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**STABLE CARBON AND NITROGEN ISOTOPE ANALYSIS ON DIETARY
RESILIENCE THROUGH TIME ON THE ANDEAN ALTIPLANO**

A Dissertation in
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by
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ABSTRACT

The South American Andes is one of the last places on Earth where early humans permanently occupy. Despite the semi-arid, harsh, high-altitude environment, contemporary Indigenous communities like the Aymara and Quechua continue to thrive, having developed genetic adaptations and cultural adaptations to combat hypobaric hypoxia, otherwise known as high altitude sickness. The Andean Altiplano is also home to many domesticated resources that include a wide variety of potatoes, quinoa, and camelids like alpacas and llamas. While many anthropological and archaeological narratives convey the significance of big game hunting, and therefore meat-heavy diets, this dissertation reveals that plant foods like geophytes played an important role in early human diets and early domestication of plant foods on the Andean Altiplano.

I ask broadly: **how does food shape cultural identity?** Through the archaeometric use to look at stable isotopes, we are able to investigate many dietary patterns through time of different ancient populations ranging from the Archaic Period (9–3.5 ka BP) to the Post Tiwanaku Period (0.75–0.38ka BP). This dissertation uses stable carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotopes to look at ancient diets on the Andean Altiplano and how diets may change over time. More specifically, this dissertation looks at Archaic Period (9–3.5 ka BP) early forager communities before the advent of agriculture, the Formative Period (3.5–1.5ka BP) and the onset of early domestication and agropastoral practices, the Tiwanaku Period (1.5–0.75ka BP) population where diet diversity is at its highest, and the Post Tiwanaku Period, or Late Intermediate Period (0.75–0.38ka BP) dispersed communities after the decline of the Tiwanaku state.

This dissertation primarily focuses on two archaeological sites, Soro Mik'aya Patjxa and Wilamaya Patjxa, during the Archaic Period where humans permanently occupied the Andean highlands. While the first chapter focuses primarily on early forager diets before the advent of agriculture, the second chapter zooms into early childhood diets of these Archaic Period individuals where stable nitrogen isotopes are used to indicate breastfeeding and weaning times. The third chapter zooms out to observe

dietary changes over time in conjunction with lake level changes of Lake Titicaca as a proxy for precipitation on the Andean Altiplano. Understanding early highland forager diets is crucial to also better understanding of how these early humans interacted with their environment and its resources.

Results from this research suggest that despite the harsh high-altitude environment and variable paleoclimate, ancient diet remains relatively the same. The first chapter reveals that early foragers in the high Andes were mostly eating C3 plants like wild potatoes despite the ongoing, traditional narrative of hunting and eating mostly meat. The second chapter investigates the early childhood diets of these hunter-gatherers, speculating that a good contender for possible weaning foods were cooked and mashed wild tubers. The third chapter consists of Archaic Period individuals I have physically and chemically processed along with meta-data drawn from other isotopic studies of different cultural periods on the Altiplano that also reveal the resiliency of tubers and potatoes through chronological time as well as a shift towards meat-dominant diet despite variable lake level changes. The results from this dissertation project suggest a strong and resilient relationship between tubers and camelids and ancient people across time.

TABLE OF CONTENTS

LIST OF FIGURES	vii
LIST OF TABLES	viii
ACKNOWLEDGEMENTS	ix
Chapter 1 INTRODUCTION.....	1
Introduction	1
Modes of Production	5
Human Behavioral Ecology in Anthropology.....	8
Prey Choice Model (PCM).....	9
Grandmother Hypothesis.....	11
Significance.....	12
Human Behavioral Ecological Frameworks in the South American Andean Altiplano ..	13
Previous Archaeological Research on the Archaic Period Sites: Soro Mik'aya Patjxa and Wilamaya Patjxa	15
Stable Carbon and Nitrogen Isotopes Analyses	19
Research Questions and Predictions	21
Chapter 2 STABLE ISOTOPE CHEMISTRY REVEALS PLANT-DOMINANT DIET AMONG EARLY FORAGERS ON THE ANDEAN ALTIPLANO, 9.0-6.5 CAL. KA.....	25
Abstract	25
Introduction.....	25
Materials and Methods.....	29
Stable Isotope Analysis of Human Bone.....	30
Zooarchaeological Analysis	32
Paleoethnobotanical Analysis.....	33
Results	34
Discussion	45
Chapter 3 STABLE ISOTOPE ANALYSIS OF DENTAL SERIAL SECTIONS SUGGESTS DELAYED WEANING AMONG EARLY FORAGERS OF THE ANDEAN ALTIPLANO, 9.0-6.5 KA.....	49
Abstract	49
Introduction.....	49
Materials and Methods.....	53
Serial Sectioning and Isotopic Characterization Methods.....	54
Age-of-weaning Estimation	55
Calculating Growth Rate (GRT) Estimation	56
Calculating Average Distance to CEJ (ADC)	56

Calculating Age of Individual Per Tooth Section	57
Weaning Age Estimate	57
Error Analysis	58
Results	58
Discussion	62
Chapter 4 THE EFFECTS OF CLIMATE AND CULTURE ON ANDEAN ALTIPLANO	
DIETS, 9-1 KA	65
Abstract	65
Introduction	66
Materials and Methods	71
Samples and Data	72
Stable Isotope Analysis	73
Lake Levels Analysis	76
Lake Levels vs. Stable Isotopes Analysis	76
Results	77
Archaic Period (9.0-3.5 ka)	77
Formative Period (3.5-1.5 ka)	78
Tiwanaku Period (1.5-0.75 ka)	79
Post Tiwanaku Period (0.75-0.38 ka)	80
Lake Levels vs. Diet Results	81
Discussion	84
Archaic Period (9.0-3.5 ka)	85
Formative Period (3.5-1.5 ka)	85
Tiwanaku Period (1.5-0.75 ka)	86
Post Tiwanaku Period (0.75-0.38 ka)	87
Overall Dietary Changes Through Time in the Andean Altiplano	87
Chapter 5 OVERALL CONCLUSIONS	90
References Cited	98
Appendix A Supplementary Materials for Chapter 2	133
Appendix B Supplementary Materials for Chapter 3	133
Appendix C Supplementary Materials for Chapter 4	144

LIST OF FIGURES

Figure 1.0: A map of the Lake Titicaca basin.....	3
Figure 1.1: A food web graph that shows $\delta^{13}\text{C}$ on the x-axis and $\delta^{15}\text{N}$ on the y-axis.....	6
Figure 2.0: Carbon and nitrogen plots	35
Figure 2.1: Bayesian mixing model results.....	41
Figure 2.2: Results of paleoethnobotanical analysis	44
Figure 3.0: Diagram of sectioned first adult molar	53
Figure 3.1: SMP/WMP individuals' serial sectioned first molars and their $\delta^{15}\text{N}$ values.....	61
Figure 3.2: A comparison of breastfeeding and weaning times	62
Figure 4.0: Diagrams and flowcharts of hypotheses and predictions	71
Figure 4.1: A map of the Andean Altiplano.....	72
Figure 4.2: A stable carbon and nitrogen isotope biplot with Archaic foragers	78
Figure 4.3: A stable carbon and nitrogen isotope biplot with Formative early agropastoralists	79
Figure 4.4: A stable carbon and nitrogen isotope biplot with Tiwanaku agropastoralists	80
Figure 4.5: A stable carbon and nitrogen isotope biplot with Post Tiwanaku agropastoralists	81
Figure 4.6: Lake level averages (x-axis) from Lake Wiñaymarka through time with stable nitrogen of each cultural periods' populations (y-axis)	83
Figure 4.7: Lake level averages (x-axis) from Lake Wiñaymarka through time with stable carbon of each cultural periods' populations (y-axis).....	84
Figure 4.8: Lake Titicaca lake levels across time	86

LIST OF TABLES

Table 1.0 : Cultural periods with associated subsistence strategy and time span in BP.	4
Table 2.0 : Summary statistics for stable isotopic control data.....	36
Table 2.1 : Human bone collagen isotopic results.	36
Table 2.2 : Inter-laboratory comparison of isotopic results.	39
Table 2.3 : Bayesian mixing model comparison.....	42
Table 2.4 : Carbonized macrobotanical materials.....	44
Table 3.0 : SMP/WMP individuals' age ranges, teeth section, and mean $\delta^{15}\text{N}$ values.....	60
Table 3.1 : SMP/WMP individuals' age ranges in comparison to other contemporary and archaeological case studies	61
Table 4.0 : A statistical summary of baseline food resources.....	73
Table 4.1 : A simplified table from Watson and Haas 2017.....	75
Table 4.2 : Lake Wiñaymarka lake levels through time	76

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Chapter 1

INTRODUCTION

Potatoes represent some of the world's earliest domesticated plants, and many varieties that were first utilized in the South American Andean Altiplano rather quickly began being cultivated globally (Beals 2019; Flores et al. 2003). Domesticated potatoes are the starchy tubers of the perennial nightshade *Solanum tuberosum*. The family and genus of potatoes represent some of the most crucial resources (wild and domesticated) for human economies and subsistence across the globe (Beals 2019; Flores et al. 2003). Tubers are a type of geophyte; the organ of plants that store energy underground such as bulbs, corms, and enlarged roots. Energy reserves of geophytes are mostly starchy carbohydrates composed in the form of dense concentrations of glucose, and are often the focus of intensified harvesting by humans (McGuire and Stevens 2017).

Although geophytes are dense in potential energy and nutrients, accessing their stored energy is another matter. By definition, geophytes develop underground, making them difficult to access compared to many other plant foods (Beals 2019; Bird and O'Connell 2006; McGuire and Stevens 2017). Moreover, many geophytes, including potatoes, have chemical adaptations that make consuming them without processing difficult. Some chemical defenses include high starch content and complex carbohydrates that are not easily digestible or toxic in their raw form (Yang et al. 2016). These chemical and physical properties thus require special handling strategies for organisms to access the potential energy.

The adoption of such specialized handling strategies has been proposed by many researchers to be a linchpin in new understandings of human evolution. For instance, paleoanthropologists and archaeologists have hypothesized that with novel environments of the early Pleistocene and attendant expansion of savanna habitats, new opportunities emerged for certain hominins to specialize in geophyte harvesting, possibly linked to the spread of early members of genus *Homo* out of Africa and through the mid-latitudes of Eurasia (O'Connell et al. 2004; Ragir 2000). Moreover, given that many geophytes require processes such as cooking or fermentation to modify, concentrate, and extract their energetic yield, a number of researchers have argued a central role for geophytes in the evolution of distinct features of human life histories, morphology, and associated patterns of caregiving and resource provisioning (Flores et al. 2003; O'Connell et al. 2004; Ragir 2000).

One of the first indicators of early tuber cooking may be associated with *H. erectus* and *H. ergaster* where paleoanthropologists have suggested the use of fire alongside potential digging tools (O'Connell et al. 2004; Wrangham et al. 1999). In fact, cooking is considered a unique and important biocultural trait that makes us human, defining the "cooking hypothesis" (Wrangham and Carmody 2010; Wrangham and Conklin-Brittain 2003; Wrangham et al. 1999). The cooking hypothesis states that the shift to cooked foods significantly shaped the ways in which humans developed evolutionarily. Cooking food also enhances our dietary and nutritive repertoire when compared to eating the same foods raw. Cooked foods are generally easier to digest when compared to their raw counterpart; this suggests that our bodies would require less energy to break down softer, cooked foods. While there are many studies that indicate the

importance of cooking and eating meat and fat that led to the evolution of larger brains in early *Homo*, I argue in this dissertation the significance of cooked geophytes, particularly tubers and potatoes, in human adaptations and evolution (Baltic and Boskovic 2015; Hardy et al. 2022; Ragir 2000; Wrangham and Conklin-Brittain 2003).

Many scholars hypothesize that hunting and grandmothers are also biocultural traits that shape the genus *Homo* (Isaac 1978; Washburn and Lancaster 1968). The key human behavior that ties together the grandmother hypothesis and the hunting hypothesis is cooperation and food sharing. The hunting hypothesis states that the traits for hunting developed through bipedalism and enhanced cognitive abilities that includes toolmaking and tool-use. However, the hunting hypothesis also implies social and behavioral changes that include cooperation, division of labor, and food sharing (Washburn and Lancaster 1968). For instance, many foraging communities hunt in cooperative groups, and if the hunt is successful, food is brought back to the camp to share with others. While the hunting hypothesis has a traditional perspective on the division of labor where men hunted and women gathered, ethnographic and archaeological studies reveal that women have played an important role in hunting activities (Bliege Bird et al. 2009; Haas et al. 2020; Isaac 1978; Washburn and Lancaster 1968). However, hunting large animals seems too unreliable to fuel our distinctive life histories.

Food security is particularly important to the reproductive success of women. As women approach the later stages of pregnancy, foraging or hunting can become difficult. This is where grandmothers become highly important in many foraging communities. The “grandmother hypothesis” states that postmenopausal women will help her daughter’s household with alloparenting, including foraging for food, which increases the

mother's reproductive success, leading to shorter interbirth intervals (Bird and O'Connell 2006; Hawkes et al. 1997, 2000; Hawkes 2003; O'Connell et al. 2004; Wrangham et al. 1999). In fact, a number of scholars have argued that geophyte harvesting is a better candidate for main subsistence than meat from hunting (Hawkes et al. 1997; Lee 2010; Woodburn 1968). An ethnographic example includes Hadza grandmothers digging up geophytes and tubers to provide food for not only the mother, but as a possible weaning food for their grandchildren too (Hawkes et al. 1997, 2000). A nutritional study also infer that cooked tubers were possible weaning foods, suggesting the potential for earlier weaning times, and thus, shorter interbirth intervals (Ugwu 2009). While it may be empirically difficult to establish quantitative evidence that supports the grandmother hypothesis, ethnographic work using historical demographic data and mathematical models reveals the adaptive nature of post-reproductive longevity in women (Hawkes 2020; Lahdenperä et al. 2004). This dissertation contributes to this ongoing empirical research on assessing the grandmother hypothesis in ancient populations by observing stable nitrogen isotopes of first molar serial sections to determine ancient individuals' age at maturity and breastfeeding and weaning times.

This dissertation is also about the resiliency and significance of Andean tubers, like potatoes, to the ancient diets with different types of subsistence economies like foraging, pastoralism, agriculture, and agropastoralism. There is a main focus on early forager diets on the Andean Altiplano, as it is important to observe which wild foods were being mostly consumed before the domestication process that brought about a wide variety of tuber domesticates. This research primarily uses stable carbon and nitrogen isotopes on ancient human bone and teeth for dietary reconstruction paired with

paleoenvironmental and paleoclimate data to infer how these drivers possibly affected ancient diet.

Generally, food and cuisine have the ability to connect and bring different individuals and communities together. Anthropologists and archaeologists have continued to study the nutritional importance and cultural significance of food in many parts of the world; more specifically in this dissertation, the nutritional and cultural importance of geophytes, like potatoes, on the Andean Altiplano. In particular, food processing, like cooking, is also important in that it can begin to shape the ways in which certain food products are later domesticated (Harris 2016; Hayden 2009; Wrangham and Conklin-Brittain 2003). How humans obtain and produce subsistence resources contributes to many anthropological discussions on decision-making, different subsistence strategies, mobility, sociocultural capital, and the overall way of life (Tucker 2024).

Modes of Production

Understanding the different modes of production, or subsistence economies, is crucial in developing questions about the processes of domestication through intensification and the cultural significance of specific staple food resources like geophytes. Some of these modes of production include foraging, pastoralism, agriculture, and mixed economies like agropastoralism. While this subsection defines and explains these different subsistence economies, there are no strict defining boundaries between each mode of production.

