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Polynesian Subsistence, Nutrient Flows, and Long-Term Socio-Ecosystem Dynamics: Insights from Stable Isotope Analysis of the Pacific Rat (*Rattus exulans*) in Island Foodwebs

By

Jillian Amy Swift

A dissertation submitted in partial satisfaction of the

requirements for the degree of

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in

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in the

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of the

University of California, Berkeley

Committee in charge:

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Abstract

Polynesian Subsistence, Nutrient Flows, and Long-Term Socio-Ecosystem Dynamics: Insights from Stable Isotope Analysis of the Pacific Rat (*Rattus exulans*) in Island Foodwebs

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Doctor of Philosophy in Anthropology

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This dissertation applies stable carbon (δ^{13}C) and nitrogen (δ^{15}N) isotope analysis to archaeological specimens of the human-transported Pacific rat (*Rattus exulans*) to investigate prehistoric patterns of subsistence, site use, and long-term socio-ecosystem dynamics on Polynesian Islands. The Pacific rat is a small commensal species characterized by low dietary selectivity and a limited home range. Its close association with past Polynesian peoples—and ubiquity in Polynesian archaeological sites—suggests that dietary change in this species can provide insight into changing island landscapes and human subsistence regimes. Pacific rat bone collagen δ^{13}C and δ^{15}N values were compared across three contrastive island socio-ecosystems: Mangareva, the Marquesas, and Tikopia.

Spatiotemporal trends in Pacific rat stable isotope ratios are related to localized changes in human activity and subsistence practices, as well as global ecosystem processes which include avifaunal extinctions, resource depression, and soil nutrient cycling. On Mangareva, temporal variations in δ^{13}C and δ^{15}N values were assessed from three sites: the Onemea site, Taravai Island (TAR-6), Nenega-iti Rockshelter, Agakauitai Island (AGA-3), and Kitchen Cave Rockshelter, Kamaka Island (KAM-1). Declining δ^{15}N values through time at all three Mangarevan sites reflect archipelago-wide socio-ecosystem changes related to site activity and avifaunal population declines. At the Hane dune site, Ua Huka Island (Marquesas), shifts in rat diet provide insight into changing Marquesan settlement and subsistence practices. On the Polynesian Outlier of Tikopia, a 650-year period of stability in rat bone collagen δ^{13}C and δ^{15}N values during the Kiki Phase (800-160 BC) suggests that mechanisms for long-term socio-ecosystem sustainability have been in place on the island for over 2000 years. These results demonstrate the capacity for stable isotope analysis of the Pacific rat to provide a new, low-impact line of evidence towards reconstructing localized patterns of site use, subsistence practices, and island ecology.

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Chapter 1

Introduction

  This dissertation applies bone collagen stable isotope analysis to archaeologically recovered remains of the Pacific rat (*Rattus exulans*) in order to investigate nutrient flows in three contrastive Polynesian island socio-ecosystems. The close commensal association of Pacific rats with past Polynesian people and archaeological sites, combined with their limited home range and omnivorous diet, render assemblages of prehistoric rat bones useful proxies for understanding paleoenvironmental and human paleodietary change. Archaeological bone collagen of Pacific rats was analyzed for carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope ratios from the islands of Mangareva (Gambier Archipelago, French Polynesia), the Hane Dune Site on Ua Huka Island (Marquesas Islands, French Polynesia), and the Polynesian Outlier of Tikopia (Solomon Islands). This chapter provides an introduction to the region, cultures, theoretical perspectives, and methodologies engaged with in this research.

The Human Colonization of the Pacific

  The Pacific Ocean covers over 30% of the Earth's surface, and its islands scattered throughout encompass at least 40,000 years of prehistory and myriad peoples and cultures. The first people to occupy this region inhabited the islands of Near Oceania, which include Papua New Guinea and parts of Island Melanesia, including the Bismarck and Solomon archipelagoes (see Green 1991). The first inhabitants of Near Oceania arrived by sea, crossing the island zone of Wallacea into the continent of Sahul, which at the time incorporated Australia, Tasmania, and New Guinea. Other islands within Near Oceania—most of these visible from nearby islands— were settled by around 30,000 years ago (Kirch 2000a; Wickler and Spriggs 1988).

  The islands of Remote Oceania, which encompass the rest of island Melanesia, Micronesia, and Polynesia, are separated by much greater distances. Voyaging to these islands required complex seafaring technology, and as a result, these islands were settled considerably later. The first people to arrive in Remote Oceania (around 3000 BP; Petchey et al. 2014) were associated with the Lapita Cultural Complex: an expansion of Austronesian-speaking peoples out of Island Southeast Asia. The Lapita culture is perhaps most famously distinguished by its dentate-stamped ceramics. In addition, the Lapita people introduced a suite of cultural practices, agricultural techniques, artifacts, and plant and animal species to Oceania (see Kirch 1997a). Evidence of Lapita arrival has been found in Near Oceania and as far east as Samoa and Tonga.

  The archipelagoes of Samoa and Tonga were first settled around 2850 BP (Burley et al. 2012), and along with Futuna and 'Uvea encompass the Polynesian Homeland region. After Lapita settlement in this area, voyaging to new islands appears to have paused for nearly 2000 years, while a uniquely Polynesian culture developed. Features of this Polynesian culture include the disappearance of Lapita pottery in favor of undecorated ceramics known as Polynesian Plainware, followed by the disappearance of ceramics altogether. In addition, a distinctly Polynesian suite of basalt adzes, shell and bone ornamentation, and fishing technologies developed. These artifacts would form the basis of the non-perishable (and therefore archaeologically recoverable) distinctly Ancestral Polynesian material culture.

  After the formation of this uniquely Polynesian culture in the Western Polynesian homeland region, long-distance voyaging resumed and the rest of the Polynesian triangle was

colonized (see Matisoo-Smith 2015 for a review of the most recent evidence for the chronology of settlement in Oceania). The Polynesian region, formed by connecting Hawaii, New Zealand, and Rapa Nui as vertices to form a triangle, is of particular interest to comparative studies as it is geographically distinct and can also be considered a culturally monophyletic unit: the islands of Polynesia were colonized rapidly by groups of people originating from the same Western Polynesian homeland with similar cultural beliefs, knowledge, practices, and languages. These island societies were relatively isolated from one another following colonization, facilitating the subsequent development of numerous unique Polynesian cultures from the same ancestral origin. Outside of the Polynesian triangle are roughly 18 islands known as Polynesian Outliers. The people of these islands speak Polynesian languages, and many trace their origins to islands in the Western Polynesian homeland region (Firth 1961; Kirch 1984). Uniquely, the Polynesian people were not the first to arrive to these islands, as they had previously been settled during the Austronesian expansion into Remote Oceania. As a result, the Polynesian Outliers carry a blend of characteristically Polynesian cultural practices with the plants, animals, and cultures of islands elsewhere in the Pacific.

Transported Landscapes: Polynesian Subsistence and Ecosystem Change

Polynesian people transported a set of familiar plant and animal species to new islands, ensuring both their survival and the continuation of Polynesian cultural practices in new island landscapes. This set of "portmanteau biota" (Crosby 1986) or canoe plants and animals (Whistler 2009) included agricultural staples such as taro (*Colocasia esculenta*), yam (*Dioscorea* spp.), and breadfruit (*Artocarpus altilis*), as well as plants with other uses such as the *ti* plant (*Cordyline fruticosa*) and the paper mulberry (*Broussonetia papyrifera*). Transported animals included the domestic pig (*Sus scrofa*), dog (*Canis lupus familiaris*), and chicken (*Gallus gallus*), and the commensal Pacific rat, as well as inadvertent 'stowaways' including geckos, land snails, weeds, and arthropods. It is unclear whether the Pacific rat should be included in this list of inadvertent stowaways or if it was introduced intentionally as a potential food source (see Matisoo-Smith et al. 1999, Matisoo-Smith and Robins 2004).

Ethnographic and historic accounts point to some consistencies in foodways and subsistence practices across Polynesian islands (see Kirch and Green 2001). Polynesian meals were centered on a starch base (such as taro, sweet potato, breadfruit, or yam), which was prepared in numerous ways including baking in an underground earth oven, fermenting, and combined with emollients to form a pudding. While staple crops could be served on their own, a "proper meal" is formed with the addition of a flesh food "relish," which encompasses both marine (e.g., fish, shellfish, turtle, marine mammals) and terrestrial (e.g., pig, dog, chicken and other avifauna) resources (Kirch and O'Day 2003).

Many Polynesian subsistence systems appear to have followed the developmental trajectory laid out by Yen (1973), which outlines an early reliance on marine resources and indigenous fauna, followed by a gradual development and intensification of agricultural regimes based around transported Polynesian crops and specialized to suit particular island environments. This developmental scenario is supported by numerous archaeofaunal assemblages from early colonization-phase sites with high proportions of avifauna, marine mammals, and an abundance of benthic and pelagic ichthyofaunal species (e.g., Anderson et al. 1994; Kirch et al. 2015; Steadman et al. 1990), as well as extensive research into the development of agricultural systems

on numerous Polynesian islands (e.g., Barber 2000; Kirch 1994; Kurashima and Kirch 2011; Ladefoged et al. 2003, 2011; Quintus et al. 2016).

Humans, their translocated species, and the development of agricultural regimes had immense and long-lasting impacts on Polynesian island ecosystems. Kirch (1983) recognized the introduction of exotic flora and fauna, fire clearance of endemic forest for agriculture, and the modification of island erosional and depositional processes as major anthropogenic influences to Polynesian landscapes. These processes and their impacts have since been demonstrated in the Cook Islands (e.g., Allen 1998; Kirch 1996; Kirch et al. 1995), Hawaii (e.g., Athens 1997; Dixon et al. 1997), Mangareva (e.g., Kirch et al. 2015), Rapa Nui (e.g., Bahn and Flenley 1992; Hunt and Lipo 2010), the Marquesas (e.g, Aswani and Allen 2009; Rolett 1992, 1998), and the Society Islands (e.g., Kahn et al. 2014, 2015; Lepofsky et al. 1996), among other cases.

Extinctions and extirpations of indigenous flora and fauna, especially avifaunal species, commonly followed human arrival to new islands. Predation by humans and other introduced species, loss of habitat from agricultural forest clearance, and competition with introduced species contributed to the loss of indigenous plants and animals. Steadman (1995) estimates an average of 10 avifaunal extinctions or extirpations per island in the Pacific. Prior to human contact, land birds on Polynesian islands had evolved in an environment without terrestrial mammalian predators, and were therefore naïve to the threat of human predation. Steadman and Kirch (1990) suggest that early human acquisition of avifauna more closely resembled a gathering, rather than hunting, activity due to a lack of predator response mechanisms. Seabird extinctions had deleterious effects on island ecosystems, restricting the transfer of marine nutrients to terrestrial soils and inhibiting seed dispersals (James 1995). An extensive body of zooarchaeological literature documents intensive human consumption and subsequent elimination of avifaunal populations in Polynesia (e.g., Holdaway 1989; Steadman 1993, 1995, 1997, 2006; Steadman and Kirch 1990; Steadman and Justice 1998; Steadman and Rolett 1996).

Transported commensal species (pig, dog, chicken, and rat) played a role in these landscape transformations as a new source of competition and predation for island flora and fauna. Although Polynesians may have attempted to transport all four of these animals to new islands, the introductions of pig, dog, and chicken were not always successful. In some cases, these species were successfully introduced but later extirpated, putatively due to trophic competition over limited resources (Kirch 2000b). Giovas (2006) determined a correlation between island size (used as a proxy for island productivity) and the persistence of pig populations into the European contact era. Bay-Petersen (1983) suggested that the elimination of pig and dog populations on small islands is not only related to terrestrial productivity, but also to the increased access to marine resources per capita on small islands, obviating the need for terrestrial protein sources.

The Pacific rat in particular has been singled out as a source of significant ecological devastation both in present and past island ecosystems (e.g., Athens et al. 2002; Harper and Bunbury 2015; Holdaway 1989; Hunt and Lipo 2007, 2010; Meyer and Butaud 2009; Mieth and Bork 2010; Porch 2008; Ruffino et al. 2015; Shiels and Drake 2015; Towns et al. 2006). Unlike the pig, dog, and chicken, the rat is widespread across the Pacific and nearly ubiquitous in Polynesia. The Pacific rat arrived on Polynesian islands devoid of natural predators (apart from humans) and without competition from other small mammals such as mice or other rat species. Left unchecked, rat populations could multiply quickly, producing several litters per year of up to 7 young according to some estimates (Kramer 1971; Moller and Craig 1987; Tamarin and Malecha 1972). Rats could have major impacts on indigenous flora and fauna: by consuming

small birds and bird eggs and native plants and plant seeds, they exacerbated the impacts of human forest clearance and hunting on these species, while also slowing their propagation. The European-introduced ship rat (*Rattus rattus*), Norwegian rat (*Rattus norvegicus*), and house mouse (*Mus musculus*) have in many cases overtaken the Pacific rat as more significant contemporary ecological menaces. However prior to these introductions, the Pacific rat appears to have been partly responsible for prehistoric species extinctions and ecosystem change.

Islands as "Model Systems"

This dissertation compares data from three separate Oceanic islands to engage with the concept of islands as model systems for understanding global socio-ecosystem processes. The term "socio-ecosystem" is employed by Barton et al. (2004) to address the inextricable connection of environments and landscapes to human society and cultural practices throughout history. The socio-ecosystem concept recognizes that neither are people "passive consumers or rapacious exploiters of ecosystems," nor ecosystems simply "a backdrop for human agency or a larder to fuel human economies" (Barton et al. 2004:254). In this dissertation I interpret rat stable isotope values within the context of developing human subsistence regimes, activities, and social structures. Variations in rat diet through time are hypothesized to reflect changes within linked social and natural landscapes.

The use of islands as model systems has encouraged cross-disciplinary collaboration between archaeologists and natural scientists to explore the relationship between humans and their environment. Burney (1997) proposed that tropical islands in the Pacific and elsewhere could serve as "paleoecological laboratories" for assessing the impacts of human arrival to new ecosystems. Vitousek (2002) asserted that Pacific Islands are useful as real model systems for understanding evolution and speciation, conservation biology, and cultural processes. Kirch (2007a) identified a number of factors which make Polynesian islands particularly appealing as contrastive model systems for understanding socio-ecosystem change: (1) a relatively late colonization of previously uninhabited islands by populations with agriculturally-based economies; (2) short, well-controlled chronologies (3000-1000 year duration); (3) a high degree of isolation after colonization; (4) clear, traceable transitions from low-density to high-density human populations; (5) transformations in sociopolitical complexity; and perhaps most importantly, (6) a common origin in an Ancestral Polynesian culture (see Kirch and Green 2001). Kirch has compared numerous island systems including Tikopia, Mangaia, Mangareva, and the Hawaiian Archipelago to isolate the role of variables such as island size, geologic age, isolation, and maximum elevation in long-term island socio-ecosystem development and sustainability (see Kirch 1997b, 2004, 2007a, 2007b).

Many researchers have attempted to determine the cause of Rapa Nui's perceived "collapse," as this has been upheld as a microcosm for global human-environment interaction and resource decline (e.g., Bahn and Flenley 1992; Diamond 2005; Hunt 2007; Hunt and Lipo 2010; Mieth and Bork 2010). Rolett and Diamond (2004) compared nine environmental variables (rainfall, elevation, area, volcanic ash fallout, Asian dust transport, uplifted coral *makatea* terrain, increases in latitude, age, and isolation) across Pacific Islands and found that rainfall and higher latitude (itself a measure of temperature declines) were key factors in evaluating island susceptibility to deforestation. They determined that Easter Island was particularly fragile, as it was at the extreme end of all variables considered.

Vitousek et al. (2004) used the Hawaiian archipelago as a model for agricultural intensification, soil nutrient cycling, and increasing social stratification. They suggested that rainfall, geologic age, and overall soil fertility were key factors in the development of extensive dryland agricultural systems and sociopolitical complexity in the leeward regions of the Hawaiian Islands. They argued that the general relationship between these variables were critical not only in Hawaiian prehistory, but could also be applied towards understanding agricultural intensification in other tropical environments. These ideas were developed more extensively in a volume edited by Kirch (2011a), which incorporated additional variables such as demography, spatial distribution, and a chronology of sociopolitical development. Baer et al. (2015) have begun to extend this research into the dryland agricultural system of Kaupō, Maui.

More recently, the ambitious Moʻorea IDEA project (Davies et al. 2016) has brought together an international collaborative network of researchers from the physical, biological, computer, informational, and social sciences who endeavor to model the entire socio-ecological system of Moʻorea. Their larger aim is to understand sustainable practices both within islands and coastal regions, and as a model for continental regions and global processes. The Moʻorea IDEA project is one of many recent initiatives to engage with the notion that humankind has become one of the most significant impacts on geological and ecological systems. As the concept of the Anthropocene (see Crutzen 2002; Steffen et al. 2011; Zalasiewicz et al. 2012) becomes more prevalent in contemporary scholarship, the modeling of human-environment interactions on Polynesian Islands can provide critical insights into global issues of resource management and sustainability (Vitousek and Chadwick 2013).

Pacific Rats as Proxies for Nutrient Flows in Island Socio-Ecosystems

Stable isotope analysis of commensal fauna has been applied to a range of anthropological topics, including paleoenvironmental reconstruction, subsistence, mobility and animal husbandry practices (e.g., Allen and Craig 2009; Craig 2009; West 2007 in the Pacific, and see reviews by Birch 2013; Zangrando et al. 2014). Previous research has applied carbon and nitrogen stable isotope ratios of archaeologically recovered dog remains as a proxy for human diet (see Guiry 2012). Although dogs were introduced to a number of Polynesian islands in prehistory (Hawaiʻi, New Zealand, Society Islands, Tuamotu Islands, the Marquesas, and Mangareva), they were frequently managed food sources with controlled diets. Dogs were often fed a vegetarian diet, and penned to restrict access to other food sources (Luomala 1960; Titcomb 1969). Thus, it is unlikely that reconstructed dog diet in Polynesia would provide a proper analog to human diet. A notable exception to this may be New Zealand, where dogs (*kuri*) were occasionally used for hunting birds and rats, could survive to old age, and had a more carnivorous diet which included human meal scraps (Clark 1997a, 1997b; Coutts and Jurisich 1973). Likewise, past Polynesian husbandry strategies of the domestic pig inhibit direct comparisons to human diet (West 2007). The commensal Pacific rat, also a mammalian omnivore, lived in similarly close association with people but does not appear to have been managed by Polynesian people and thus may provide a better proxy for human diet.

Guiry and Gaulton (2015) established critical groundwork for the application of stable isotope analysis of rats as proxies for past human diet and activity. Contemporary ecological studies support the idea that rat diets are highly generalized, and that rat dietary stable isotope ratios will reflect an averaging out of locally available resources (e.g., Caut et al. 2008; Hobson et al. 1999; Ruffino et al. 2011). However, Guiry and Gaulton caution that archaeological sites

represent complex social and natural ecosystems, which carry additional complicating factors. They suggest greater intra-annual resource variation, different predator-prey relationships (humans in particular), and interspecific competition may cause rats to adopt specialized feeding behaviors. Although past Polynesian people may not have intentionally managed rat diet, it is possible that the threat of their predation altered rat feeding behavior in habitation sites and other areas of high human density. Despite these warnings however, Guiry and Gaulton demonstrated change in rat diet through time which they were able to correlate with changing socioeconomic conditions at Ferryland, Newfoundland.

Pacific rat remains are recovered frequently from Polynesian archaeological sites, and it appears the species was successful in establishing the human household as an ecological niche. On Kapiti Island, New Zealand, Bramley (2014) observed home ranges of between 26-89 m in diameter for the Pacific rat, compared to home ranges of 218-916 m in diameter for the larger Norway rat. The Pacific rat rarely burrows, instead preferring open areas with good ground cover or disturbed areas such as villages and households (Dwyer 1978; Taylor 1975). Rats may have spent considerable time in the roof thatching of Polynesian households, opportunistically scavenging food scraps while human dwellers slept (see Oliver 2002:83). A recent study by Morand et al. (2015) in contemporary mainland Southeast Asia found that the Pacific rat was particularly specialized to household sites compared to other sympatric rat species. Uniquely, *R. exulans* was found almost exclusively in households within villages, rather than in natural habitats.

Much of our understanding of Pacific rat diet comes from contemporary ecological studies. This rat species has been observed consuming insects, snails, land crabs, lizards, turtle hatchlings, bird eggs, and even other rats (Spennemann 1997). However, many dietary studies have found Pacific rat diet to be primarily vegetal, with most protein derived from arthropods rather than terrestrial or marine resources of a higher trophic level (e.g., Bunn and Craig 1989; Shiels et al. 2013). Pacific rat diet has also been shown to vary based on seasonal resource availability. Bone collagen stable isotope data represent an averaging of diet over longer timespans and cannot detect seasonal variation in diet, however this seasonal sensitivity further suggests that rats dwelling in households will reflect the resources available within or nearby these structures.

Modern studies do not necessarily provide a robust analog to prehistoric Pacific rat diet. European arrival on Polynesian Islands introduced a suite of new flora and fauna as well as new cultural practices which led to transformations in island landscapes as well as human subsistence practices and activities. Introduced species included previously unknown predators such as the domestic cat (*Felis catus*) and competitors such as the black rat, brown rat, and house mouse. These introductions impacted Pacific rat populations and may have led to significant deviance from pre-European diet and behavior. Further, these contemporary studies have focused on rats living away from human habitation sites. The diet of rats living within contemporary Polynesian village and household contexts has not been studied. Bone collagen stable isotope analysis of Pacific rat remains from other Polynesian archaeological sites indicate at least occasional dietary inputs of high trophic level proteins (Commendador et al. 2013; Richards et al. 2009).

Preparation and Analysis of Bone Collagen for Carbon and Nitrogen Stable Isotope Ratios

The application of carbon and nitrogen stable isotope analysis to archaeological bone collagen has proven an effective tool in paleodietary studies (see Katzenberg 2008; Schwarcz

and Schoeninger 1991; Sealy 2001). An isotope is a molecule of a particular element which contains the same number of protons and electrons as other molecules of that element but varies in its number of neutrons. Isotopes can be either stable, meaning they do not undergo radioactive decay (e.g., ^{12}C and ^{13}C) or radioactive (e.g., ^{14}C). The addition of a neutron changes very little about a molecule, however the slight increase in atomic mass allows for small but predictable variation in the way isotopes are distributed before and after a physical or chemical reaction. In general, heavier isotopes tend to react more slowly, and form stronger chemical bonds. The difference between the stable isotope ratios of the substrates and products of a reaction is known as *fractionation*, and this process forms the basis of all stable isotopic analyses (see reviews by Hoefs 1987; Sharp 2007).

Carbon and nitrogen stable isotopes fractionate in predictable ways throughout ecosystems and foodwebs. A significant source of carbon fractionation originates in the different photosynthetic pathways used by plants (Bender 1968; 1971). C_3 plants tend to have $\delta^{13}C$ values in the range of -34 to -21‰, while C_4 plant $\delta^{13}C$ values fall between -15 to -8‰. Crassulacean Acid Metabolism (CAM) plants often have $\delta^{13}C$ values that fall between the ranges of C_3 or C_4 plants. Most Polynesian economic crops are C_3 plants, however sugarcane (a Polynesian crop plant) and most tropical grasses are C_4. While terrestrial plants derive most carbon from atmospheric CO_2, carbon in marine systems is derived from a mix of sources including terrestrial detritus and dissolved bicarbonate. Thus, marine primary producers tend to have significantly less negative $\delta^{13}C$ values compared to terrestrial plants, though these values vary depending on species, tissue, and location (Lee-Thorp 2008; Schoeninger and DeNiro 1984).

Nitrogen stable isotope ratios are useful in determining the trophic level of a species, as an enrichment of 3-5‰ occurs between producers and consumers for every "step" up the trophic ladder. An average figure of 3-3.5‰ is frequently employed in dietary studies (Bocherens and Drucker 2003; DeNiro and Epstein 1981; Minagawa and Wada 1984). Because marine foodwebs have long chains of producers and consumers, N stable isotope ratios of marine systems tend to be more enriched (greater abundances of ^{15}N) than their terrestrial counterparts. Nitrogen fixing plants, which include legumes, sugar cane, and blue-green algae draw on atmospheric N_2 and tend to have lower $\delta^{15}N$ values compared to non-fixers that rely on soil N which is more enriched (Schoeninger and DeNiro 1984). N stable isotope ratios are also influenced by numerous environmental factors, including temperature, aridity, and salinity (DeNiro and Hastorf 1985).

