes it more challenging to identify the proportions of plants and animals in the diet, as the size of the trophic level enrichment changes. Chemical fertilisers would not have been used in ancient Fiji, but animal manure may have been (Ramsay 1999). Animal manure has high $\delta^{15}N$ values (Bogaard *et al.* 2007) and seabird guano has a $\delta^{15}N$ value of 38.1‰. This material which is enriched in ^{15}N can significantly alter the $\delta^{15}N$ values of soils and plants in coastal sites (Szpak *et al.* 2012). Other agricultural practices may also affect $\delta^{15}N$ values. The use of swidden agriculture and burning of forests in Fiji in the past and present (Roos *et al.* 2016) can change the normal distribution and cycling of nutrients in soils for a short time, increasing $\delta^{15}N$ values (Szpak 2014).

Environmental variation is particularly prominent in marine $\delta^{15}N$ values, as the isotope composition of dissolved nitrate and ammonium in water sources is dependent on the local environment (DeNiro 1987). There is considerable variation of $\delta^{15}N$ values in the Pacific Ocean, affecting the $\delta^{15}N$ values of marine plants (Schoeninger & DeNiro, 1984). In coral reef environments, common in Oceania, there is a greater abundance of N_2-fixing organisms like cyanobacteria which depletes $\delta^{15}N$ values in reef fish compared to pelagic fish (Leach *et al.* 2003). However, localised nitrogen upwelling, such as seen in the $\delta^{15}N$ values of fish from the Marquesas, leads to increased $\delta^{15}N$ values in primary producers (Michener and Kaufman, 2007: 249) and ultimately in the tissues of fish around these islands (Fey *et al.* 2021). These differences mean that the nitrogen isotopic composition of marine species exploited by people in the past could vary significantly based on location and other environmental factors, not just the trophic position of those species. Furthermore, Boulanger *et al.* (2024: 1) have recently demonstrated ecological and geographic variation in $\delta^{13}C$

and δ^{15}N values in Southeast Asian and Pacific fish species, highlighting the importance of "locally-based baseline datasets".

2.4. Sampling to understand isotopic variation in Oceania

Ideally, samples of faunal or plant species from the same site or island of interest are needed to place results into their temporal and spatial context (Kinaston *et al.* 2013; Makarewicz and Sealy 2015). Faunal (and plant) samples that come from the period and location of the archaeological site under investigation allows us to better capture the local environment, including isotopic variation. Including a wide variety of species, particularly fish species with different dietary behaviours and ecological niches, is crucial for characterising local isotope ecologies. The relevance of marine ecology, including marine niches, is clear in the isotopic data derived from modern Southeast Asian and Pacific fish species (Boulanger *et al.* 2025). Fish habitats, dietary behaviours, and life-histories all have the potential to contribute to isotopic variation at particular sites or islands in the Pacific.

However, the identification of archaeological fish remains to a family level or more narrowly to genus or species, in particular in relation to SIA, has not always been possible. Fragmented and poorly preserved faunal material frequently hinders species-level identification of fish in the region. An advantage of our work is that the remains of fish from multiple families were identified, though species-level identification was not always possible. The fish families studied in this paper are of fish that were economically important species in Oceania and reflect the diverse range of fish that Waya Islanders may have consumed. These fish are from different marine niches, including different diets and living in different types of marine environments within fishing distance of Waya Island. While our sample sizes are small, the context-appropriate samples aid in expanding the understanding of isotopic variation in the resources consumed around a small island.

Another common issue with dietary isotope analyses in Oceania is small sample sizes, largely due to limited numbers of remains (human, non-human animal, and plant) and generally poor preservation. It can be challenging to obtain faunal samples, which are crucial for contextualising human carbon and nitrogen isotope data. As mentioned previously, one frequently employed technique for overcoming this issue is to use baseline data either from modern samples or previously published data for an island or region (Kinaston *et al.* 2013; Kinaston and Buckley 2013). This approach has advanced our understandings of past human diets across the Pacific using SIA, but, given the significant land- and marine-scape variation across Oceania, it can be expected that there will be variability in faunal (consumer) isotope values across space and time. Indeed, spatial and ecological variation in carbon and nitrogen isotopes could potentially obscure the interpretations of diets in Oceania, particularly testing hypotheses about marine resource consumption between people on different islands or changes in the importance of marine foods over time. Ultimately, the assumption of a static and homogenous Pacific isotopic marine baseline means that dissimilarities in isotopic results between groups might be missed, or that dietary differences could be assumed when those differences are driven by different local isotope ecologies.

3. Materials

Human and faunal bone from two sites was analysed in this study. The Y2-25 "Olo" site is a coastal flat at Yalobi Bay at the southern end of Waya Island. It was first occupied approximately 2700 cal BP. The Y2-39 "Qaranicagi" site is a rock shelter 100m above sea level over Yalobi Bay and was also first occupied approximately 2700 cal BP until recent times as the cave is still used as a refuge from cyclones (Figure 1). These occupation dates are based on radiocarbon analyses, and the presence of early ceramic styles (Cochrane 2004).

Table 1: Summary of human and faunal samples from Waya Island, Fiji analysed in this paper and from Field *et al.* (2009) to create a Waya Island dietary baseline.

Species	Current paper (n)	Field *et al.* (2009) (n)	Overall (n)
Human (Y2-25)	1	8	13
Human (Y2-39)	2	2	4
Pig (*Sus*)	3	-	3
Turtle (*Chelonioidea*)	1	-	1
Bird (unidentified)	1	-	1
Diodontidae	2	-	2
Acanthuridae	1	-	1
Labridae	1	-	1
Carangidae	2	-	2
Lethrinidae	1	1	2
Lutjanidae	1	-	1
Mullidae	1	-	1
Scorpaenidae	1	-	1
Fish (not identified)	-	2	2

In addition to the 14 human collagen samples (10 individuals) from the two Waya Island sites successfully analysed by Field *et al.* (2009), three individuals were analysed in this study (Table 1). Y2-25-1 was excavated by Hunt *et al.* (1999). This individual was a middle-aged male (40-50 years) (Pietrusewsky *et al.* 1997) buried at the Y2-25 site 2760-2470BP, correlating with the initial occupation of Waya Island. From the Y2-39 site, two individuals were analysed. The 10–12-year-old juvenile was dated to 760-660 BP. This juvenile was excavated by a University of Hawai'i field school in 2001 (Cochrane *et al.*, 2004). The remains were found in an earth-oven feature and showed some post-mortem modification including cut marks and burning (Cochrane *et al.*, 2004; Pietrusewsky *et al.*, 2007). This individual was included in the study by Field *et al.* (2009) but did not meet the collagen quality criteria so was not included in their results. Fragmentary remains of an adult at the Y2-39 site were also excavated by the field school (Cochrane *et al.*, 2004). These remains were not associated with an interment and were found in the midden of the rock shelter. These remains date to a similar period as the Y2-39 juvenile (Pietrusewsky *et al.*, 2007).