While all human societies tend to be structured around central base provisioning, foraging economies are generally characterized by relatively high residential mobility (Isaac 1978). Despite this high mobility, and what is often portrayed as relatively low environmental impact, many foraging communities heavily alter their landscapes in order to acquire staple resources (Bird et al. 2016). For instance, in the ancient Andes, foraging groups would cooperate and drive wild camelids into *chaccus*, or V-shaped game drives, that also double as corrals. Wild camelids staying within these corrals contribute fertilizer for plant species like geophytes or tubers, where ancient humans eventually harvest and intensify (Alvard and Kuznar 2001). Many anthropologists study foragers under the lens of human behavioral ecology and its frameworks like foraging theory and prey choice model that will be later discussed (Alvard 1998; Hames and Vickers 1982; Koster and Bird 2024; Madsen and Schmitt 1998; Svizzero 2016; Woodburn 1968).

Pastoralism, on the other hand, includes managing and consuming domesticated, herbivorous animals like cattle, camelids, and other ungulates (Capriles and Tripcevich 2016; Little 2015). Many pastoralists also have high residential mobility, similar to foragers, despite having to care for domesticated animals. In fact, pastoralists can be highly mobile because their material wealth, the domesticated herd animals, are also mobile. Oftentimes, these types of mobility are broken up into further categories such as pastoral nomadism, where mobility is all year round, or transhumant pastoralism, where mobility is typically seasonal, and spans across different geographic environments (Borgerhoff Mulder et al. 2010). For example, anthropologists have found that archaeological and ethnographic evidence of Andean transhumant pastoralists move their domesticated camelids up and down from the Andean highlands to the lowlands in

accordance with the changing wet and dry seasons (Capriles and Tripcevich 2016). In the Andean context, camelids, like alpacas and llamas, are crucial staple animal resources because not only do they contribute labor, wool, and meat, their dung also helps fertilize grazing lands where Andean pastoralists are also known to cultivate the abundance of tubers in higher altitudes (Webster 1973).

Farming economies are generally based on the maintenance, management, distribution, and consumption of domesticated resources (Rindos 2013). For well over a century, a significant amount of anthropological work has focused on the origins and spread of intensified farming, including mechanically enhanced agriculture. Much of this research suggests that processes of intensification in handling of food resources such as potatoes are fundamentally involved in shifts to (and between) modes of production such as foraging and farming (Greaves and Kramer 2014). Unlike foraging and pastoralism, farmers (especially agriculturalists) reduce residential mobility, remaining mostly sedentary in order to tend to domesticated resources, increasing incentives for accumulating material wealth (Rindos 2013). While agriculture is a broad, encompassing term, there are various types of agricultural practices. One such example that is familiar to many in the Western world is industrial agriculture where domesticated foods are mass produced and shipped globally (Harris and Fuller 2014). Popular archaeological studies on the origins of agriculture and domestication includes the Fertile Crescent in Western Asia and North Africa as well as the Andean Altiplano in South America where one of the most globally industrialized food crops are the hundreds of varieties of potatoes (Erickson 1988; Haas and Viviano Llave 2015; Lev-Yadun et al. 2000).

Agropastoralism is simply defined as a combination of agricultural practices alongside pastoral practices (Lane 2006). The significant difference between agropastoralism and other subsistence strategies, like foraging, is that agropastoralists material wealth is more sedentary, resulting in lower mobility when compared to foraging communities where material wealth is constantly moving. Highly researched and studied ethnographic cases of agropastoralism include the Indigenous Quechua and Aymara in the south central Andes in South America where they grow and manage several domesticated species like an abundant variety of potatoes and camelids (Erickson 1988; Lane 2006; Marsh 2016).

There are no strictly defined boundaries between these subsistence strategies; people often use a combination of these modes of production to produce, maintain, and consume foods, frequently called “mixed economies” (Tucker 2024). A combination of these different types of subsistence strategies mentioned above can also pave the way for domestication processes through intensification of various food resources (Morgan 2015). Human communities have continued to adapt to environmental and climatic changes by changing and shifting between wild and domesticated foods (Tucker 2024).

Human Behavioral Ecology in Anthropology

Many anthropological, archaeological, and ecological studies of the domestication of foods and the origins and spread of agriculture focus on understanding processes that may shape variability in modes of subsistence, especially social and ecological contexts that influence subsistence intensification and transitions from foraging to farming

(Morgan 2015). Much of the influential work has been based in contemporary Indigenous communities, investigating resource use through the lens of human behavioral ecological (HBE). Archaeological applications have utilized HBE frameworks of economic decision-making to generate a wide array of well warranted inferences about ancient subsistence patterns. One of these HBE frameworks includes foraging theory.

Foraging theory was developed under the theoretical umbrella of evolutionary ecology to generate hypotheses about decision-making strategies involved in utilizing landscapes and acquiring, handling, and transporting material resources (Koster and Bird 2024). It has been used to frame a wide range of questions about resource use, from decision-making in Indigenous communities who rely on foraging as the main mode of subsistence (e.g. Bird et al. 2009; Smith et al. 1983), to strategies of mineral prospecting and mobility among miners in late 19th century Colorado (Glover 2008), to acquisition patterns among car thieves (Vandeviver et al. 2023).

Prey Choice Model (PCM)

Foraging theory also has a long tradition in archaeological and ethnoarchaeological settings, especially in applications of models such as the prey choice model (PCM) (Koster and Bird 2024). The PCM is ultimately about decision-making with these basic assumptions: goal, decision, constraints, and currency (Stephens and Krebs 1986). The assumed goal is that the agent will maximize their overall return rate—where the assumed currency is energy—with the assumed decision being to handle on-encounter or to continue the search. An assumed constraint to this model is the Poisson

process where an encounter with a given resource does not indicate that there are more or less of those resources nearby—it assumes the agent making decisions on handling that resource on encounter, and that encounter does not change the search.

If these assumptions from the PCM hold, then we are able to quantitatively calculate this model where e is mean energy yield per prey type, h is mean pursuit and processing time per type, E is the mean energy yield of all prey types, T is total time required to search and handle ($s+h$) all types:

$$e/h > E/T_{s+h}$$

Conversely, if $e/h < E/T_{s+h}$, then it is predicted that the agent will pass over the prey type to continue searching for other prey types. However, archaeologists use the PCM to assume that larger sized prey items like deer will have high post encounter return rates (e/h), but this is usually never actually measured (Bird et al. 2009; Morin et al. 2022). For instance, archaeologists that use this model assume that hunters will always go after highly ranked prey like deer or other large mammals when encountered. However, many ethnographic and ethnoarchaeological accounts reveal that foraged plant foods consist of the majority of foraging communities' diets (Koster and Bird 2024; Lee 2010; Madsen and Schmitt 1998). The PCM also assumes that the environment or climate is consistent or constantly stable, which is not always the case. For example, while archaeologists using this model may suggest that early foragers relied on large terrestrial mammals like camelids on the Andean Altiplano, bioarchaeological and stable isotopic evidence suggests that plant foods, in particular tubers, were the primary food resource as many of the tuber varieties in the high altitude are highly resilient to changing environments and climates (Chen et al. 2024; Flores et al. 2003; Watson and Haas 2017). While models like

the PCM may be useful in predicting ancient decision-making and foodways, it may draw inaccurate conclusions. This dissertation uses HBE frameworks and models like the PCM paired with quantitative methods like stable isotopes analysis to form more accurate conclusions on ancient diets.

Grandmother Hypothesis

How humans interact and share food between or within communities is significant in that food security is also considered a prerequisite for health (Kaplan et al. 1985; Rankoana 2017). The grandmother hypothesis, framed within evolutionary ecology, is a good example of how researchers have approached questions about trade-offs that shape variability in how we, as humans, provide consistent food for offspring through divisions of childcare and alloparenting (Hawkes 2003; Hawkes et al. 2000; O'Connell et al. 2004). Human females tend to live well beyond their reproductive years. Many anthropologists argue that this longer lifespan contributes to reproductive success through alloparenting and providing additional resources for their daughters and their daughter's offspring (Hawkes 2003; Hawkes et al. 2000; O'Connell et al. 2004). One example of the grandmother hypothesis is ethnographic evidence of lactating Hadza mothers providing one source of food for their offspring through breastmilk. In turn, Hadza grandmothers will actively dig up deeply rooted tubers to provide another source of food for her daughter and grandchildren—possibly weaning food—that may also increase nutritional properties and diet diversity, ensuring infant survivability, thus also resulting in shorter interbirth intervals for the mother (Hawkes 2003; Ugwu 2009).

The grandmother hypothesis has been closely observed in historical and contemporary contexts that generally reveal that maternal grandmothers play crucial roles in the survival rates of children (Sear and Mace 2015). Many bioarchaeological assemblages of ancient foragers have minimal elderly adults potentially due to poor preservation (Hawkes and Blurton Jones 2005). While this hypothesis is difficult to test in an archaeological context, this dissertation uses quantitative methods like stable nitrogen isotopes to observe early or late weaning times in ancient Andean forager societies from adult first molars.

Significance

Theoretical frameworks from HBE, like the ones mentioned above, allows archaeologists to make predictions on ancient human behavior in regards to how ancient communities were interacting with their environment (Bird and O'Connell 2006; Byers and Ugan 2005; Madsen and Schmitt 1998; Morin et al. 2022). Theoretical frameworks and their respective models provide explicit assumptions that are useful for generating hypotheses with testable predictions. Many models, like the PCM, produce broad potential, but are precise enough to show where the assumptions are violated by specific, contextualized, observations. For example, an archaeological case study that focused on specialized late Pleistocene megafauna hunting across North America used PCM in conjunction with quantitative zooarchaeological methods to reveal that late Pleistocene hunters were hunting small game as well (Byers and Ugan 2005). Another archaeological example includes investigations in northwestern Utah at Lakeside Cave where

excavations and analysis of human coprolite reveal heavy investment in grasshopper consumption rather than deer hunting, going against foraging theory and the PCM (Madsen and Schmitt 1998). This dissertation aims to use HBE frameworks like the ones mentioned above in conjunction with quantitative methods like using stable isotopes to evaluate ancient diet, cultural adaptations to the high altitude in terms of weaning, and the resiliency of specific staple food crops on the Andean Altiplano.

Human Behavioral Ecological Frameworks in the South American Andean Altiplano

While there is an abundance of archaeological work using HBE frameworks in many parts of the Western world, these perspectives are not yet frequently considered in ancient South American Andean highland foragers despite it being a center for domestication of many food products that are used and consumed around the world today (Capriles et al. 2016; Capriles and Albarracin-Jordan 2013; Haas et al. 2017, 2020; Haas and Viviano Llave 2015; Rademaker et al. 2014). Some archaeological investigations of ancient Andean foragers include how pre-Hispanic people come to eventually permanently occupy the highlands (Capriles et al. 2016; Haas et al. 2017; Rademaker et al. 2014). Other archaeological excavations also focus on the emergence of agropastoralism in the Lake Titicaca basin at sites like Chiripa (Bruno and Whitehead 2003; Capriles 2018).

However, the Andean highlands is best known for the geographically wide-spread socioeconomic complexity of the Inca empire before Spanish colonization, where agropastoralism was their main mode of subsistence (Table 1.0) (Delaere and Capriles

2020). Lake Titicaca, best known for being one of the highest freshwater lakes at ~3,800 meters above sea level, is also best known for being the center of domestication of many popular and commonly consumed or used food resources today like potatoes, quinoa, and camelids like alpacas and llamas (Kuznar 1989, 1993; Martínez et al. 2015; Pearsall 2008).

Cultural Period	Subsistence Strategy	Time (ka)
Archaic	foraging	~9.0–3.5ka
Formative	early agropastoralism	3.5–1.5ka
Tiwanaku	agropastoralism	1.5–0.75ka
Post Tiwanaku/Late Intermediate Period	agropastoralism	0.75–0.38ka
Inca	agropastoralism	1476–1534

Table 1.0. Cultural periods with associated subsistence strategy and time span in BP.

Despite these popularly consumed domesticated foods, not much is known about the exact domestication timeline of these food resources. However, there are some scholarly discussions on the initial domestication processes in the Andean highlands that use ecological frameworks (Kuznar 1989, 1993; Martínez et al. 2015; Pearsall 2008). Most of the ecological and anthropological literature on the initial processes of domestication through intensification highlights the initial domestication of camelids using HBE frameworks paired with results from zooarchaeological analysis (Kuznar 1989, 1993; Mengoni Goñalons 2008; Yacobaccio 2004). While some human behavioral ecological frameworks like foraging theory and PCM highlights the economic importance of camelid domestication, this dissertation research suggests the significance of the initial domestication of plant foods such as geophytes (Chen et al. 2024).

Previous Archaeological Research on the Archaic Period Sites: Soro Mik'aya Patjxa and Wilamaya Patjxa

Although most Latin American archaeology focuses on the origins of agropastoralism in the Andes with an even more narrow focus on initial state formations, like Tiwanaku or Wari, research and discussions on the peopling of the Andes and its ancient early hunter-gatherers is growing (Capriles et al. 2016; Haas et al. 2017; Haas and Viviano Llave 2015; Rademaker et al. 2014). Again, some of the staple crops that were domesticated on the Altiplano with dietary and cultural significance include geophytes, chenopods, and camelids. Studying these particular highland food resources and ancient forager diets on the Altiplano through the lens of HBE allows archaeologists to speculate and predict what these early human adaptive behaviors were like in harsh environments like the high altitude.

Figure 1.0. A map of the Lake Titicaca basin with the purple circle representing the location of Archaic Period sites Soro Mik'aya Patjxa and Wilamaya Patjxa.



Archaeological satellite and pedestrian surveys reveal two Archaic Period sites named Soro Mik'aya Patjxa and Wilamaya Patjxa in the Lake Titicaca basin as shown and labeled in Figure 1.0. Recent archaeological excavations reveal a total of 24 human burials from Soro Mik'aya Patjxa ($n = 15$) and Wilamaya Patjxa ($n = 9$) (Haas et al. 2017, 2020). Stable oxygen isotopes suggest that individuals from Soro Mik'aya Patjxa were permanently occupying the highlands rather than moving back and forth between the lowlands and highlands (Haas et al. 2017). Further research using proteomic analysis of teeth enamel paired with bioarchaeological techniques reveal that men and women both occupied the highlands, and that archaeological excavations of numerous projectile points and lithic scrapers were not just associated with male burials, but also female burials (Haas et al. 2020). While it is clear through excavations, paleoethnobotanical, zooarchaeological and bioarchaeological analysis that ancient foragers were hunting wild large terrestrial mammals, like Andean deer, guanaco, and vicuña, and foraging wild chenopods and tubers, it is unclear which of these important food resources were first intensified (Haas et al. 2017, 2020; Haas and Viviano Llave 2015; Watson and Haas 2017). There are a few HBE frameworks that are used to make these predictions on which food resource may have been initially intensified like costly signaling theory and the domestication mutualism model (Aldenderfer 2006; Kuznar 1989, 1993).