Stable isotope abundances are measured through an isotope ratio mass spectrometer (IRMS). Samples are converted to gas form, ionized, and accelerated into a focused ion beam. This beam of charged isotopes then enters a magnetic field which causes the particles to accelerate in an arced path. As acceleration is mass-dependent, each isotope assumes a different trajectory (heavier molecules follow an arc with a larger radius than lighter molecules) allowing them to become spatially separated by mass upon exiting the magnetic field. These mass-separated ion beams are directed into a series of Faraday cups which generate an electrical current proportional to the number of molecules to impact the cup. The strength of the current from each Faraday cup is then measured to calculate the relative proportion of each isotope within the sample.

Stable isotope abundances are expressed as ratios of the heavier isotope to the lighter isotope (e.g., $^{13}C/^{12}C$). However, because the differences in isotopic abundances are so small, these ratios are not expressed as absolute values but relative to an internationally established standard, and in parts per thousand (‰). These results are expressed in δ notation, where

$$\delta X = [(R_{sample} \div R_{standard}) - 1] * 1000‰.$$

For C and N stable isotope ratios, this formula becomes:

$$\delta^{13}C = [(^{13}C_{sample}/^{12}C_{sample} \div ^{13}C_{standard}/^{12}C_{standard}) - 1] * 1000‰$$

and

$$\delta^{15}N = [(^{15}N_{sample}/^{14}N_{sample} \div ^{15}N_{standard}/^{14}N_{standard}) - 1] * 1000‰$$

The standard for calculating $\delta^{13}C$ values is PeeDee Belemnite (PDB), a cretaceous marine fossil (*Belemnitella americana*) from the PeeDee formation in South Carolina. Because this standard is enriched in ^{13}C relative to most extant plants and animals, $\delta^{13}C$ values derived from archaeological bone collagen and potential food sources tend to be negative. The standard for calculating $\delta^{15}N$ values is an accepted standardized value for atmospheric air (Ambient Inhalable Reservoir, or AIR). $\delta^{15}N$ values tend to be positive numbers, as AIR is depleted in ^{15}N relative to most samples.

This study utilizes C and N stable isotope ratios from bone collagen of the Pacific rat. Bone collagen, the organic portion of bone, is comprised of amino acids, some of which cannot be synthesized *de novo* and instead come from dietary proteins. As such, bone collagen is heavily weighted towards the protein component of diet (Ambrose and Norr 1993; Tieszen and Fagre 1993). Bone collagen is remodeled over time, however for small short-lived species such as rats this tissue records the average diet consumed during most of the individual's lifespan (see Tieszen et al. 1983).

There are several methods of preparing bone collagen for stable isotope analysis, and the choice of method is often dependent on time, money, and available equipment and laboratory facilities. A recent meta-analysis by Sealy et al. (2014) compared the older, simpler method (after Ambrose 1990) with the more intensive ultrafiltration method (after Brown et al. 1988; Longin 1971) and determined there were no statistically significant differences between the results produced from either method. The first method involves demineralization of bone chunks in dilute hydrochloric acid (HCl) followed by a dilute sodium hydroxide (NaOH) treatment to remove humic contaminants. This treatment produces a collagen 'pseudomorph,' which is overwhelmingly composed of bone collagen but may also contain small amounts of other proteins such as osteocalcin. The latter method is more rigorous and includes a gelatinization and ultrafiltration step to isolate bone collagen. Pestle et al. (2014) further confirmed the comparability of results across labs using different preparation methods, equipment, and calibrations. They found that major differences in preparation methods employed by different laboratories did not have a significant effect on stable isotope results. Rather, the largest differences in results were introduced through variations in instrumentation and standardization. They suggest that resulting $\delta^{13}C$ and $\delta^{15}N$ values from the same sample may vary between labs by up to 0.6‰ and 0.9‰ respectively (their Minimum Meaningful Difference, or MMD).

Bone collagen preservation can be assessed through several measures, the most widely accepted of which is the ratio of preserved carbon to nitrogen in the sample (atomic C:N ratio). Glycine, which comprises over 1/3 of the amino acid sequence of bone collagen, has a 2:1 ratio of carbon to nitrogen, which contributes to bone collagen's unique C:N ratio. Most other amino acids have a much higher C:N ratio, and intact collagen is estimated to have a roughly 3:1 ratio

of carbon to nitrogen. Archaeological bone collagen samples are generally accepted as intact if they fall within the range of 2.9-3.6 (Ambrose 1990; DeNiro 1985), though some laboratories use a more restricted range of 3.1-3.5 (van Klinken 1999). Secondary quality control indicators include collagen yield (by weight %), as well as wt% C and wt% N within the sample. Modern bone is comprised of approximately 20-22 wt% collagen. Minimum collagen yield cutoffs vary depending on the study region, and range from 0.5-5% (Pestle and Colvard 2012; Schwarcz and Schoeninger 1991; van Klinken 1999). The characteristic concentrations of carbon and nitrogen in intact bone collagen are roughly 35 wt% and 11-16 wt%, respectively (van Klinken 1999). Analysis of amino acid composition may also be used to assess collagen preservation, though this can be costly, time consuming, and inefficient (see DeNiro and Weiner 1988). More subjective methods of assessing collagen are by morphological integrity (if the resulting collagen retains a semblance of its original shape) and by color. Pure collagen is pale yellow to white, whereas contaminated collagen will take on a brownish hue (Koch et al. 1994).

Carbon and Nitrogen Stable Isotope Analysis in Remote Oceania

Carbon and nitrogen stable isotope analysis has recently been applied to both human and animal remains in Remote Oceania to investigate changing human diet, subsistence systems, and ecology across time and space. A study by Leach et al. (1996) enumerated several limitations to stable isotopic dietary studies in the Pacific. These included the wide variety of potential food sources in coastal systems, the similarity in values between inshore reef sources and terrestrial C_4 sources, and the influence of marine-derived sediments on terrestrial plant $\delta^{15}N$ and $\delta^{13}C$ values. Degraded bone collagen in tropical environments can serve as a further hindrance to archaeological stable isotope studies in the Pacific (see Van Klinken 1999). However, a wealth of research over the past several decades has demonstrated the effectiveness of this analytical technique in the tropical Pacific.

Some of the earliest stable isotopic analyses in the Pacific were conducted on human bone collagen from the Mariana Islands. McGovern-Wilson and Quinn (1996) analyzed bone collagen of ten individuals recovered from burials at Afetna, Saipan and found that $\delta^{13}C$ and $\delta^{15}N$ values corresponded to greater marine resource inputs—particularly of offshore fish—than previously indicated by the faunal record. Ambrose et al. (1997) compared the diet of several human populations from three different islands within the Marianas (Guam, Rota, Saipan) during the Latte Period (AD 1000 to historic contact). The study analyzed both the organic (bone collagen) and mineral (hydroxyapatite) components of bone and found a significant input of C_4 plants to the diet of Saipan individuals relative to those from Guam and Rota. This study suggested that C_4 plants such as seaweed and sugarcane played a more significant dietary role in some regions of the Pacific than previously thought.

Stable isotope analysis of individuals from Fiji shows considerable spatiotemporal variation in human diet. Valentin et al.'s (2006) bone collagen analysis of nine elite individuals from late prehistoric/early historic burials at the Korotuku burial mound, Cikobia, North Fiji demonstrated a predominantly vegetal diet with some contributions from high trophic level marine resources. In contrast, analysis of a canid tooth from the same burial context indicated dog diet contained significant inputs of shellfish. Based on these stable isotope data and a high frequency of dental caries, the authors suggested that the people buried at Korotuku had a highly selective diet based around frequent consumption of high-value foods including puddings and pelagic fish (see Leach 2003). In contrast, bone collagen and apatite analysis conducted by Jones

and Quinn (2009) on a population of nine individuals from Nayau, Aiwa Levu, and Aiwa Lailai indicated that Fijian diet was composed primarily of C_3 plants supplemented by reef resources, rather than pelagic fish. Early occupants also appear to have consumed C_4 plants, which the authors suggest may have come in the form of sea grapes. The dietary differences between these populations may be related to status differences, with elite members of society having more frequent access to high trophic level proteins. A study by Field et al. (2009) confirmed variations in Fijian diet which extended beyond age, class, and status distinctions. Stable isotope analysis of 26 individuals from Sigatoka Valley and Waya Island (2700-300 BP) were compared to assess differences in Fijian diet related to geographic variability. Human diet in the Sigatoka Valley remained predominantly terrestrial. The diet of individuals from Waya Island became more terrestrial over time, but continued to be dominated by marine resources into late prehistory. The authors suggested that smaller islands with less arable land likely retained marine-focused diets throughout prehistory.

Two studies by Valentin et al. (2010) and Kinaston et al. (2014) assessed the diet of Lapita populations (3000-2500 BP) from the Teouma Site, Efate Island, Vanuatu. Valentin et al.'s (2010) analysis of 23 individuals found significant dietary contributions from terrestrial fauna (over 50% of total protein consumption), as well as some terrestrial plants, shellfish, and inshore fish. Terrestrial food sources may have included indigenous fauna such as bats, reptiles, and birds, or introduced domestic fauna such as pigs, rats, and chickens. Kinaston et al. (2014) expanded this study with the addition of carbon, nitrogen, and sulfur (S) stable isotope data from 49 individuals and a collection of dietary baseline stable isotope data from modern and archaeological flora and fauna. This study confirmed the importance of terrestrial animals to Lapita diet, in addition to reef sources and sea turtles. While horticultural systems were likely being established at this time, they appear to have been less important to overall Lapita subsistence compared to later populations. In addition, male individuals had a larger range of $\delta^{15}N$ and $\delta^{13}C$ values and overall higher $\delta^{15}N$ values than female individuals, indicating males had a more varied diet with greater access to high trophic level proteins.

Within Polynesia, an analysis by Valentin et al. (2011) of 14 individuals from Tutuila Island, American Samoa (1000-150 BP) found diet to be predominantly terrestrial with some contributions of reef fish and shellfish, along with declining marine resource consumption through time. Stantis et al. (2015) analyzed carbon, nitrogen, sulfur, and strontium (Sr) stable isotope ratios of 41 individuals recovered from the 'Atele burial site, Tongatapu Island, to assess human diet and mobility in Tonga (500-150 BP). Although the diet of the entire population was focused primarily on terrestrial plant and marine protein sources, they discovered significant dietary differences related to sex and social status. Similar to Kinaston et al.'s (2014) results from Vanuatu, females had lower $\delta^{15}N$ values than males. Individuals recovered from a burial mound associated with commoners had less negative $\delta^{13}C$ values compared to individuals recovered from a burial mound interpreted as more elite. The increased proportion of terrestrial sources in elite diet likely came in the form of more prestigious manifestations of terrestrial crops (such as puddings), though this type of culinary elaboration cannot be detected through stable isotope analysis (Stantis et al. 2015).

Kinaston et al. (2013) similarly used C, N, and Sr isotope analysis of 38 individuals from the Wairau Bar site on the South Island of New Zealand to assess human diet and mobility. The Wairau Bar site is one of the earliest known sites in New Zealand (late 13th century AD). Significant differences in stable isotope ratios between three distinct groups of human burials (Group 1 versus Groups 2 and 3) led Kinaston et al. (2013) to suggest the individuals in Group 1

may come from a colonizing population. Brown and Thomas (2015) later reevaluated these data and argued that burial groups could not be distinguished based on stable isotope ratios, dietary differences were best explained by sex differences, and Sr stable isotopic variation could not distinguish Group 1 as a founding population. Kinaston et al. (2015) responded to Brown and Thomas (2015), arguing that they misunderstood the purpose of their study and their claims were invalid. Kinaston et al. (2015) noted that their study was not attempting to establish burial groups using isotope data, but rather to assess patterns within *pre-existing* burial groups identified by archaeological analysis. In addition to problems with Brown and Thomas' (2015) interpretations of the isotopic data, Kinaston et al. (2015) argued that their data-driven analysis, detached from supporting archaeological and ethnographic lines of evidence, was poorly supported and inconsistent with previous interpretations of New Zealand subsistence and prehistory.

Bone collagen analysis of 99 individuals from the Namu burial ground (750-300 BP), Taumako Island (Southeastern Solomon Islands) provides stable isotopic dietary information from a Polynesian Outlier (Kinaston et al. 2013). Overall, diet on Taumako during this time consisted of terrestrial C_3 resources and a range of marine proteins including reef fish and shellfish as well as high trophic level, offshore species. Diet also varied according to status and sex differences within Taumako society. Based on associated grave goods in burials, the wealthiest individuals had less negative $\delta^{13}C$ and higher $\delta^{15}N$ values than the rest of the population, and male individuals had higher $\delta^{15}N$ values than females (though elite females still had higher $\delta^{15}N$ values than non-elite males and females). Elite members of Taumako society appear to have had more frequent access to high trophic level (and highly valued) proteins, including offshore fish, pig, dog, and turtle.

Several stable isotopic studies within Polynesia have also focused on the diet of terrestrial animals. Allen and Craig (2009) conducted stable isotope analysis on bone collagen from humans, pigs, and dogs recovered from Aitutaki, Southern Cook Islands. Their findings showed a transition from a largely marine-based diet to one more focused on terrestrial resources for all three species over time, as well as declining human consumption of marine carnivores. They also observed a restriction in pig $\delta^{13}C$ and $\delta^{15}N$ values in later prehistory which may be an indication of resource depression and tighter management of pig populations. Pig and dog were both extirpated from Aitutaki prior to European contact, presumably due to competition between humans and domesticates over limited food resources (see Kirch 2000b). Studies by Richards et al. (2009) and West (2007) from the Hanamiai Dune site, Tahuata Island provide new insight into Marquesan diet and animal husbandry. Richards et al. (2009) analyzed bone collagen from pig, dog, rat, and marine fauna as well as four human teeth not associated with human remains. The four human bone samples analyzed did not have a strongly marine diet. Rather, dietary protein was obtained largely from terrestrial mammals such as pigs, dogs, and perhaps rats. West's (2007) intensive analysis of pig husbandry in the Marquesas included bone collagen stable isotope analysis of pig remains through time at the Hanamiai site. He argued that the temporal variation seen in pig diet suggested that pigs were allowed to return to a feral state upon initial introduction to the Marquesas, and were re-domesticated once a productive agricultural system had developed.

Commendador et al. (2013) analyzed 41 human teeth along with 132 archaeologically recovered specimens of terrestrial and marine fauna to assess changing diet on Rapa Nui (Easter Island). Their results indicate a largely terrestrially-based diet with protein inputs from rats and chickens, and minimal inputs from marine sources. They observe an overall decline in $\delta^{15}N$ values over time and suggest that this may be related to increasing reliance on agricultural

products due to terrestrial resource depression and declining animal populations. They also note that this decline could be the result of changing soil-plant baseline ^{15}N. Numerous biogeochemical factors can influence nitrogen stable isotope ratios in plants and soils, and the authors suggest potential changes in rainfall patterns, soil N availability, and decreasing inputs of ^{15}N-enriched seabird guano may have lowered baseline δ^{15}N.

Dissertation Outline

The following chapters present analyses of carbon and nitrogen stable isotope ratios from Pacific rat bone collagen recovered from three distinct island contexts. Chapter 2 presents stable isotope data from three separate islands on the almost-atoll of Mangareva (Gambier Islands, French Polynesia). Temporal declines in δ^{15}N values at all three of these sites indicate large-scale changes in island nutrient flows, likely related to the massive avifaunal extinctions that occurred shortly after human arrival to the archipelago. Chapter 3 examines rat stable isotope ratios through time at the Hane Dune Site on Ua Huka Island (Marquesas Islands, French Polynesia). Results from this site support the close relationship between human and rat diet in Polynesian prehistory, and indicate a later shift towards intensified agriculture and animal husbandry. Chapter 4 examines changing rat diet on the Polynesian Outlier of Tikopia, and finds evidence for a long history of island socio-ecosystem sustainability. Finally, Chapter 5 concludes by placing these three case studies in comparative perspective and suggests future directions for the application of small mammal stable isotope ecology towards understanding human subsistence and environmental change.

Chapter 2

Stable isotope analysis of Pacific rat (*Rattus exulans*) from archaeological sites in Mangareva (French Polynesia): Implications for nutrient flows in island socio-ecosystems

__Introduction__

The analysis of diet-derived bone collagen $\delta^{13}C$ and $\delta^{15}N$ from archaeologically recovered faunal remains can provide paleoecological insights through the reconstruction of ancient food webs and the trophic position of humans and other animals within those webs. Small-bodied mammals in particular have proven effective proxies for paleoclimatic reconstructions (e.g., Gehler et al. 2012; Hynek et al. 2012); the analysis of commensal archaeofaunal species can generate new evidence for investigations into long-term human-environment interaction (ecodynamics). Here we report bone collagen $\delta^{13}C$ and $\delta^{15}N$ stable isotope data for 84 Pacific rats (*Rattus exulans*) from three archaeological sites in the Mangareva Islands (Gambier Archipelago) to investigate the implications of changing foodweb dynamics and trophic positioning for this species through time in this southeastern Polynesian archipelago.

Recent attention to bone collagen $\delta^{13}C$ and $\delta^{15}N$ values of commensal fauna demonstrates their utility in investigations of paleoecology, animal husbandry, and human diet (e.g., Birch 2013; Guiry 2012; Stevens et al. 2008; Zangrando et al. 2014). Stable isotope analysis of domestic pigs (*Sus scrofa*) and dogs (*Canis familiaris*) in Polynesia has shed light on the intensification of pig husbandry in the Marquesas Islands (Richards et al. 2009; West 2007) and provided indications of resource stress and competition between humans and domestic species on Aitutaki, Cook Islands (Allen and Craig 2009). The commensal association of rats with humans suggests that the reconstructed diet of rats recovered from archaeological contexts can provide a local understanding of nutrient inputs and resource availability. Guiry and Gaulton (2015) utilized bone collagen stable isotope analysis of past black rat (*Rattus rattus*) populations at Ferryland, Newfoundland to assess changes in human social and economic practices between the 17th and 18th centuries. While they caution against utilizing rat $\delta^{13}C$ and $\delta^{15}N$ as a direct proxy for human diet, their study demonstrated that archaeological rat remains present a new source of evidence for understanding past human foodways, activities, and ecodynamics. The low dietary selectivity, limited home range (Atkinson and Moller 1990), and ubiquity of the Pacific rat in Polynesian island prehistory position it as an ideal species for exploring localized change in island foodwebs and nutrient flows. The stable isotope data from Mangareva document changes in rat dietary $\delta^{13}C$ and $\delta^{15}N$ through time across diverse archaeological contexts and indicate large-scale transformations in island ecodynamics and human subsistence activities.

Three recently excavated sites in the Mangareva Islands provide the data for this analysis (Figure 2.1). All three sites offer stratified archaeological sequences with abundant Pacific rat remains throughout the duration of human occupation. The sites also vary in geographic location, timing and duration of human site use, as well as site function and history. The Onemea Site (TAR-6) is an open-air deposit containing the earliest evidence for human activity in the Mangareva Islands. Well-stratified deposits from two rockshelter sites, Nenega-iti (AGA-3) and Kitchen Cave (KAM-1) provide contexts for investigating long-term site ecology, human activity, and rat diet.
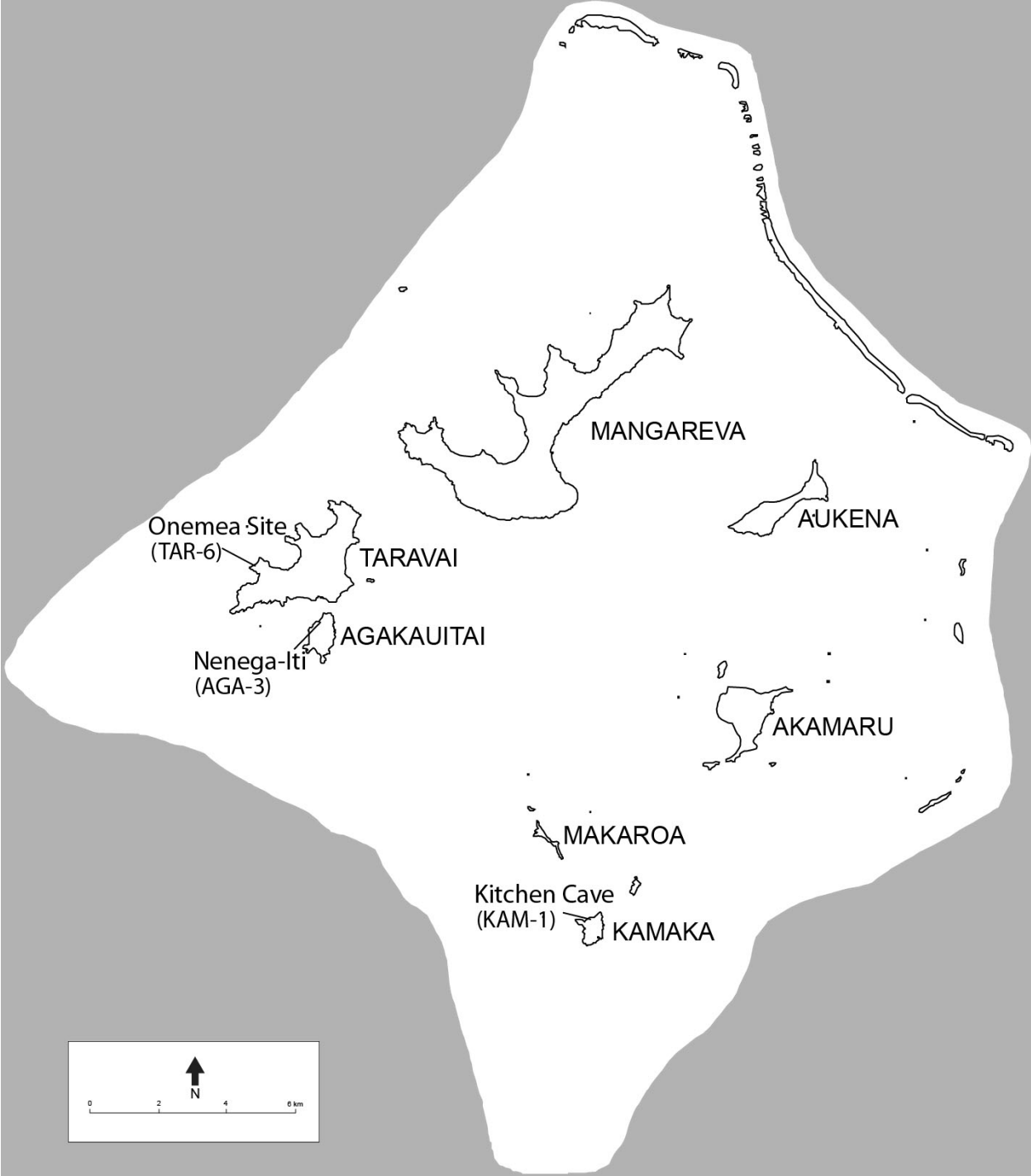
Figure 2.1: Map of the Mangarevan archipelago and surrounding barrier reef with labeled study sites.

The Pacific Rat in Polynesian Ecosystems

The Pacific Rat (*Rattus exulans*) is ubiquitous throughout Polynesia, typically appearing in archaeological sites concurrent with the earliest evidence for initial human occupation. Although it is virtually certain that rats required human agency to arrive on new islands, it remains unclear whether Polynesians intentionally transported the Pacific rat as a potential food source or passively transported them as "stowaways" on Polynesian voyaging canoes (Matisoo-Smith 1994; Tate 1935). In Mangareva, rats were reportedly not eaten, although they were known to be consumed in other Polynesian islands such as Mangaia (Kirch et al. 1995; Matisoo-Smith et al. 1999; Hiroa 1938:194). The human-mediated transport of rats to new islands has allowed rats to serve as useful proxies for understanding the human colonization of the Pacific through ancient DNA analysis (e.g., Matisoo-Smith 1994; Matisoo-Smith et al. 1999), and the early presence of *R. exulans* in Polynesian archaeological sites provides directly dateable, short-lived materials for estimating the first arrival of Polynesians to new islands (Anderson 2004; Kirch 2011a; Wilmshurst et al. 2008).