All of the faunal samples analysed in this paper were excavated from the Y2-25 site (Table 1). They are archaeological samples and date to a similar period as the Y2-25 individuals, approximately 2800-2400 BP, with the exception of three samples identified in Table 2. The three samples are from a more recent context. The samples analysed in this work have been added to the previous faunal samples described by Field *et al.* (2009) to expand the current data for Waya Island. It is important to note, however, the small sample size within each family, particularly for the fish, often represented by just one sample.

4. Methods and analysis

4.1. Faunal analysis

All faunal bones were identified by KK and JL, with the assistance of Patricia Pillay by comparing diagnostic elements with those from reference collections of held at the University of Auckland. Confirmation of human osteology was by Littleton. Samples with no diagnostic elements or those that were too small were not selected for further analysis. An exception to this was the bird bone sample, which could not be identified. Like the rest of the Pacific Islands, Waya Island has no native land mammals (excluding bats). Terrestrial animals such as pigs and chickens were an important food source in later communities, so it is still important to analyse these species when possible. Photos of all bone elements selected for destructive analysis were taken prior to sampling.

4.2. Statistical analysis

Statistical analysis was carried out in R Studio v+375 (R Core Team 2023) using the following packages: ggplot2 (Wickham 2016), car (Fox and Weisberg 2019), rPhyloPic (Gearty *et al.* 2023) and rKIN (Eckrich *et al.* 2020). Correlograms assessing the relationships between different quality control (QC) criteria were created using the ggcorrmat() function in ggplot2 set to non-parametric (Spearman's rank-order correlation). MANOVA analysis of the fish isotopic data was conducted in R 4.4.1 following guidance from Kabacoff (2015), including tests for the assumptions underlying a one-way MANOVA, multivariate normality and homogeneity of variance-covariance matrices. KUD (Kernal utilization density) is a non-parametric spatial statistical method used to estimate the probability density of 'niches' and in the case of isotopic data represents isotopic niche. We used the rKIN package for our KUD analysis (Eckrich *et al.* 2020) to visualise fish niches.

4.3. Sample preparation and analysis

The destructive analysis in this paper was permitted by the Fiji Museum (23 July 2001, permit no. C01/2, granted to EC). Following recording of the skeletal material, including photography, the collagen samples were prepared using a modified protocol from Sealy *et al.* (2014) (described as the MPI method and is a modified Longin method). The detailed method for demineralisation can be found in the supplementary material.

Of the 27 bone samples analysed as part of this research, 11 failed either during demineralization or after analysis, giving a success rate of ~60%. Samples from larger bone fragments and bones of visibly better preservation (not chalky, bleached, or crumbling) led to more success. Of the samples that failed, eight returned a collagen yield less than 1% or completely disintegrated during the demineralization so no collagen sample remained. Lyophilized collagen samples with a yield greater than 1% and material that visibly looked like collagen (white, fibrous, and shiny) were sent for IRMS analysis.

Stable carbon and nitrogen isotopic compositions were determined using a Carlo Erba NC 2500 elemental analyser connected to a Europa Hydra 20/20 continuous flow isotope ratio mass spectrometer at Isotrace Analytical (Dunedin, New Zealand). Stable carbon and nitrogen isotopic compositions were calibrated relative to the VPDB and AIR scales using USGS40, USGS41, and EDTA.

Measurement uncertainty was evaluated using an in-house gelatin (GLT). Using the equations provided by Szpak *et al.* (2017), precision ($u(R_w)$) was determined to be ± 0.08 ‰ for δ^{13}C and ± 0.11 δ^{15}N on the basis of repeated measurements of calibration standards, the internal reference material, and sample replicates. Accuracy or systematic error ($u(bias)$) was determined to be ± 0.19 for δ^{13}C and ± 0.15 for δ^{15}N on the basis of the difference between the observed and known δ values of the check standard. Total analytical uncertainty was estimated to be ± 0.20 ‰ for δ^{13}C and ± 0.19 for δ^{15}N (see Supplementary Materials for more information).

Collagen quality was assessed using collagen yield, as a crude indicator, with C:N, %wtC, %wtN, δ^{13}C, and δ^{15}N as criteria for identifying samples potentially impacted by contamination or degradation (Table 2). No correlation was found in these samples between C:N and δ^{13}C (Supplementary Figure 1). Guiry and Szpak (2021) found that QC indicators differ across broad taxonomic groups and therefore taxa-specific, and for fish, temperature-specific, differences in QCs should be considered in multispecies studies. As seen in Supplementary Figure 1b-c, taxa-specific correlograms of quality criteria do not suggest contamination, though there is some suggestion that some collagen samples were more degraded than others, as reflected in the strong, positive correlation between %wtC and %wtN. There is no significant relationship between C:N and δ^{13}C in the samples analysed as part of this study (Supplementary Figure 2; $r_s(17) = -0.05$, $p = 0.86$). This assessment of the quality of the collagen from the samples in the study demonstrates that humic contamination is not an issue for these samples, and overall, the collagen quality is acceptable for dietary isotope analysis. A more detailed justification of the samples included for analysis in the results can be found in the supplementary materials.