Costly signaling is a framework within behavioral ecology in which organisms make costly, or damaging, signals to their fitness that is broadcasted to the population where this costly signal ultimately shows off quality, desirable, but costly, traits. An evolutionary example of costly signaling in a biological setting would be the sexual dimorphism of peacocks. Male peacocks are typically decorated in extravagant or ornate,

colorful feathers that signals to female peacocks their good health. While this is an honest signal of good health and desirable biological traits, it is also considered costly in that these colorful feathers make male peacocks easy targets for predators. Costly signaling can also be seen in human behavior (Aldenderfer 2006; Bliege Bird et al. 2001; Bliege Bird and Smith 2005). For example, ethnographic research on contemporary marine foragers, the Meriam, found that spearfishing and turtle hunting were costly signals based on using other ecological frameworks like the PCM (Bliege Bird et al. 2001). In an archaeological setting, particularly in the Andes, scholars use costly signaling theory paired with knowledge of camelid ecology to make inferences about the initial processes of early domestication (Aldenderfer 2006). For instance, early pre-Hispanic foragers were assumed to have been intensifying camelids on the Altiplano. Several archaeological evidence of high camelid management and consumption include zooarchaeological assemblages from various early sites like Soro Mik'aya Patjxa and Wilamaya Patjxa as well as excavations in *chaccus*, or game drive traps that were purposefully built to trap wild camelids (Haas et al. 2020; Haas and Viviano Llave 2015). Hunting large game is an honest signal of physical strength, endurance, and high fitness. Conversely, managing and caring for a herd of camelids can be considered a costly signal because it costs time and other resources. However, the long-term benefits of herding generally outweigh the short-term benefits of hunting due to higher food security if herding (Aldenderfer 2006).

Consequently, costly signaling theory in an Andean context as stated above also delves neatly into another ecological framework called domestication mutualism. Domestication mutualism is similar to costly signaling theory in the Andean literature in that it also highlights the importance of the initial domestication of camelids before other

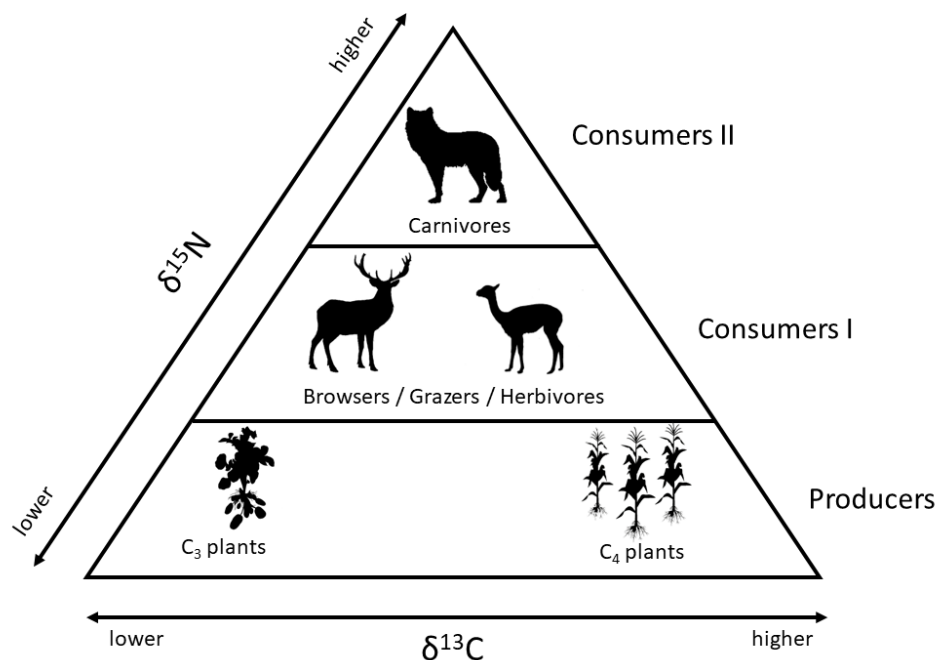
food resources (Alvard and Kuznar 2001). Although the initial domestication of camelids is stated implicitly, wild plant resources like chenopods or tubers are also highlighted in the domestication mutualism model (Kuznar 1993). The domestication mutualism model suggests a symbiotic relationship between camelids and plants like wild quinoa. Camelids are considered foregut fermenters, a digestive process in which foods will be regurgitated and chewed again, allowing the hard outer shell of wild quinoa seeds to be removed and disintegrated. This allows wild quinoa to be easily and quickly replanted in well fertilized soils of these early camelid corrals where ancient humans will forage and consume wild quinoa with ease (Kuznar 1993). While the domestication mutualism model implies the initial domestication of camelids by taking into consideration early corrals, plant foods, like wild chenopods in this case, are also highlighted in the discussion. Although there is a strong bias of early camelid consumption and intensification due to better preservation, plant foods like quinoa and potatoes must also be considered in early domestication processes on the Andean Altiplano.

While these HBE frameworks and perspectives, like costly signaling theory, PCM, and domestication mutualism models, can help in predicting which wild foods were domesticated first, there is a strong archaeological preservation bias towards camelids. However, empirical, quantitative methods, like using stable isotopes, paired with these ecological frameworks can provide further discussion on what wild food resources were initially intensified before the domestication process from early archaeological sites like Soro Mik'aya Patjxa and Wilamaya Patjxa.

Stable Carbon and Nitrogen Isotopes Analyses

Archaeometric methods such as stable carbon and nitrogen isotopes analyses can be used to recreate past individual diets (Schoeninger 2014). Stable carbon isotope ($\delta^{13}\text{C}$) analysis reveals the different plant photosynthetic pathways— C_3 , C_4 , or CAM—where C_3 plants typically range between -20‰ to -37‰ , C_4 plants range between -20‰ to -9‰ , and where CAM plants have wider ranges that encompass both C_3 and C_4 plant $\delta^{13}\text{C}$ values (Kohn 2010; Rounick and Winterbourn 1986). Stable nitrogen isotope ($\delta^{15}\text{N}$) analysis reveals the different trophic levels of each specimen where higher $\delta^{15}\text{N}$ suggests a more carnivorous diet and lower $\delta^{15}\text{N}$ suggests a more herbivorous diet (O'Connell et al. 2012). Stable carbon and nitrogen isotopes are paired analyses that can suggest what an individual was consuming where $\delta^{13}\text{C}$ is on the x-axis and $\delta^{15}\text{N}$ is on the y-axis (Figure 1.1).

Figure 1.1. A food web graph that shows $\delta^{13}\text{C}$ on the x-axis and $\delta^{15}\text{N}$ on the y-axis with the lower tier representing producers, middle tier representing herbivores, and the top tier, or top of the food chain, as carnivores.



While many peer-reviewed, published articles use stable carbon and nitrogen isotopes to reconstruct the ancient diet of human individuals, this dissertation includes a stable carbon and nitrogen isotope compilation of possible wild and domesticated food resources that are indigenous to the high Andes. For instance, many popular C_3 plants in the Andean Altiplano include tubers and chenopods while C_4 plants like maize were traded in from where they were cultivated in the lowlands. Other popular domesticates that are indigenous to the Andes also include camelids like alpacas and llamas. This compiled baseline dataset combined with isotope values from human bone collagen clearly illustrates what past Andean human diets were like where the phrase “you are what you eat” is applicable.

Research Questions and Predictions

This dissertation takes a closer look at the ancient food economies of highland foragers and how diet diversity may change and transform over time by using archaeometric stable isotopes analysis. While this research mostly focuses on pre-Hispanic forager diets of the Andean Altiplano, there is also a diachronic analysis of ancient diets from the Archaic Period to the Late Intermediate Period or Post Tiwanaku Period (see Table 1.0). This study encompasses food and cuisine in the Andes by how ancient pre-Hispanic communities interact with their given environment and how those interactions with food change through time using human behavioral ecological frameworks and models. More broadly, I ask: **how does food shape cultural identity?**

Research on diet diversity of foragers are oftentimes conducted on contemporary ethnographic cases that use HBE frameworks like foraging theory, grandmother hypothesis, PCM, and costly signaling theory (Alvard 1998; Hames and Vickers 1982; Hawkes and Blurton Jones 2005; Morin et al. 2022; O’Connell et al. 2004; Smith et al. 1983). However, it is dangerous to correlate contemporary foragers with ancient hunter-gatherers given that the environment, climate, and culture were different in the past compared to the present. These HBE frameworks can still be used to develop working models, theories, or hypotheses and predictions on how ancient human populations interacted with their environment—especially in harsh semi-arid environments like the Andean Altiplano where food resources were seemingly scarce (Mark S. Aldenderfer 2006; Alvard and Kuznar 2001; Kuznar 1989, 1993; Pearsall 2008, 2014).

One of the specific questions I ask in this dissertation research is: **How were early ancient foragers on the highlands interacting with food resources?** In answering this question, I use a variety of archaeological and archaeometric techniques paired with some of the human behavioral ecological frameworks previously discussed that heavily suggest the initial intensification of large, terrestrial mammals like wild camelids (Aldenderfer 2006; Kuznar 1989, 1993). Early ancient foragers that have permanently occupied the Andean Altiplano like individuals from Soro Mik'aya Patjxa and Wilamaya Patjxa were expected to hunt a majority of their food based on the number of lithic materials excavated from these Archaic Period sites (Kitchel et al. 2021). Ecological frameworks like optimal foraging theory applied on these foragers also suggests that hunting and consuming game was their main mode of subsistence (Smith et al. 1983). Based on previous zooarchaeological research, high counts of lithic materials, and these behavioral ecological frameworks, *it is predicted that a large portion of these forager diets should be large terrestrial mammals like camelids or deer*. However, multiple lines of empirical evidence can be drawn with the use of stable isotope analysis on human bone.

Another specific question I ask is: **When were ancient highland foragers weaning their offspring off breastmilk and permanently onto solid foods?** Since the pre-Hispanic foragers at Soro Mik'aya Patjxa and Wilamaya Patjxa have permanently occupied the highlands, it is important to know the early and childhood diets of these individuals and how they have adapted to the high altitude. Some ethnographic case studies researching contemporary highland Indigenous communities on the Tibetan Plateau and Andean Altiplano reveal later weaning times around 3-4 years old than

compared to lowland communities around 1-2 years old (Dang et al. 2005; Vitzthum 2013, 1992). These later weaning times may be due to the “weaning foods availability” hypothesis where the lack of available or accessible weaning foods results in longer breastfeeding times and later weaning times (Sellen and Smay 2001). It also states that ideally, mothers would begin the weaning process as soon as there is access to good weaning foods. For instance, there are ethnographic observations and accounts of Hadza grandmothers digging up and foraging deeply rooted geophytes like tubers for mothers and the mothers’ offspring, supporting the grandmother hypothesis (Hawkes et al. 1997; Sellen 2009; Sellen and Smay 2001). One archaeological study that looks at breastfeeding and weaning times of pre-Hispanic individuals from northern Chile’s Atacama desert revealed a mixture of early and late weaning times along with prolonged physiological stress (King et al. 2018). Based on these highland ethnographic and archaeological accounts paired with theoretical frameworks, *it is predicted that these ancient highland foragers would prolong breastfeeding and have later weaning times due to a lack of available weaning food, and to ensure infant survivability in a physiologically stressful, high-altitude environment.* Using stable nitrogen isotopes on serially sectioned human first molars can not only provide quantitative data paired with life history frameworks like the grandmother hypothesis, stable nitrogen isotopes can also further clarify which wild food resources were first being intensified and used as a weaning food.

Finally, I also ask: **How have ancient diets changed in relation to climatic and environmental shifts over time on the Andean Altiplano?** The resilience and vulnerability of staple food crops during times of environmental and climatic decline can result in cultural decline too. For instance, an archaeological case study on ancient

agricultural systems of the Maya lowlands found that multiple periods of drought resulted in sociopolitical decline (Douglas et al. 2016; Gill et al. 2007). However, further archaeological research on the classic Maya lowland population also reveals that communities with higher diet diversity had higher resilience to the changing environment and climate (Ebert et al. 2019). This dissertation research similarly looks at diet diversity and food resilience using stable carbon and nitrogen isotope analysis across a span of time from the Archaic Period to the beginnings of the Late Intermediate Period, or the Post Tiwanaku period (see Table 1.0). Based on previous archaeological excavations and isotope analysis, the Tiwanaku cultural period had high diet diversity due to consistent trade between the highland communities and lowland communities including staple lowland crops like maize (Bandy 2004; Berryman 2010; Stanish et al. 2010). This dissertation takes a closer look at what each cultural period populations were mostly consuming up to the decline of the initial state formation, Tiwanaku. *It is predicted that as subsistence strategies change over time, so will diet with the highest diet diversity spread during the Tiwanaku Period where lake levels are also high.* Stable isotope analysis paired with observing changing lake levels of Lake Titicaca are used to determine overall dietary changes between cultural periods and any changes to the environment and climate, respectively.

Chapter 2

STABLE ISOTOPE CHEMISTRY REVEALS PLANT-DOMINANT DIET AMONG EARLY FORAGERS ON THE ANDEAN ALTIPLANO, 9.0-6.5 CAL. KA

ABSTRACT

Current models of early human subsistence economies suggest a focus on large mammal hunting. To evaluate this hypothesis, we examine human bone stable isotope chemistry of 24 individuals from the early Holocene sites of Wilamaya Patjxa (9.0–8.7 cal. ka) and Soro Mik'aya Patjxa (8.0–6.5 cal. ka) located at 3800 meters above sea level on the Andean Altiplano, Peru. Contrary to expectation, Bayesian mixing models based on the isotope chemistry reveal that plants dominated early highland forager diets. Paleoethnobotanical data further show that tubers may have been the most prominent subsistence resource. These findings update our understanding of earliest forager economies and the pathway to agricultural economies in the Andean highlands. The findings furthermore suggest that the initial subsistence economies of early human populations adapting to new landscapes may have been more plant oriented than current models suggest.

INTRODUCTION

The extent to which early human subsistence economies relied on meat versus plant foods is debated (Pontzer et al. 2018; Speth 2010). Current understanding of the earliest subsistence economies of the Andean highlands suggest that meat was the major

subsistence resource. Early Holocene assemblages, 11–5 cal. ka, consistently reveal abundant camelid and deer remains, projectile points, and scrapers suggesting hunting-oriented economies (Aldenderfer 1998; Lavallée et al. 1995; Lynch 2014; MacNeish et al. 1983; Núñez et al. 2002; Rademaker et al. 2014; Rick 1980; Rick and Moore 1999; Yacobaccio 2017). For example, Rick (1980)²⁹⁰ concluded that, “The settlement pattern [of the Junín region] and the faunal collections [from the site of Pachamachay] strongly support the hypothesis that vicuña, or similar camelids, were the major food source for *puna* [ecosystem] hunter-gatherers.” Such observations are furthermore consistent with diet breadth models, which suggest that early hunter-gatherer populations would tend to target high-ranked large mammals before resorting to plant foods (Mark S. Aldenderfer 2006; Alvard and Kuznar 2001; Bird and O’Connell 2006).

Recent analyses of materials from the Archaic Period sites of Soro Mik’aya Patjxa (8.0–6.5 cal. ka) and Wilamaya Patjxa (ca. 8.9 cal. ka), located on the Andean *Altiplano* (High Plateau), provide new opportunities to evaluate these economic models for early highland foragers. Similar to previous research, an abundance of projectile points, scrapers, and lithic debitage indicate considerable investment in the hunting of large terrestrial mammals, likely camelid and deer (Haas et al. 2017; Haas and Viviano Llave 2015; Kitchel et al. 2021). Preliminary zooarchaeological investigations reveal abundant large-mammal bone, consistent with a hypothesis of large mammal hunting (Haas et al. 2020; Haas and Viviano Llave 2015). Groundstone artifacts, though informal and infrequent, suggest some degree of investment in plant resources (Haas et al. 2020; Haas and Viviano Llave 2015). Distinctive dental wear patterns on the upper incisors, known as lingual surface attrition of the maxillary anterior teeth suggest intensive tuber

processing (Watson and Haas 2017). Collectively, studies of the Soro Mik'aya Patjxa and Wilamaya Patjxa materials indicate diverse diets of large mammals and plants with an emphasis on large-mammal hunting, consistent with previous findings at other Andean highland sites.