Previous archaeological research has documented the frequently extensive transformations to Polynesian island landscapes following human arrival, including the introduction of nonnative species, clearance of native forest, increased rates of erosion and sedimentation, soil nutrient depletion, and extinction and extirpation of indigenous flora and fauna (e.g., Allen 1998; Burney et al. 2001; Kirch 1983, 1996; Kirch and Hunt 1997). Attention has recently turned to the impacts of Polynesian-introduced plants and animals within island socio-ecosystems, and it is now recognized that rats in particular played a key role in the extirpations and extinctions of indigenous biota on oceanic islands (e.g., Athens et al. 2002; Holdaway 1989). Pacific rats multiply rapidly (Kramer 1971; Moller and Craig 1987; Tamarin and Malecha 1972), though in most continental regions populations are kept in check by other natural predators such as snakes, cats, or birds of prey. However, the absence of native terrestrial carnivores on Oceanic islands apparently allowed rat populations to multiply extremely rapidly.

Pacific rats are opportunistic omnivores that will actively prey upon a range of species including insects, snails, small lizards, turtle hatchlings, and bird eggs and small birds (Norman 1975; Spenneman 1997). *R. exulans* diet tends to be more carnivorous than that of the black rat (*R. rattus*) though still predominantly vegetal. Modern gut content analysis demonstrates protein contributions derived primarily from arthropods (Shiels et al. 2013). Relying on modern rat dietary studies, however, may be problematic as rat diet varies based on numerous factors including sex, age, local ecology, and seasonal resource availability (Bunn and Craig 1989). Dramatic differences between pre- and post-European contact Polynesian landscapes, historic introductions of new predators, and modern competition and niche partitioning between *R. exulans* and the European-introduced black rat, Norwegian brown rat (*R. norvegicus*), and house mouse (*Mus musculus*) have undoubtedly transformed the foraging behavior of *R. exulans*, thus making modern gut content studies poor analogs for assessing prehistoric Pacific rat diet.

Pollen cores from the 'Ewa Plain, O'ahu (Hawaiian Islands) demonstrate massive forest decline after the arrival of Pacific rat but prior to significant human activity in this region, leading Athens et al. (2002) to suggest that rat predation on indigenous vegetation—rather than forest clearance for agricultural activities—was the most likely cause for initial native forest decline and avifaunal habitat loss. In contrast, on Nihoa Island, where rats were never introduced, native palm forests persist (Hunt and Lipo 2010). The abundance of rat-gnawed *Jubaea* palm seeds discovered on Rapa Nui (Easter Island) has sparked debate over the extent to

which rat predation contributed to the deforestation that eventually led to the society's so-called 'collapse' (Diamond 2005; Hunt and Lipo 2007, 2010; Mieth and Bork 2010).

Rat impact on indigenous avifauna through direct predation and habitat destruction is evidenced in numerous studies of modern seabird populations on islands with and without rats (e.g., Brooke et al. 2010; Caut et al. 2008; Jones et al. 2008; Towns et al. 2006). Analyses of Polynesian archaeofaunal assemblages present a consistent trend of rapid disappearances of a range of land bird and seabird species shortly after human (and rat) arrival to Polynesian islands (Steadman 2006). C and N stable isotope analysis of modern Norwegian rats has connected ^{15}N-enriched rat diets to the decline of nesting island seabird populations (e.g., Hobson et al. 1999; Major et al. 2007). The diet of rats analyzed in these studies fell into several regionally-dependent dietary groups, reflecting the observed heterogeneous distributions of island resources. The observed dietary adaptability makes rats particularly effective island predators, and suggests that rat diet is sensitive to local resource availability. Thus, dietary change through time in rat populations can provide insight into localized processes of socio-ecosystem change.

Materials and Methods

Background

Mangarevan prehistory presents a particularly dramatic case of environmental transformation following human—and rodent—arrival. Mangareva is an almost-atoll of 10 small volcanic islands encircled by a barrier reef on the easternmost boundary of French Polynesia. The encompassing barrier reef fosters a rich lagoon environment, standing in stark contrast to a depauperate terrestrial landscape. Archaeobotanical analyses document the transition from indigenous forest cover to a landscape dominated by Polynesian economic plants after human arrival (Kirch et al. 2015). Steep hill slopes with thin soils and little remaining forest cover provide minimal opportunity either for agricultural productivity or nesting seabird habitat. Agriculture is restricted to small coastal arboricultural patches and limited root crop cultivation in valley floors. Early written accounts of Mangareva describe a deforested landscape dominated by *Miscanthus* grasslands (Cooke 1935). However, archaeological excavations have uncovered evidence for a richer, more diverse Mangarevan ecosystem prior to human arrival.

Zooarchaeological analyses document steep declines in indigenous seabird populations shortly after human arrival, as well as the disappearance of three landbird species: an extinct heron and two extirpated columbids (Steadman and Justice 1998; Worthy and Tennyson 2004). Human and rat predation combined with the replacement of primary forest with coconut arboriculture (seabirds generally avoid nesting in coconut palms; Young et al. 2010) likely deleteriously impacted avifaunal communities in early prehistory. Seabird decline would have led to depletion of key soil nutrients from marine subsidies, perpetuating a cycle of terrestrial landscape degradation and resource stress.

Along with rats, Polynesians transported three other terrestrial vertebrates on long-distance colonizing voyages: the domestic pig, dog, and chicken. Remains of all three have been recovered from excavations in Mangareva, though never in abundances that would indicate a strong reliance on these animals for food; all three species disappeared from the islands prior to European contact (Green and Weisler 2004). In contrast, marine resources—especially of inshore and lagoonal species—were abundant. There is little evidence for resource depletion in the lagoon environment and no statistically significant changes in measurements of marine mollusks

and fish vertebrae through time in Mangarevan archaeological sites (Conte and Kirch 2004; Kirch et al. 2015).

Study Sites

The Pacific rat assemblages analyzed in this study were recovered from recent excavations directed by Patrick Kirch and Eric Conte (Conte and Kirch 2004; Kirch et al. 2010, 2015).

The Onemea Site (TAR-6)

The Onemea site on Taravai Island provides the earliest evidence of human occupation in the Mangareva Islands. Multiple radiocarbon dates place the first human activity in Layer III at approximately AD 950 (Conte and Kirch 2004; Kirch et al. 2010). The site appears to have been mainly a campsite for hunters and fishermen. Kirch et al. (2010) characterize Layer III as a palimpsest representing several centuries of repeated, brief visits to the site. Abundant avifaunal remains with taphonomic modifications indicative of human cooking and consumption demonstrate that one purpose of these visits was seabird exploitation. More intensive use of the site is evident in Layer II, where multiple earth ovens and the presence of fishing gear indicate a series of repeated visits to the site over a period of about two hundred years (from ca. AD 1200-1400), after which time Onemea appears to have been largely abandoned. Layer I postdates human occupation of the site.

Nenega-Iti Rockshelter (AGA-3)

The Nenega-iti Rockshelter on Agakauitai Island was tested by Conte and Kirch in 2003 (Conte and Kirch 2004), and expanded excavations were carried out at the site in 2012 (Kirch et al. 2015). Rat bone samples were recovered from the main trench (units D9, E9, and F9), which abuts and extends out from the rockshelter wall (see Kirch et al. 2015, fig. 3). The stratigraphic sequence at AGA-3 begins with Layer IV, marking the initial occupation of the site sometime in the 13th century AD. Layer IV continues until the mid-17th century and is followed by a colluvial deposit (Layer III) that, while thick, may only represent a single depositional event. The final occupation phase, Layer II, terminates around the beginning of the 19th century. The site was not used regularly after European contact, although a historic religious medallion recovered from Layer II-1 suggests some brief post-contact visitation. Unlike Onemea, the Nenega-iti Rockshelter was likely a permanent habitation site with evidence for various human activities, including food remains, pearl shell fishhooks, branch coral abraders, bone thatching needles, and numerous basalt adzes.

Kitchen Cave (KAM-1)

Site KAM-1 on Kamaka Island was given the name Kitchen Cave by Roger Green, who first excavated the site in 1959 (Green and Weisler 2000). Kitchen Cave was re-excavated in 2012 and 2014 under the direction of Kirch, and excavated materials are presently under analysis. Rat elements were selected from both the 2012 and 2014 excavation assemblages. Kamaka is a particularly small, isolated, and resource-poor island even for Mangareva, and it is uncertain whether people continuously occupied the island throughout its prehistory. Kitchen Cave would have been a welcoming location to visitors or inhabitants as an expansive shelter with a permanent cave drip for fresh water. Recent AMS dates on short-lived botanical taxa from

the 2012 and 2014 excavations place the first occupation of Kitchen Cave at around AD 1300, with a continuous sequence of occupation phases through the mid-18th century (Kirch 2015).

Stable Isotope Analysis

Pacific rat elements were selected for stable isotope analysis by calculating Minimum Number of Individuals (MNI) by excavation level to maximize sample sizes while limiting potential resampling of the same individual. Appendicular elements were selected whenever possible, as differential rates of bone turnover have been observed between appendicular and cranial versus axial elements for *R. norvegicus* (Wolfe and Klein 1996). However, as the Pacific rat is a short-lived species it is unlikely that bone turnover rates would significantly differentiate dietary $\delta^{13}C$ and $\delta^{15}N$ values between bone elements.

Specimens were sonicated with ultrafiltered water for four hours, dried, and abraded to remove surface contaminants. Samples were cut into ~1 mm chunks and bone collagen was extracted using a modified version of Ambrose (1990; and see Sealy et al. 2014), producing collagen 'pseudomorphs.' Samples over 20 mg were treated with 0.5 M HCl with fresh HCl applied every 24 hours until bone chunks lost their mineral structure and became springy to the touch. Samples weighing less than 20 mg were treated with a more dilute solution of 0.25 M HCl to prevent excessive sample loss. All samples were treated with a 0.1 M NaOH solution for 24 hours to remove humic contaminants. Samples were rinsed and freeze dried for 48 hours.

Dry samples from sites TAR-6 and AGA-3 were analyzed simultaneously for carbon, nitrogen, and sulfur contents (% dry weight) and carbon (C), nitrogen (N), and sulfur (S) stable isotope ratios. KAM-1 samples were analyzed simultaneously for C and N contents (% dry weight) and C and N stable isotope ratios only. Analyses were conducted via elemental analyzer/continuous flow isotope ratio mass spectrometry using a CHNOS Elemental Analyzer (vario ISOTOPE cube, Elementar, Hanau, Germany) coupled with an IsoPrime 100 mass spectrometer (Isoprime Ltd., Cheadle, UK). All isotope analyses were conducted at the Center for Stable Isotope Biogeochemistry at the University of California, Berkeley. Long-term external precision for C, N, and S isotope analyses is 0.1‰, 0.15‰, and 0.5‰ respectively.

Stable isotope data recovered from bone collagen was assessed for various measures of preservation (see Table 2.1 for the results of the analysis and quality control indicators). Modern bone contains approximately 22% collagen by weight, and Pestle and Colvard (2012) recommend a minimum of 0.5% collagen preservation for archaeological bone samples recovered from tropical environments. More stringent requirements applied in other regions range from 1-5% collagen (e.g., Ambrose 1990; Schwarcz and Schoeninger 1991; van Klinken 1999) and the majority of samples met this requirement, with all samples falling above 0.5% collagen preserved. Four samples fell outside the recommended C/N ratio range of 2.9-3.6 (Ambrose 1990; DeNiro and Weiner 1988; van Klinken 1999) and were eliminated from study. Nine samples dissolved during demineralization and were not analyzed.

Samples from TAR-6 and AGA-3 were analyzed for stable sulfur isotope data ($\delta^{34}S$), however all resulting values hovered around ~20‰, the same $\delta^{34}S$ value as ocean water (Chukhrov et al. 1980; Peterson and Fry 1987). Although $\delta^{13}C$ and $\delta^{15}N$ values similarly suggest a marine component to many diets (see below), $\delta^{34}S$ values on small islands such as those of Mangareva are likely heavily influenced by the sea spray effect (Richards et al. 2001). Sulfur stable isotope data will not be discussed further.

Table 2.1: Results of *Rattus exulans* bone collagen carbon and nitrogen stable isotope analysis and quality control indicators from The Onemea Site (TAR-6), Nenega-Iti Rockshelter (AGA-3), and Kitchen Cave (KAM-1).

Sample No.	Excavation Unit	Layer	Element	Side	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	% C	% N	C:N Ratio
KAM-1-1	B3	I	Femur	R	-19.5	9.6	43.07	15.51	3.24
KAM-1-2	B3	I	Femur	R	-14.5	14.1	26.51	9.2	3.31
KAM-1-3	B3	II	Femur	L	-14.3		33.25	11.98	3.24
KAM-1-4	B3	II	Femur	L	-15.7	15.4	26.51	9.40	3.29
KAM-1-5	B3	II	Femur	L	-12.8	13.9	32.43	11.67	3.24
KAM-1-7	B3	III	Femur	L	-12.2	13.2	41.75	14.58	3.34
KAM-1-8	B3	III	Femur	L	-12.1	12.0	30.07	10.20	3.44
KAM-1-9	B3	III	Femur	L	-16.7		30.16	10.29	3.42
KAM-1-10	B3	III	Femur	L	-14.6	13.7	42.52	14.81	3.35
KAM-1-11	B3	III	Tibia	L	-14.8	15.4	42.81	15.06	3.32
KAM-1-12	B3	III	Tibia	L	-17.0	16.2	43.60	15.03	3.38
KAM-1-13	B3	III	Femur	L	-14.9	15.3	42.10	14.57	3.37
KAM-1-14	B3	III	Mandible	L	-15.1	14.3	43.79	15.44	3.31
KAM-1-16	B3	III	Humerus	L	-14.8	14.1	42.97	14.86	3.37
KAM-1-17	B3	IV1	Femur	R	-19.0		34.82	11.89	3.42
KAM-1-18	B3	IV1	Humerus	R	-18.7	19.4	43.13	14.94	3.37
KAM-1-19	B3	IV1	Humerus	R	-15.2	11.1	43.34	15.01	3.37
KAM-1-21	B3	IV1	Innominate	R	-17.2	16.5	43.83	15.01	3.41
KAM-1-22	B3	IV1	Tibia	R	-17.2	17.3	43.57	14.91	3.41
KAM-1-23	B3	IV2	Femur	L	-16.1	14.8	27.37	9.25	3.45
KAM-1-24	B3	IV2	Femur	L	-19.1	16.1	42.92	14.83	3.38
KAM-1-25	B2	IV2	Innominate	L	-15.6	17.5	45.88	16.89	3.17
KAM-1-26	B4	IV2	Femur	L	-16.6	18.4	37.66	13.57	3.24
KAM-1-32	C3	IV2	Femur	R	-19.4	16.0	42.74	14.91	3.34
KAM-1-33	C3	IV2	Femur	R	-12.2	14.9	46.08	16.70	3.22
KAM-1-31	B4	V	Humerus	L	-18.9	20.1	45.85	16.86	3.17
KAM-1-34	C3	V	Femur	R	-16.2	16.6	48.14	17.09	3.29
KAM-1-35	C3	V	Femur	L	-14.1	15.1	37.17	12.93	3.37
KAM-1-28	B4	VI	Femur	L	-15.9	19.7	47.07	19.66	3.25
KAM-1-29	B4	VI	Femur	L	-15.5	16.9	37.10	12.88	3.35
KAM-1-30	B4	VI	Humerus	L	-13.7	14.6	49.19	17.08	3.36
AGA-3-2	E9	II1	Mandible	R	-15.4	11.4	46.24	15.63	3.45
AGA-3-3	E9	II2	Tibia	R	-16.7	13.2	45.42	15.12	3.50
AGA-3-4	E9	II2	Humerus	L	-16.8	13.3	43.39	14.02	3.61
AGA-3-5	E9	II2	Humerus	L	-17.4	14.2	47.26	16.85	3.27
AGA-3-6	E9	II2	Humerus	L	-13.8	12.4	43.65	14.45	3.52
AGA-3-7	E9	II2	Humerus	L	-15.7	13.8	42.40	14.79	3.34
AGA-3-8	E9	II3	Mandible	L	-18.2	12.7	39.70	14.14	3.28
AGA-3-9	E9	II3	Mandible	L	-16.4	14.5	42.42	15.01	3.30

AGA-3-10	E9	II3	Mandible	L	-13.9	14.9	41.06	14.02	3.42
AGA-3-11	E9	II3	Femur	R	-18.6	14.2	44.09	14.88	3.46
AGA-3-12	E9	IV3	Innominate	R	-19.6	15.0	40.33	14.14	3.33
AGA-3-13	E9	IV3	Innominate	R	-18.9	10.5	35.96	11.89	3.53
AGA-3-14	E9	IV3	Innominate	R	-15.5	12.9	43.08	15.32	3.28
AGA-3-15	E9	IV3	Innominate	R	-17.5	12.2	42.59	15.41	3.23
AGA-3-16	E9	IV4	Ulna	L	-18.6	12.0	43.81	15.20	3.36
AGA-3-17	E9	IV5	Tibia	L	-14.4	14.0	40.25	14.46	3.25
AGA-3-18	E9	IV5	Tibia	L	-18.5	12.1	38.92	13.10	3.46
AGA-3-19	E9	IV5	Tibia	L	-15.0	12.0	41.81	14.46	3.37
AGA-3-20	E9	IV5	Tibia	L	-17.4	14.6	41.94	14.48	3.38
AGA-3-21	E9	IV5	Tibia	L	-19.2	12.2	40.41	13.42	3.51
AGA-3-22	F9	II1	Femur	R	-11.1	8.7	38.34	12.98	3.45
AGA-3-23	F9	II2	Femur	R	-10.2	7.6	30.11	10.47	3.36
AGA-3-24	F9	II2	Femur	R	-17.9	13.4	43.75	14.23	3.59
AGA-3-25	F9	II2	Femur	L	-17.0	13.6	28.57	9.95	3.35
AGA-3-26	F9	II2	Femur	L	-12.6	10.8	39.02	13.82	3.29
AGA-3-27	F9	II2	Femur	L	-16.3	12.0	33.25	11.66	3.33
AGA-3-28	F9	II2	Femur	L	-18.1	13.8	37.11	11.89	3.64
AGA-3-29	F9	II3	Tibia	R	-16.9	15.1	39.99	14.40	3.24
AGA-3-30	F9	II3	Tibia	R	-18.4	14.5	39.71	14.01	3.31
AGA-3-31	F9	III	Femur	L	-17.9	13.8	20.58	6.93	3.46
AGA-3-32	F9	III	Femur	L	-15.8	12.0	34.14	11.96	3.33
AGA-3-33	F9	III	Femur	L	-18.3	12.7	34.31	11.74	3.41
AGA-3-34	F9	IV1	Femur	L	-19.9	17.0	34.47	11.57	3.48
AGA-3-35	F9	IV1	Femur	L	-17.4	13.2	39.44	14.13	3.26
AGA-3-36	F9	IV1	Femur	L	-18.8	14.5	37.00	13.24	3.26
AGA-3-37	F9	IV1	Femur	L	-17.7	14.4	33.62	11.91	3.29
AGA-3-38	F9	IV2	Humerus	R	-16.9	12.4	37.31	13.12	3.32
TAR-6-1	5	I	Mandible	L	-17.9	8.6	46.34	17.23	3.14
TAR-6-2	5	IIA	Tibia	R	-19.2	9.6	48.54	17.78	3.19
TAR-6-3	5	IIA	Tibia	R	-19.6	13.1	47.27	16.49	3.34
TAR-6-4	5	IIA	Femur	R	-19.4	12.8	47.52	16.85	3.29
TAR-6-5	5	IIB	Mandible	L	-19.1	11.6	46.75	17.06	3.20
TAR-6-6	5	IIB	Vertebra	-	-19.6	12.5	44.89	16.00	3.27
TAR-6-7	6	I	Mandible	R	-19.6	11.0	46.38	16.25	3.33
TAR-6-8	6	I	Mandible	R	-16.2	5.2	47.07	16.84	3.26
TAR-6-9	6	IIA	Tibia	L	-18.7	12.8	48.29	17.31	3.25
TAR-6-10	6	IIA	Cranial Fragment	R	-13.4	12.4	47.46	17.15	3.23
TAR-6-11	6	IIB	Humerus	L	-16.1	14.1	47.56	16.84	3.30
TAR-6-13	6	IIB	Tibia	R	-18.9	12.3	45.22	16.16	3.26
TAR-6-16	11	I	Femur	L	-19.3	6.5	48.38	17.25	3.27

TAR-6-17	11	IIA	Mandible	R	-18.8	8.5	48.99	18.04	3.17
TAR-6-18	11	IIA	Humerus	L	-18.6	8.5	48.65	17.84	3.18
TAR-6-19	11	IIA	Humerus	R	-14.0	12.1	46.37	16.02	3.38

Results

In small, short-lived mammals, the organic portion of bone (bone collagen) records the chemical signatures of the average diet consumed during the whole lifetime of the animal. Bone collagen is made up of amino acids and is heavily weighted towards the protein component of diet (Ambrose and Norr 1993; Tieszen and Fagre 1993). Carbon stable isotope ratios (δ^{13}C) are primarily useful in distinguishing the dietary contributions of C_3 and C_4 plants or marine dietary inputs (DeNiro and Epstein 1978; Schoeninger and DeNiro 1984). Most Polynesian-introduced economic plants are terrestrial C_3 plants, and hence it is largely assumed that C_4 plants are not a significant factor in islander diet, though Jones and Quinn (2009) document some prehistoric human consumption of C_4 plants on Fiji in the form of sea grapes. Although negligible to human diet, sugar cane, tropical grasses and grass seeds are often C_4 plants and may have contributed to rat diet either through direct consumption or consumption of C_4 terrestrial animals. Rat bone collagen δ^{13}C values have been reported as ~3‰ more positive than diet, though this may vary with dietary change (Lee-Thorp et al. 1989). Nitrogen stable isotope values increase as an individual rises through a local food chain. Along each "step" in the food chain, an associated increase in δ^{15}N by approximately +3.5‰ is expected (Bocherens and Drucker 2003; DeNiro and Epstein 1981; Minagawa and Wada 1984). Marine food webs are more complex with many levels of consumers and therefore marine carnivores—particularly seabirds and marine mammals—have higher δ^{15}N values than terrestrial counterparts.

Results of rat bone collagen stable isotope analysis from all sites are plotted in Figure 2.2, while Table 2.2 presents mean δ^{13}C and δ^{15}N values for each archaeological site by stratigraphic layer. Individual rat δ^{13}C and δ^{15}N values vary significantly demonstrating a diverse and adaptable diet. An archipelago-wide trend of declining δ^{15}N values emerges with implications for major transformations in nutrient flows within human-centered foodwebs in Mangareva.

Table 2.2: Mean *Rattus exulans* bone collagen δ^{15}N and δ^{13}C values by layer at each site.

	Excavation Layer	Mean δ^{13}C	Mean δ^{15}N
Onemea (TAR-6)	IIB	-18.4 ± 1.6‰	12.6 ± 1.1‰
	IIA	-18.0 ± 2.3‰	10.8 ± 2.3‰
	I	-18.3 ± 1.5‰	7.8 ± 2.5‰
Nenega-iti (AGA-3)	IV	-17.7 ± 1.7‰	13.3 ± 1.6‰
	III	-17.3 ± 1.4‰	12.9 ± 0.9‰
	II3	-17.1 ± 1.8‰	14.3 ± 0.9‰
	II2	-15.7 ± 2.5‰	12.5 ± 1.9‰
	II1	-13.2 ± 3.0‰	10.1 ± 1.9‰
Kitchen Cave (KAM-1)	VI	-15.0 ± 2.5‰	17.1 ± 2.5‰
	V	-16.4 ± 2.4‰	17.3 ± 2.6‰
	IV	-16.9 ± 2.1‰	16.2 ± 2.3‰
	III	-14.7 ± 1.7‰	14.3 ± 1.4‰
	II	-14.3 ± 1.5‰	14.7 ± 1.0‰
	I	-17.0 ± 3.6‰	11.8 ± 3.2‰

The Onemea Site (TAR-6)

A total of 16 rat skeletal elements from the main trench at Onemea (Test pits 5, 6, and 11; Kirch et al. 2010) provided bone collagen stable isotope data. Limited sample size resulted in only two samples analyzed from Layer III, both of which dissolved during demineralization. Collagen preservation is a persistent problem in tropical and subtropical environments due to frequent cycles of precipitation and evaporation (see Pestle and Colvard 2012). The Onemea site is more exposed than the two rockshelter sites, and Layer III is comprised of fine-grained Aeolian-transported, calcareous sands with few organics apart from recovered faunal material, conditions that are detrimental to collagen preservation. Absent representation from Layer III, Layer II was subdivided into two components of roughly equal depth to provide chronological resolution. However, these are arbitrary divisions within a continuous cultural layer, so the resulting temporal divisions should be interpreted with some caution. Sample TAR-6-13 was recovered from a pit hearth feature associated with Layer IIB. The sample shows no signs of extreme heating and its isotope ratios are consistent with other samples recovered from the layer (DeNiro et al. 1985).