5. Results

5.1.1. Waya Island Human Results

The human adults analysed in this study have isotope values that overlap with the other adults from these sites analysed by Field *et al.* (2009) (Figure 2 A). The Y2-39 juvenile however has different stable isotope values to others analysed from Waya Island, with lower δ^{13}C (-18.5‰) and δ^{15}N (7.9‰) values compared to the adults.

When these results are compared against other values for Fijian Islands (Figure 2 B) they cover a very similar range of isotope values with the exception of the Late Sigatokan samples which have more negative δ^{13}C values. Further comparison to published human δ^{13}C and δ^{15}N values from Vanuatu (Kinaston *et al.* 2014) show that the range of Fijian human (including this study) δ^{13}C values is comparable to samples from Vanuatu but shows an overall lower and less variable range of δ^{15}N values.

Table 2. δ^{13}C and δ^{15}N values and collagen quality indicators of human and faunal bone collagen. All samples fall within the accepted 'envelope' for QCs for archaeological collagen (Ambrose 1990; DeNiro 1985).

Sample ID	Species	Yield	δ^{13}C	%C	δ^{15}N	%N	C:N
LBL001a	Human Y2-25-1	3.64	-15.2	37.7	10.9	14.3	3.07
LBL002b	Human Y2-39	2.21	-18.5	36.2	7.9	13.8	3.07
LBL003b	Human Y2-39	3.16	-16.5	38.3	10.1	14.6	3.05
LBL004a*	Sea Turtle (*Chelonioidea*)	7.20	-9.9	36.1	4.4	13.9	3.02
LBL007a	Pig (*Sus*)	4.38	-16.4	34.4	9.3	13.0	3.07
LBL009a	*Diodontidae*	11.36	-11.8	47.0	8.2	17.9	3.07
LBL010a	*Acanthuridae*	9.87	-9.2	18.1	5.2	7.1	2.96
LBL013a	*Labridae*	6.53	-10.5	42.2	7.2	15.8	3.17
LBL014a*	*Carangidae*	7.89	-11.3	23.5	9.3	9.3	2.95
LBL015a	*Carangidae*	6.17	-12.8	34.2	9.4	13.1	3.06
LBL017a	*Lethrinidae*	1.08	-9.7	38.3	10.3	14.1	3.16
LBL019a*	*Lutjanidae*	15.54	-12.9	20.3	8.8	7.7	3.06
LBL020a	*Mullidae*	6.29	-12.9	14.5	7.4	5.6	3.02
LBL022a	*Diodontidae*	9.85	-11.8	16.5	8.1	6.3	3.04
LBL023a	*Scorpaenidae*	9.63	-10.2	40.6	10.1	15.1	3.13
LBL025a	Bird (unidentified)	1.29	-13.6	34.3	6.3	12.2	3.29

*samples are not contemporaneous with the rest and are from an upper undated layer