Despite general agreement of various lines of evidence, the evidence remains indirect. Preservation biases that favor projectile points and animal bone compared to plant materials could, to some extent, inflate the hunting signal (Adovasio et al. 2001; Kornfeld et al. 1996; Waguespack 2005). The biases of previous researchers who have generally been males from a culture in which hunting is a distinctly masculine pursuit could furthermore inflate the hunting signal (Gero and Conkey 1991). It was ostensibly for this reason that ethnography famously revealed plant foods to play a prominent role in forager economies—Arctic economies aside—in contrast to earlier models that emphasized hunting (Lee 2018, 1979; Roosevelt 2005). Thus, current archaeological models and evidence leave considerable room for interpretive error.

A more direct but previously unexplored measure of early Andean diets is stable isotope chemistry of human bone. A study of bone isotope chemistry of six early Holocene (8.2–8.0 cal. ka) individuals, including four children and two adults, from the Andean highlands of Argentina finds evidence for tuber and herbivore consumption with breastfeeding and environmental aridity enriching the isotopic values (Killian Galván et al. 2016). The current analysis examines the diets of 25 Archaic Period foragers at the highland archaeological sites of Soro Mik'aya Patjxa and Wilamaya Patjxa using stable carbon and nitrogen isotopes in conjunction with more traditional zooarchaeological and paleoethnobotanical approaches. These assemblages date to the early Holocene,

collectively spanning 9.0–6.5 cal. ka (Haas et al. 2017, 2020). Given current models of early highland economies, which point to a mixed diet of animals and plants with an emphasis on large mammals, we should expect to observe the human osteological samples from Soro Mik'aya Patjxa and Wilamaya Patjxa to exhibit dietary carbon ($\delta^{13}\text{C}_{\text{diet}}$) and nitrogen ($\delta^{15}\text{N}_{\text{diet}}$) values between those of local fauna and flora with a bias toward the means of the faunal $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values.

This expectation follows from well established relationships between the isotopic composition of human bone and the foods that humans consume (Richards and Trinkaus 2009; Schoeninger 2014). Stable nitrogen isotopes ($\delta^{15}\text{N}$) vary with trophic level. Stable carbon isotopes ($\delta^{13}\text{C}$) vary with photosynthetic pathway. Such isotopic values in human bone chemistry can provide insights into major subsistence resources including C_3 plants, C_4 plants, mammals, and fish. Although stable isotope analysis does not offer taxonomic specificity beyond those broad categories, by coupling isotopic insights with zooarchaeological and paleoethnobotanical insights, it may be possible to move beyond preservation biases to gain more accurate estimates of human diets. Given current understanding of highland Archaic diets, we expect zooarchaeological analysis of the Archaic Period sites to reveal an abundance of faunal remains including vicuña, guanaco, or taruca with few small mammal, fish, or bird remains. Paleoethnobotanical analyses should reveal abundant wild chenopod seeds or tuber remains.

MATERIALS AND METHODS

Recently discovered human burials and other cultural pit features—possibly roasting or storage pits—at the Early-Late Archaic Period archaeological sites of Soro Mik'aya and Wilamaya Patjxa afford an opportunity to evaluate models of early subsistence practices on the Andean Altiplano. A series of radiocarbon dates place Soro Mik'aya Patjxa securely in the Middle to Late Archaic Periods (8.0-6.5 cal. ka) (Haas et al. 2017). Radiocarbon dates and artifact typology broadly place Wilamaya Patjxa in the Early to Late Archaic Periods (ca. 11-5 cal. ka) (Haas et al. 2020).

Portions of the two sites were systematically excavated with site matrix and feature fill screened using 6 mm and 1 mm screens, respectively. For each cultural feature, 10-liter bulk soil samples were taken for flotation analysis unless the feature consisted of less than 10L, in which case all feature sediment was collected for flotation. Flotation procedures followed d'Alpoim Guedes et al. (2014) and Lennstrom and Hastorf (1992) using a modified version of Watson (1976) flotation machine.

The excavations revealed 18 cultural pit features at Soro Mik'aya Patjxa and 39 at Wilamaya Patjxa. From these, 16 individuals were discovered at Soro Mik'aya Patjxa and 12 at Wilamaya Patjxa. Here, we describe the laboratory methods for the three analytical approaches including isotopic, zooarchaeological and paleoethnobotanical approaches.

Samples of human remains were excavated and exported under Peruvian Ministry of Culture Permit numbers 064-2013-DGPA-VMPCIC/MC and 138-2015-VMPCIC/MC.

Stable Isotope Analysis of Human Bone

Stable isotope chemistry is performed in four different labs including the University of California Davis Stable Isotopes Facility (UCDSIFS), University of California Irvine W.M. Keck Carbon Cycle Accelerator Mass Spectrometer (KCCAMS) Facility, the University of Arizona Accelerator Mass Spectrometry Lab (AMS), and the Penn State University Laboratory for Isotopes and Metals in the Environment (LIME). Collagen extraction for the UCDSIFS and LIME submissions is performed at the UC Davis Archaeometry Lab following the protocol of Eerkens et al. (2014). Collagen extraction for the KCCAMS submissions follows the protocol described by Haas et al. (2020).

To assess the extent of diagenetic alterations to bone collagen, we consider atomic C/N ratios with the expectation that reliable readings will exhibit C/N ratios in the range of 3.1–3.6 (DeNiro 1985). As an additional quality control measure, we compare the resultant $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for three of the individuals—SMP9, SMP16, and WMP6—to values previously reported in radiocarbon analyses performed by The University of Arizona AMS laboratory (Haas et al. 2017) and the KCCAMS facility (Haas et al. 2020).

Baseline $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for candidate subsistence resources, including C_3 plants, C_4 plants, camelid, or freshwater fish, are compiled from published sources (Barberena et al. 2011; Grant 2017; Miller et al. 2010, 2021; Szpak et al. 2013). To the extent possible, control samples are restricted to archaeological samples from the central Andean highlands. For any modern samples included, $\delta^{13}\text{C}$ values are corrected by

+1.5‰ for Suess effects. For any lowland samples included, $\delta^{13}\text{C}$ values are offset +2‰ for and $\delta^{15}\text{N}$ values by -1.5‰ based on the regression equations of Szpak et al. (2013). $\delta^{13}\text{C}$ bone collagen samples are adjusted using a -2.4‰ offset if terrestrial (DeNiro and Epstein 1978) and -3.7‰ offset if aquatic (Guiry and Hunt 2020; Keegan and DeNiro 1988) to adjust for meat-bone offset.

Bayesian mixing models are used to estimate the dietary composition of the Soro Mik'aya Patjxa and Wilamaya Patjxa individuals using the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of the consumers and potential food resources. Children ($n=4$) are excluded from the model to prevent breast-feeding effects from influencing the results. Previous research shows that trophic offsets can vary widely due to a variety of environmental and trophic effects (Cheung and Szpak 2021; Killian Galván et al. 2016; Ugan and Coltrain 2011). Given the antiquity of the system under investigation, the mobility of humans, and the volatility of isoscapes over time, it is difficult to know which trophic correction factors apply to dietary regime under consideration. We therefore consider the range of possible trophic enrichment factors along with variance terms for both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$. For $\delta^{13}\text{C}$, we use trophic enrichment factors ranging between 4.5–6.0‰, in 0.5‰ increments, with a standard deviation of 0.63‰ (Cheung and Szpak 2021). For $\delta^{15}\text{N}$, we use trophic enrichment factors ranging between from 3–6‰, in 1‰ increments, with a standard deviation of 0.74‰ (Cheung and Szpak 2021). Considering all possible combinations of trophic enrichment factors results in 16 models for evaluation.

All models assume uniformed priors given the lack of prior knowledge on the relative dietary contributions of the broad resource classes. Although it might be tempting

to draw on zooarchaeological and archaeobotanical data for informative priors, differential preservation of faunal and floral artifacts precludes this possibility.

Model runs assume both residual and process error, a chain length of 1 million, burn-in of 5000, thinning of 500, and three chains. For dietary estimates, we report median values and 95% credible intervals for each subsistence resource and each model. Model convergence is assessed using Gelmen-Rubin and Geweke diagnostics, and the models are compared to one another using leave-one-out cross-validation information criterion (LOOic) and Akaike Information Criterion (AIC) weights (Stock, Andrew L. Jackson, et al. 2018). All computation is performed using R statistical computing language (Vienna 2023) with Bayesian mixing modeling performed using MixSIAR package (Stock, Andrew L. Jackson, et al. 2018). Although other packages for mixing modeling are available (e.g., FRUITS) (Fernandes et al. 2014), we use MixSIAR (Stock, Andrew Jackson, et al. 2018) because of its currency, documentation, integration with R statistical computing language, and accessibility via open-source Linux operating systems (Cheung and Szpak 2022). All code is made available in the supplementary materials.

Zooarchaeological Analysis

New faunal data are reported for Soro Mik'aya Patjxa. Wilamaya Patjxa data are derived from a previous investigation by Noe (Haas et al. 2020). For newly reported materials, all animal bone is weighed and counted. Although abundant, the animal bone is highly fragmented, likely due to intensive processing, making more precise taxonomic identification difficult. The method presented here serves to broadly distinguish between

human, small mammal, large mammal, bird, and fish bone. Animal bone fragments are distinguished from human bone based on bone macrostructure where (a) human bone tends to be more porous than animal bone, (b) cortical bone tends to be thicker relative to bone diameter in animals compared to humans, (c) diaphyseal trabecula tends to be present in human but absent in animal bone, and (d) human cranial vaults tend to have thick dipole while animal cranial vaults tend to be more compact (Mulhern 2009). More detailed faunal analysis is ongoing, but the coarse analytical approach taken here is sufficient to address the broad dietary question at hand.

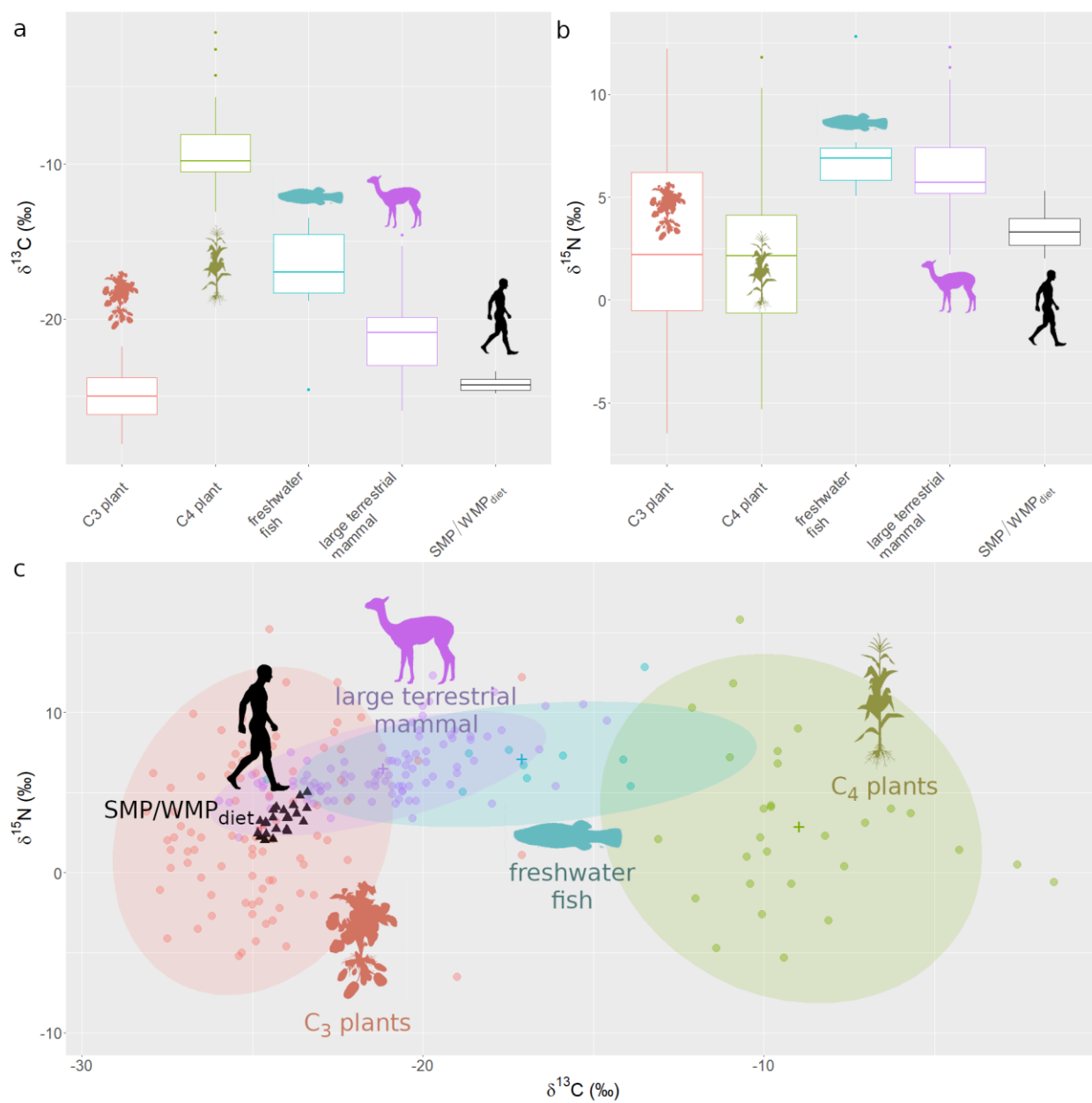
Paleoethnobotanical Analysis

All Soro Mik'aya Patjxa features, which include burial pits and pits of unknown function, are subject to macrobotanical analysis. Samples are sorted using a stereoscopic light microscope with 10 to 40X magnification. Due to environmental conditions in the central Altiplano and the antiquity and exposed nature of the sites, it is highly unlikely that uncarbonized plant remains would have preserved, so analysis is restricted to carbonized remains. Macrobotanical remains are sorted into different tissue categories including seeds, wood, and parenchyma. Parenchyma refers to plant storage tissue. These distinct carbonized tissues with thin-walled cells are believed to be tuber fragments by paleoethnobotanists working in the Altiplano. All specimens are identified to the most specific taxonomic level possible. Paleoethnobotanical analysis is restricted to Soro Mik'aya Patjxa with Wilamaya Patjxa paleoethnobotanical analysis is ongoing.

RESULTS

Isotopic control samples compiled from the literature include 42 large mammals, 95 C₃ plants, 20 C₄ plants, and 10 fish samples, all from high-altitude locations. The data reveal strong clustering of carbon and nitrogen values by category (Figure 2.0, Table 2.0) providing an ideal baseline for comparison with the human bone samples reported here (Table 2.1). Twenty-four individuals from Soro Mik'aya Patjxa (SMP) and Wilamaya Patjxa (WMP) show $\delta^{15}\text{N}_{\text{diet}}$ values ranging from 2.0‰ to 5.3‰ with a mean of 3.4‰ (see Figure 2.0a) and $\delta^{13}\text{C}_{\text{diet}}$ values ranging from -24.3‰ to -22.9‰ with a mean of -23.7‰ (see Figure 2.0b).