Rat δ^{13}C and δ^{15}N values reflect mixed diets composed of C_3 plants with marine or C_4 protein contributions. Three individuals from Layer II have significant marine dietary inputs, indicated by more positive C and N stable isotope ratios. Food sources that may have contributed to enriched δ^{15}N values at Onemea include high trophic level reef and marine fish or chickens (*Gallus gallus*) with C_4 diets (Figure 2.3). Through time, rat δ^{13}C values remain relatively consistent, while mean δ^{15}N values decline through a span of one to two trophic levels from 12.6 ± 1.1‰ in Layer IIB to 10.8 ± 2.3‰ in Layer IIA and finally 7.8 ± 2.5‰ in Layer I (Bocherens and Drucker 2003; Minagawa and Wada 1984). These changes begin in Layer IIA, though small sample sizes limit the certainty of this trend.
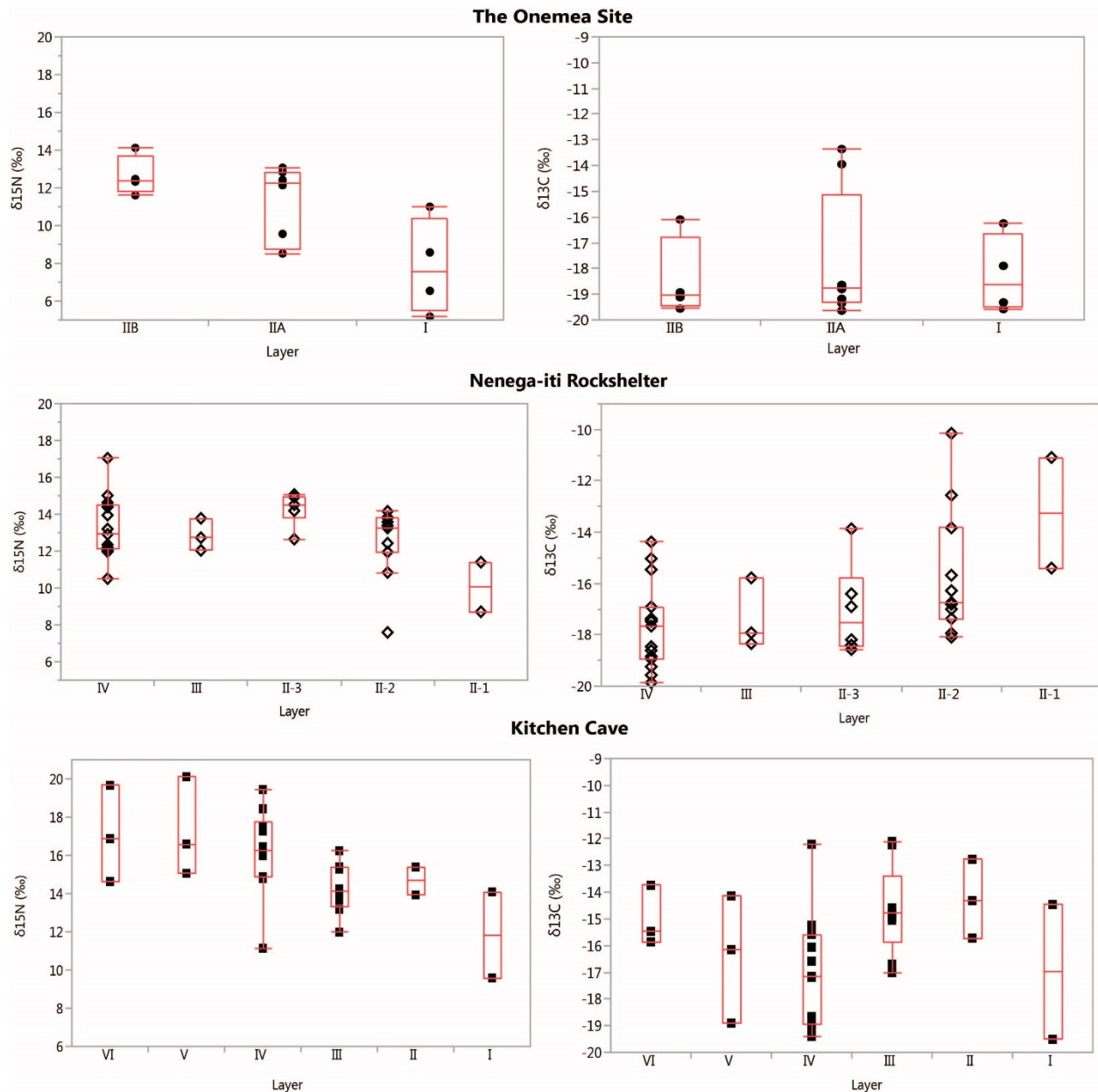
Figure 2.2: Distributions of *Rattus exulans* bone collagen δ¹⁵N and δ¹³C by layer at all three sites.

This shift was likely influenced by the cessation of frequent site use after Layer II. While Mangarevan people were actively hunting and fishing at Onemea, rats would have had opportunities to scavenge high trophic level protein sources including marine fish and seabirds from meal scraps. Without people to provide easy access to high trophic level sources after the site was abandoned, rats likely shifted to wild foraging for plant matter and more easily obtainable terrestrial protein sources, such as arthropods. Rat diet from Layer I may also be influenced by dramatic ecosystem changes brought about by European arrival. The introduction of new predators and competition from the black rat, brown rat, and house mouse may have significantly affected diet and foraging behavior (Shiels et al. 2013). The rats at Onemea have the lowest overall δ¹⁵N values of all three study sites. This may be related to Onemea's primary

function as a fishing camp with nonpermanent habitation. Less consistent access to human food scraps would create an averaging out of high and low trophic level proteins over the rat's lifetime, resulting in comparatively lower δ^{15}N values.
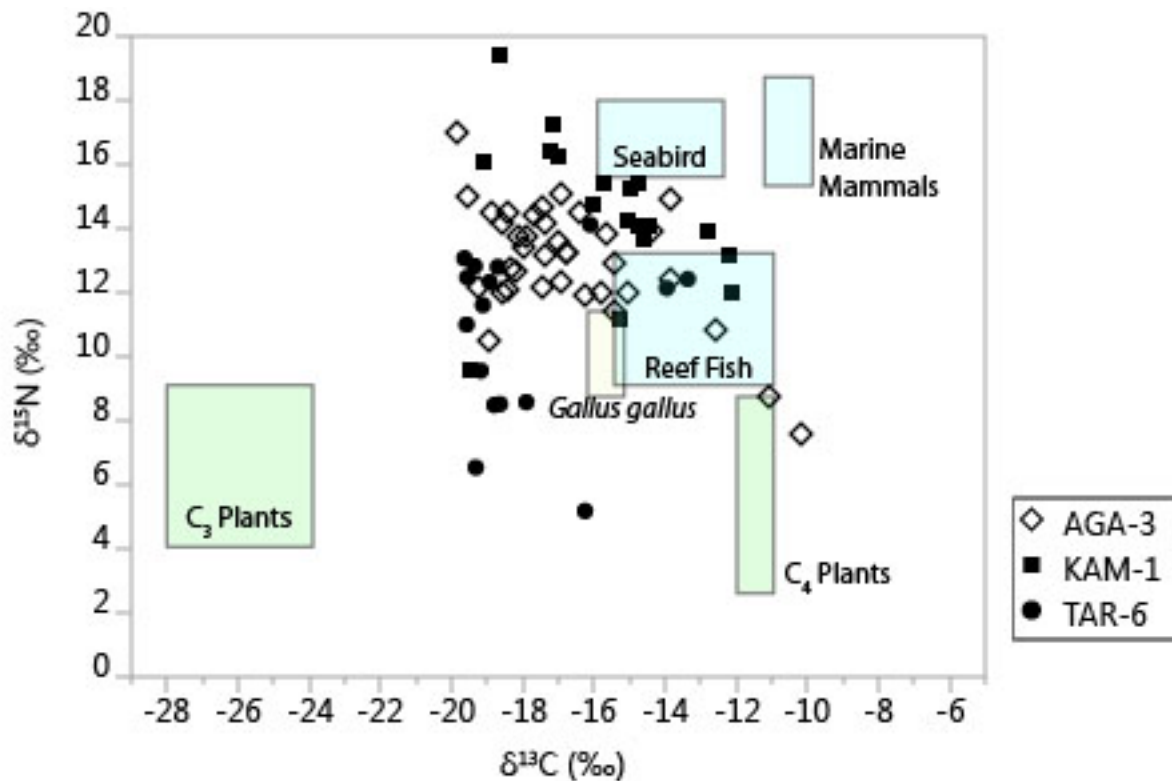
Figure 2.3: Distributions of rat bone collagen δ^{13}C and δ^{15}N values in parts per mil (‰) for all three case study sites with baseline δ^{13}C and δ^{15}N values of potential dietary contributions, compiled from previously published material (Allen and Craig 2009; Beavan Athfield et al. 2008; Brooke et al. 2010; Jones and Quinn 2009; Richards et al. 2009). Values have not been adjusted for trophic fractionation.

Nenega-Iti Rockshelter (AGA-3)

A total of 37 rat bones were included for analysis from Nenega-iti Rockshelter. Two samples have C:N ratios slightly higher than 3.6, however their stable isotope ratios are in line with other rats from the same context and all other quality control indicators suggest that these collagen samples are intact. Results from Nenega-iti show minimal change in δ^{13}C and δ^{15}N values over time. Bone collagen samples from the earliest layer (Layer IV) are slightly more enriched in ^{15}N (13.3 ± 1.6‰) with more negative δ^{13}C values (-17.7 ± 1.7‰), and Layer II rat bone collagen δ^{15}N values are slightly lower (12.8 ± 2.0‰) with less negative δ^{13}C values (-15.9 ± 2.5‰). Layer III rats were recovered from a nearly sterile depositional event with minimal evidence of associated human activity, however their values are similar to those from rats found in Layer IV and Layer II-3. Within Layer II, a trend emerges of δ^{15}N values becoming more depleted (from 14.3 ± 0.9‰ in Layer II-3 to 10.1 ± 1.9‰ in Layer II-1) and δ^{13}C values becoming less negative (from -17.1 ± 1.8‰ in Layer II-3 to -13.2 ± 3.0‰ in Layer II-1) through time. Higher and less variable δ^{15}N values compared to Onemea likely reflects a sequence of

more permanent human habitation which granted rats frequent access to high trophic level food scraps such as fish, pig, and dog.

Kitchen Cave (KAM-1)

Rats at Kitchen Cave present the most elevated δ^{15}N values of all three sites analyzed (mean δ^{15}N at KAM-1 is 15.4 ± 2.4‰ compared to 13.0 ± 1.8‰ at AGA-3 and 10.7 ± 2.6‰ at TAR-6). The range of δ^{13}C values is similar to those from TAR-6 and AGA-3. As with the previous two sites, δ^{15}N values are highest in the earliest phase of human occupation (mean δ^{15}N in Layer VI is 17.1 ± 2.5‰) and decline through time (11.8 ± 3.2‰ in Layer I). The earliest excavation layers from Kitchen Cave show consistently higher N and variable C stable isotope ratios. A shift towards declining δ^{15}N values and less negative δ^{13}C values begins in Layer III. Seabirds and marine mammals, which tend to have elevated δ^{15}N values due to their high position in marine food webs, are the only food groups sufficiently enriched in ^{15}N to account for the highest δ^{15}N values in Layers IV, V, and VI.

Seabird Population Decline and Nutrient Flows on Mangareva

We hypothesize that the archipelago-wide decline in rat bone collagen δ^{15}N values in Mangareva is related to dramatic reductions in seabird populations that occurred within two to three centuries following Polynesian arrival (Steadman and Justice 1998; Worthy and Tennyson 2004). Depletion of ^{15}N in rat bone collagen occurs shortly after a significant decrease is observed in recovered avifaunal remains from all three sites (see Figure 2.4). Diminishment of avifaunal populations could have impacted rat bone collagen δ^{15}N in two non-mutually-exclusive ways: directly, through the removal of a ^{15}N-enriched protein source from rat diet, and indirectly through the removal of ^{15}N-enriched seabird guano deposits from terrestrial soils.

Early rat δ^{13}C and δ^{15}N values, particularly from KAM-1, suggest protein inputs from high trophic level marine sources. Reported bone collagen δ^{13}C and δ^{15}N values for seabirds range from approximately -17 to -12‰ and 16 to 18‰ respectively (Brooke et al. 2010; Richards et al. 2009), and for marine mammals -10.3 ± 0.5‰ and 17.6 ± 2.2‰, respectively (Richards et al. 2009). Analyses of zooarchaeological assemblages from Mangarevan archaeological sites provide little evidence for pelagic fishing or hunting of marine mammals. Thus, the most readily available food source to provide high trophic level protein contributions to rat diet would have been seabirds. Throughout Mangareva's archaeological history, people largely procured marine foods from the archipelago's rich lagoon environment, which shows minimal indication of resource depletion through time (Kirch et al. 2015; Weisler and Green 2013). There is no indication that rat diet became more inclusive of terrestrial C$_3$ inputs over time; it is likely that as seabird communities diminished these dietary inputs were replaced by lagoon resources that would have been obtained via scavenging human food scraps (AGA-3, KAM-1), or by wild foraging for terrestrial C$_4$ resources (TAR-6).
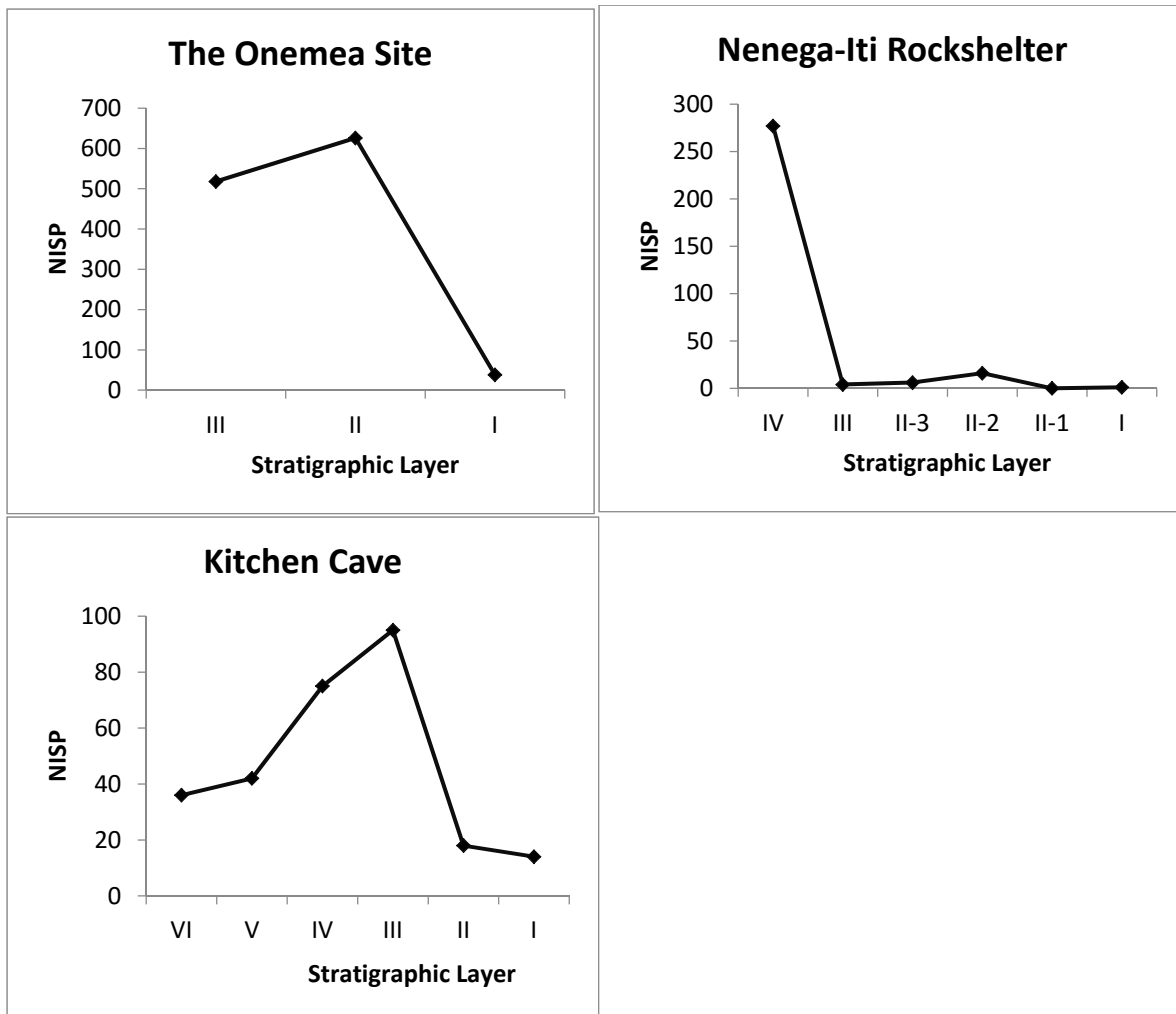
Figure 2.4: Stratigraphic distributions of avifaunal remains by Number of Identified Specimens (NISP) at all three sites.

Allen and Craig (2009) note similar temporal declines in δ^{15}N values for human, pig, and dog bone collagen from Aitutaki, Cook Islands. They attribute this trend to marine resource depression beginning sometime around the 14th or 15th century, and the faunal record from Aitutaki demonstrates declines in fishing and decreased consumption of marine carnivores. Mangarevan rat stable isotope ratios may document a similar trend, however instead of a depleted marine ecosystem, declining seabird populations and terrestrial resource depression drove the changes observed in rat diet. It appears that Mangarevan rat (and by extension human) diet became more reliant on lagoon resources as seabirds and terrestrial resources diminished. Indeed, decreasing seabird populations may have helped maintain lagoon system productivity in the face of increasing human predation through the elimination of significant avian predation (Wainwright et al. 1998).

Recent studies correlate seabird guano fertilization to greater soil productivity as well as higher baseline N availability and δ^{15}N values in island ecosystems (e.g., Anderson and Polis 1999; Briggs et al. 2012; Fukami et al. 2006; Mizota and Naikatini 2007; Szpak 2014). Small

island ecosystems in particular are often heavily reliant on marine-derived nutrient subsidies, and the removal of guano inputs on Mangareva would have impacted agricultural productivity as well as lowered baseline δ^{15}N values. Modern artificial fertilizers tend to have δ^{15}N values of around 0‰, while plants fertilized with animal manure are generally more enriched in ^{15}N. Due to the unique process by which seabirds metabolize and excrete nitrogen, seabird guano deposits can have δ^{15}N values of around 27‰ (Szpak et al. 2012). Observed δ^{15}N values between primary producers fertilized with versus without seabird guano differ by up to +11‰ (Wainwright et al. 1998). Removal of guano from an ecosystem would therefore lower δ^{15}N values across primary producers and this effect would resonate through entire island foodwebs, creating an artificial appearance of species trophic decline with no direct change to diet.

Diminishment of seabird populations likely occurred at different rates and intensities on individual islands within Mangareva. Though seabirds are rarely observed on Taravai (TAR-6) or Agakauitai (AGA-3) Islands today, communities of nesting or roosting frigate birds and terns persist on more isolated Kamaka Island (KAM-1). Due to Kamaka's comparatively high degree of isolation and present-day seabird species richness and abundance, it and two other nearby, unoccupied islets in the southern end of the archipelago (Manui and Makaroa) have been proposed as refuges for remaining seabird populations (Waugh et al. 2013). These factors likely also account for the persistently higher δ^{15}N values in rat bone collagen analyzed from KAM-1.

Conclusion

Our analysis indicates that rat dietary δ^{13}C and δ^{15}N values were influenced both directly and indirectly by the decimation of seabird populations in the Mangarevan island ecosystem. At all three study sites, the elimination of seabirds after Polynesian arrival is reflected in a decline through time in rat bone collagen δ^{15}N values, as well as new dietary regimes. At Nenega-iti and Kitchen Cave, less negative δ^{13}C values suggest that avifaunal protein was replaced with marine resources from Mangareva's rich lagoon environment. As rats could not have acquired these resources on their own, they likely came in the form of human meal scraps. At Onemea, rats would have come into contact with humans less frequently, especially after site abandonment. As seabird populations declined and Mangarevan people abandoned Onemea, rat diet transitioned to foraging for terrestrial C_3 and C_4 resources.

Soil-plant dynamics interact with baseline ecosystem ^{15}N enrichment in numerous complex ways, and recent studies have only begun to highlight the implications these factors have for stable isotopic reconstructions of ancient diets (see Szpak 2014). Our results suggest that seabird guano input to soil nutrient cycling is a significant variable that can greatly impact N stable isotope ratios in small island ecosystems. Future stable isotope analyses of archaeological materials in these regions must carefully consider the significance of ecosystem dynamics in reconstructing past diet. Additional research into the complexities of shifting baseline δ^{13}C and δ^{15}N values and their distributions throughout foodwebs is critical for proper contextualization and interpretation of stable isotope ratios.

Chapter 3

Coastal subsistence and settlement at the Hane Dune Site, Ua Huka (Marquesas Islands): New insights from Pacific rat (*Rattus exulans*) stable isotope analysis

__Introduction__

The Hane dune site on Ua Huka Island in the Marquesas figures prominently in long-standing discussions over the chronology of East Polynesian settlement and prehistoric Marquesan subsistence. Pioneering excavations by Yosihiko Sinoto (Sinoto 1966; Sinoto and Kellum 1965) demonstrated the site's long archaeological sequence and early radiocarbon dates likely associated with the first phase of human occupation on the archipelago. Although its chronology and prehistory has long been debated by archaeologists, the site itself has remained virtually untouched since Sinoto's intensive excavations in 1964-5. Here we revisit the Hane dune site to analyze materials from renewed excavations in 2009 (see Conte and Molle 2014) and apply a new technique towards investigating subsistence and ecology in the Marquesas. We present bone collagen stable isotope δ^{13}C and δ^{15}N data from 33 Pacific rat (*Rattus exulans*) specimens recovered from three phases of site use at the Hane dune site to investigate changing site use and subsistence practices in the Hane valley.

Guiry and Gaulton (2015) have reviewed the potential applications and limitations of utilizing stable isotope analysis of rat remains as a human behavioral proxy. Their analysis of black rats (*Rattus rattus*) from Ferryland, Newfoundland indicates commensal rats can provide localized insights into changing site use, foodways, and activity patterns. The Pacific rat was selected for this study due to its omnivorous diet, small home range, and wide distribution throughout the Pacific (Roberts 1991; Williams 1973). This commensal species is often found associated with human activity in the earliest layers of Polynesian archaeological deposits. AMS radiocarbon dates of Pacific rat bone collagen have been used as a proxy for the arrival of human settlers to new islands, and have contributed to the development of the commensal model of colonization in the Pacific (Anderson 2004; Kirch 2011b; Matisoo-Smith 1994, 2002, 2009; Matisoo-Smith et al. 1999; Wilmshurst et al. 2008). It remains unclear whether the Pacific rat was introduced to the Polynesian islands intentionally or as inevitable stowaways on voyaging canoes. Rats were reportedly considered a food source on some islands, including Mangaia, Niue, and Easter Island (Matisoo-Smith et al. 1999). On Mangaia, rats were elevated to the level of a delicacy, and the phrase "sweet as a rat" was employed to favorably describe foods (Gill 1894:315; Kirch et al. 1995). In the Marquesas, rats were evidently not a valued food source. However, Handy notes that it was rumored in Taiohae, Nuku Hiva, that the impoverished upland-dwellers with limited access to marine resources were driven to eating rats either braised or mashed raw with breadfruit paste (Handy 1923:199).