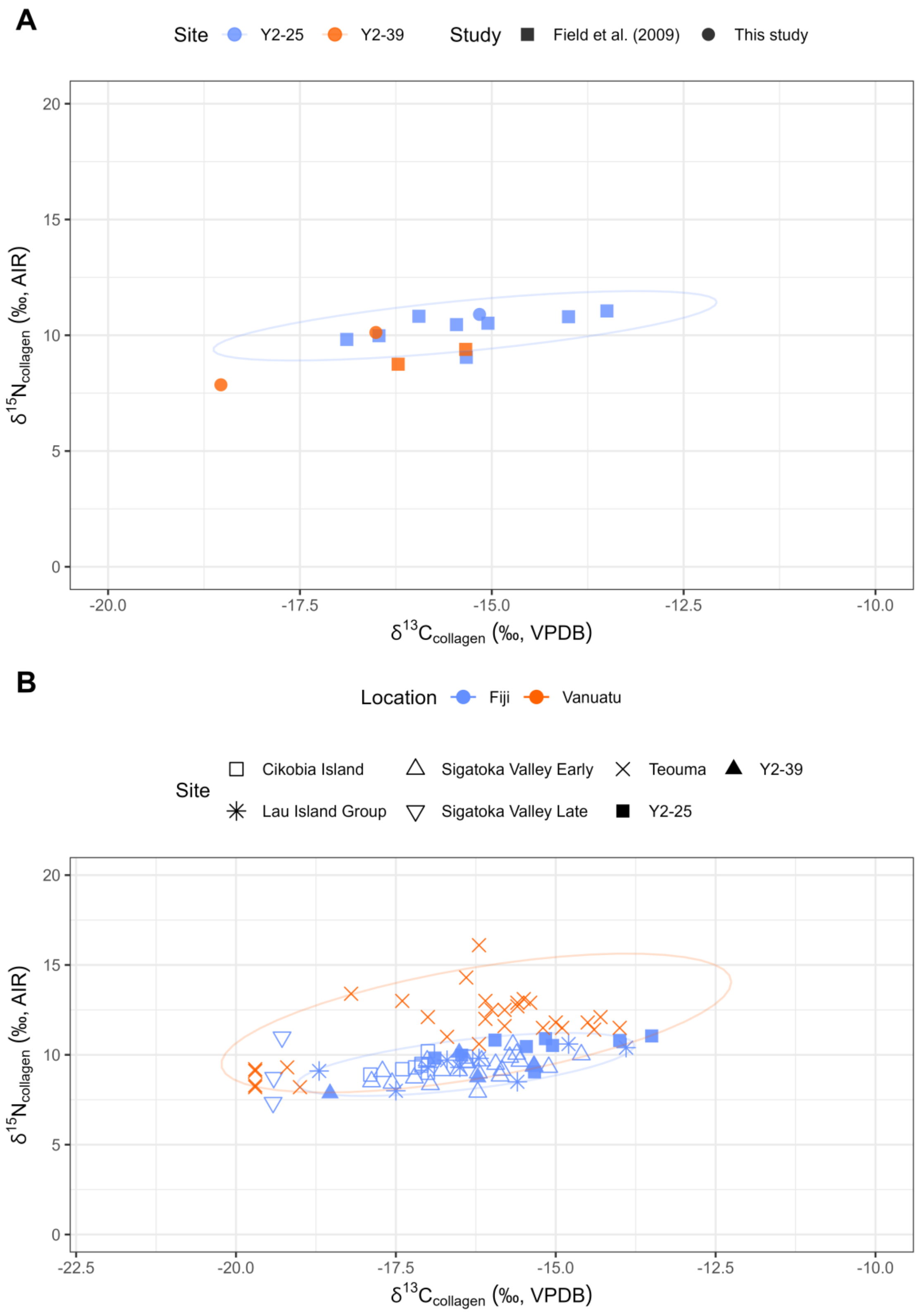

Figure 2: A) Comparison of δ^{13}C and δ^{15}N values from Waya Island individuals analysed in this study and others from Waya Island from Field *et al.* (2009). From the Field study, five samples likely from one individual were averaged for this plot (F 12, 20, 28, 29 and 34). 95% confidence ellipse shown for site Y2-25. Site Y2-39 did not have enough samples for ellipse generation. B) Comparison of δ^{13}C and δ^{15}N values from human individuals analysed in this study and previous studies in Fiji to individuals from Vanuatu (95% confidence ellipses generated by location). The Y2-25-1 and Y2-39 adults grouped with other individuals from their respective sites (n=14) (Field *et al.*, 2009), Y2-39 juvenile presented separately. Other values from Lau Islands (n=9) (Jones & Quinn, 2009a), Cikobia, Fiji (n=8) (Valentin *et al.*, 2006), Bourewa, Viti Levu (n=21) (Stantis *et al.*, 2016), Sigatoka, Viti Levu (n=26) (Field *et al.*, 2009; Phaff *et al.*, 2016). Sigatoka individuals grouped by time periods due to distinct dietary changes at 1300 BP; 1435-1300 BP (n=23) (Phaff *et al.*, 2016), 1300-1174 BP (n=2) (Field *et al.*, 2009), 250-150 BP (n=1) (Field *et al.*, 2009) Values from Teouma, Vanauatu (n=49) (Kinaston *et al.* 2014).

5.2. Waya Island Faunal Results

The δ^{13}C and δ^{15}N values for marine turtle, bird, and pig from this study are plotted against other values for archaeological animals from Fiji and French Polynesia in Figure 3. The low δ^{15}N value and more negative δ^{13}C value of the Waya Island marine turtle from this study is consistent with an herbivorous diet of marine seagrasses. The pig sample is the first pig to be successfully analysed from Waya Island and had δ^{13}C and δ^{15}N values similar to another pig from the Lau Islands. All three pigs in this comparison have similar δ^{15}N values, however the sole pig from Sigatoka Valley is markedly more depleted in ^{13}C compared to the other two pigs.

The Waya Island bird sample from this study could not be identified to species. It was thought to be a chicken; however, it has a low δ^{15}N and more positive δ^{13}C value compared to other Fijian chickens. Another possibility is that it was a seabird, however the low δ^{15}N value seen by this sample does not align with the known diets of other seabirds in Polynesia (Brooke *et al.*, 2010; Richards *et al.*, 2009). What is definitive is that the unidentified bird from Waya Island has a lower δ^{15}N value than any of the other bird samples compared in Figure 3 (3.2‰ from chicken mean and 12.1‰ from the seabird).

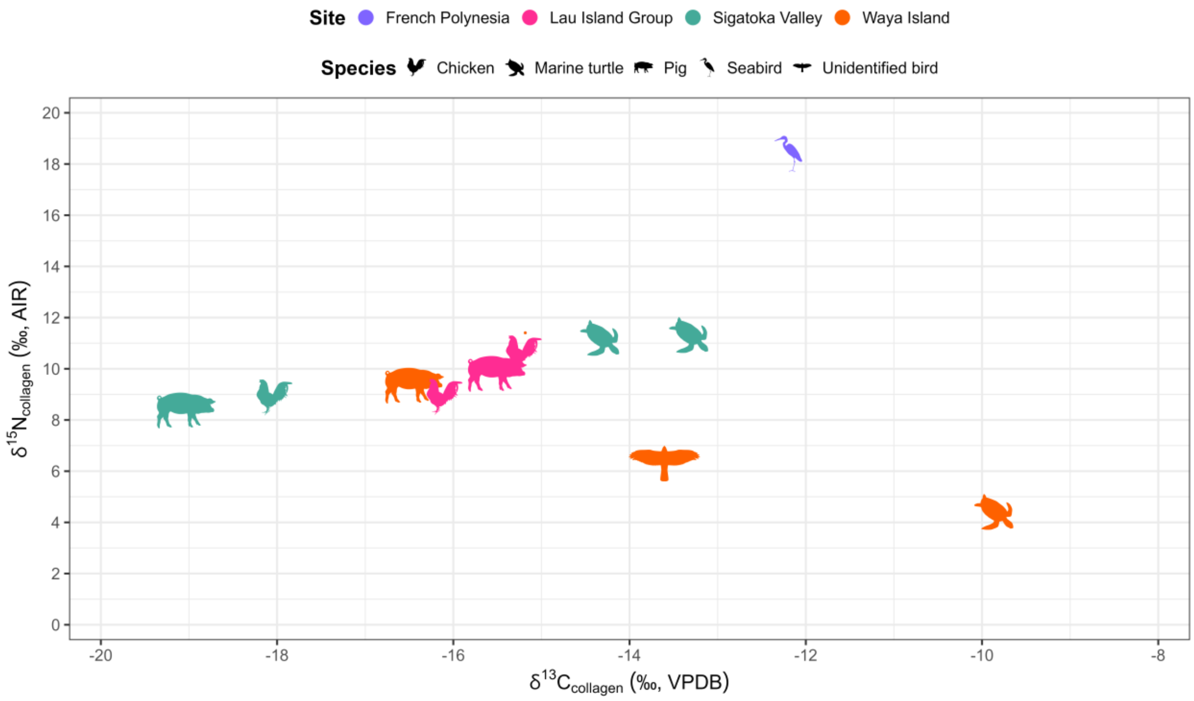

Figure 3: δ^{13}C and δ^{15}N values for marine turtle, bird, and pig data from Fiji and Pacific Islands. Waya Islands samples from this study are represented by rectangles. Comparative samples are from: chicken and pig values from Lau Islands and Viti Levu (Field *et al.*, 2009; Jones and Quinn, 2009a; Phaff *et al.*, 2016); seabird from French Polynesia (Richards *et al.*, 2009); turtle values from Viti Levu (Phaff *et al.*, 2016).