Figure 2.0: Carbon and nitrogen plots for control samples and 25 human bone samples from Soro Mik'aya Patjxa and Wilamaya Patjxa, indicating a plant-dominant diet. a) $\delta^{13}\text{C}_{\text{diet}}$ values are consistent with those of C₃ plants with slight enrichment from some other resource types. b) $\delta^{15}\text{N}_{\text{diet}}$ values are most consistent with those of plants. c) Biplot of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values are consistent with a mixed diet principally based on C₃ plants with low levels of enrichment from some other resource. Dietary values assume $\delta^{13}\text{C}$ TEF=5.5‰, $\delta^{15}\text{N}$ TEF=6‰ based on mixing model results (see Table 2.4). Dots = individual samples, ellipses = 95% variance ranges for each category, and crosshairs = mean values by category (see Tables 2.0 and 2.2).



population	n	$\delta^{13}\text{C}$ mean (‰)	$\delta^{13}\text{C}$ sd (‰)	$\delta^{15}\text{N}$ mean (‰)	$\delta^{15}\text{N}$ sd (‰)	references
C ₃ plants	84	-24.74	2.12	2.87	4.64	(Miller et al. 2010, 2021)
C ₄ plants	29	-8.96	2.72	2.88	4.89	(Miller et al. 2010, 2021; Szpak et al. 2013)

freshwater fish	10	-17.09	3.24	7.11	2.20	(Miller et al. 2021)
large terrestrial mammal	96	-21.16	2.31	6.52	2.35	(Grant 2017; Grant et al. 2018; Killian Galván et al. 2016; López M. et al. 2017)
SMP/WMP _{diet} *	24	-24.22	0.42	6.42*	0.88	NA
*Dietary values assume $\delta^{13}\text{C}$ TEF=5.5‰, $\delta^{15}\text{N}$ TEF=6‰ based on mixing model results (see Table 2.3).						

Table 2.0. Summary statistics for stable isotopic control data for high-altitude Andean food resources and archaeological samples from Soro Mik'aya Patjxa (SMP) and Wilamaya Patjxa (WMP). See Supplementary Materials for sample data.

burial	age class ^a	element	lab ^b	$\delta^{13}\text{C}_{\text{raw}}$ (‰)	$\delta^{15}\text{N}_{\text{raw}}$ (‰)	$\delta^{13}\text{C}_{\text{diet}}^{\text{c}}$ (‰)	$\delta^{15}\text{N}_{\text{diet}}^{\text{c}}$ (‰)	atomic C/N	date (95% cal. BP) ^d
SMP 1	child	parietal (squama)	UCDSIF	-18.11	10.82	-23.61	7.82	3.2	n.d.
SMP 2	adult	temporal (petrous portion)	UCDSIF	-18.89	9.93	-24.39	6.93	3.3	n.d.
SMP 3	adult	rib 10 (left)	UCDSIF	-18.91	9.19	-24.41	6.19	3.2	7565-7177 (Haas et al. 2017)
SMP 4	adolescent	rib 1 (left)	UCDSIF	-19.28	8.23	-24.78	5.23	3.2	7565-7177 (Haas et al. 2017)
SMP 5	adult	hand mid phalanx (right)	UCDSIF	-18.73	11.31	-24.23	8.31	3.2	6856-6569 (Haas et al. 2017)
SMP 6	adult	metatarsal 5 (left)	UCDSIF	-19.28	9.22	-24.78	6.22	3.3	7153-6756 (Haas et al. 2017)
SMP 7	adolescent	hand proximal phalanx (right)	UCDSIF	-19.14	8.02	-24.64	5.02	3.2	6780-6510 (Haas et al. 2017)
SMP 8	adult	hand proximal phalanx (right)	UCDSIF	-19.34	8.47	-24.84	5.47	3.2	7160-6885 (Haas et al. 2017)

SMP 9	adult	hand proximal phalanx (left)	UCDSIF	-18.48	8.61	-23.98	5.61	3.2	7465-7317 (Haas et al. 2017)
SMP 10	adult	hand proximal phalanx (left)	UCDSIF	-18.21	9.70	-23.71	6.70	3.2	6907-6574 (Haas et al. 2017)
SMP 11	adult	rib (right)	UCDSIF	-18.90	9.43	-24.40	6.43	3.2	6883-6669 (Haas et al. 2017)
SMP 12	adult	rib (left)	UCDSIF	-19.12	9.09	-24.62	6.09	3.2	n.d.
SMP 13	child	temporal (petrous portion)	UCDSIF	-17.90	11.01	-23.40	8.01	3.3	6883-6669 (Haas et al. 2017)
SMP 15	adult	hand proximal phalanx (left)	UCDSIF	-18.81	8.74	-24.31	5.74	3.2	n.d.
SMP 16	adult	mandible (right)	UCDSIF	-18.81	10.11	-24.31	7.11	3.3	7247-7009 (Haas et al. 2017)
WMP 1	adult	tibia frag (side indeterminate)	UCDSIF	-18.46	9.45	-23.96	6.45	3.9	n.d.
WMP 2	adult	long bone diaphysis fragment	KCCAMS	-18.60	8.70	-24.10	5.70	3.3	n.d.
WMP 3	adult	bone frag	UCDSIF	-18.59	9.90	-24.09	6.90	3.4	n.d.
WMP 5	adult	left petrous portion	UCDSIF	-17.91	10.04	-23.41	7.04	3.4	n.d.
WMP 6	adolescent	indeterminate bone fragment	UCDSIF	-19.11	9.15	-24.61	6.15	3.6	8992-8651 (Haas et al. 2020)
WMP 7	adult	left scapula	KCCAMS	-19.10	8.40	-24.60	5.40	3.2	n.d.
WMP 8	adolescent	3 rd molar	LIME	-18.73	9.76	-24.23	6.76	3.2	n.d.
WMP 9	child	cranial fragment	KCCAMS	-18.50	8.70	-24.00	5.70	3.2	n.d.
WMP 10	child	cranial fragment	KCCAMS	-18.30	10.20	-23.80	7.20	3.2	n.d.

	mean	-18.72	9.42	-24.22	6.42		
	standard deviation	0.42	0.88	0.42	0.88		
*age classes as defined by Buikstra and Ubelaker (1994)							
^b UCDSIF=UC Davis Stable Isotope Facility; KCCAMS=UC Irvine Keck Carbon Cycle Accelerator Mass Spectrometry facility; LIME=Penn State University Laboratory for Isotopes and Metals in the Environment							
^c Dietary values assume $\delta^{13}\text{C}$ TEF=5.5‰, $\delta^{15}\text{N}$ TEF=3‰ based on mixing model results (see Table 2.3).							
^d calibrated using Southern Hemisphere Calibration Curve 2020 (Hogg et al. 2020).							

Table 2.1. Human bone collagen isotopic results for Soro Mik'aya Patjxa and Wilamaya

Patjxa individuals. See Appendix A for additional metadata.

Quality control measures indicate that the archaeological stable isotope values reported here are reliable. Atomic C/N ratios for all but one sample—WMP1—fall within the acceptable range of 3.1–3.6 (see Table 2.1), indicating that diagenetic processes have not significantly altered the collagen (DeNiro 1985). Furthermore, the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values from the four previously reported radiocarbon dates (Haas et al. 2017, 2020) are in close agreement with less than 1.3‰ separating values reported among the three labs (Table 2.2).

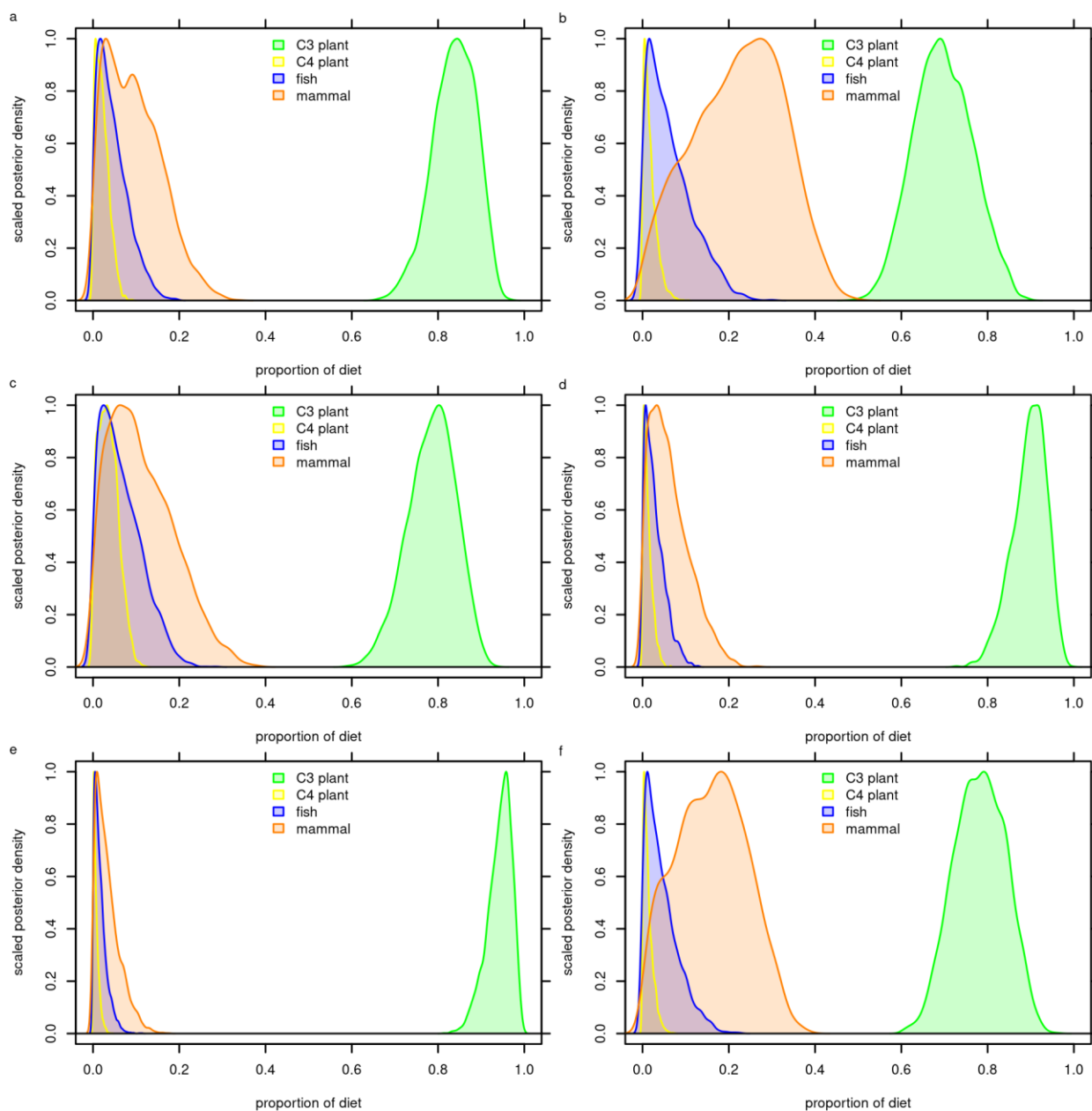
individual	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)	¹⁴ C comparisons					
			lab	lab ID	¹⁴ C age (B.P.)	C/N _{atomic}	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)
SMP 9	-18.5	8.6	AMS	AA107345 (Haas et al. 2017)	6529±41	3.2	-19.2	7.9
SMP 16	-18.8	10.1	AMS	AA107490 (Haas et al. 2017)	6259±38	3.3	-18.8	9.7
WMP 6	-19.11	9.2	KCCAMS	UCIAMS 212748 (Haas et al. 2020)	8035±20	3.2	-18.8	8.2
			KCCAMS	UCIAMS 212749 (Haas et al. 2020)	7965±25	3.3	-19.0	8.0

Table 2.2. Inter-laboratory comparison of isotopic results showing consistent results and acceptable atomic C/N ratios. UCDSIFS compared to AMS and KCCAMS.

The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values fall closest to the mean of C_3 plants with slight enrichment from some other set of resources indicating a C_3 dominant diet and excluding the possibilities that mammals, C_4 plants, or fish comprised large portions of the diet (see Figure 2.0c). All of the Bayesian mixing models indicate adult diets dominated by C_3 plants, with median C_3 plant values ranging from 60–95% and median mammal values ranging from 3–33% for all 16 models. Geleman and Geweke model diagnostics are consistently zero or near zero, indicating that all models are plausible.

The best-fit Bayesian mixing model (Table 2.3) indicates that C_3 plants comprised approximately 94% (86–98%) of the average adult diet with meat comprising just 3% (0–12%), fish 1% (0–6%), and C_4 plants 0% (0–2%; Figure 2.1). This model generated the lowest LOOic value and the lowest AIC weight and is based on a $\delta^{15}\text{N}$ trophic enrichment of $3.00 \pm 0.74\text{‰}$ and a $\delta^{13}\text{C}$ trophic enrichment of $6.00 \pm 0.63\text{‰}$. However, three other models produced equivalent AIC weights of 0.00, and four other models produced weights under 0.05, suggesting virtually equivalent model performance. Among these models, median C_3 plant estimates range from 60–94% and mammal estimates range between 3–33%. These results show that the particular trophic enrichment factors, ranging from 3–6‰ for $\delta^{15}\text{N}$ and 4.5–6.0 for $\delta^{13}\text{C}$, have little effect on the broad dietary estimates. All models indicate a plant dominant diet with median values for C_3 plants ranging between 60–94% and mammals ranging between 3–33%. Thus, all credible subsistence models indicate that plant foods comprised the majority of individual diets and meat played a secondary role. These findings are inconsistent with the working hypothesis of a meat-dominant diet and instead suggest a plant-dominant diet among early forager populations of the Andean Altiplano, 9.0–6.5 cal. ka.