Pacific rats are omnivores with a diet that varies seasonally and between regions (Bunn and Craig 1989; Shiels et al. 2013). Although modern observational and gut-content studies have shown that rat diet is primarily vegetal, rats have been observed to predate a range of species including insects, turtle hatchlings, small birds and bird eggs (Norman 1975; Duron et al. 2015; Spenneman 1997). However, modern studies of Pacific rat diet are not necessarily reliable analogs for the past, as Polynesian landscapes have undergone massive transformations since European contact and the introduction of new predators and competition has likely further impacted Pacific rat diet. Pacific rat dietary selectivity may prohibit the utility of this species as a

direct proxy for human diet; however, temporal changes in rat diet provide useful insight into transformations in local site ecology and patterns of human activity and resource use.

Subsistence and Settlement in the Marquesas Islands

The Hane Dune Site and the Marquesan Cultural Sequence

The first archaeological investigation of the Marquesas Islands was undertaken by Robert Suggs (1961), who conducted extensive survey and excavation on the island of Nuku Hiva. Suggs established a cultural sequence for the region which—though his absolute chronology has proven problematic—stands as an influential outline of settlement and prehistory for the entire Marquesan archipelago (Sinoto 1970; Rolett 1998). More recently, Allen (2004) presented an updated chronology for this sequence, maintaining the names and overall themes of Suggs' original culture historical periods: The Settlement Period (AD 900-1100) sees the first arrival of Polynesians to the islands, and is characterized by small, less permanent habitation in the most favorable (largely coastal) areas of the islands. Subsistence was focused on experimentation with agricultural systems and the exploitation of easily depleted indigenous prey such as naïve avifauna, turtles, and marine mammals. The Developmental Period (AD 1100-1300) shows a decline in native fauna along with more permanent habitation and increasing reliance on agricultural products. In the Expansion Period (AD 1300-1600), populations grow and begin to move into valley interiors, and the reliance on agricultural and domestic products intensifies. Finally, the Classic Period (AD 1600-1970) is marked by increasing conflict between settlements in neighboring valleys, accompanied by movement of habitation sites further inland and the elaboration of monumental architecture.

The Hane dune site, an expansive dune complex located in Hane Bay on the southern end of Ua Huka Island (Figure 3.1), was first excavated by Yosihiko Sinoto in 1964-5 (Sinoto 1966). Sinoto's investigations uncovered a continuous stratified deposit dating back to the earliest phase of human occupation in the archipelago; consequently, the site has played a key role in understanding Marquesan colonization and prehistory (Allen 2004; Conte and Molle 2014; Sinoto 1970). Sinoto compared the Hane assemblage with the artifacts used in Suggs' cultural sequence and suggested that the Hane site likely contained deposits dating to even earlier than those found at Nuku Hiva. Following debate over the accuracy of the radiocarbon chronology established by Sinoto (see Anderson et al. 1994; Kirch 1986; Rolett 1998; Spriggs and Anderson 1993), the Hane dune site was reexcavated by G. Molle and E. Conte in 2009. Reevaluation of the site established a new chronological and cultural sequence with three main phases (see Conte and Molle 2014; Molle 2011). The earliest phase (Phase I) marks the initial settlement of the dune at around 900 CE. Phase II establishes long-term sustained human occupation and the development of the site into a coastal hamlet around the beginning of the 13th century. After this, the site complex appears to have been abandoned and occupation shifted to the valley interior. Phase III shows a return to the site along with a drastic change in site use: the appearance of human burials and probable funerary structures in the 15th and 16th centuries suggests that the site functioned as a cemetery, rather than as a residential complex, in later prehistory.
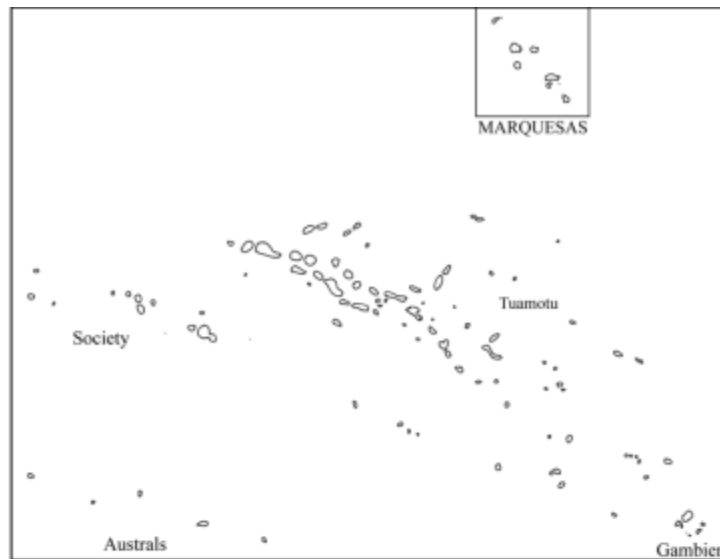
Figure 3.1: Map of the Marquesas Islands with the Hane dune site labeled, and inset map of French Polynesia.

Subsistence trends in the Marquesas

Ethnographic and historic accounts (e.g., Dening 1974; Handy 1923) describe the Marquesan subsistence economy as one dominated by breadfruit arboriculture and storage. As in other Polynesian societies, the Marquesan meal consisted of a starch base (often breadfruit paste or *popoi*), which could be eaten on its own or complemented by a flesh food "relish" to form a complete meal (Kirch and O'Day 2003). The islands were plagued by frequent periods of drought and to stave off famine, fermented breadfruit (*ma*) was stored underground in large fermentation pits. The intensification of pig husbandry in the Marquesas may also have been a response to unpredictable harvests, as a form of storage 'on the hoof' (see Dye 2014; Vayda et al. 1961; West 2007). However, high value foods were often under the control of the island's elite, who maintained full orchards of breadfruit trees and the largest *ma* pits. They managed the distribution of communal *ma* in times of drought, as well as the distribution of pig meat at feasts and large fish catches (Dye 1990; Handy 1923:168).

It is difficult to extricate pre-contact changes in subsistence practices at the Hane dune site from those of the entire archipelago, as studies from Hane have helped form the basis of much of our understanding of past Marquesan subsistence. Kirch's (1973) pioneering analysis of floral and faunal assemblages from Ha'atuatua, Nuku Hiva Island, the Hane dune site, and several other sites on Ua Huka Island was the first to demonstrate a temporal shift from marine-oriented hunting and gathering activities to terrestrially-focused subsistence through agriculture and animal husbandry. According to Kirch's analysis, at Hane, seabirds and other marine resources comprised a significant portion of the Settlement Period faunal assemblage. During the Developmental Period, focus began to shift towards an agricultural economy centered on breadfruit and other Polynesian-introduced crops. This terrestrial focus intensified during the Expansion and Classic Periods, with reduced fishing and increasing investment in pig husbandry. Dye's (1990) analysis focusing on marine resources from the same sites further confirms the later preference of pig and shellfish (inland and nearshore prey) over offshore marine resources.

Sweeney et al. (1993) questioned these studies by Kirch and Dye, suggesting that aggregating data from multiple sites, utilizing bone weight and meat weight to quantify resource use, and evaluating these data through the use of closed arrays (percentage comparisons) biased interpretations of the relative importance of terrestrial versus marine resource contributions. Using rank order abundances and focusing solely on the Hane dune site assemblage, Sweeney et al. found minimal change in the subsistence economy apart from a drop-off in avifaunal remains over time. Anderson et al.'s (1994) reanalysis of the Hane sequence likewise supported the decline of avifauna and turtles, but did not indicate an increase in pig or shellfish remains through time. They argued that there was little evidence for a shift from marine to terrestrial resource use at the site. Dye (1996), however, pointed out that in limiting themselves to the Hane dune site assemblage, Sweeney et al.'s (1993) sample size was significantly reduced, leading to sampling bias. Dye further argued that the closed arrays used in his and Kirch's (1973) analyses speak to the relative importance of food groups through time which, though this may not establish absolute increases in terrestrial mammal remains, demonstrates real trends in the waning importance of marine exploitation and intensification of agriculture and pig husbandry. Davidson et al. (1999) endeavored to reanalyze the fish remains from Hane, newly identifying tuna (*Scombridae*) remains in the assemblage through the presence of caudal vertebrae. These demonstrated a statistically significant decline in tuna fishing through time, though they emphasized that tuna fishing remained a comparatively important activity even in late prehistory.

Research from elsewhere in the Marquesas supports a shift from frequent marine exploitation to intensified arboriculture and pig husbandry. At the Hanamiai dune site, Tahuata Island, Rolett (1992, 1998) documented a decline in avifaunal species, increasing emphasis on arboriculture and pig husbandry, and a movement from off-shore fishing to inshore marine resource exploitation, a similar pattern to that seen at Hane by Kirch (1973) and Dye (1990). Stable isotope analysis of pig remains from Hanamiai suggests pig husbandry began around AD 1200 and intensified through time, demonstrated by restricted pig dietary variability in later prehistory (Richards et al. 2009; West 2007). The diets of rat, pig, and dog at Hanamiai all indicated greater inputs of marine protein during the early phases of occupation at the site, followed by increasing focus on terrestrial resources and the disappearance of avifauna (Richards et al. 2009; Steadman and Rolett 1996). At Anapua Rockshelter, Ua Pou Island, Leach et al. (1997) likewise found that although tuna remains were more prevalent than in most other Polynesian sites, offshore fishing—and perhaps all fishing practices—appeared to decline over time. Employing C and N stable isotope analysis of the Pacific rat as a new line of evidence towards understanding changes in site use and resource distribution can aid in resolving these debates over long-term subsistence patterns in the Marquesas Islands.

Materials and Methods

Bone collagen δ^{13}C and δ^{15}N stable isotope analysis has proven effective in reconstructing the diets of individual humans and animal species (Katzenberg 2008; Sealy 2001). Bone collagen is synthesized from dietary amino acids and is thus weighted towards the protein component of diet (Ambrose and Norr 1993; Tieszen and Fagre 1993). The abundance of C and N stable isotopes in bone collagen are expressed in δ notation as ratios relative to established standards and measured in parts per mil (‰), where: $\delta = [(Rsample/Rstandard) – 1] * 1000$. R represents the ratio of stable isotopes, here either ^{13}C/^{12}C or ^{15}N/^{14}N. The standards for C and N stable isotope analysis are Vienna Pee Dee Belemnite (VPDB) and atmospheric nitrogen (also known as Ambient Inhalable Reservoir—AIR), respectively.

The photosynthetic pathways of C_3, C_4, and CAM plants lead to differential stable carbon isotopic fractionation, with C_3 plants having δ^{13}C values in the range of -34 to -21‰, and C_4 plants in the range of -15 to -8‰. CAM plants can resemble either C_3 or C_4 plants, and often have δ^{13}C values falling between those of C_3 and C_4 plants (Bender 1971). This differential fractionation is carried up the food chain resulting in more negative δ^{13}C values in C_3 consumers than in C_4 consumers. Marine primary producers take in carbon from a mix of sources, though generally have carbon stable isotope ratios resembling those of C_4 plants. Thus, carbon stable isotope ratios can also aid in distinguishing terrestrial versus marine inputs (Schoeninger and DeNiro 1984). δ^{13}C values in rat bone collagen have been reported as roughly 3‰ more positive than diet, however this fractionation may be influenced by variations in diet (Lee-Thorp et al. 1989). δ^{15}N values further aid in assessing relative marine and terrestrial dietary contributions, as well as trophic position. A stepwise ^{15}N-enrichment between trophic levels results in consumers having δ^{15}N values roughly 3.5‰ higher than their food sources (Bocherens and Drucker 2003; DeNiro and Epstein 1981; Minagawa and Wada 1984). Marine foodwebs tend to be more complex with many levels of consumers, so these systems are generally more enriched in ^{15}N, with higher δ^{15}N values, than their terrestrial counterparts.

The rat bone elements analyzed in this study were selected from the faunal assemblage of the 2009 reexcavations of the Hane dune site (see Conte and Molle 2014). Elements were

selected for stable isotope analysis by calculating Minimum Number of Individuals (MNI) by layer within each 1 x 1 m excavation unit in order to maximize sample sizes while minimizing the chance of resampling from the same individual. Effort was made to select appendicular over cranial or axial elements, as these three categories have previously demonstrated differential rates of turnover in brown rats (*Rattus norvegicus*; Wolfe and Klein 1996). However, some axial elements were selected due to small sample sizes. It is assumed that bone collagen turnover rates will not significantly impact dietary $\delta^{13}C$ and $\delta^{15}N$ values between elements, as *Rattus exulans* is a relatively short-lived and small-bodied species, surviving around 1 year in the wild (Atkinson and Towns 2001). Although bone collagen turnover occurs more rapidly in small-bodied animals, bone collagen $\delta^{13}C$ and $\delta^{15}N$ values reflect a long-term average of diet and likely represent the majority of the rat's short lifespan.

All bone elements were sonicated with ultrafiltered water for four hours, dried, and abraded to remove adhering surface contaminants. Samples were then cut into approximate 1 mm chunks and collagen was extracted following a modified version of Ambrose (1990; and see Sealy et al. 2014). Samples weighing over 25 mg were treated with 0.5 M HCl with fresh acid applied every 24 hours until bone chunks demineralized. Samples weighing under 25 mg were treated with a more dilute 0.25 M HCl solution in order to slow reaction time and prevent excessive sample loss. After demineralization, all samples were treated the same. Samples were then rinsed with ultrafiltered water and treated with 0.1 M NaOH for 24 hours to remove humic contaminants. Following treatment, samples were rinsed again and freeze dried for 48 hours. Dry samples were analyzed simultaneously for C and N contents (% dry weight) and C and N stable isotope ratios. Analyses were conducted via elemental analyzer/continuous flow isotope ratio mass spectrometry using a CHNOS Elemental Analyzer (vario ISOTOPE cube, Elementar, Hanau, Germany) coupled with an IsoPrime 100 mass spectrometer (Isoprime LTd., Cheadle, UK). Analyses were conducted at the Center for Stable Isotope Biogeochemistry at the University of California, Berkeley. Long-term external precision for C and N isotope analysis is 0.1‰ (C) and 0.15‰ (N).

Results

The results of *R. exulans* bone collagen $\delta^{13}C$ and $\delta^{15}N$ stable isotope analysis are presented in Table 3.1, along with quality control indicators. The primary means of assessing collagen preservation is the ratio of carbon to nitrogen in the sample, or the C/N ratio. The C/N ratio should resemble that of modern bone collagen, and samples are likely to be contaminated if they fall outside the range of 2.9-3.6 (Ambrose 1990; DeNiro and Weiner 1988; van Klinken 1999). One sample did not meet this criterion and was eliminated from analysis. Modern bone contains approximately 22% collagen by weight, and the recommended amount of collagen preservation in archaeological samples recovered from most environments ranges from 1-5% (Ambrose 1990; Schwarcz and Schoeninger 1991; van Klinken 1999). However, in tropical environments where bones are exposed to high temperatures, frequent rains, and microbial activity, this is more difficult to attain. Pestle and Colvard (2012) demonstrate that 0.5% collagen preservation in bones recovered from tropical and subtropical environments can still be viable. Other secondary indicators of collagen preservation include the concentration of carbon and nitrogen in bone collagen. Intact bone collagen contains roughly 35% carbon by weight, and should contain around 11-16% nitrogen by weight (Van Klinken 1999).

Table 3.1: Results of carbon and nitrogen stable isotope analysis of *Rattus exulans* bone collagen, along with quality control indicators.

Sample Number	Square	Layer	Cultural Phase	Element	Side	$\delta^{13}C$	$\delta^{15}N$	% C	% N	C:N	% Coll
HAN-1	E8	A	IV	Mandible	R	-18.3	8.1	44.96	16.31	3.22	13.71
HAN-2	E10	B	III2	Tibia	L	-18.6	11.2	46.48	17.01	3.19	4.26
HAN-3	E7	B/C	III2	Innominate	R	-18.6	11.2	46.48	17.01	3.19	11.56
HAN-4	E7	C	III1	Tibia	L	-17.5	11.2	45.41	16.51	3.21	12.40
HAN-5	E7	C	III1	Tibia	L	-19.0	13.1	46.81	16.92	3.23	11.90
HAN-6	E7	C	III1	Femur	R	-18.4	11.1	46.19	16.80	3.21	9.89
HAN-7	E7	C	III1	Femur	R	-17.6	11.9	45.63	16.39	3.25	9.06
HAN-8	E8	C	III1	Humerus	L	-19.0	12.3	46.16	16.70	3.22	13.95
HAN-9	E8	C	III1	Humerus	L	-17.1	9.9	44.17	16.08	3.20	3.79
HAN-10	E7	E	II	Femur	R	-18.2	13.4	45.02	15.40	3.41	3.81
HAN-11	E7	E/F	II	Femur	R	-12.8	12.0	49.95	16.66	3.50	6.39
HAN-12	E8	F	II	Ulna	R	-17.2	9.1	46.64	16.46	3.31	6.73
HAN-13	E9	F	II	Femur	R	-17.5	15.2	33.03	11.68	3.30	1.55
HAN-14	E7	G	II	Femur	L	-14.2	17.1	47.07	16.85	3.26	4.10
HAN-15	E8	G	II	Tibia	L	-16.1	15.9	41.68	14.47	3.36	2.73
HAN-16	E8	G	II	Tibia	L	-16.6	19.7	46.42	16.16	3.35	4.29
HAN-17	E9	G	II	Mandible	R	-14.5	16.4	46.45	16.54	3.28	3.78
HAN-18	E9	G	II	Mandible	R	-19.0	11.2	43.12	15.44	3.26	4.29
HAN-19	E9	G	II	Mandible	R	-16.3	18.1	48.88	17.77	3.21	9.95
HAN-20	E7	H	I	Humerus	L	-16.0	17.3	42.95	14.20	3.53	4.76
HAN-21	E7	H	I	Humerus	L	-16.1	15.7	47.45	15.55	3.56	8.52
HAN-22	E7	H	I	Humerus	L	-14.1	15.2	42.77	15.13	3.30	7.39
HAN-23	E7	H	I	Humerus	R	-17.4	13.7	44.42	15.55	3.33	12.40
HAN-24	E9	H	I	Femur	R	-15.7	14.5	43.43	15.49	3.27	6.97
HAN-26	E9	H	I	Femur	L	-17.3	13.8	42.07	13.85	3.54	4.67
HAN-27	E8	I	I	Humerus	L	-20.8	8.1	45.28	15.73	3.36	1.31
HAN-28	E8	I	I	Humerus	L	-16.4	12.6	43.14	15.36	3.28	8.41
HAN-29	E9	I	I	Humerus	R	-12.6	16.2	43.95	15.35	3.34	3.24
HAN-30	E9	J	I	Femur	L	-13.9	15.2	35.89	11.94	3.51	3.67
HAN-31	E9	J	I	Innominate	R	-14.1	14.8	35.94	12.56	3.34	8.22
HAN-32	E10	J	I	Femur	R	-13.1	15.3	42.44	15.03	3.30	7.34
HAN-33	E10	J	I	Mandible	L	-16.3	15.5	43.33	15.67	3.23	8.93
HAN-34	E10	J	I	Mandible	R	-13.8	16.7	44.12	15.25	3.37	3.04

Rat bone collagen $\delta^{13}C$ and $\delta^{15}N$ values have been plotted by the cultural phases for the Hane dune site established by Conte and Molle (2014) in Figure 3.2. A final phase, Phase IV, was established for this study to demarcate the top aeolian sand layer deposited after the site was no longer under permanent use (designated Layer A by Conte and Molle). Table 3.2 provides

mean $\delta^{13}C$ and $\delta^{15}N$ values for each cultural phase. Rat diet is similar in Phases I and II, though in Phase II $\delta^{15}N$ values vary more widely (14.8 ± 3.3‰ compared to 14.6 ± 2.2‰ in Phase I), while $\delta^{13}C$ values become slightly more negative (-16.2 ± 1.9‰ compared to -15.5 ± 2.2‰ in Phase I). It is likely that due to more permanent human habitation in Phase II, rats had more frequent access to high trophic level marine sources as well as more variety in available food scraps. In both Phases I and II, rat diet appears to be a mixture of C_3 and C_4 sources with significant inputs from high trophic level marine sources. Rat diet becomes more terrestrially focused in Phase III, with $\delta^{13}C$ becoming more negative (-18.1 ± 0.8‰) and $\delta^{15}N$ values declining by roughly one trophic level (11.5 ± 1.0‰; Bocherens and Drucker 2003; Minagawa and Wada 1984). Only a single sample represents rat diet after site abandonment (Phase IV), but this continues the trend towards more terrestrial and lower trophic level inputs. However, a more precise temporal provenience cannot be established for this element, and dietary change here may be largely a byproduct of the large-scale transformations to Marquesan ecosystems following European arrival.

Table 3.2: Mean rat bone collagen $\delta^{13}C$ and $\delta^{15}N$ values by cultural phase from the Hane dune site.

Phase	n	Mean $\delta^{13}C$	Mean $\delta^{15}N$
I	14	-15.5 ± 2.2‰	14.6 ± 2.2‰
II	10	-16.2 ± 1.9‰	14.8 ± 3.3‰
III	8	-18.1 ± 0.8‰	11.5 ± 1.0‰
IV	1	-18.3‰	8.1‰

Richards et al. (2009) report $\delta^{13}C$ and $\delta^{15}N$ values of several marine species from the Marquesas Islands. These data suggest that rats in Phases I and II were likely consuming marine carnivores such as snappers, groupers, jackfish, and tuna. For example, reported $\delta^{13}C$ and $\delta^{15}N$ values for two species of tuna (*Gymnosarda unicolor* and *Katsuwonus pelamis*) are -11.5 ± 2.5‰ and 12.3 ± 2.7‰, respectively. Rats with the most elevated $\delta^{15}N$ may also have been consuming seabirds, whose reported bone collagen $\delta^{13}C$ values range from -17 to -12.2‰ and $\delta^{15}N$ values from 15-18.4‰ (Brooke et al. 2010; Richards et al. 2009). Surprisingly, reported $\delta^{15}N$ values for two species of parrotfish (*Scarus* sp. and *Calotomus* sp.)—a predominantly herbivorous reef fish—are much higher than those of most other fish analyzed at 18.8 ± 0.4‰ (see Richards et al. 2009 Appendix for $\delta^{13}C$ and $\delta^{15}N$ values of additional marine species). This variation speaks to the complexity of marine foodwebs as well as variations in diet and ecology within fish families. Shifts in both $\delta^{13}C$ and $\delta^{15}N$ values in Phase III indicate rat diet became more oriented towards terrestrial and C_3 resources, though there may still be some inputs from nearshore fish and shellfish. Elevated $\delta^{15}N$ values in some rats may also be associated with increased consumption of terrestrial domesticates, particularly chickens (*Gallus gallus*) and pigs (*Sus scrofa*). Reported $\delta^{13}C$ values for chickens recovered from Pacific Islands range widely (-21 to -15‰), depending on region and resource availability. $\delta^{15}N$ values for chickens (10.4 ± 1.5‰) tend to fall within the lower end of reported values for inshore fish (Jones and Quinn 2009; Storey et al. 2010). Dietary and osteological evidence from Marquesan archaeological contexts suggests that pigs were more intensively managed in later prehistory, and their diets varied from terrestrial- to marine-based depending on the husbandry strategies employed (Richards et al. 2001; West 2007).
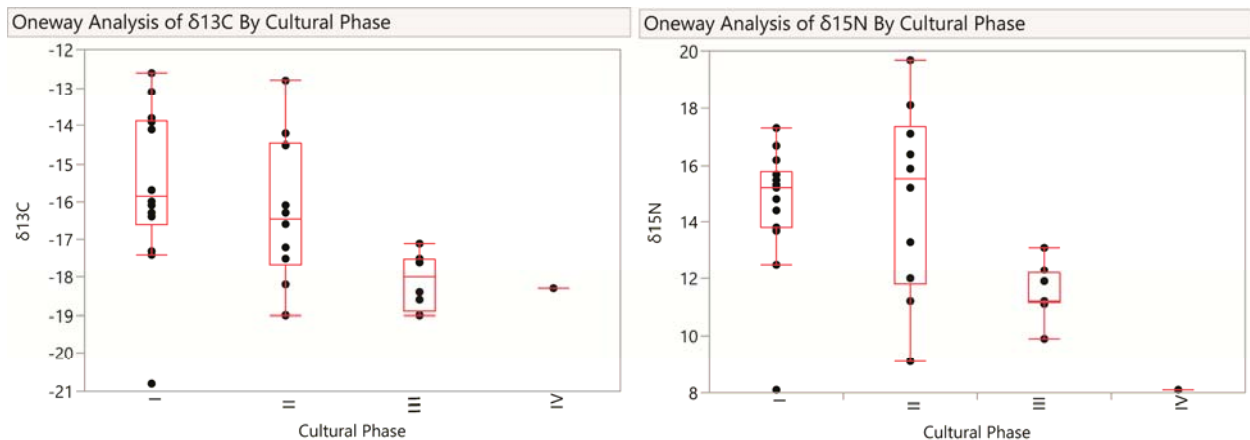
Figure 3.2: δ^{13}C and δ^{15}N values for Pacific rat (*Rattus exulans*) bone collagen by cultural phase at the Hane dune site.