The Waya Island fish analysed in this study come from a variety of families and encompass a $\delta^{13}C$ range from -12.9‰ to -9.2‰ and a $\delta^{15}N$ range from 5.2‰ to 10.3‰ (Figure 4). The Waya Island archaeological fish values vary by family, though the sample sizes are too low for statistical evaluation. Likewise, as might be expected, diet type seems to be particularly relevant for the $\delta^{15}N$ values of the fish, with the herbivorous fish showing the lowest $\delta^{15}N$ values. However, small sample sizes prevent more rigorous evaluation of what is driving the $\delta^{13}C$ and $\delta^{15}N$ variation among the fish excavated at Waya Island.

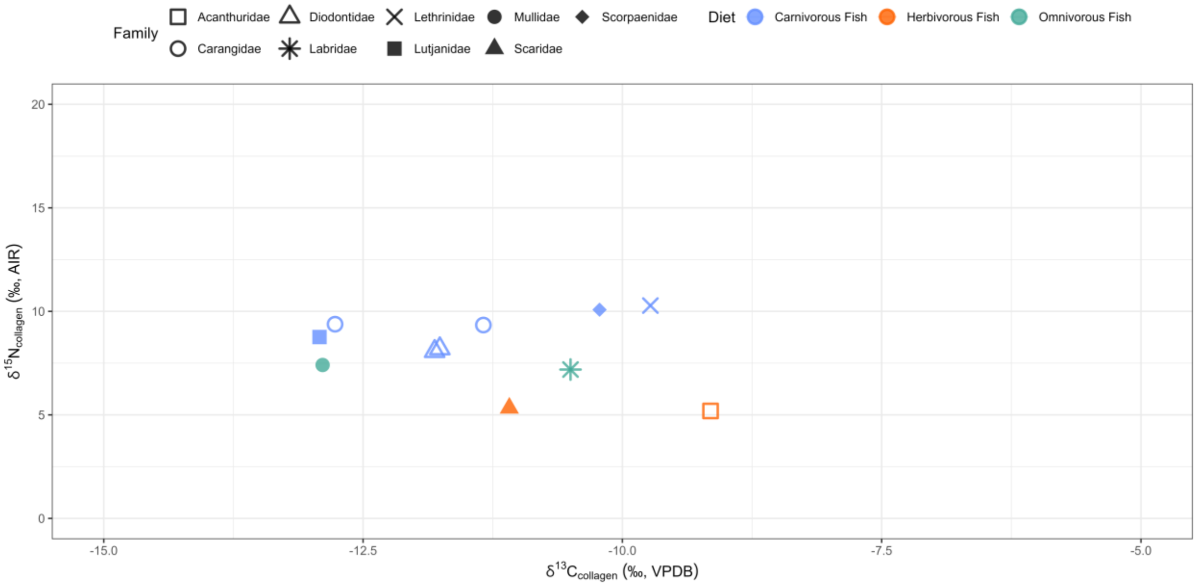

Figure 4: Bi-plot of the fish sampled in this study from Waya Island by family and dietary classification. Given that fish from within the same family do not always have similar diets, it is possible that fish within a particular family may be isotopically variable.

However, plotting these fish against fish values from elsewhere in the south Pacific demonstrates that there is structured variation in both carbon and nitrogen isotope values between island groups (Figure 5). The structure of this variation suggests that island group (spatial location) is a strong contributor to the isotopic niche of fish regardless of their diet. To understand the role that the diet of fish was playing in this structuring, a MANOVA was conducted to determine whether there is a difference between carbon and nitrogen isotope values for fish from across the Pacific, the location of these fish, and their dietary category (herbivorous, omnivorous, and carnivorous).

There were significant differences in isotopic values based on location and diet ($F(6, 64) = 10.489$, $p < 0.001$; $F(4, 64) = 4.188$, $p = 0.004$) when both isotopic values were considered together. Taking carbon and nitrogen values separately and using both location and diet as predictors, carbon isotope values vary significantly by location ($F(3, 64) = 6.844$, $p = 0.001$) but not by diet ($F(2, 64) = 0.277$, $p = 0.760$). Predictably, nitrogen isotope values vary by diet ($F(2, 64) = 10.349$, $p < 0.001$) but less expectedly, they also vary significantly by location ($F(3, 64) = 24.772$, $p < 0.001$). There is no significant interaction effect between location and diet for the combined test or for the separate assessment of carbon and nitrogen isotope values (full MANOVA results can be found in the supplementary materials).