Figure 2.1. Bayesian mixing model results for the four best-fit models showing that C₃ plants comprised *the majority* of the diet and mammals played a secondary role in the subsistence economies of Soro Mik'aya Patjxa and Wilamaya Patjxa. a. $\delta^{13}\text{C}$ TEF=4.5‰, $\delta^{15}\text{N}$ TEF=3‰, median C₃ plant =60%, median mammal =33%. b. $\delta^{13}\text{C}$ TEF=5.0‰, $\delta^{15}\text{N}$ TEF=3‰, median C₃ plant =75%, median mammal =19%. c. $\delta^{13}\text{C}$ TEF=5.5‰, $\delta^{15}\text{N}$ TEF=3‰, median C₃ plant =86%, median mammal =9%. d. $\delta^{13}\text{C}$ TEF=6‰, $\delta^{15}\text{N}$ TEF=3‰, median C₃ plant =94%, median mammal =3% (see Table 2.4).



model	TEF ^a		estimated dietary contribution (%) ^b				Gelman diagnostic ^c	Geweke diagnostic ^d	LOOic ^e	Akaike weight
	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	C3 plants	C4 plants	fish	mammals				
1	4.5	3	60(42-77)	0(0-3)	4(0-49)	33(2-52)	2,0,0	2,0,1	-38.6	0.00
2	5.0	3	75(60-88)	1(0-3)	4(0-21)	19(1-37)	1,0,0	0,0,8	-36.0	0.00
3	5.5	3	86(75-95)	1(0-3)	3(0-11)	9(0-23)	0,0,0	4,0,0	-35.7	0.00
*4	6.0	3	94(85-98)	0(0-2)	1(0-6)	3(0-12)	0,0,0	0,2,0	-35.4	0.00
5	4.5	4	62(50-78)	1(0-3)	4(0-20)	32(5-48)	0,0,0	0,2,2	-50.0	0.04

6	5.0	4	75(62-87)	1(0-4)	4(0-16)	20(2-36)	0,0,0	1,2,1	-48.5	0.02
7	5.5	4	86(75-95)	1(0-3)	3(0-10)	10(0-23)	0,0,0	0,3,0	-48.1	0.01
8	6.0	4	93(85-98)	0(0-2)	1(0-6)	4(0-13)	0,0,0	0,0,0	-47.3	0.01
9	4.5	5	70(58-83)	1(0-6)	6(0-19)	22(2-40)	2,0,0	0,0,1	-52.8	0.14
10	5.0	5	78(67-89)	1(0-4)	4(0-14)	16(1-31)	0,0,0	0,0,6	-51.9	0.09
11	5.5	5	88(77-96)	1(0-3)	2(0-10)	8(0-21)	0,0,0	1,3,1	-51.6	0.08
12	6.0	5	94(85-98)	0(0-2)	1(0-6)	3(0-13)	0,0,0	1,0,2	-51.1	0.06
13	4.5	6	79(67-88)	3(0-8)	6(0-17)	10(1-28)	0,0,0	3,1,0	-53.0	0.16
14	5.0	6	84(73-92)	2(0-6)	4(0-12)	9(0-24)	0,0,0	2,1,0	-52.7	0.14
15	5.5	6	90(81-96)	1(0-4)	2(0-8)	6(0-17)	0,0,0	0,7,0	-52.8	0.14
16	6.0	6	95(87-99)	0(0-2)	1(0-5)	3(0-10)	0,0,0	1,1,0	-52.5	0.12

^aTEF=trophic enrichment factor

^bposterior probability median (95% range)

^cvariables > 1.01, variables > 1.05, variables > 1.1 (27 variables)

^dnumber of variables outside 95% confidence level for each of three chains (should be <2, or 5% of 27 variables)

^eleave-one-out cross validation information criterion (LOOic) for assessing model efficacy. Smaller values indicate more powerful models.

*best approximating model based on LOOic and Akaike weight. Smaller values indicate more efficacious models and relative strength, respectively.

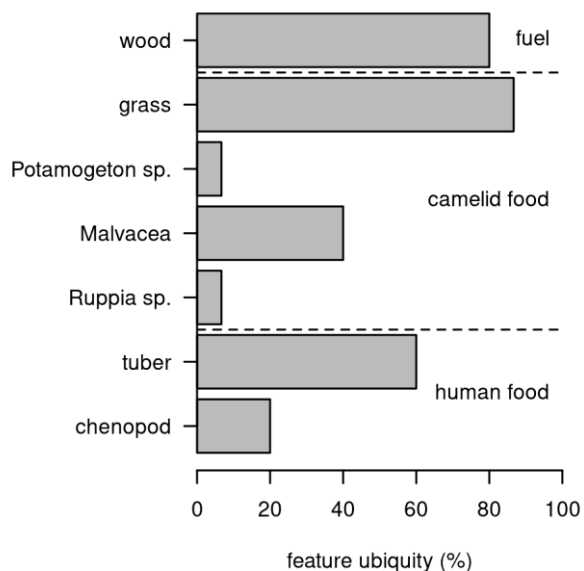
Table 2.3. Bayesian mixing model comparison considering different trophic enrichment factors.

Zooarchaeological and paleoethnobotanical observations offer some taxonomic precision beyond the broad food categories used in the stable isotope analysis. Excavations at Soro Mik'aya produced 3193 fragments of animal bone (number of individual specimens or NISP) from across the site. Of the total specimens, the most frequently identified category included 200 large mammal fragments with only trace amounts of small mammal, bird, and fish bones reported (Haas and Viviano Llave 2015). Most of these large mammal bones were burned (n=150; 75%). A previously published assessment of 341 faunal bone elements from Wilamaya Patjxa faunal assemblage similarly revealed that camelid and deer bone were the most frequently identified taxa with 17 camelid and 5 deer elements observed (Haas et al. 2020). Notably absent, again,

are small mammals, birds, and fish. These data indicate that the slight enrichment observed in the carbon and nitrogen values in the human bone was likely due to large mammal consumption and not small mammals, fish, or birds.

The most abundant plant-food specimens in the Soro Mik'aya Patjxa paleoethnobotanical assemblage is parenchyma tissue, identified as tuber fragments with 52 specimens found in 9 of 15 features (Figure 2.2, Table 2.4). Chenopod seeds are nearly absent with just three wild specimens observed among three features. The most abundant paleoethnobotanical samples are non-food resources including wood fragments ($n=448$) and grass (*Poaceae*) seeds ($n=161$) observed in nearly every feature. The wood most likely reflects use as fuel. Similarly the small grass seeds likely reflect fuel use whether from burning grasses or the dung of camelids (Bruno and Hastorf 2016). The small grass seeds are typical of the region, and none of the taxa are suitable for human consumption but are excellent forage for camelids. This finding is consistent with a model of early wild tuber consumption and other lines of evidence that suggest intensive tuber use in the region during the Archaic Period (Jorgensen et al. 2023; Rumold and Aldenderfer 2016; Watson and Haas 2017).

Figure 2.2. Results of paleoethnobotanical analysis from features at Soro Mik'aya Patjxa. Ubiquity is measured as the proportion of archaeological features containing each taxon. Values based on 15 features, 300L of flotation, and 688 paleoethnobotanical artifacts (see Table 2.4).



feature	flotation volume (L)	human food		camelid food				fuel	total
		<i>Chenopodium</i> sp.	parenchyma	<i>Ruppia</i> sp.	Malvaceae	<i>Potamogeton</i> sp.	<i>Poaceae</i>	wood	
2	27	0	25	0	2	0	3	57	87
3	23	0	1	1	0	0	8	20	30
4	31	1	4	0	12	0	57	75	149
5	25	0	8	0	2	0	29	33	72
6	18	0	1	0	1	1	4	35	42
7	1	0	0	0	0	0	1	0	1
8	5	0	0	0	0	0	0	2	2
9	10	0	3	0	0	0	5	7	15
10	25	1	0	0	2	0	10	91	104
13	33	0	1	0	0	0	2	19	22
14	12	0	6	0	0	0	1	49	56
14/15*	13	0	2	0	0	0	4	41	47
15	10	0	0	0	0	0	6	8	14
16	48	1	1	0	3	0	28	0	33
17	9	0	0	0	0	0	0	0	0
18	10	0	0	0	0	0	3	11	14
total	300	3	52	1	22	1	161	448	688

*sample contexts mixed. Excluded from ubiquity calculations.

Table 2.4. Carbonized macrobotanical materials from Soro Mik'aya Patjxa flotation

samples.

DISCUSSION

The stable isotope, faunal, and paleoethnobotanical evidence from the sites of Soro Mik'aya Patjxa and Wilamaya Patjxa converge to indicate that C₃ plants, likely wild tubers, comprised the major component of early forager diets on the Andean Altiplano and that meat, including vicuña and taruca, played a secondary role. C₄ plants, small mammals, fish, and birds appear to have played negligible roles in these early subsistence economies. The findings presented here depart from current thinking about early Andean highland diets and force a reconsideration of existing economic models.

One possible explanation for the unexpected emphasis on plant foods among this early highland population may be that large mammal populations had been severely reduced by 9 cal. ka. Although the Wilamaya Patjxa assemblage includes the earliest archaeological period of the region—the Early Archaic Period, 11.0–9.0 cal. ka—it is restricted to the latter end of the period (Haas et al. 2020). It is currently unclear when human populations first arrived in the region, but if they arrived as early as 11 cal. ka., then humans would have been hunting the region for 2,000 years prior to the earliest individuals under investigation. This would certainly have been enough time to decimate the region's animal population in the absence of animal conservation strategies (Rick 1980). A second possibility is that the earliest populations simply did not engage in hunting to the extent previously thought. Previous research suggests that prey choice models may over-estimate the dietary values of large mammals whether due to physical risk (Lupo and Schmitt 2016), prey behavior (Lupo et al. 2020), or economic risks associated with long encounter intervals (Bird et al. 2009). A third explanatory possibility

is that early highland populations relied heavily on hunting large mammals but incorporated animal digesta into their diets (Garvey 2023), which could simultaneously account for both the archaeological signatures of hunting—animal bone and projectile points—and the depleted nitrogen values in human bone chemistry observed here. Evaluating these hypotheses will ultimately require investigation of earlier archaeological assemblages.

These findings furthermore hold implications for our understanding of domestication in the high Andes. Pearsall (2014) and Kuznar (1993) proposed that plant management commenced after camelids were managed in corrals. In this view, camelids transported plant seeds to corrals where they thrived in soils fertilized by camelid dung, creating a mutually beneficial relationship between camelids, plants, and human communities. Versions of this model suggest that *Chenopodium* spp. (including the crops quinoa and kañawa) and the tuber maca (*Lepidium mevenii* Walp.) were domesticated in this way. These coevolutionary processes also likely led to the domestication of potatoes (*Solanum tuberosum* L.) and up to 15 other species of roots and tubers in the Andes (Flores et al. 2003). Consistent with this model, chenopod seeds, maca tubers, and managed camelids appeared after about 4,000 years ago at the rock shelter site of Panalauca where the sizes of chenopod and maca specimens increased through time (Pearsall 2014). Recent research into domestication mutualism supports the Andean version of the camp follower hypothesis showing that chenopods, tubers, and camelids were likely domesticated in tandem as complementary foods (Langlie and Capriles 2021).

While current models suggest initial co-evolutionary processes involving maca, chenopod, and camelid intensification in the highlands, the paleoethnobotanical evidence

presented here fails to find strong evidence of early intensive chenopod use on the Altiplano during the Archaic period. This may reflect preservation biases given the small and delicate nature of wild chenopod seeds. Alternatively, it may be that chenopods did not become economically important in the region until sometime after 6.5 cal. ka. A later incorporation of chenopods into the diet would be consistent with prey choice models given the low post-encounter return rates of small seeds relative to tubers (Joyce et al. 2022).

The finding of tuber fragments at Soro Mik'aya Patjxa is consistent with the role of tubers in the early stages of the co-evolutionary process. However, the tuber fragments are unlikely to be maca, which is a more northerly taxon. Several tuber species could potentially account for the tubers observed at Soro Mik'aya Patjxa, but they are most likely associated with wild potato species, which are concentrated in the region and were likely domesticated there (Hawkes 1989; Hijmans and Spooner 2001; Jorgensen et al. 2023; Spooner et al. 2005). Additional sites on the Altiplano should be examined with particular attention to contemporaneous sites that would assess replicability of the current findings and to non-contemporaneous sites that would afford diachronic comparisons.

In sum, the results presented here are consistent with a model of human-tuber-camelid co-evolutionary dynamics beginning approximately 9,000 years ago on the Andean Altiplano. These findings support an updated model of Archaic Period subsistence practices in the high Andes in which forager subsistence economies 9.0–6.5 cal. ka. emphasized plant foraging with lesser attention to large mammal hunting and a virtual absence of small animal hunting and fishing. This resource base may have

catalyzed potato and camelid domestication in the subsequent Terminal Archaic Period after 5 cal. ka (Rumold and Aldenderfer 2016).

These findings further highlight the need to re-evaluate anthropological understanding of early forager diets more generally. Current perspectives vary with some models emphasizing the primacy of plants and others of animals (Pontzer et al. 2018; Speth 2010) with plant foraging becoming increasingly important relatively late in time on the eve of agriculture (Stiner 2001). This may still be so, but the current analysis suggests that the shift to plant-foraging economies may have happened relatively rapidly, evidently having transpired in less than 2,000 years in the Andean case. This observation resonates with recent archaeological theory and findings that reveal a prominent role for plant foods in early forager diets (d'Alpoim Guedes et al. 2014; Hardy et al. 2022; Henry et al. 2011) and ethnographic findings of the 1960s when, contrary to dominant thinking of the time, many subsistence economies once thought to be meat-dominant were shown to be plant-dominant (Lee 1979; Roosevelt 2005). Stable isotope chemistry gives archaeologists the opportunity to reliably extend such investigations into the deep past. The current study arrives at a similar place to the earlier ethnographic findings—plant foods were central to early human economies.

Chapter 3

STABLE ISOTOPE ANALYSIS OF DENTAL SERIAL SECTIONS SUGGESTS DELAYED WEANING AMONG EARLY FORAGERS OF THE ANDEAN ALTIPLANO, 9.0-6.5 KA

ABSTRACT

Previous research identifies delayed weaning as a behavioral adaptation to life at high altitude in the Andean and Tibetan highlands. When this behavior commenced is unknown. This research examines the stable isotope chemistry of dental serial sections in Archaic Period forager populations of the high Andes to estimate weaning ages and the potential onset of delayed weaning practices on the Andean Altiplano. Preliminary results suggest that Archaic foragers of the Altiplano, 9.5-6.5 cal. ka, commonly delayed completion of the infant weaning process until 4-6 years of age. This estimate is later than both modern lowland weaning ages of 1-2 years and modern highland weaning ages of 3-4 years. Results suggest that delayed weaning was an early behavioral adaptation to high-altitude lifeways, which may have served to mitigate high infant mortality rates in a cold, hypoxic, resource-limited landscape.

INTRODUCTION

Human adaptation to high elevation environments is an active area of research that considers genetic and behavioral response to cold, hypoxic conditions. Genetic studies reveal that both Tibetan and Andean Indigenous communities have developed separate biological outcomes for high-altitude adaptation (Aldenderfer 2003, 2006; Beall

2006, 2007; Haas 2023). Indigenous Andean communities, for example, have higher hemoglobin counts while Tibetan communities have higher oxygen-saturation (Beall 2007).

Despite considerable investigation into the genetic adaptations to high-altitude living, particularly in Tibet and the Andes, few studies examine behavioral adaptations to high-altitude living (Beall 2006, 2007; Bigham et al. 2013; Simonson et al. 2012; Torchetti 1994). Potential behavioral mechanisms of high-elevation adaptation in the Andes include delayed weaning and chewing coca leaves to mitigate the symptoms of hypoxia. Delayed weaning is a common strategy among highland Indigenous populations on the Tibetan and Andean plateaus where harsh, high-altitude, resource-limited environments create conditions that challenge infant survival (Dang et al. 2005; Moore et al. 2004, 2011; Vitzthum 2013). Weaning refers to the transition from breastfeeding to solid foods (Halcrow et al. 2017). Weaning times vary greatly around the world based on cultural and economic practices. Tibetan pastoralists that live in the highlands tend to prolong breastfeeding times up to 6 months as compared to lowland populations at 4 months (Dang et al. 2005). Andean highlanders begin weaning at 3-4 years old while their lowland counterparts begin weaning earlier at the ages of 1-2 years (Vitzthum 2013, 1992).

The specific mechanism relating delayed weaning to high-altitude adaptation is unclear. Breastfeeding not only provides the offspring with a reliable source of nutrients, but also serves to reduce the fertility of the mother and thus increase inter-birth intervals. Thus, delayed weaning could serve to increase inter-birth intervals; this would therefore reduce foraging demands on families by reducing the number of mouths to feed (Kachel

et al. 2011). Another hypothesis for delaying weaning times could be that infants who feel cold and hypoxic stress may have higher metabolic rates and thus greater feeding demands. Some scholars have also proposed that the unavailability of weaning foods fundamentally delays the weaning process (Sellen and Smay 2001). This suggests that breastfeeding and weaning times are dependent on environmental and climatic mechanisms. However, studies comparing different cultural systems reveal that “no qualitative evidence that such populations lacked foods appropriate for weaning” (Sellen and Smay 2001). Despite having the appropriate weaning foods available, certain populations still delayed weaning.