Discussion

Rat dietary change at the Hane dune site as expressed through bone collagen C and N stable isotope ratios corresponds with the interpretations of Hane subsistence proposed by Kirch (1973) and Dye (1990). Rat diet shifted from having access to high trophic level marine proteins in Phases I and II to a more terrestrially-focused diet in Phase III, with less frequent access to marine sources and protein inputs from a lower trophic level. Figure 3.3 plots rat dietary δ^{13}C and δ^{15}N values from all three cultural phases in relation to potential food sources. Early marine proteins may have come from pelagic and bottom-dwelling carnivorous fish or seabirds. These resources were likely available in the form of leftover meal scraps for rats who occupied human households as their primary ecological niche, though rats may also have hunted for seabird hatchlings and eggs (Norman 1975; Spenneman 1997). These high trophic level marine resources would have become scarce in Phase III as seabird populations were greatly diminished, and as people shifted their residences from the coast to inland locations.

The change in activity at the Hane dune site from permanent habitation site to largely ceremonial complex between Phases II and III likely also impacted food consumption practices, limiting the resources available to commensal scavengers such as rats. Without permanent human occupation at the site, rats may have been forced to rely more frequently on wild foraging for terrestrial resources. Marine contributions to rat diet in Phase III seem to have been reduced though not entirely eliminated. Even after the cessation of site use in the early 17th century, Conte and Molle (2014) suggest that Hane Bay would have been a desirable fishing locale, and likely continued to be visited by groups of fishermen either living further inland or in another location within the coastal area. However, the frequency and nature of fishing practices may have changed: marine dietary inputs in Phase III appear to come from low trophic level fish and shellfish, likely exploited from nearshore habitats. Analysis of fishhook assemblages from the Marquesas further confirm this movement away from offshore fishing, as more diverse fishing kits in early prehistory were replaced with assemblages predominantly of the simple, jabbing hook type (Sinoto 1966; Suggs 1961; Rolett 1998). Dye (1990) suggests these changes resulted from intensified social stratification and warfare, processes which gave elites more control over canoes and access to prime fishing locations, and which made offshore excursions a more dangerous venture. Hook-and-line fishing with simple jabbing hooks, along with other fishing

methods which leave no trace in the archaeological literature such as netting, trapping, and poisoning, would have been ideal for exploitation of the nearshore environment.

Davidson et al.'s (1999) reanalysis of the ichthyofaunal remains recovered from Sinoto's excavations of the Hane dune site suggest that although pelagic tuna fishing declined through time, it remained an important aspect of fishing practices at Hane into late prehistory. This insight provokes an exploration into the different types of evidence gleaned from the faunal versus stable isotopic indices. As Allen and Craig (2009) note, these two archives each come with their own set of potential biases but when combined can better inform interpretations of past subsistence. Zooarchaeological assemblages are subject to taphonomic and recovery processes which may favor certain species or elements, as well as cultural depositional processes which accumulate the activities of numerous groups over large spans of time. In contrast, dietary information from stable isotope analysis is tied to particular individuals—introducing bias through dietary preference—and represents a shorter period of time. In this case, the analysis of Pacific rat elements represents individual diet for around one year (Atkinson and Towns 2001). Davidson et al. found an MNI of 14 for late-period Scombridae, compared to 94 in the early period (Davidson et al. 1999; Table 7). This small number—the product of a few fishing excursions—is not likely to significantly influence rat stable isotope $\delta^{13}C$ and $\delta^{15}N$ values.
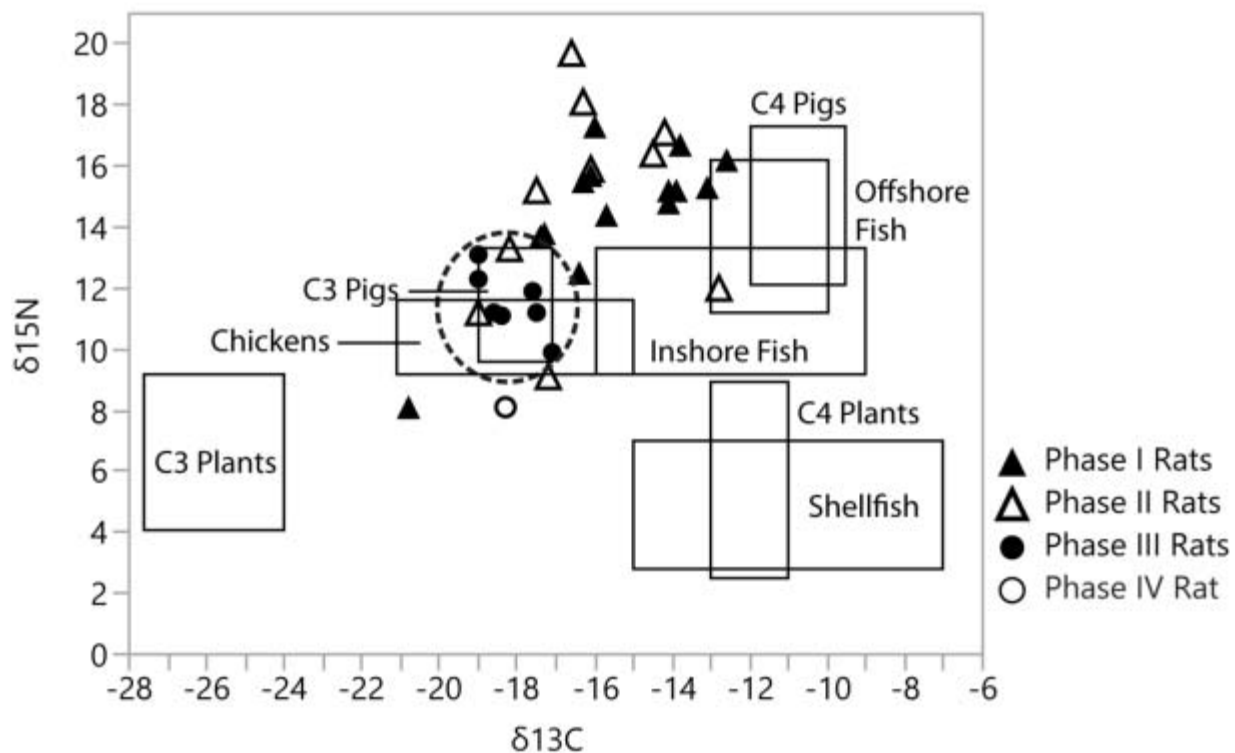
Figure 3.3: $\delta^{13}C$ and $\delta^{15}N$ values for Pacific rat (*Rattus exulans*) bone collagen from all three cultural phases plotted with background values for potential food sources. Dotted circle highlights dietary shift in Phase III. Values have not been adjusted for dietary fractionation. Background values estimated from Allen and Craig 2009; Brooke et al. 2010; Kinaston et al. 2014; Richards et al. 2009; Storey et al. 2010.

It is also interesting to note that the majority of Scombridae remains from Hane identified by Davidson et al. (1999) are caudal vertebral elements. Handy (1923:167-168) describes the process of dividing a successful catch onshore, while afterwards families returned to their homes further inland to enjoy the spoils. Occasionally—particularly after important deep-sea expeditions—the chief would take the catch further into the valley to his "feast place" or a ceremonial plaza (*tohua*) to divide the meal. The head of the fish, as the fattiest, oiliest and often the portion most valued by Polynesians (Kirch and O'Day 2003; O'Day 2004) was likely the domain of the chief and consumed where the elites resided. This activity would have become more prevalent through prehistory as chiefs gained more power and control over fishing practices. Further, it suggests that a large portion of fish catches would have been consumed and disposed of at inland sites, inaccessible to coast-dwelling rats. These depositional factors may result in an underrepresentation of the actual amount of offshore fish consumed in the later Hane faunal assemblages. However, an increase in the overall abundance of shellfish and inshore fish remains in later prehistory still points to significant changes in the Marquesan fishing industry on Ua Huka Island (Kirch 1973; Dye 1990).

In aggregate, stable isotope data from multiple *R. exulans* individuals provides insight into large-scale trends through time at a particular location. The Pacific rat's limited home range suggests that although these data may not speak to island-wide trends, they can provide a new line of evidence towards interpreting the subsistence record at the Hane dune site. Differences between human and rat dietary preferences may limit isotopically reconstructed rat diet's use as a direct proxy for human diet; however, significant shifts in δ^{13}C and δ^{15}N values between Phases I/II and Phase III demonstrate a clear transition in the site's occupational history and intensity of use. This provides a new window into understanding localized patterns of activity and subsistence practices in the coastal region of Hane.

Conclusions

As one of the most studied sites in the Marquesas, settlement and subsistence practices at Hane figure prominently in present understandings of the archipelago's long-term prehistory. The results presented here conform to initial interpretations of Hane subsistence as primarily marine-oriented in its earliest phases, later transitioning to a terrestrial economy of breadfruit arboriculture and intensive pig husbandry (Kirch 1973; Dye 1990). Pacific rat bone collagen δ^{13}C and δ^{15}N values indicate a reduction in both quantity and quality of marine inputs available at the dune complex by Phase III. Although Hane likely continued to act as a prime fishing location for the inhabitants of the valley, marine resource exploitation represented in the Hane coastal area became focused on nearshore resources such as shellfish and low trophic level inshore fish. Catches from the less frequent offshore fishing excursions were likely brought inland to be reallocated by the chief and consumed. The revised chronological sequence of the Hane dune site (Conte and Molle 2014) indicates this transition occurred around the 14th century following an initial abandonment of the dune for several decades. Broadly, this would place these developments in the early Expansion Period (Allen 2004), consistent with the settlement pattern and subsistence trends outlined by Suggs (1961) for Nuku Hiva. Investigations of other sites in the Marquesas (e.g., Allen 2004; Rolett 1998) suggest that similar subsistence and settlement trends occurred throughout the archipelago, though with local variation in timing and process.

The results presented here would not be properly contextualized without previous intensive analyses of Hane's archaeofaunal record. A detailed analysis of the rich assemblage of marine remains from the 2009 excavations is currently in progress and will bring further insight into long-term changes in marine subsistence at Hane. This study provides a new line of evidence into human subsistence and activity at the Hane dune site, suggesting that cultural depositional practices—particularly in later prehistory—may introduce bias both the faunal and isotopic subsistence archives. Stable isotope analysis of small commensal species can provide new insight into local site activity and ecology, as well as complement archaeofaunal and ethnographic analyses to create greater resolution on past subsistence activity.

Chapter 4

Pacific rat (*Rattus exulans*) diet as proxy for human-ecosystem dynamics on Tikopia: A stable isotopic record of long-term stability in a Polynesian Outlier

Introduction

The island of Tikopia is often presented as an example of a long-term sustainable island society with a resilient agricultural ecosystem (e.g., Diamond 2005; Kirch 2007a; Mertz 2002). Tikopia is a Polynesian "Outlier," one of about 18 islands located geographically outside the Polynesian triangle region but whose inhabitants speak Polynesian languages and trace their ancestry to Polynesia (see Fig 4.1). The arrival of Polynesians on Tikopia was likely concurrent with the colonization of the eastern portion of the Polynesian triangle by voyagers from a West Polynesian homeland (the Samoa, Tonga, Futuna, 'Uvea region). However, Tikopia's archaeological history extends back much further than the arrival of Polynesians, to the initial Austronesian expansion into Remote Oceania. These first people to settle Tikopia arrived roughly 2800 years ago (Kirch and Yen 1982; Kirch and Swift in submission).

Although it is a small island (4.6 km^2), Tikopia has proven capable of supporting a relatively dense population. The island owes its stability in part to its geologically young age (ca. 90,000 years) and nutrient-rich soils. A relatively large portion of the island is made up of cultivable land. Its success is also due to the generations of human inhabitants who actively managed Tikopia's landscape and developed a complex, multi-story sustainable agricultural system which combines arboriculture with field cropping. However, population control also played a key role in maintaining the island's long-term resilience: the Tikopia ensured their population never exceeded the island's carrying capacity through several growth-limiting mechanisms, which included infanticide, enforced celibacy, prevention of contraception, abortion, sea voyaging, and warfare (Borrie et al. 1957; Firth 1936:173-4).

The concept of islands as "model systems" for global ecosystem functioning has grown in popularity as humans are increasingly recognized as a force for planet-wide change (e.g., Davies et al. 2016; Vitousek 2002, 2004; Warren et al. 2015). The Polynesian islands in particular are suited to such analyses due to their relatively short chronologies, agriculturally-based economies, and common origin from a West Polynesian homeland (see Kirch 2007a). As a Polynesian Outlier, Tikopia's long archaeological history and blend of Melanesian and Polynesian cultural influences presents a contrastive study to islands within the Polynesian triangle. Tikopia has figured into discussions of long-term socio-ecosystem dynamics in Polynesia through comparison with other islands including Mangaia, Hawaii, and Mangareva (Kirch 1983; 1997b; 2007a).

The following research presents bone collagen stable isotope data from Pacific rat (*Rattus exulans*) remains recovered from archaeological sites on Tikopia to explore long-term island socio-ecosystem dynamics through the lens of a small, commensal omnivore. Stable isotope analysis of small-bodied mammals has proven effective in paleontological contexts for providing localized, high-resolution paleoenvironmental data (e.g., Gehler et al. 2012; Grimes et al. 2008; Hynek et al. 2012). In archaeological contexts, the diet of commensal rat species is also sensitive to changes in human behavior. These dietary changes in rat populations through time offer insights into shifts in local ecosystems as well as human activities, including changing site use and subsistence practices (see Guiry and Gaulton 2015). On Tikopia, these data can be used to

explore pre-Polynesian and Polynesian landscape transformations and subsistence economies in what has been called a "model of the sustainable microcosm" (Kirch 1997b:35).
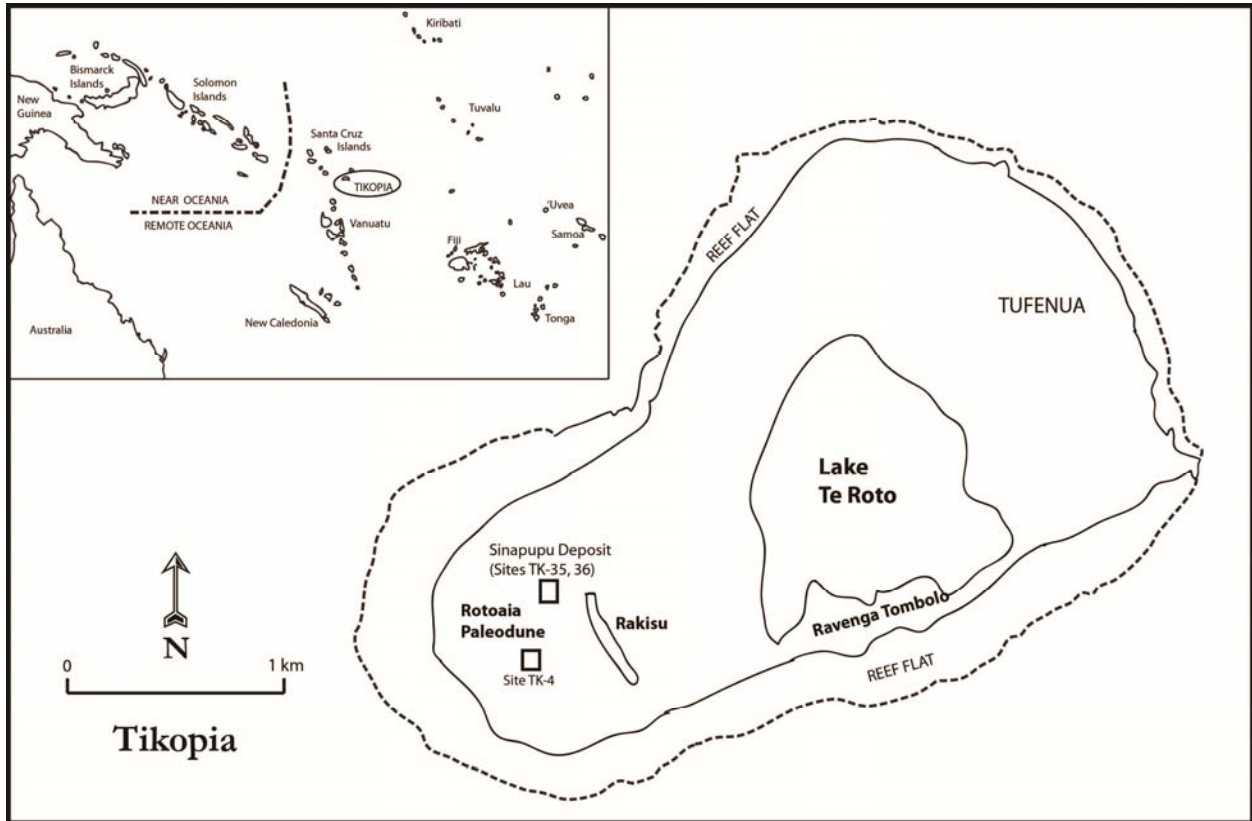
Figure 4.1: Map of Tikopia with study sites labeled, and inset map showing Tikopia and the divide between near and remote Oceania.

Long-Term Human Ecodynamics on Tikopia

Kirch and Yen's (1982) pioneering excavations on Tikopia established a nearly three-thousand year sequence of occupation, with evidence for an ever-evolving island ecosystem in the hands of purposeful land managers. The Tikopian archaeological sequence can be divided into four main cultural phases: the Kiki, Sinapupu, Tuakamali, and Historic Phases. Recently, Kirch and Swift (in submission) revisited the chronological sequence established by Kirch and Yen's original radiocarbon dates (Kirch and Yen 1982:Table 50), and augmented these with 13 new AMS radiocarbon dates obtained on samples from the original Kirch and Yen excavations. The results of Bayesian analysis incorporating both original and new AMS radiocarbon dates have further refined the chronological sequence for Tikopia (see Table 4.1).

Tikopian cultural phases were established by Kirch and Yen (1982) based on changes in ceramic and other artifact assemblages, however these phases are also accompanied by significant transitions in island geomorphology, the faunal record, and other artifact assemblages. The beginning of the Kiki Phase, marking the earliest arrival of people on Tikopia, occurred around 2745 BP (795 cal BC) based on new AMS dates from the TK-4 and TK-36 sites (Kirch and Swift, in submission). Kiki Phase ceramics were largely locally-made, sand-tempered

earthenware, some of which were decorated with distinctly Lapita-style dentate-stamped motifs (see Dickinson 1998; Kirch 1997b; Mead et al. 1975). The transition to the Sinapupu Phase (160 BC to AD 1110) is distinguished by cessation of local pottery manufacture in favor of a smaller quantity of imported, volcanic-sand tempered and well-fired ceramics. These ceramics are not of the Lapita style, but rather bear incised and appliquéd designs in the style of the later Mangaasi ceramic series identified in Vanuatu (see Bedford 2006; Garanger 1972). The final phase prior to European contact, the Tuakamali Phase (AD 1110-1780), is characterized by the cessation of ceramic use altogether as well as the appearance of distinctly Polynesian-style material culture, including pearl shell trolling lures, basalt adzes, and bone and shell ornaments. Kirch and Yen (1982) interpret the beginning of the Tuakamali phase as marking the arrival of voyagers from the West Polynesian homeland, the direct ancestors of Tikopia's contemporary social groups. Tikopian oral traditions (Firth 1961) likewise trace the origins of the island's several lineages to specific islands in West Polynesia.

Table 4.1: Revised chronology and distinguishing features of Tikopia's prehistoric cultural phases.

Phase	Duration	Key Features
Kiki	800 to 160 BC	Locally-produced, Lapita-style ceramics; heavy exploitation of marine resources, avifauna, fruit bats; slash-and-burn agriculture
Sinapupu	160 BC to AD 1110	Imported Mangaasi-style ceramics; population growth; intensification of agricultural production and pig husbandry; fire use declines with the beginning of tree cropping
Tuakamali	AD 1110 to 1780	Arrival of Polynesian people; formation of Ravenga Tombolo and Lake Te Roto; cessation of agricultural fire use; development of multi-story arboricultural cropping system; late extirpation of pig

Tikopian geomorphology and land use underwent significant changes during this roughly 2500 year span, due to a combination of natural processes (such as sea level change) combined with active landscape management practices by the Tikopia. Mid-Holocene sea level declines led to shoreline progradation, while clearance and land use on hillsides accelerated erosion and generated an influx of nutrient-rich sediment to lowland areas. These processes had a twofold effect on Tikopian subsistence through time: an increase in the total cultivable land area, and restriction in the total area of accessible reef flat. Early Tikopian agriculture focused on shifting cultivation and intensive use of fire, indicated by extensive charcoal in the deeper strata at Rakisu (Kirch and Yen 1982:154). By the late Sinapupu and Tuakamali Phases, fire use had been abandoned in favor of developing a complex arboricultural system of Polynesian socio-economic crops which mimicked natural forest cover. This new arboricultural system restabilized hillside slopes, slowing the deposition of new sediment onto coastal flats. However, another significant geomorphologic change occurred during the Tuakamali Phase: the formation of the Ravenga tombolo on the eastern side of the island, which created a large lake (Te Roto) in the center of the island. The tombolo developed naturally over the course of several centuries, though the Tikopia actively prevent its erosion by constructing sea walls and infilling the lake margin (Kirch and Yen 1982:11).

Faunal evidence corroborates these changes in Tikopian subsistence and island ecology. Early Kiki Phase assemblages are typical of colonization-phase sites throughout Remote

Oceania, with an early reliance on wild resources including marine fauna, native avifauna, and fruit bats. Evidence for depression in these resources through time exists in the form of decreasing mollusk size and abundance in post-Kiki Phase deposits as well as the extinction of at least six avifaunal species (Kirch 1983: Table 47; Steadman et al. 1990). As these resources diminished through the Kiki Phase, the Tikopia began to experiment with agricultural systems, and increasingly relied on cultivated resources over wild hunting and foraging. By the Sinapupu Phase, an agricultural economy focused on shifting cultivation and animal husbandry (pigs and chickens) had developed. Although the Tikopia continued to exploit marine resources from the surrounding reef, progradation of the island's beach ridges had eliminated nearly half of the formerly available reef area (Kirch 1983; Kirch and Yen 1982:107).

Considerable changes occurred in the Tikopian subsistence system during the Tuakamali Phase. The beginning of this phase saw the new arrival of voyagers from the West Polynesian homeland. The use of fire in land clearance ceased almost entirely while the complex arboricultural system observed ethnohistorically developed. Multistory orchard gardening of Polynesian tree crops (e.g., coconut, breadfruit, Polynesian chestnut) and intensively mulched field crops (yams, taro) formed the backbone of a largely sustainable agroeconomy (Kirch and Yen 1982:38-39). This new agricultural system mimicked the structure of the natural forests it replaced, providing new habitat for nesting avifauna (Steadman et al. 1990). The formation of the Te Roto Lake created new opportunities for cultivating communities of lake fish (milkfish, mackerel) and hosting duck (*toroa*) populations on the lake surface. Pig husbandry continued in the Tuakamali Phase, however at some point prior to Western contact, the decision was made to eliminate pigs from the island. This decision was purportedly due to pigs becoming an overwhelming pest to orchard crops (Firth 1959:34). Kirch (2000b) argued this decision ultimately reflects trophic competition between pigs and humans over limited resources, a phenomenon seen on several other small islands.