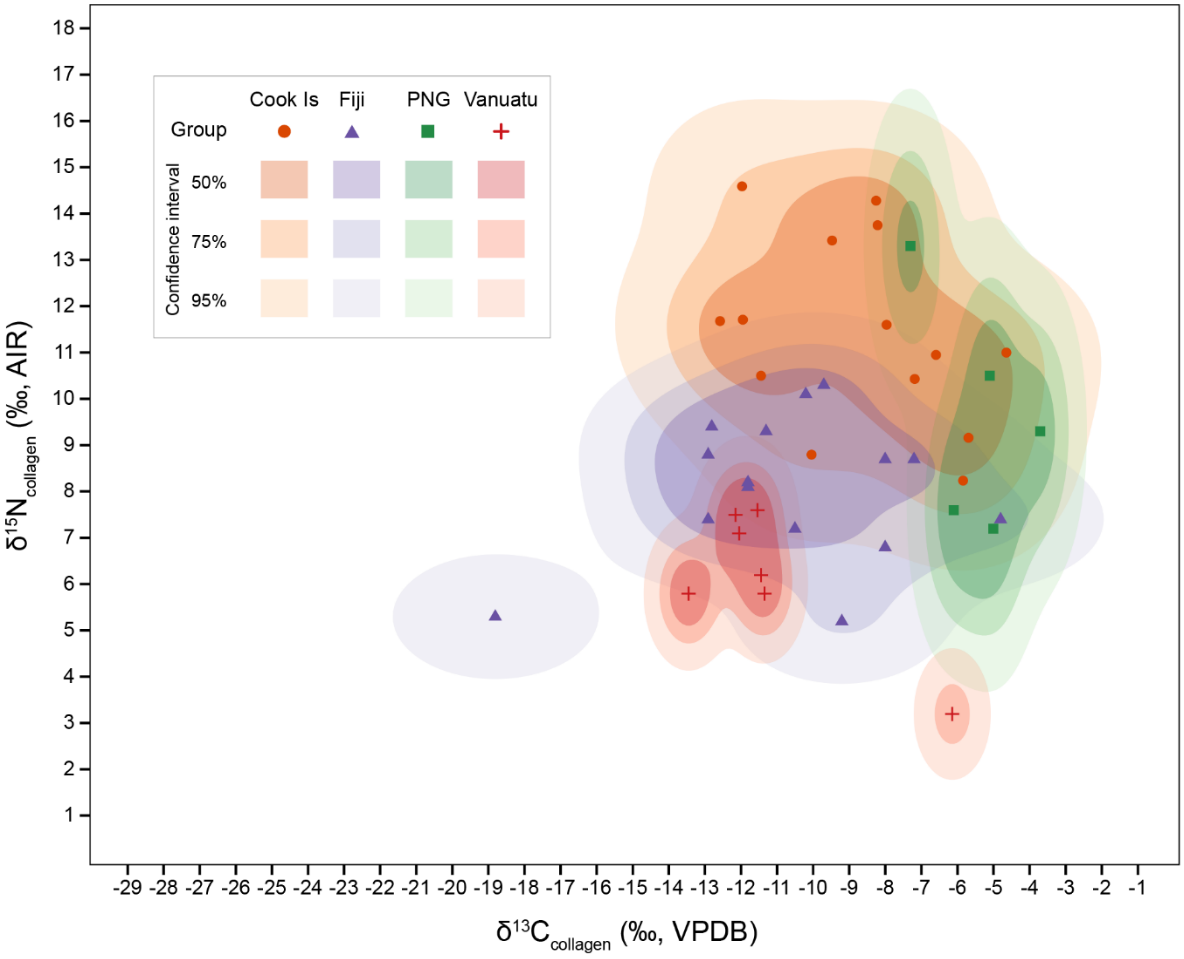

Figure 5: Kernal utilization densitiy (KUD) analysis of fish samples from across the southwest Pacific using rKIN package in RStudio. Fish samples are from Waya Island (Field *et al.*, 2009), Lau Islands (Jones & Quinn, 2009a), Papua New Guinea (Kinaston *et al.*, 2013), Vanuatu (Kinaston *et al.* 2014), and the Cook Islands (Craig, 2009). The modern Vanuatu and Cook Islands samples were adjusted from flesh values, 3.7‰ was added to the δ^{13}C values and 0.6‰ to the δ^{15}N values (Craig, 2009). A further 0.86‰ was added to δ^{13}C values of these samples to adjust for the Suess effect (Craig, 2009).

6. Discussion

6.1. Considering the faunal data

This study has expanded the archaeological faunal carbon and nitrogen isotope data available for Waya Island. Previously, only three fish samples with just one identified to a family level had been analysed (Field *et al.*, 2009). We have contributed δ^{13}C and δ^{15}N data from identified fish samples representing a number of different families, a marine turtle, an unidentified bird, and a pig.

6.1.1. Fish

The fish values from Waya Island, as a whole, fit within the Pacific baseline used in previous studies in Oceania (e.g. Allen and Craig 2009, Craig 2009, Jones and Quinn 2009a, Kinaston *et al.* 2014, Stantis *et al.* 2015, Valentin *et al.* 2024). However, analysis of those Pacific results demonstrates significant structuring and variation in those fish values. Carbon values across the Pacific vary by location but not by the groupings of diet (herbivorous, omnivorous). This suggests that environmental isotopic variation, which has a strong impact on the carbon isotope values of primary producers, like phytoplankton, impacts fish carbon isotope values spatially. Nitrogen isotope values vary significantly by diet and by location in fish, but without a clear interaction effect. While it is not surprising that diet (i.e. trophic level) is a significant predictor, that there is markedly different δ^{15}N values by location is important.

The structuring of this variation raises the possibility that comparisons of human isotopic data from across Oceania to test differences in diet across space or time could reflect more than different consumption of marine resources but also reflect the different isotopic marine ecologies people were sourcing marine foods from. The patterning of fish values demonstrates the significance of having context-appropriate samples for comparison as opposed to broad-based comparisons which incorporate unexpected sources of variation. Identifying fish families is useful as fish may live in different marine environments and studying them can show how past people interacted with these environments and different fishing strategies (Clark & Szabó, 2009). However, location is important as a single predictor.

In the case of nitrogen isotope values in marine contexts, δ^{15}N of primary producers is determined by a complex suite of factors, including: nutrient source (Altabet 2001); nitrogen assimilation dynamics via isotopic discrimination in different biological processes (Gruber and Sarmiento 1997; Rafter *et al.* 2010); and biogeochemical oceanic processes (Altabet 2001; Grove *et al.* 2016; Lorrain *et al.* 2015; Martínez-Rincón and Acosta-Pachón 2022; Rafter *et al.* 2010; Yoshikawa *et al.* 2006). Spatial variation in δ^{15}N values of primary producers (POM) was found in the Pacific Ocean basin and mirrored in high tropic level consumers (Lorrain *et al.* 2015) and it has been demonstrated that localised upwelling and the Island Mass Effect, an oceanographic phenomenon where productive, nutrient-dense waters surround islands and atolls, impacts the isotopic values of modern tuna across the Pacific (Martínez-Rincón and Acosta-Pachón 2022). Both basin-scale and local processes impacting δ^{15}N values in primary producers and consumers is consistent with the spatially structured Pacific 'baseline' fish isotopic data analysed here.