Another potential link is that prolonged breastfeeding could be a strategy for smoothing over resource shortfalls, which may be more common in marginal environments such as high-altitude environments. Alternatively, delayed weaning may confer other health benefits to children in frigid, hypoxic environments that stress human immune systems. Medical research shows that breastfeeding transmits immune function from mothers to infants. Given that infant mortality rates are elevated in high-elevation environments, parents may have attempted to offset such effects by delaying the weaning process.

Whatever the particular mechanism, ethnographic data are clear in showing a relationship between high-altitude environments and delayed weaning behavior in human populations. The extent to which these dynamics were relevant among early inhabitants of these environments is currently unknown. Because contemporary populations are part of complicated global dynamics, they are imperfect models of past behavior.

Understanding the breastfeeding behavior of past human societies thus requires

investigation of those populations rather than projection of ethnographic behaviors onto them.

Although the archaeological record does not offer clear insights into potential mechanisms by which delayed weaning confers adaptive advantages to highland populations, it does allow us to evaluate general predictions for the ostensible relationship between altitude and weaning times. If delayed weaning was indeed an important adaptive response that allowed humans to people high elevation environments, then we would expect to observe delayed weaning practices among the earliest high-altitude populations. Until recently, such inferences would have been impossible. However, the relatively recent development of stable isotope serial sectioning of human first molars allows archaeologists to make accurate estimates of weaning ages (Eerkens et al. 2011). Human teeth grow incrementally from the crown to the root of the tooth. Based on this incremental growth, researchers are able to precisely serial section teeth in 1mm sections to determine any significant changes in diet during an individual's childhood. More specifically, stable nitrogen isotope analysis is used to make inferences on weaning times.

The discovery of early human remains at Soro Mik'aya Patjxa and Wilamaya Patjxa, 3800 meters above sea level, offers an opportunity to evaluate whether early Holocene populations of the Andean highlands deployed delayed weaning as an adaptive strategy. This study estimates the weaning times of a population of Archaic Period foragers on the Andean Altiplano, 9.5-6.5 cal. ka, by using stable nitrogen isotope analysis of first adult molars. If these early human populations deployed delayed weaning practices, we should be able to detect it in isotopic composition of their first molars.

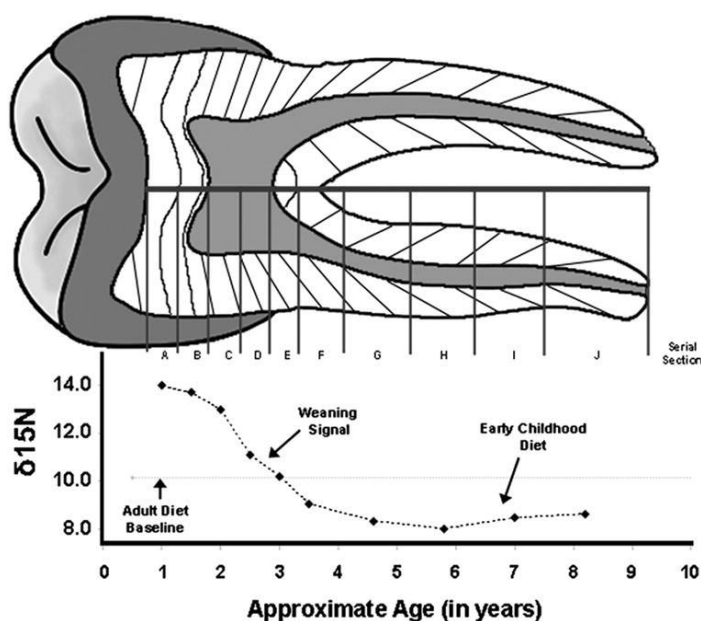


Figure 3.0. Diagram of sectioned first adult molar with a graph observing stable nitrogen isotopes through an individual's early life from Eerkens et al. (2011).

MATERIALS AND METHODS

Archaeological materials come from Archaic Period sites Soro Mik'aya Patjxa (8-6.7 cal. ka) and Wilamaya Patjxa (9.5-6.5 cal. ka). The sites are located on the Andean Altiplano. Both open-air archaeological sites contained lithic material, ocher, fragmented bone of large terrestrial mammals, and human burials (Haas et al. 2020; Haas and Viviano Llave 2015). Previous archaeological work concludes that individuals from both sites were permanently occupying the Andean highlands (Haas et al. 2017, 2020). Excavations at the two sites resulted in the recovery of 28 individuals. Teeth were recovered from 5 adult individuals at Soro Mik'aya Patjxa and 5 more adult individuals from Wilamaya Patjxa. We serial sample first molars from adult individuals and

characterize $\delta^{15}\text{N}$ values for the serial sections in order to estimate weaning ages. Here, we describe the serial sections and isotopic characterization methods, and methods for estimating weaning ages.

Serial Sectioning and Isotopic Characterization Methods

Adult first molars are collected from each human burial for stable isotope analysis. Teeth measurements of specific landmarks (i.e. CEJ, ART, DEJ) are recorded in Excel where the estimated growth rates are calculated, corresponding to estimated age at each teeth serial section. A program, WEAN, is used to further solidify the estimated weaning age of each individual and is compared to this study's calculations (Ganiatsou et al. 2023).

First molars were selected from each individual. Teeth are sawed in half and cleaned using a Dremel drill to strip the enamel and cementum in order to reveal the dentin. The teeth are then chemically processed using the methods of Eerkens et al. (2011). Samples are left in glass vials to demineralize in 0.5N hydrochloric acid (HCl) for several days until soft. They are then rinsed three times in deionized water (dH₂O). Samples are submerged briefly in 0.1N sodium hydroxide (NaOH) to remove any humic acids from soils. They are then rinsed three times in dH₂O.

Individual demineralized teeth are cut using a scalpel on methanol-wiped petri dishes with a ruler placed underneath. Each tooth is serial sectioned in even 1-2 millimeter segments from crown to root tip (Figure 3.0). Each serial section is placed in

glass vials and submerged in 0.01N HCl with vented caps and placed on a heating block on a low temperature (70 degrees Celsius) overnight to gelatinize.

Teeth sections are then transferred to previously weighed vials to be refrigerated overnight. Gelatinized samples in glass vials are then frozen using liquid nitrogen and then placed on a lyophilizer to draw out the collagen.

Collagen is extracted from the vials to be weighed (0.4-0.7mg) and placed in tin capsules. Serial sectioned samples are then sent to the Light Isotopes Lab at the Pennsylvania State University to be processed and analyzed using a PDZ Europa ANCA-GSL elemental analyzer interfaced to a PDZ Europa 20-20 isotope ratio mass spectrometer. Values returned are ^{13}C (‰, VPDB), TOC (%), ^{15}N (‰, AIR), and TON (%).

Age-of-Weaning Estimation

Age-of-weaning is indicated by the age of the serial section with the most depleted (i.e., lowest) nitrogen value. It is therefore necessary to estimate the individual's age for each serial section. The process of estimating the age of a given serial section requires a series of calculations and assumptions about the growth rate of human teeth, which we outline here.

First, after a given tooth is cut in half, but before serial sectioning, we estimate tooth length, T_i (mm), using scaled digital photographs. Because dental growth rates vary by individual, measurement of each tooth is important for estimating the ages of a serial section. A 10 mm scale bar is placed in each photograph. Digital photographs are imported into GIMP image editing software, where pixel measurements are derived using

the measurement tool. T_l is found as the product of the digitally measured tooth length (pixels), T_p , and a scale factor, which is based on the measurement of a 10 mm scale bar, S_p (pixels), in the image. Thus, tooth length is found as follows:

$$T_l = T_p * 10 / S_p$$

Calculating Growth Rate (GRT) Estimation

For growth rate calculations, each tooth landmark must be calculated separately with the tooth millimeter abbreviated as TMM with the knowledge that DEJ to CEJ growth is roughly 2.75 years, and CEJ to ART growth is roughly 6.75 years.

Measurements from DEJ to CEJ is,

$$TMM / 2.75$$

Measurements from CEJ to ART is,

$$TMM / 6.75$$

Measurement of CEJ is,

$$[(TMM / 2.75) + (TMM / 6.75)] / 2$$

Calculating Average Distance to CEJ (ADC)

To calculate the average distance to CEJ from DEJ or ART, the number of tooth sections, or abbreviated to TS , must be counted, which will be used later on. Add together the tooth millimeters (TMM) from DEJ to CEJ, and then add the TMM from CEJ to ART:

$$TMM_{(DEJ \rightarrow CEJ)} + TMM_{(CEJ \rightarrow ART)} = \sum TMM$$

No calculations for CEJ are required as it is simply,

$$CEJ = 0$$

Because the distance to CEJ is equal to 0, the sum of the distance from DEJ to CEJ and CEJ to ART is,

$$\sum 0 = 0_{CEJ} + \sum TMM / TS$$

Therefore, the average distance to CEJ (ADC) is calculated using this formula with CEJ equal to 0:

$$\sum 0 + \sum TMM / TS = ADC$$

Calculating Age of Individual Per Tooth Section

With the knowledge that the development and growth of the CEJ is approximately 2.75 years, we can calculate the age of each tooth section from DEJ to CEJ using the average distance to CEJ (ADC) and the growth rate (GRT), which is:

$$2.75 - ADC / GRT$$

And the age of each tooth section from CEJ to ART:

$$ADC / GRT + 2.75$$

Weaning Age Estimate

We use two methods to estimate weaning ages from the serial section $\delta^{15}\text{N}$ values—visual and model-fitting approaches. In the visual approach, weaning times are estimated by identifying the lowest stable nitrogen isotope values. The age estimate for

this value is considered the weaning age estimate (Figure 3.0). Uncertainty is defined as the range of age estimates for the serial sections that immediately precede and antecede the section with the lowest $\delta^{15}\text{N}$ value. The quantitative approach to estimating weaning age uses the method of Ganiatsou et al. (2023) who have created a cross-platform computation tool called WEaning Age FiNder (WEAN).

Error Analysis

In order to assess inter-observer and inter-laboratory error, two of us (Chen and Canale) independently examined different first molars from common individuals. Processing methods were constant for both individuals. However, Canale conducted her analysis at the UC Davis Archaeometry Lab where wet laboratory methods slightly differ from Chen, who conducted her analysis at Penn State's Human Paleoecology and Isotope Geochemistry Lab. Despite the differences in laboratory and wet laboratory methods, the results from both Chen and Canale are similar. Isotopic values, temporal trends, and weaning-age estimates are compared for these individuals to assess analytical replicability.

RESULTS

The effort resulted in the characterization of 84 serial sections from the first molars of ten individuals, including five from Soro Mik'aya Patjxa (SMP) and five from Wilamaya Patjxa (WMP). A pilot analysis of one sample conducted by Canale showed a

dip in nitrogen close to 5 years old for SMP 4, indicating that that individual had ceased breastfeeding and had weaned onto solid foods. This preliminary result inspired us to expand the sample size. Chen therefore attempted to reproduce Canale's results and expand the sample to include first molars from other individuals at both archaeological sites. This effort resulted in recreating early childhood diets of ten individuals from Archaic period sites, Soro Mik'aya Patjxa and Wilamaya Patjxa. Each tooth generated an average of 8 sections. Although, most teeth serial sections produced enough collagen for analysis, some sections had to be combined in order to meet the weight requirement (0.4-0.7mg). Bone collagen samples from Chen et al. (2024) were also included to indicate overall diet in comparison to early childhood diet of each individual (Table 3.0).

$\delta^{15}\text{N}$ values for successful samples range between 7.97‰ and 10.47‰. Some individuals display clear signals of weaning, such as SMP 4, SMP 7, SMP 8, and WMP 6, while some, like WMP 4, WMP 9, and SMP 11, display constant downward or upward trends. Breastfeeding and weaning times from SMP 12, WMP 1, WMP 4, and WMP 8 are especially unclear because they seem to not follow any particular patterns (Figure 3.1). When comparing the $\delta^{15}\text{N}_{\text{raw}}$ bone collagen to the $\delta^{15}\text{N}$ tooth mean, a majority of individuals have high starting nitrogen values that are higher than $\delta^{15}\text{N}_{\text{raw}}$ bone collagen (Table 3.0). The average nitrogen values for all teeth samples begin to dip downwards at around a wide range of 2-8 years old, suggesting the cessation of breastmilk. The average age of the weaning process from calculations based on this study is 5.31 years old, a notably older age when compared to contemporary highland communities. The WEAN estimates follow closely with an average age of 6 years old.

Comparison of results from the pilot study, conducted by Canale, and this expanded study show similar patterns of weaning times (see Figure 3.2). Inputting Canale’s pilot data into WEAN resulted in an estimated weaning age at 5 years old. Although both Canale and Chen produced similar weaning patterns for individual SMP 4, the age at which this individual was weaned according to Canale’s preliminary study is 5 years old while Chen’s results, in this study, recorded a weaning age at 4 years old. This difference may be due to the number of serial sections each researcher managed to cut— Canale produced a total of 8 viable serial sections while Chen produced 6 viable serial sections. Despite these differences in total of sections, the general weaning pattern remains the same from Canale’s pilot study to this current study.

Table 3.0. SMP/WMP individuals’ age ranges, teeth section, and mean $\delta^{15}\text{N}$ values.

Atomic C:N ratio values for each serial section are in Paper 2 Supplementary Materials.

*Values from Chen et al. 2024.

Individual	Age (years)	Tooth	$\delta^{15}\text{N}_{\text{raw}}$ bone (‰)*	$\delta^{15}\text{N}$ tooth mean (‰)	Estimated Weaning Age (years) (lower-upper age range)	WEAN estimates (years)
SMP 4	12-15	RM1	8.23	8.85	4.08 (2.75-5.41)	4.22
SMP 7	18-20	RM1	8.02	8.62	4.06 (2.75-5.36)	4.31
SMP 8	30-40	LM1	8.47	8.11	8.38 (7.91-8.85)	5.95
SMP 11	25-35	RM1	9.43	9.71	2.75 (1.85-3.60)	NA
SMP 12	35-45	RM1	9.09	8.36	4.38 (3.92-4.85)	5.70
WMP 1	25-30	LM1	9.90	7.97	4.91 (3.83-5.98)	7.17
WMP 4	13-15	RM1	9.45	10.47	NA	NA
WMP 6	18-21	RM1	8.10	9.61	6.14 (5.01-7.27)	7.14
WMP 8	NA	RM1	NA	9.64	5.73 (4.24-7.22)	7.54
WMP 9	NA	LM1	8.7	9.37	7.38 (6.45-8.30)	NA
				Average Age (years)	5.31	6.00

Table 3.1. SMP/WMP individuals' age ranges in comparison to other contemporary and archaeological case studies on breastfeeding and weaning times.