Unlike islands within the Polynesian triangle, Tikopia lies to the west of the "*exulans*-only" line (Roberts 1991) of rat distribution, which separates most islands in Remote Oceania by virtue of having only a single rat species (*R. exulans*) prior to European contact. A second rat species, the large spiny rat (*Rattus praetor*) was introduced prehistorically to Tikopia. It was not found in the earliest archaeological deposits of the island (site TK-4), but seems to appear several hundred years after initial colonization, in the Late Kiki Phase. Flannery et al. (1988) suggested that *R. praetor* arrived on Tikopia through continued contact with other islands in the Solomon archipelago. Relatively little is known about the large spiny rat, which is likely native to New Guinea and is presently found there and on several other islands in Near Oceania. However, it is now extinct on Tikopia (White et al. 2000). Unlike the Pacific rat, which creates nests and husking stations, the spiny rat is a strong burrower and—while still an opportunistic feeder— appears to have been less commensally associated with people (Taylor et al. 1982). Spiny rat remains are easily distinguishable from the Pacific rat due to their larger size, and indeed *R. exulans* remains greatly outnumber those of *R. praetor* in all sites from Kirch and Yen's excavations (1982:280). Although the two rat species may have been sympatric, it does appear that the Pacific rat was more successful in colonizing the Tikopian household as an ecological niche.

Materials and Methods

Several characteristics of the Pacific rat position it as an ideal proxy species for local cultural and environmental change on Tikopia. The rat is widely distributed across the Pacific, and was apparently transported to Polynesian islands with some of the earliest human voyagers to settle new islands. Because of this, Pacific rats have also been used as a proxy for human colonization and migration in Polynesia (the 'commensal model' for the settlement of the Pacific; Matisoo-Smith 2009) and the chronology of initial human arrival to new islands (Anderson 2004; Kirch 2011b; Wilmshurst et al. 2008). Pacific rats are omnivores with low dietary selectivity and a limited home range (26-89 m in diameter; Atkinson and Moller 1990; Bramley 2014), which suggests their diet can reflect the full range of resources available at a particular site. Although modern Pacific rat diet is predominantly vegetal, this species has been observed predating a large range of animal species for protein, including arthropods, turtle hatchlings and eggs, small birds and bird eggs, and even other rats (Campbell et al. 1984; Norman 1975; Spenneman 1997). This wide range of potential dietary inputs, as well as the Pacific rat's close association with human activities and food sources, suggest that rat diet will change through time along with variations in human subsistence, resource use, and landscape management practices.

Study Sites

Pacific rat remains were analyzed from three separate sites on Tikopia (TK-4, TK-35, and TK-36; see Fig 1) excavated by Kirch and Yen in 1977-78, which contain deposits from all three prehistoric cultural phases: Kiki, Sinapupu, and Tuakamali. These sites are all situated on the Rotoaia Paleodune, an arc-shaped series of former beach ridges in the center of the western lowland region of the island (Faea District). Although the dune is presently 200+ meters inland from the modern coastline, these sites were located near the original shoreline at the time of their prehistoric occupation. Today, the Rotaia region is intensively cultivated with nutrient-rich organic sediment that accumulated during centuries of prehistoric occupation and midden deposition in the area.

Site TK-4 is a large (4500+ m^2) settlement site containing the earliest evidence for human occupation on Tikopia. Pacific rat remains were analyzed from the intact cultural Layer II, which represents the Kiki Phase. This layer can be further stratigraphically subdivided into earlier (C2) and later (C1) subphases to provide further chronological resolution within this 650-year time period (see Kirch and Yen 1982:99). Sites TK-35 and TK-36 are both included within the Sinapupu beach ridge sequence, which contains rich deposits from the Kiki, Sinapupu, and Tuakamali phases (see Kirch and Yen 1982:89, Fig 37).

Stable Isotope Analysis

Carbon and nitrogen stable isotope ratios have proven useful in reconstructing the diet of archaeologically recovered human and faunal remains (see Katzenberg 2008; Sealy 2001). Bone collagen is synthesized from dietary amino acids and thus is weighted towards the protein component of diet (Ambrose and Norr 1993; Tieszen and Fagre 1993). Stable isotope abundances are expressed in delta (δ) notation as ratios between two isotopes (e.g., ^{13}C/^{12}C) relative to an established standard, and expressed in parts per thousand (‰) where: δ =

[(Rsample/Rstandard) – 1] * 1000. The established standards for C and N stable isotope analysis are calibrated to Pee Dee Belemnite (PDB) and atmospheric nitrogen (Ambient Inhalable Reservoir, or AIR), respectively.

Carbon stable isotope ratios are primarily useful in distinguishing between C_3 and C_4 plant consumption, as well as between terrestrial C_3 and marine resources. Differential discrimination of ^{13}C between Calvin cycle (C_3), Hatch-Slack cycle (C_4), and Crassulacean Acid Metabolism (CAM) photosynthetic pathways result in distinct ranges of $\delta^{13}C$ values. $\delta^{13}C$ values of C_3 plants tend to fall between -34 to -21‰, and C_4 plants between -15 to -8‰. CAM plants tend to have $\delta^{13}C$ values falling between the ranges of C_3 and C_4 plants, though may also resemble C_4 plants. Carbon intake in marine systems comes from a mix of sources including terrestrial detritus and dissolved bicarbonate, and in general produce $\delta^{13}C$ values resembling those of C_4 plants.

Nitrogen stable isotope ratios are primarily useful in determining trophic position, and can also aid in distinguishing terrestrial versus marine resource contributions. $\delta^{15}N$ values can be influenced by numerous factors, including environmental conditions, physiology, and diet; however in general, an approximate 3.5‰ increase in $\delta^{15}N$ values accompanies every "step" up the trophic ladder (Bocherens and Drucker 2003; DeNiro and Epstein 1981; Minagawa and Wada 1984). Because marine systems are complex, containing many levels of producers and consumers, marine resources tend to be more enriched in ^{15}N than their terrestrial counterparts.

The collections from Kirch and Yen's 1977-78 archaeological excavations are curated at the Bernice Pauahi Bishop Museum; the specimens used in this analysis were acquired through a destructive analysis loan. A total of 87 rat femora were selected for analysis, taking care to select only left or right sides for each excavation level to minimize the possibility of resampling from the same individual. Between levels, femora were compared for potential matching pairs to further reduce the chances of double sampling.

Bone elements were sonicated for four hours in ultrafiltered water, dried, and abraded to remove adhering surface contaminants. Specimens were then crushed to ~1 mm chunks using an agate mortar and pestle. Collagen extraction proceeded following a modified version of Ambrose (1990; and see meta-analyses by Pestle et al. 2014; Sealy et al. 2014). Samples weighing over 20 mg were treated with 0.5 M HCl, and samples under 20 mg with 0.25 M HCl, with fresh acid applied every 24 hours until demineralized. Following demineralization, all samples were rinsed with ultrafiltered water and treated with 0.1 M NaOH for 12 hours. Samples were then rinsed and freeze dried for 48 hours, and weighed into tin caps. Dry samples were analyzed simultaneously for C and N contents (% dry weight) and C and N stable isotope ratios using a CHNOS Elemental Analyzer (vario ISOTOPE cube, Elementar, Hanau, Germany) and IsoPrime 100 mass spectrometer (Isoprime LTd., Cheadle, UK). Analyses were conducted at the Center for Stable Isotope Biogeochemistry at the University of California, Berkeley, with long-term external precision of 0.1‰ (C) and 0.15‰ (N).

The primary means of evaluating bone collagen is the ratio of preserved carbon to nitrogen (C/N Ratio) in the sample. Samples with C/N ratios falling outside the range of 2.9-3.6 may be contaminated and were eliminated from analysis (Ambrose 1990; DeNiro and Weiner 1988; van Klinken 1999). Secondary quality indicators include the quantity of bone collagen, as well as the weight percent carbon and nitrogen preserved in the sample. Modern bone is composed of approximately 22%collagen by weight, and archaeological samples recovered from tropical and subtropical contexts should contain at least 0.5% collagen (Pestle and Colvard

2012). C and N concentrations within samples should approximate that of modern bone collagen: roughly 35% carbon and 11-16% nitrogen by weight (van Klinken 1999).

Out of 87 specimens, 9 samples dissolved during demineralization and could not be analyzed. Of the 78 samples that were analyzed for C and N stable isotope ratios, only 28 produced C/N ratios within the recommended range of 2.9-3.6. In most cases, eliminated samples contained low % wt nitrogen, resulting in C/N ratios well above 3.6. Although the small number of viable samples from the Tikopia assemblage limits interpretation to some degree, these results are not atypical of assemblages recovered from tropical and subtropical environments. A metaanalysis by Pestle and Colvard (2012) determined that samples with at least 0.5% preserved collagen, as well as proportional loss of %C and %N in degraded collagen samples (C/N ratio between 2.9-3.6) in tropical contexts possess sufficiently unaltered collagen to produce accurate $\delta^{13}C$ and $\delta^{15}N$ values. Collagen degradation occurred differentially between temporal phases, with 14 of 37 (38%) samples lost in the Kiki Phase, 30 of 35 (86%) lost in the Sinapupu Phase, and 14 of 15 (93%) lost in the Tuakamali Phase. There was no correlation between collagen degradation and sample age (contra Pestle and Colvard 2012). Rather, local site conditions such as soil acidity and water percolation appear to have had the strongest impact on collagen preservation. Laboratory, time, and cost constraints prohibited an analysis of amino acid composition of bone collagen samples, however in future studies this could aid in determining whether preferential amino acid loss occurred during *in situ* bone collagen degradation (see Tuross 2002).

Radiocarbon dating of select *Rattus exulans* samples from Tikopia provides further reassurance regarding the accuracy of $\delta^{13}C$ and $\delta^{15}N$ values of bone collagen samples which meet minimum quality control requirements. A total of 11 rat bone samples were split, with half analyzed for bone collagen C and N stable isotope ratios by the author and half submitted to the W.M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory at the University of California, Irvine for radiocarbon dating and independent C and N stable isotope analysis. Of these 11 samples, four contained sufficient quantities of bone collagen for AMS radiocarbon analysis, and two of these four were large enough for both ^{14}C and C & N stable isotope analysis (TKR-12, TKR-41). Samples TKR-12 and TKR-41 differed in $\delta^{13}C$ values between labs by 0.06‰ and 0.12‰ respectively, while $\delta^{15}N$ values demonstrated a slightly larger variance of 0.5‰ and 0.01‰ (respectively). These values are within the range of expected inter-laboratory variation based on differences such as sample preparation, instrumentation, and calibration (see Pestle et al. 2014). AMS dating results aligned well with the expected date ranges for these samples based on their stratigraphic contexts, suggesting that the remaining collagen preserved in these samples did not undergo differential deterioration. Although this sample is admittedly small, it provides reassurance that specimens meeting minimum quality control standards within this assemblage do produce viable bone collagen.

Results

Table 4.2 presents $\delta^{13}C$ and $\delta^{15}N$ values and quality control indicators for the 28 samples with sufficiently preserved bone collagen for further analysis. Kiki Phase rat elements were recovered from site TK-4 (early Kiki) and site TK-36 (early and late Kiki). All Sinapupu Phase rats with well-preserved bone collagen were recovered from site TK-35. The single Tuakamali Phase element was recovered from site TK-36. The loss of 68% of the total assemblage resulted in adequate representation for the Kiki Phase—such that this phase can be divided into early and

Table 4.2: Pacific rat bone collagen δ¹³C and δ¹⁵N values with quality control indicators for the Kiki, Sinapupu, and Tuakamali Phases on Tikopia.

Sample ID	Site	Square	Level/Layer	Element	Side	% C	% N	C:N	%Coll	δ13C	δ15N	Phase
TKR-3	TK-4	O18III	II	Femur	L	35.81	12.56	3.33	1.73	-15.3	15.9	Kiki (C2)
TKR-7	TK-4	P18IV	II	Femur	L	40.97	13.93	3.43	4.66	-19.9	11.9	Kiki (C2)
TKR-9	TK-4	P18IV	II	Femur	L	40.78	14.09	3.38	5.42	-18.8	12.6	Kiki (C2)
TKR-10	TK-4	R16II	II	Femur	L	39.22	13.20	3.47	12.79	-15.3	12.3	Kiki (C2)
TKR-11	TK-4	R16II	II	Femur	L	23.17	8.23	3.29	9.39	-14.8	12.0	Kiki (C2)
TKR-12	TK-4	R16II	II	Femur	L	18.11	5.96	3.54	13.57	-17.1	13.4	Kiki (C2)
TKR-14	TK-4	R16II	II	Femur	L	43.51	15.35	3.31	3.40	-17.2	13.2	Kiki (C2)
TKR-15	TK-4	S15II	II	Femur	L	38.05	12.69	3.50	1.12	-14.1	15.1	Kiki (C2)
TKR-18	TK-4	U17II	II	Femur	L	27.56	9.23	3.49	8.95	-18.9	14.3	Kiki (C2)
TKR-19	TK-4	U17II	II	Femur	L	39.36	13.42	3.42	3.16	-17.4	16.1	Kiki (C2)
TKR-20	TK-4	U18IV	II	Femur	L	32.56	10.76	3.53	3.82	-20.2	12.8	Kiki (C2)
TKR-23	TK-4	U18IV	II	Femur	L	37.36	12.79	3.41	3.87	-15.7	12.5	Kiki (C2)
TKR-26	TK-4	W13	II	Femur	L	44.94	15.02	3.49	2.52	-19.4	12.4	Kiki (C2)
TKR-87	TK-4	R16III	II	Femur	L	21.06	7.20	3.48	25.39	-15.0	13.3	Kiki (C2)
TKR-36	TK-35	A3	2	Femur	R	43.76	14.81	3.45	1.16	-20.2	10.9	Sinapupu
TKR-38	TK-35	C2	2	Femur	R	29.86	10.37	3.36	3.36	-18.6	8.1	Sinapupu
TKR-40	TK-35	A2	3	Femur	R	21.76	7.29	3.48	3.88	-19.3	9.2	Sinapupu
TKR-41	TK-35	A2	3	Femur	R	23.82	7.72	3.60	5.84	-19.3	9.8	Sinapupu
TKR-53	TK-36	A4	I (lower)	Femur	R	43.52	15.37	3.30	17.27	-23.0	8.7	Tuakamali
TKR-55	TK-36	A1	II	Femur	L	33.40	11.06	3.52	1.12	-20.4	11.7	Kiki (C1)
TKR-56	TK-36	A1	II	Femur	L	41.44	14.23	3.40	1.21	-18.9	13.9	Kiki (C1)
TKR-58	TK-36	A4	II	Femur	L	31.49	10.37	3.54	2.16	-18.5	12.9	Kiki (C1)
TKR-59	TK-36	A4	II	Femur	L	30.03	9.77	3.59	6.72	-16.3	13.1	Kiki (C1)
TKR-60	TK-36	A4	II	Femur	L	40.65	13.20	3.59	1.28	-17.0	13.0	Kiki (C1)
TKR-61	TK-36	A4	II	Femur	L	43.87	15.00	3.41	1.33	-17.9	11.7	Kiki (C1)
TKR-62	TK-36	A4	II	Femur	L	45.33	14.97	3.53	2.01	-18.9	11.3	Kiki (C1)
TKR-63	TK-36	B1	II	Femur	L	31.89	10.42	3.57	2.36	-15.9	13.0	Kiki (C1)
TKR-68	TK-36	A3	III (lower)	Femur	L	29.00	9.68	3.50	7.19	-17.7	15.0	Kiki (C2)

late subphases—a small number of Sinapupu Phase samples, and only a single individual as representative of the Tuakamali Phase. Although the data set is inadequate to fully represent changing rat diet throughout the entire Tikopian sequence, it does provide insight into the Kiki and Sinapupu Phases. Most notably, these data point to a long span of relative stability in rat bone collagen $\delta^{13}C$ and $\delta^{15}N$ values, followed by an apparent decline in $\delta^{15}N$ and more negative $\delta^{13}C$ values in later prehistory (Figure 4.2).

Mean $\delta^{13}C$ and $\delta^{15}N$ values change little between the early and late Kiki Phases, with differences of +0.9‰ and -0.9‰ respectively (see Table 4.3 for descriptive statistics). Although fewer samples were successfully analyzed from the Sinapupu Phase, these individuals have $\delta^{13}C$ and $\delta^{15}N$ values that are statistically distinct from Kiki Phase rats, particularly with respect to nitrogen stable isotope ratios, which are depleted in ^{15}N relative to Kiki Phase rats. $\delta^{13}C$ values from Sinapupu Phase rats fall in line with Kiki Phase rats, but are restricted to the more negative values within this range (-19.3 ± 0.6‰). The single rat bone element from the Tuakamali Phase, while obviously not constituting a representative sample, suggests a continuation of the trend towards more negative $\delta^{13}C$ and lower $\delta^{15}N$ values.

The Kiki Phase deposits contain a record of relatively stable Pacific rat diet for around 650 years following the initial human settlement of Tikopia. Although these data suffer from sample size issues, the available sample of Sinapupu and Tuakamali Phase rats suggests shifts in rat diet occurred between phases. The data for these chronological trends come from three separate sites (TK-4, TK-35, and TK-36), which are less than 400 m distant from each other on the Rotoaia paleodune. Thus, regional variation can be ruled out as the cause for change in rat diet between cultural phases. Rather, rat dietary shifts are presumably related to changing socio-ecosystem dynamics, particularly with respect to agricultural regimes and subsistence practices.

Table 4.3: Descriptive statistics for Pacific rat bone collagen $\delta^{13}C$ and $\delta^{15}N$ values by cultural phase on Tikopia.

Phase	n	$\delta^{13}C$				$\delta^{15}N$			
		Mean	SD	Min	Max	Mean	SD	Min	Max
Early Kiki (C2)	15	-17.1	2.0	-20.2	-14.1	13.5	1.4	11.9	16.1
Late Kiki (C1)	8	-18.0	1.5	-20.4	-15.9	12.6	0.9	11.3	13.9
Sinapupu	4	-19.3	0.6	-20.2	-18.6	9.5	1.2	8.1	10.9
Tuakamali	1	-23.0	n/a	-23.0	-23.0	8.7	n/a	8.7	8.7
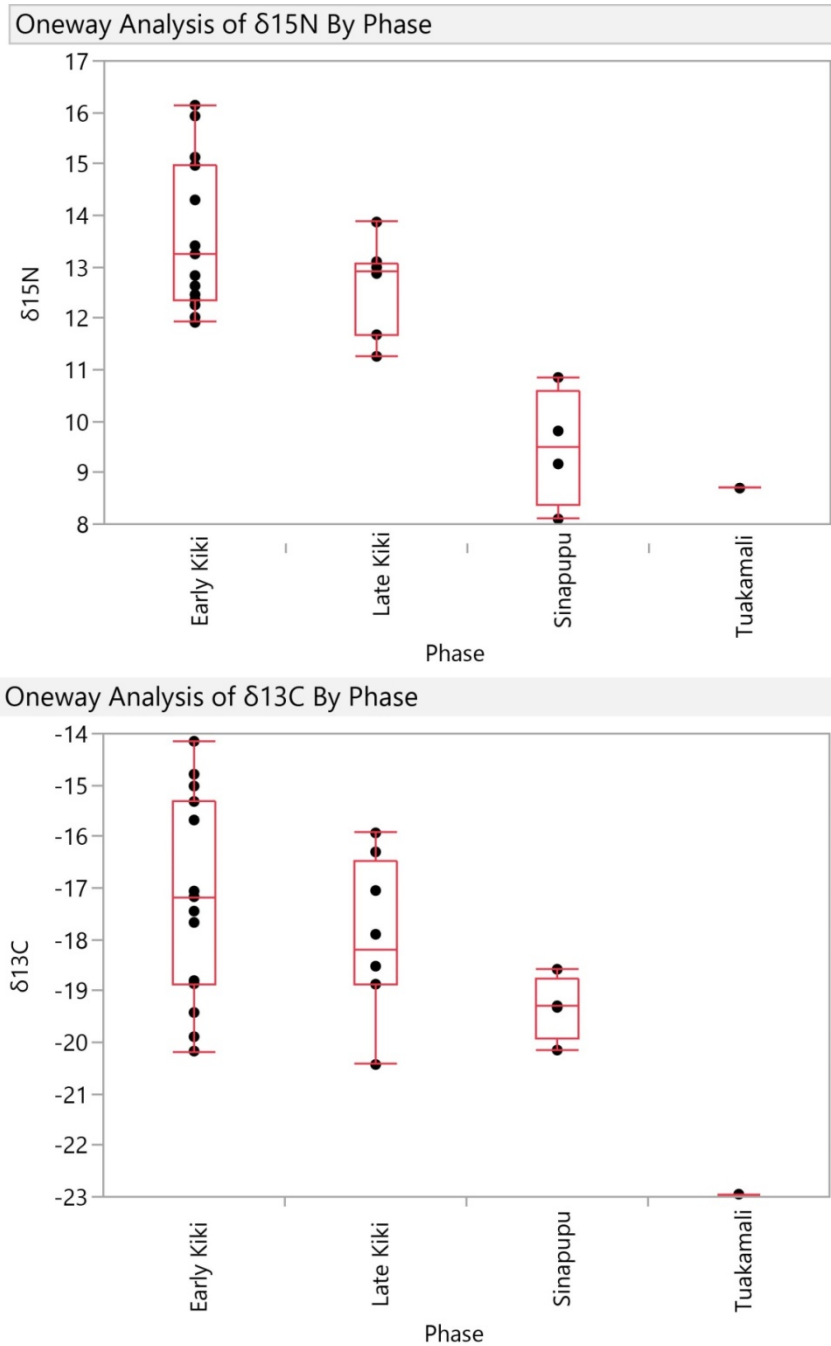
Figure 4.2: Pacific rat bone collagen δ¹³C and δ¹⁵N values by cultural phase.

Socio-Ecosystem Dynamics and Pacific Rat Stable Isotope Ratios

Figure 4.3 plots rat bone collagen $\delta^{13}C$ and $\delta^{15}N$ values by cultural phase, as well as estimated values for potential food sources. These estimates were derived from previously published C and N stable isotope ratios from archaeological studies in other islands of the Pacific

(Allen and Craig 2009; Brooke et al. 2010; Kinaston et al. 2014; Richards et al. 2009; Storey et al. 2010). Diet, physiology, and environmental factors can influence diet-to-tissue fractionation. In general, rat bone collagen $\delta^{13}C$ values have been reported as roughly 3‰ more positive than diet (Lee-Thorp et al. 1989), while $\delta^{15}N$ values are approximately 3.5‰ higher than diet (Bocherens and Drucker 2003; DeNiro and Epstein 1981; Minagawa and Wada 1984).

Tikopia's rich reef environment and intensive agricultural system are evident in rat bone collagen $\delta^{13}C$ and $\delta^{15}N$ values as early as the Kiki Phase. Early Kiki Phase rats appear to have consumed a mix of C_3 terrestrial resources as well as reef fish, some offshore fish, and potentially some seabirds for a small number of individuals. In the late Kiki Phase, these high trophic level marine resources such as avifauna and offshore fish are not at all apparent in diet. Late Kiki Phase diet was more focused on terrestrial resources, with small inputs from reef sources. This is coincident with declines in avifaunal remains as well as inshore, benthic, and pelagic fish between the early and late Kiki Phases (Kirch and Yen 1982; tables 40 and 43). By the Sinapupu Phase, rat diet was largely terrestrial C_3 focused. Although there appears to have been greater dietary restriction in the Sinapupu Phase, this may be a result of sampling. Kirch and Yen (1982) note an abrupt transition between the Kiki and Sinapupu phases, in both ceramic assemblages and site activity. Settlement began to expand and shifted seaward as the shoreline prograded. This settlement expansion is suggestive of an increasing population. A significant increase in pig remains indicates intensification of the terrestrial production system during this time, and associated declines in marine faunal abundances further confirm this movement towards greater reliance on terrestrial resources. Pig remains continue to appear in abundance throughout Tikopia's faunal record until the late Tuakamali Phase. Stable isotopic data from the single rat from this phase, with $\delta^{13}C$ and $\delta^{15}N$ values indicative of a C_3 terrestrial diet, is consistent with such continued investment in terrestrial agricultural production.