6.1.2. Turtle

The different δ^{15}N value (~6.9‰ lower) for the Waya Island turtle compared to other archaeological Fijian turtles samples could reflect dietary differences, for example turtles consuming more seagrasses compared to fish (trophic level), differences in δ^{15}N across the spatial area the animals are eating from (spatial variation in δ^{15}N), life-history related differences in diet/habitat (age related differences), or time as this sample was from a more recent context. It has been shown in modern green turtles in the eastern Pacific that diet alone could not explain the variability in δ^{15}N values and that isotopic differences at the base of the food web are causing this variability (Seminoff *et al.* 2021).

With the addition of the Waya Island turtle, the range of isotope values for archaeological turtles has been significantly expanded. It is possible that this turtle is a different species to those previously analysed. Since variation in locations and diets is reflected in turtle isotope values (Godley *et al.*, 1998), it is impossible at present to know if the difference between the Waya Island turtle and the other Fijian turtles is due to different foraging ecology among different species, different diets among individuals of the same species, or age-related differences in diet. Clearly more turtles of known species and location need to be sampled.

6.1.3. Birds

The bird sample of unknown species from Waya Island was not consistent with other bird isotopic values Fiji or elsewhere in Oceania. Chickens and seabirds are found in faunal assemblages from Fiji (Worthy and Clark 2009). However, this sample is not consistent with other chicken values from Fiji, noticeably depleted in ^{15}N in comparison (Figure 4). However, this difference does not exclude the possibility that this bird was a chicken, as the diets of these birds may have varied in response to human management and human dietary change.

Seabirds, as shown in a study in the northeast Pacific, demonstrate considerable variation depending on where they are eating (Hobson *et al.* 1994). Additionally, the bone of migratory seabirds will reflect a mixture of food sources consumed along their migration routes for the duration of time that the specific bone element turns over. The complexity of seabird diets for isotopic analysis, including the mixture of different isotopic food sources and their feeding preferences, mean that the few archaeological values of seabirds from the Pacific Islands are almost certainly not capturing that range of isotopic values that can be expected from birds living or feeding in marine environments.

A comparison of the unidentified bird isotope values from Waya Island and the fish values shows that it is unlikely this bird was consuming any of the fish analysed in this study. The low nitrogen value of the bird means that the δ^{15}N value of its food must have been around 1-3‰ taking into account trophic enrichment.

While chickens and seabirds are known food resources ethnographically (Jones and Quinn 2009b; Jones 2011), this bird may be neither. The nitrogen isotope value is more consistent with a land bird which are particularly common in the Fijian islands in faunal remains (Worthy and Clark 2009). The issue of unidentified samples is exemplified in this bird sample from Waya Island, where interpretation of the isotopic is belayed by a lack of species identification and comparative data.

6.1.4. Pigs

The Waya Island pig sample is within the range of other pigs sampled from Fiji (-20.5‰ to -15.5‰), with a more positive δ^{13}C (-16.4‰) value compared to the mean (-18.2‰, n=5). This 5‰ range covers almost exclusively terrestrial C_3 diets and mixed diets with the incorporation of marine or C_4 resources, though it does not fully extend into exclusively marine diets as seen in some pigs from Hanamiai, French Polynesia (Richards *et al.* 2009). The spread in δ^{13}C values from pigs across Fiji suggests that these animals may have eaten isotopically different diets on different islands or perhaps reflect temporal or spatial differences in human management practices of this species. Pigs, and other domesticated species, have been excluded from isotopic 'baselines' for the Pacific because of assumed differences in isotope values related different husbandry practices (e.g., Kinaston and

Buckley 2013), however their results do reveal aspects of human-animal interactions (as in Richards *et al.* 2009). From the few pig samples from Fiji, we can see that there may be an opportunity to reflect on the carbon and nitrogen isotopic variation within sites (time), or between sites or islands groups and consider how this variation is being produced in the context of how pigs are managed by people and the resources available to invest into these animals.

6.2. Human diets on Waya Island

It was expected that the diets of the humans analysed in this study would be similar to those previously analysed by Field (2009). This expectation was met for the adult individuals from both sites (Y2-25 and Y2-39) and is consistent with the interpretation that these individuals were eating a mixture of marine and terrestrial resources. One possible interpretation of this mixed diet is that the small size of Waya Island limited agricultural practices, and marine resources were readily available. While the isotopic results largely support this hypothesis, isotopic data do not provide direct evidence.

One of the challenges interpreting the Waya Island human diets, and mixed diets in general, is that it is unclear how much variation in the $\delta^{13}C$ of terrestrial resources is contributing to the 'mixed signal'. The spread in $\delta^{13}C$ (-18.5‰ to -13.5‰) among the humans at Waya is evidence that people were consuming a range of resources with various carbon isotope values, in different quantities. There is no clear Waya Island 'diet' that can be discerned from these results. The question is: what is driving this $\delta^{13}C$ variation in the humans?

While it is possible this large range of $\delta^{13}C$ values reflects purely different amounts of marine consumption among individuals, we would expect to see a stronger positive correlation between $\delta^{13}C$ and $\delta^{15}N$ if marine food consumption alone was resulting in this pattern. Another possibility is that there is more $\delta^{13}C$ variability in the C_3 plants and terrestrial resources on Waya Island than previously understood. The dry nature of the island has resulted in the success of a drought resistant vegetation on the island (Gardner 2018). Plants under water stress or in regions with less rainfall tend to be enriched in ^{13}C and studies have shown variable impacts on the $\delta^{15}N$ value of the plant depending on the plant's mechanism of responding to aridity (Fain 2022; Handley *et al.* 1999; Hartman 2011). Additionally, Gardner (2018) notes that there are a considerable number of legume trees present in this 'dry zone forest' – legumes are typically depleted in ^{15}N. Without understanding the plant isotopic composition on Waya, it is hard to say if/how this impacted the human isotopic values, but it points to the importance of considering local ecologies and potential inter-island differences in ecologies. Future research could consider sampling modern vegetation on the island, while considering that anthropogenic and climate changes to soil and species composition could complicate their direct applicability to the past.

Alternatively, or perhaps concurrently, this variation could reflect the consumption of marine foods with highly variable isotopic values. However, resolving what is contributing to these highly varied diets would need further investigation, of both the isotopic land- and seascapes of Waya Island and nearby islands and ideally compound-specific isotope analysis (CSIA-AA).

The results of the juvenile (10-12 years old) from the Y2-39 site are unusual compared to the adults at Waya Island, but comparable to the later burials from Sigatoka (250-150 BP) (Field *et al.*, 2009). The lower $\delta^{13}C$ and $\delta^{15}N$ values suggest the child was eating more terrestrial, C_3 resources (e.g. domesticated animal products or starchy plants) compared to the terrestrial-marine based diet of adults. One explanation for this difference might be that children were snacking and foraging on plants like fruits. Independent snacking by children has been seen throughout Fiji although the observations are of children snacking on lagoon and reef shellfish which would result in a stronger marine signal (Jones & Quinn 2009b; Pollock 1992).

A similar difference between childhood and adult diets was noted at Bourewa (Vitu Levu) where δ^{13}C values of tooth root dentine (representing childhood diets between ~5 to 10 years) were more negative than bone collagen δ^{13}C values. These findings suggest that people ate more terrestrial (C_3) foods during childhood than in adulthood (Stantis *et al.*, 2016). In contrast to the Waya Island child, on Bourewa, the δ^{15}N values of the dentine, formed in childhood but after the cessation of breastfeeding, were higher than those of bone collagen representing adult diet. Nevertheless, the difference between childhood and adult values does confirm observations in Fiji and elsewhere (Uripiv, Vanuatu in Kinaston *et al.* 2014) that childhood diets do not necessarily align with adult diets. This difference is possibly because of child behaviour or because certain foods are given to or withheld from children dependent on their age. Although, it is also possible the child was not from Waya based on its context on top of an earth oven (Field *et al.* 2009). It is also important to recognise that the overall small sample size for the Waya Island humans also means that dietary isotopic variation may have been underestimated.

6.3. The importance of local context

There are advantages to non-specific baselines for addressing archaeological questions, as they tend to include more data with multiple species and more samples per species, thus accounting for inter-individual variation within a species. In the absence of site-specific data these baselines provide an important reference for archaeological human and faunal data for dietary interpretations. However, it is crucial to recognise that local isotopic ecologies are dynamic, subject to anthropogenic and non-anthropogenic change, and are tied to specific biogeochemical processes that are invisible in amalgamated data from large spatial or temporal spans. Indeed, 'local' biogeochemical processes like the Island Mass Effect impact most Pacific reef systems, with variable strength determined by environmental and anthropogenic factors (Grove *et al.* 2016), may result in environmentally (spatially) driven isotopic variation within and between islands.

Since significant δ^{13}C and δ^{15}N spatial variation is shown the bottom of marine food webs in the Pacific Ocean (e.g., Horii *et al.* 2025) and is also seen in consumer species (e.g., Martínez-Rincón and Acosta-Pachón 2022), the applicability of archaeological fish values from across the Pacific to the interpretation of human diets at particular sites and across time should be carefully evaluated case by case. Interpretation of archaeological human and non-human animal diets on the Pacific islands, particularly changes in diet over time and space, based solely on generalised baselines should be rigorously evaluated, particularly relating to the consumption of marine food resources.

The Waya Island local values can be used as an example for how context specific data can fine-tune dietary information, resulting in more specific dietary reconstructions. The Bourewa site on Viti Levu is similar to the Y2-25 site on Waya Island. Both Fijian sites are coastal with an abundance of marine resources. Despite a difference in time periods, with individuals analysed by Stantis *et al.* (2016) dating to 750-150 BP, these people had a predominantly marine-based diet reflected in their high δ^{13}C values. Individuals from the Bourewa site and from the Y2-25 Waya Island site (those in this study and from Field *et al.* (2009)) had similar δ^{13}C values but different δ^{15}N values. The mean

δ^{15}N values for the people from Bourewa and the carnivorous and omnivorous fish samples were similar (8.63‰ and 8.75‰ respectively) suggesting people were not eating these fish groups. However, the Waya Islanders had enriched δ^{15}N values (10.37‰) which suggests that carnivorous and omnivorous fish like Carangidae and Lutjanidae (9.4 and 8.8‰ respectively) were more likely a part of Waya Island diets in comparison. While people from both Waya Island and Bourewa relied on marine foods in their diet, we now have some preliminary evidence that the fish species being consumed were different.

This information is only discernible isotopically if context-specific data are available and can be used along with other lines of evidence to test hypotheses related to marine resource strategies in future research. The Waya Island faunal values contribute to the generation of context-specific archaeological isotopic data, which we hope will contribute to future work in Fiji, considering local practices and human-animal interactions, as well as interrogate sources of isotopic carbon and nitrogen variation in marine and island environments in the past.

7. Conclusion

Oceania is not an environmentally homogenous region. Differences in island size, substrates, marine environments, and species distributions and habitats all contribute to substantial variation in resources and in the isotopic values of certain environments (and variation in those values). Therefore, developing an understanding of local isotope ecologies is crucial when applying isotopic analyses to understand the diets of people who lived on these islands. Characterising local isotope ecologies requires sampling of archaeological faunal material for carbon and nitrogen isotope analyses. However, it also requires consideration of environmental variation across the region of interest, which may involve looking to literature within the field of marine ecology. Our data, though of a limited sample size, can be used as a starting place for thinking about the isotopic land- and sea-scapes of Waya Island and other Yasawa Islands in Fiji.

Supplementary Materials

The supporting information can be downloaded at https://doi.org/10.70460/jpa.v16i1.391 S1: Additional methods and data

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Data Availability Statement.

The data this paper is based on are available in the Supplementary Information.

Partnerships

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Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, KK, CBS, EC, and JL; methodology, KK and CBS; formal analysis, KK and CBS; resources, EC and JL; writing—original draft preparation, KK and CBS; writing—review and editing, CBS, JL, and EC; visualization, CBS; supervision, EC and JL; funding acquisition, JL. All authors have read and agreed to the published version of the manuscript.

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