Bone collagen $\delta^{13}C$ and $\delta^{15}N$ values reflect an averaging out of dietary inputs throughout most of an individual rat's lifetime. However, several non-dietary factors may also influence C and N stable isotope ratios in bone collagen and other tissues, including physiology and local environmental variables such as temperature and annual precipitation (Amundson et al. 2003). In particular, declines in avifaunal populations after initial human arrival and changing fire use in agricultural systems could have significant impacts on baseline N availability and $\delta^{15}N$ values. These baseline impacts to soil N would have flowed through entire foodwebs, potentially resulting in variable N stable isotope ratios without any direct dietary change. Additionally, the introduction of the spiny rat in the late Kiki Phase may have influenced Pacific rat diet and feeding behavior.

The decline of land and seabird populations—often to the point of species extinctions or extirpations—is a common pattern following initial human arrival on new islands. Hunting, predation by introduced animals (especially rats; see Brooke et al. 2010; Caut et al. 2008; Jones et al. 2008), and habitat destruction all contributed to diminished seabird populations (Athens et al. 2002; Steadman 1995). On Tikopia, avifauna faced similar population declines as well as the extinction or extirpation of 2 land bird and 4 seabird species (Steadman et al. 1990). However, Kirch (2007a) notes that prehistoric human impact to Tikopia's avifaunal communities was far less severe than on other islands such as Mangaia, Mangareva, and the Marquesas. The orchard garden system which developed and intensified through time on Tikopia would have provided ample habitat for nesting seabird communities, particularly in later prehistory.
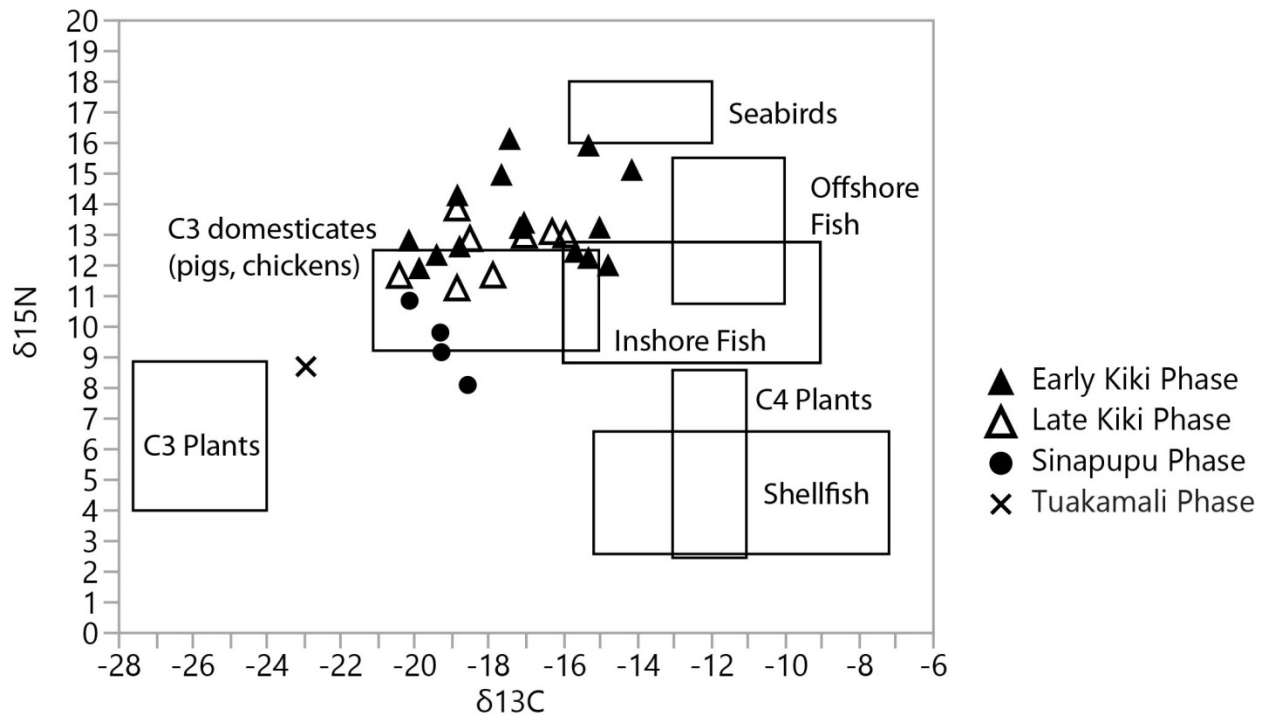
Figure 4.3: Pacific rat bone collagen δ¹³C and δ¹⁵N values from Tikopia by phase, with estimated values for potential food sources. Possible dietary sources were estimated from previously published carbon and nitrogen stable isotope ratios from elsewhere in the Pacific (Allen and Craig 2009; Brooke et al. 2010; Kinaston et al. 2014; Richards et al. 2009; Storey et al. 2010).

Nesting seabirds in particular can provide a critical soil nutrient resource in guano, which is high in N content and enriched in ^{15}N (Anderson and Polis 1999; Briggs et al. 2012; Fukami et al. 2006; Mizota and Naikatini 2007). Szpak et al. (2012) have shown that plants fertilized with seabird guano have significantly higher δ^{15}N values than unfertilized plants. This ^{15}N enrichment was shown to vary based on the quantity of guano inputs, with heavily fertilized plants having the highest δ^{15}N values. However, this study also demonstrated that overfertilization with seabird guano can be detrimental, creating high concentrations of ammonium which can inhibit plant growth. Changing abundances of nesting seabird communities on Tikopia over time might have caused soil δ^{15}N values—and therefore rat bone collagen δ^{15}N values—to fluctuate. Fertilization with other animal dung can likewise lead to ^{15}N-enriched soils, though to a lesser degree than heavy bird guano inputs. On Tikopia, the presence of pigs until late prehistory may have provided an additional source of fertilizer. It is unclear whether the Tikopia used pig feces as fertilizer in prehistory, however this practice is known to increase δ^{15}N values in plants by as much as 5.6‰ (see Szpak et al. 2012; Table 5).

The use of fire for forest clearance and agricultural production can likewise influence baseline δ^{15}N values. As Szpak (2014:7) notes, the impact of fire on ^{15}N enrichment is inconsistent across studies, however in general fire use and the accumulation of charred material in soils tends to temporarily increase δ^{15}N values by up to +8.6‰. Continuous application of fire to the same region would continue to maintain ^{15}N-enriched soils. However, upon cessation of fire use, soil and foliar δ^{15}N values begin to decline and can return to their pre-fire levels in a

matter of a single decade (LeDuc et al. 2013). Fire use for forest clearance and shifting cultivation during the earlier time periods on Tikopia is well-documented (Kirch and Yen 1982:154). Extensive slash-and-burn agricultural practices were established in the Kiki Phase and continued for several centuries. This practice began to diminish through the Sinapupu Phase as the complex arboricultural system used today was in development. In the Tuakamali Phase and at present, fire is rarely used in agricultural practice on the island. These changes in fire use surely impacted δ^{15}N values throughout Tikopia's terrestrial ecosystem. However, more research on the complexities of nitrogen stable isotope biogeochemistry in archaeological foodwebs must be conducted to establish the degree to which these practices impacted Tikopia and other tropical island systems (see review by Szpak 2014).

The arrival of the large spiny rat in the late Kiki Phase may also have affected Pacific rat C and N stable isotope ratios. Competition with a larger-bodied, sympatric rat species may have limited Pacific rat population growth as well as changed its diet and feeding behavior (see Grant 1972). Such changes have been observed between the Pacific rat and the Norway rat (*Rattus norvegicus*) and black rat (*Rattus rattus*) in other Pacific island regions. In general, the Pacific rat prefers grasslands and open areas with ample ground cover, and in the absence of competition from other species it will expand its distribution into other niches including households and gardens (Dwyer 1978; Taylor 1975). The Pacific rat can exist sympatrically alongside both Norway and black rats, however this tends to result in restricted access to food, lower quality diets, and dwindling Pacific rat populations (Harper and Veitch 2006; Russell and Clout 2005). Greater overall abundances of the Pacific rat in Tikopian archaeological sites throughout prehistory suggest that the Pacific rat had a closer commensal relationship with humans than the spiny rat. Although larger-bodied rats tend to have more competitive success, the faunal record would indicate that the Pacific rat was more successful in establishing human-occupied zones as a primary niche. In this case the Pacific rat's size may have served it well, as this would have made it easier to hide from human site occupants. Further, Russell et al. (2015) have shown that even in sites where the Pacific rat faces competition from a larger rat species (*R. rattus*), Pacific rat trophic position does not decline and δ^{13}C and δ^{15}N values from liver and muscle tissue do not change significantly. Thus, it appears unlikely that the presence of the large spiny rat would have had a strong influence on Pacific rat bone collagen δ^{13}C and δ^{15}N values.

Conclusion

The archaeological record of Polynesian islands represents an accumulation of hundreds of years of experimentation and adaptation to new island landscapes. On Tikopia, multiple lines of evidence point to a record of long-term sustainability on a small, relatively isolated island. Young, nutrient-rich agricultural soils allowed for an intensification of terrestrial production and pig husbandry for centuries on an island that is uncharacteristically small to support such sustained use and high population density (Bay-Petersen 1983; Giovas 2006; Kirch 2007a). However, Tikopia's long-term sustainability came at a cost: active population regulations which ensured that the carrying capacity of the island was never exceeded. Bone collagen stable isotope analysis of the Pacific rat presents a record of 600-plus years of relative stability during the Kiki Phase, almost the same length as entire prehistoric sequences on many islands within the Polynesian triangle. Rat diet on Tikopia changed in later prehistory, showing similar trends to other Polynesian islands with declining δ^{15}N values and less negative δ^{13}C values in the Sinapupu and Tuakamali Phases. These changes happened gradually, and only after several

hundred years of permanent human occupation. Although Tikopian subsistence changed substantially throughout prehistory, these data indicate that the Tikopia were knowledgeable, active managers of their island landscape and resources for over 2000 years. The intensive, arboriculture-oriented Polynesian Outlier society documented by Firth (1936, 1939) is only the most recent iteration of these conscious management practices.

      Stable isotope analysis of small commensal animals such as the Pacific rat can provide a new window into past subsistence practices and island socio-ecosystem dynamics. Current research has begun to highlight the significant impact of biogeochemical processes on interpretations of archaeological stable isotope data. In particular, past human activities provide numerous pathways for significant modifications to island landscapes and baseline ^{15}N abundance (see review by Szpak 2014). Further difficulty lies in attempting to compare δ^{13}C and δ^{15}N values across regions and other island systems. Without extensive knowledge of ecosystem processes and location-specific δ^{13}C and δ^{15}N values of potential food sources for all locations under study, cross-regional comparisons remain problematic. As these processes become better understood, proxy data from Pacific rat stable isotope analysis will continue to develop as a powerful tool towards understanding long-term human-environment interactions and sustainable practices.

Chapter 5

Conclusions: Mangareva, the Marquesas, and Tikopia in Comparative Perspective

This dissertation has demonstrated variation in Pacific rat δ^{13}C and δ^{15}N values through time across three separate island socio-ecosystems. By placing these three island case studies in comparative perspective, patterns emerge which provide insight into past human subsistence systems and anthropogenic landscape transformation. Figure 5.1 presents mean Pacific rat bone collagen δ^{13}C and δ^{15}N values through time for all three island case studies. It is tempting to make direct comparisons of C and N stable isotope ratios between these three island groups, however various factors including island latitude, environment, rainfall, foodweb dynamics, and prehistoric human activity can create region-specific variation in δ^{13}C and δ^{15}N values which inhibit the effectiveness of external absolute value comparisons. What can be more easily compared, however, are the overall trends in Pacific rat stable isotope ratios at each site, and what these tell us about island socio-ecosystem dynamics.

All rat bones analyzed in this dissertation were recovered from archaeological contexts, primarily habitation sites. The exceptions are rats from the Onemea site (Mangareva), which was an intensively used hunting camp in early Mangarevan prehistory, and from the late Hane specimens. The Hane dune site appears to have transitioned from a habitation site to a ceremonial, funerary site towards the end of its occupation. The rats from all three prehistoric phases on Tikopia, as well as the two non-habitation contexts, contain some of the most negative δ^{13}C values and fall in the lower range of δ^{15}N values, suggesting a more terrestrially-focused diet. The high δ^{15}N and less negative δ^{13}C values of rats recovered from Mangarevan and Marquesan habitation contexts indicate significant inputs of marine proteins. Rats would not have been able to acquire marine resources on their own, and thus it appears these rats were receiving a large portion of their dietary protein intake in the form of human meal scraps. This further supports the notion that changes to rat diet at habitation sites through time should reflect transformations in human subsistence practices.

Pacific rat δ^{13}C values exhibit wide variation, becoming either less negative (Mangareva) or more negative (Tikopia, Hane) through time. In the case of Mangareva, a rich lagoon environment with an exceedingly depauperate terrestrial landscape, people (and rats) maintained a strong reliance on marine resources, even into late prehistory. These results align with previous interpretations by Field et al. (2009) from the Fiji Islands, which suggested that smaller islands with limited agricultural productivity would retain more marine-focused diets into late prehistory compared to larger islands even within the same archipelago. Intensified agricultural production may indeed have been the preferred outcome in such scenarios when possible, according to linguistic evidence and ethnographic accounts which point to the importance ascribed to staple crops in everyday meals relative to other foods (Kirch and Green 2001:144). In contrast, rat bones recovered from the Hane dune site in the much larger Marquesas Archipelago show more negative δ^{13}C values over time. This change suggests an increasing reliance on the intensified breadfruit arboriculture and pig husbandry regimes which continued into the historic phase. Despite Tikopia's small size, the island's relatively large zones of arable land and geologically young, nutrient-rich soils supported an intensive multi-story orchard gardening system for several centuries. Tikopia was also able to support pig husbandry for an uncharacteristically long duration compared to other islands of its size.
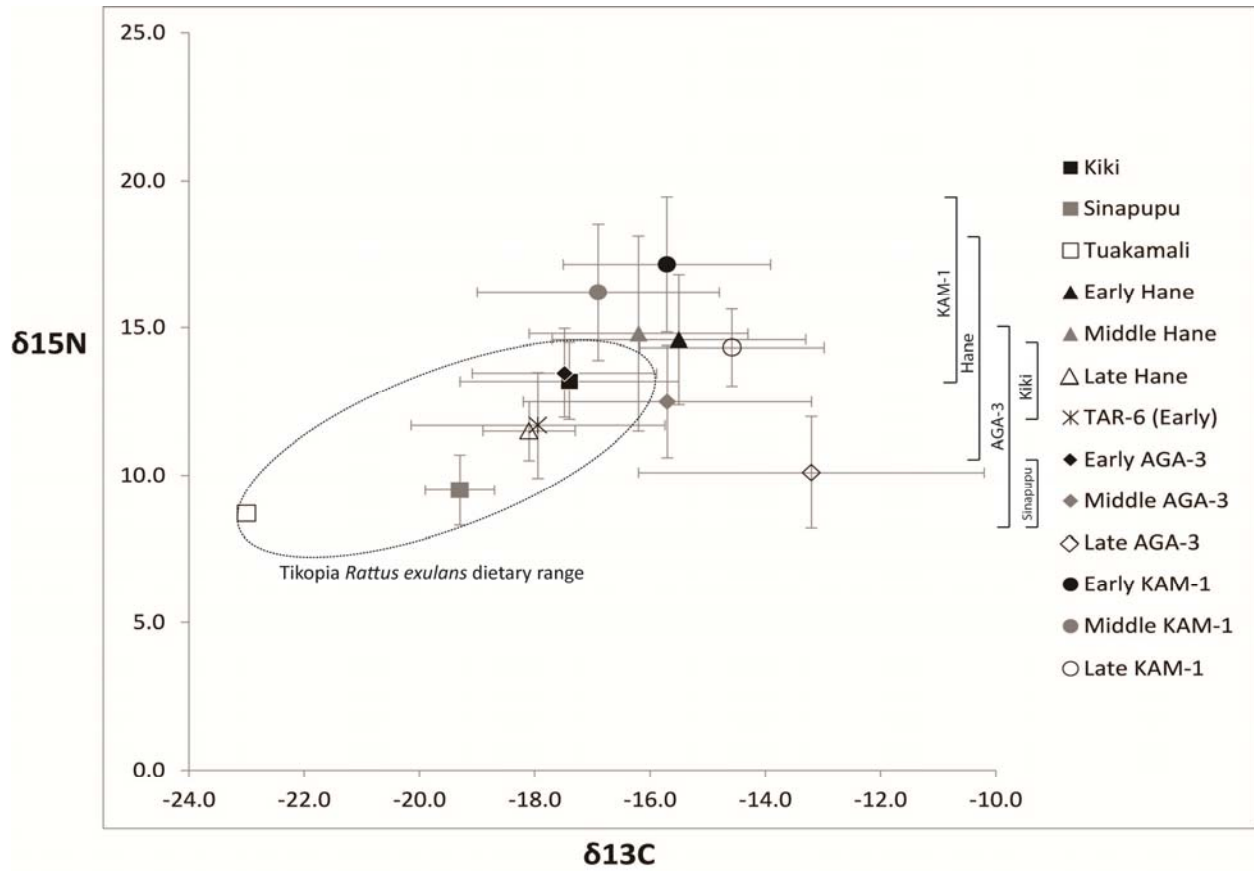
Figure 5.1: Mean (+1SD) *Rattus exulans* bone collagen δ^{13}C and δ^{15}N values for the Kiki, Sinapupu, and Tuakamali Phases and for early, middle, and late Mangareva and Marquesas sites, with bracketed ranges for δ^{15}N values at each site.

One consistent trend seen across all three island systems is a decline in δ^{15}N values through time by as much as 7.5‰ (a value equivalent to roughly 2 trophic levels; Bocherens and Drucker 2003; Minagawa and Wada 1984). Several possible explanations for this widespread ^{15}N depletion on Polynesian islands have been posited in this dissertation. Potential influencing factors include resource depression, avifaunal extinctions and decreasing seabird guano inputs to terrestrial systems, cessation of fire use as an agricultural strategy, and human dietary change (increasing investment in terrestrial resources coupled with declining high trophic level marine fauna). These factors apparently had varying degrees of impact on each system, though what is most remarkable is the difference in time scales over which ^{15}N depletion took place. On Mangareva, this process took place over the course of roughly 600 years, from AD 1200-1800 (see Kirch et al. 2015). Similarly, the prehistoric cultural sequence at the Hane dune site spans a little over 600 years, from AD 900 to the 1500s (Conte and Molle 2014). In contrast, an equivalent decline in δ^{15}N values on Tikopia took place through the Kiki and Sinapupu Phases, a span of roughly 1900 years. Notably, δ^{15}N values remain relatively consistent throughout the Kiki Phase which in itself is approximately 650 years long (see Kirch and Yen 1982 and forthcoming publication by Kirch and Swift).

Resource depression is a well-documented phenomenon in all three island systems after human arrival, whether in the form of avifaunal extinctions (Anderson et al. 1994; Steadman and Justice 1998; Steadman and Kirch 1990; Worthy and Tennyson 2004), soil nutrient depletion

(Kirch et al. 2015), or declining marine mollusk size (an indication of pressure on marine resources; Kirch and Yen 1982). It appears likely that resource stress, the one constant process across all three island case studies, is responsible for such dramatic declines in Pacific rat $\delta^{15}N$ values and changes to island baseline ^{15}N enrichment. Allen and Craig (2009) found evidence for similar stress on Aitutaki (Cook Islands) in changing stable isotope ratios of domestic pig populations over time: Later pigs had a more restricted diet as well as overall lower bone collagen $\delta^{15}N$ values. If, as this dissertation and other studies suggest, ^{15}N depletion does correlate with island resource depression, then the consistent range of $\delta^{15}N$ values in Pacific rat bone collagen throughout the Kiki Phase on Tikopia speaks to a long history of island socio-ecosystem sustainability. Further, these results suggest that such mechanisms for long-term sustainability were in place long before the Tuakamali (Polynesian) Phase.

Future Directions for Stable Isotope Studies of the Pacific Rat

The decline in Pacific rat bone collagen $\delta^{15}N$ values over time appears to be at least partially related to resource depression, diminishing avifaunal populations, and—as a result—island-wide ^{15}N depletion. However, the degree to which these processes drove changes to baseline N stable isotope ratios is uncertain. The incorporation of other stable isotopic data, such as analyzing archaeologically-recovered specimens of short-lived plant species for C and N stable isotope ratios, could provide a second line of evidence for changing island baseline $\delta^{15}N$. As archaeological plant specimens from Polynesian archaeological sites would likely come in the form of charcoal, this research would also require further investigation into the impacts of carbonization on $\delta^{15}N$ values of Polynesian flora (see Bogaard et al. 2007; DeNiro and Hastorf 1985; Vaiglova et al. 2014).

Modern ecological studies have provided new insights into Pacific rat diet and feeding behavior, however they represent imperfect analogs to prehistoric Pacific rat diet. Modern rats are generally recovered from 'natural' habitats, located away from human households. Research comparing the diets of rats recovered away from villages versus those found in households would provide an indication of how human presence and new food sources impact rat diet. In addition, most ecological studies employ gut content or stable isotope analysis of high-turnover tissue such as hair, blood, muscle, and liver. Future research incorporating these modern tissues with bone collagen would provide long-term resolution of rat diet throughout its entire lifespan, as well as build new connections between archaeological bone collagen and the sample substrates frequently employed in contemporary ecological studies.

Comparative analysis of islands as model systems provides a fruitful avenue for isolating the mechanisms that contribute to long-term island socio-ecosystem sustainability. A number of researchers have contributed to the collection of floral and faunal $\delta^{13}C$ and $\delta^{15}N$ values specific to the Oceanic region (e.g., Allen and Craig 2009; Beavan Athfield et al. 2008; Field et al. 2009; Jones and Quinn 2009; Kinaston et al. 2014; Richards et al. 2009; Storey et al. 2010; Yoshinaga et al. 1991). However, region-specific differences in island ecology inhibit direct comparisons of stable isotope ratios from multiple islands. Processes such as fertilization, fire ecology, and species extinctions and extirpations can have significant impacts on $\delta^{13}C$ and $\delta^{15}N$ values across both space and time. Such changes to island baseline stable isotope ratios carry implications both for the study of rats as paleoecological proxies and for stable isotopic analyses of archaeological human remains from Pacific contexts. The results of this dissertation suggest that not only is it necessary to establish a highly localized collection of baseline $\delta^{13}C$ and $\delta^{15}N$ values for potential

food sources, but to provide a temporal calibration for these values as well. Further collection and analysis of floral and faunal specimens tied to particular spatiotemporal contexts will continue to generate the baseline stable isotope data necessary for cross-regional comparisons.

While this research has revealed great potential for the Pacific rat to serve as a proxy for nutrient flows in island socio-ecosystems, disentangling the myriad influences on rat stable isotope ratios requires multiple additional lines of archaeological and paleoecological evidence. Pacific rat dietary changes are tied to changing Polynesian subsistence systems, as rats recovered from household contexts appear to reflect the range of resources available to past human inhabitants. As a short-lived species with a limited home range, rat stable isotope ratios (δ^{15}N values in particular) can additionally serve as a barometer for local ecosystem change and resource depression. In many regions of the Pacific, it is difficult or inappropriate to destructively analyze human remains. Further, stable isotope analysis of humans and Pacific rats lend different insights into patterns of prehistoric human food consumption: stable isotope analysis of human populations provides long-term *dietary* data tied to particular *individuals*, while stable isotope analysis of Pacific rat populations provides long-term *subsistence* data tied to particular *sites*. The Pacific rat is commonly recovered in abundance from Polynesian archaeological sites. Stable isotope analysis of this small commensal species provides a new, low-impact method for reconstructing past Polynesian subsistence and paleoenvironments.

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