Community	Location	Subsistence Strategy	Archaeological or Contemporary	Weaning Times	Source
Soro Mik'aya Patjxa / Wilamaya Patjxa	Andean Altiplano	Foraging	Archaeological	5-6 years old	This study
Chinese	Tibetan Plateau	Pastoralism	Contemporary	~2 years old	Dang et al. 2005
Quechua	Andean Altiplano	Agropastoralism	Contemporary	~2 years old	Vitzthum 1992
Marsh Creek	California	Foraging	Archaeological	3-4 years old	Eerkens et al. 2011
Atacama	Atacama Desert, Chile	Agropastoralism	Archaeological	1.5-3.5 years old	King et al. 2018
Tsimane	Bolivian Amazon	Foraging	Contemporary	~2 years old	Martin et al. 2016
Mayan	Guatemala	Agriculture	Contemporary	~2 years old	McKerracher et al. 2017
Jomon	Japan	Foraging	Archaeological	2.3-5.5 years old	Tsutaya et al. 2016

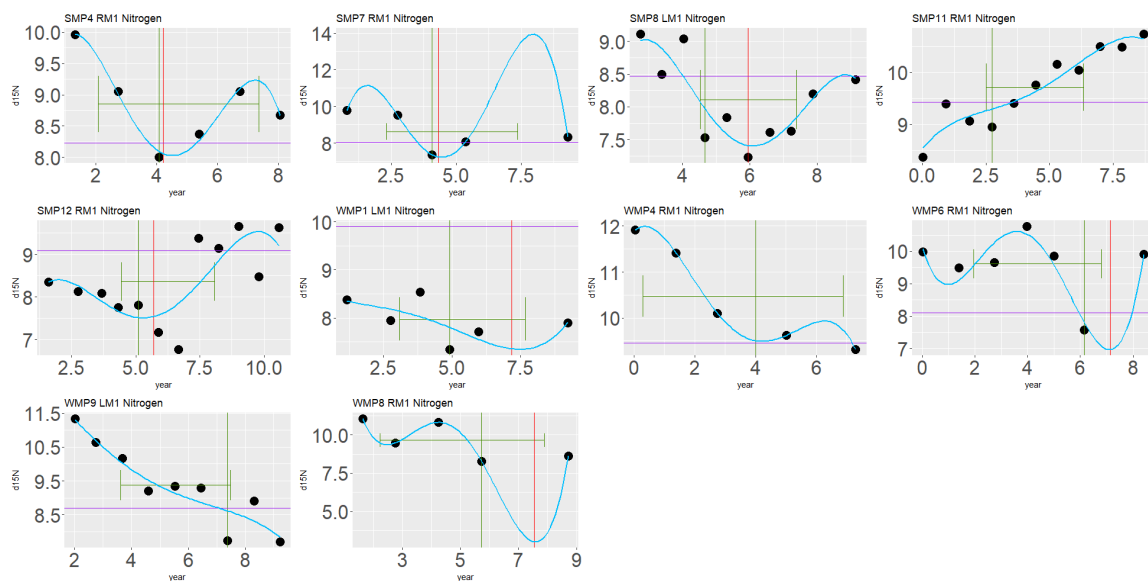


Figure 3.1. SMP/WMP individuals' serial sectioned first molars and their $\delta^{15}\text{N}$ values.

Red lines indicate the weaned age from WEAN. Green lines indicate estimated weaned age from this study's calculations with green horizontal lines as error bars. Purple horizontal lines indicate $\delta^{15}\text{N}_{\text{raw}}$ bone values from Chen et al. 2024. Blue curves indicate a linear regression model using a fourth order polynomial from the WEAN program (Ganiatsou et al. 2023).

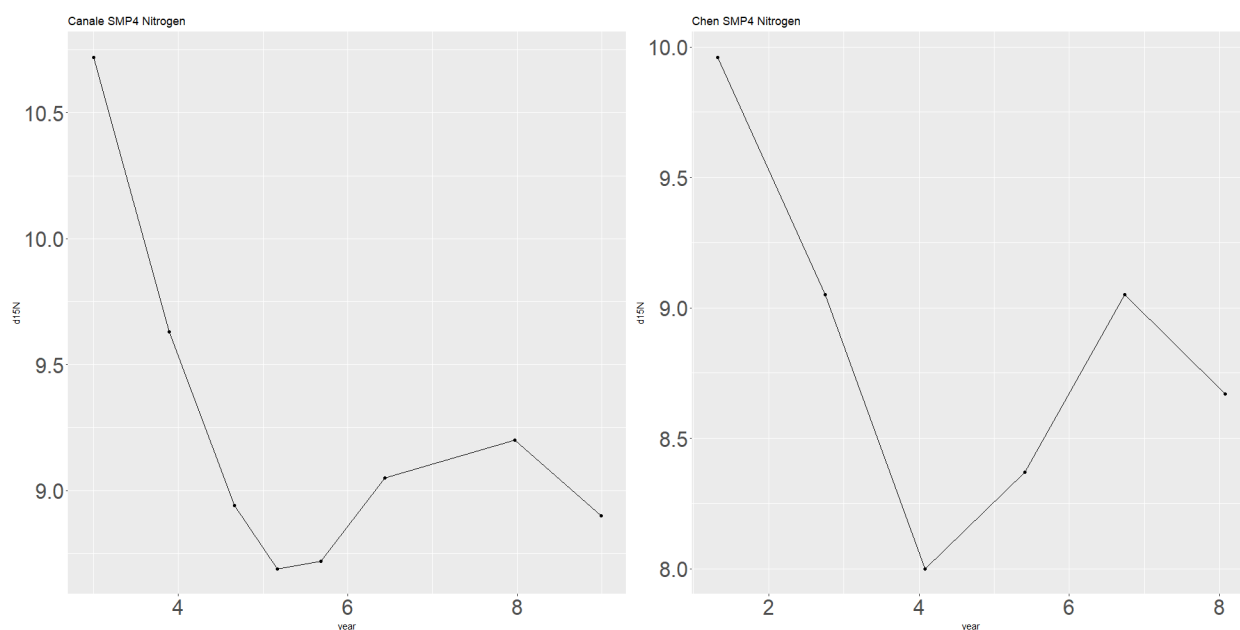


Figure 3.2. A comparison of breastfeeding and weaning times of SMP4 by Canale (left) and Chen (right), resulting in similar weaning time patterns.

DISCUSSION

The stable nitrogen isotopes from Soro Mik'aya Patjxa and Wilamaya Patjxa suggest that seven individuals were breastfed and weaned between 2-8 years old with an average age of 5.31 years old with the youngest individual being 2.75 years old and the oldest individual being 8.38 years old. WEAN also produced similar age averages at 6 years old. Average mean $\delta^{15}\text{N}$ for teeth sections of these ten individuals are 8.88‰. Individuals from Wilamaya Patjxa seem to have been weaned later when compared to individuals from Soro Mik'aya Patjxa. The average age at weaning for individuals from Wilamaya Patjxa is 6.04 years old while the average age of weaning for individuals from Soro Mik'aya Patjxa is 4.73 years old.

It is unclear if these pre-Hispanic individuals at Soro Mik'aya Patjxa and Wilamaya Patjxa have developed genetic adaptations to living in high-altitude or not. While contemporary high-altitude communities in the Andes have this genetic adaptation, children are still being weaned at later ages (3-4 years old) compared to their lowland counterparts (1-2 years old) (Vitzthum 2013). In this study, most pre-Hispanic individuals from these Archaic Period sites began weaning even later. High stress environments like high-altitude living could possibly result in later weaning ages to ensure infant survivability. However, some individuals from Soro Mik'aya Patjxa and Wilamaya Patjxa display unclear weaning signals as mentioned and specified in the results.

Similar research has been conducted on pre-Hispanic individuals from the Atacama Desert where some individuals have rising nitrogen values over time instead of the typical downward trend in values that occur when the process of weaning begins (King et al. 2018). This upward nitrogen trend in the Atacama study can be explained by physiological stress of the individual early on in their infancy where the mother may not be able to provide breastmilk. Food substitutions for breastmilk, such as cooked tubers mashed into a paste, may have been available instead of breastmilk (Ugwu 2009). However, cooked tubers may still be difficult for infants to digest compared to breastmilk, potentially forcing the infant's body to undergo more physiological stress, resulting in increasing nitrogen values. While the human burials in the Atacama Desert study suggests bioarchaeological markers for prolonged malnutrition, this is not the case for Soro Mik'aya Patjxa and Wilamaya Patjxa individuals. Skeletal indicators for physiological stress like dental enamel hypoplasia were not present in the Archaic Period individuals. Instead, previous stable isotopic studies at Soro Mik'aya Patjxa and

Wilamaya Patjxa reveal that individuals were mostly consuming C₃ plants and some camelids like vicuña or deer (Chen et al. 2024). Bioarchaeological indicators for tuber processing were also evident skeletally (Watson 2014). Further lines of evidence like paleoethnobotanical analysis also suggest heavy tuber consumption. It is therefore plausible for these individuals to feed their infants and children cooked tubers as complementary weaning food, or even as primary food in lieu of breastmilk. This may suggest that wild tuber cooking preparations were effective in providing enough sustenance for offspring to survive in the high-altitude environment that is abundant in tubers.

Nutritional studies on root crops and tubers like potatoes reveal that they are not high in nutrients, even after cooking, compared to other possible food resources like legumes (Ugwu 2009). However, nutritional findings on tubers reveal that despite a lack of nutrients, potatoes still have physical qualities that make good weaning foods and possibly adequate breastmilk substitutes: easy and quick to prepare, easy to consume after cooking, and microbiologically safe (Ugwu 2009).

Despite the availability of tubers as food, this study reveals that the findings are consistent with the hypothesis that delayed weaning was an early cultural solution to solving the adaptive challenges of living on the Andean Altiplano. Further archaeological and genetic research can further reveal whether or not Soro Mik'aya Patjxa and Wilamaya Patjxa individuals have already developed the genetic adaptation to living on the highlands. Rigorous mathematical analysis of the $\delta^{15}\text{N}$ tooth low points could also further our understanding of the process of delayed weaning among other ancient highland foragers.

Chapter 4

THE EFFECTS OF CLIMATE AND CULTURE ON ANDEAN ALTIPLANO DIETS, 9-1 KA.

ABSTRACT

The ancient Andes is one of the few regions in the world where gathering and hunting intensified to result in the domestication of a variety of food products that would ultimately achieve global importance. This outcome is remarkable given the harsh, semi-arid, and hypobaric environment, and the driving dynamics remain unclear. Here, I present an analysis of variability in stable isotope signatures from samples of human bone collagen to investigate dietary change in the Andean Altiplano over some millennia. While many archaeological and paleoecological studies emphasize the importance of climate in driving human dietary variation, our analysis fails to find a strong relationship between climate change and dietary diversity. Instead, we find that sociopolitical organization exerted the greatest effect on Andean Altiplano dietary variability. In particular, the emergence of complex governing bodies of the Tiwanaku state had the most profound effect on dietary change in the region. On one hand, Altiplano subsistence economies were remarkably stable in the face of climate change with the potato as a regenerative, constant, and staple highland crop persisting for millennia. On the other hand, dramatic subsistence change resulted from major sociopolitical reorganization marked by the emergence of the Tiwanaku state.

INTRODUCTION

Food systems are both a fundamental reflection and driver of the processes by which we organize our sociopolitical relationships and interact with their surrounding environment (Mintz and Bois 2002). The ways in which people procure, process, and distribute food within different modes of production—foraging, pastoralism, agriculture, agropastoralism, and other mixed economies—is the basis of variable patterns networks of human relationships. Broadly speaking, changes in livelihood strategies often covary with climatic and environmental change, and the socioecological dynamics involved can shape patterns in decision-making resulting in intensification and domestication of certain food resources (Kennett and Winterhalder 2006; Koster and Bird 2024; Morgan 2015; Tucker 2024). Foraging theory suggests a general mechanism for domestication. As encounter rates with highly ranked resources decline, resource selection should broaden to increasingly incorporate lower ranked resources characterized by high handling costs. Intensified relationships with such resources can result in early domestication (e.g. Piperno 2011).

Research based in foraging theory suggests that climate change affects intensification and social organization (such as property regimes). These interactions can influence subsistence strategies, leading to a greater reliance on lower-rank resources—particularly energetically dense plants with high handling costs—thus driving processes of domestication (Bettinger et al. 2010; Bowles and Choi 2013). Bettinger and colleagues (2010) propose that climatic fluctuations in the late Pleistocene may have constrained processes of subsistence intensification in critical ways: environmental variability

maintained payoffs for high residential mobility, which in turn decreased incentives for handling low-ranked resources, maintaining storage facilities, and investing in institutions to manage property typical of agricultural societies. This may explain why, despite the spread of people into most major regions of the world by about 15,000 years ago, a heavy reliance on farming was not widespread until after 13,000 years ago, and in many regions of the world was not present until the early to mid-Holocene.

Ethnographic work with contemporary mobile foragers demonstrates the fundamental relationships between high mobility, material egalitarianism, lack of storage, and de-intensified subsistence (Kelly 1983, 2013). Cultural norms integrated in such systems may shift when more stable climates ultimately modify trade-offs that lead to increased population density, constraints on residential mobility and conditions in which individuals simultaneously adopt storage and hoarding conventions (Bettinger et al. 2010). Conventions of storage, hoarding, and defense underwrite institutions of private property, without which there are few incentives for investing in farming practices (Bowles and Choi 2013). Thus, conditions favorable for the independent development of farming practices in different regions, and the spread of agricultural systems worldwide, may have been limited until the end of the Younger Dryas.

The Archaic Period (~9.0–3.5ka) in the south central Andes is best characterized for the late Pleistocene to early Holocene transition where the environment and climate were favorable for human occupation in the highlands (Aldenderfer 1989, 1998; Capriles et al. 2018; Haas and Viviano Llave 2015). Recent archaeological investigation suggests that these early human foragers have permanently occupied the Andean Altiplano, intensifying many of its wild resources including wild potatoes, quinoa, and camelids

(Chen et al. 2024; Haas et al. 2017; Haas and Viviano Llave 2015; Rick 1980; Watson and Haas 2017).

During the Formative Period (3.5–1.5ka) in the Andean Altiplano, there was persistent regional moisture and regular precipitation based on lake level analyses of Lake Titicaca (Baker et al. 2009; Guédron et al. 2023; Tapia et al. 2003). This consistent climate during this cultural time period precipitated the beginnings of agriculture and pastoralism in the Andean Altiplano. The abundance and continuity of wild food resources that were intensively used in the highlands thus were able to be cultivated and later domesticated (Bruno 2014; Bruno and Whitehead 2003; Miller et al. 2021). Archaeological studies also reveal advancements in technologies during this cultural period where raised field agriculture became prevalent (Bruno 2014; Guédron et al. 2023). Ethnoarchaeological evidence of initially growing human populations at the advent of agriculture in the Andean Altiplano suggests small-scale management of land and food through nested hierarchies within and between families oftentimes called *ayllus* or *markas* (Albarracin-Jordan 1996).

Tiwanaku (1.5–0.75ka), one of the earliest states in the Andean Altiplano, rose through agricultural intensification and rapid population growth (Bruno 2014; Erickson 1988). Sociopolitical growth like the rise of the Tiwanaku state also implies the rise of social inequality, which can be seen using household archaeological perspectives and also recently through the use of stable isotope analysis of human bone (Berryman 2010; Janusek 2002, 2006). An abundance of different food resources like potatoes, quinoa, freshwater fish, domesticated camelids, and maize traded in from the lowlands characterized the diet of individuals during the Tiwanaku Period based on previous

isotopic research (Berryman 2010). However, despite this abundance and widespread varieties of food, it is unlikely that individuals throughout the Tiwanaku state were equally consuming these foods.

Despite the rapid urbanization and sociopolitical organization of Tiwanaku, this initial state experienced an equally quick decline due to various factors like major climate variability that resulted in rapid environmental changes (Arnold et al. 2021; Binford et al. 1997; Budja 2015; Janusek 2004; Ortloff and Kolata 1993; Williams 2010). This study focuses on precipitation based on lake levels and determining dry periods—not necessarily periods of drought. Many paleoecological studies reveal that intense drought was one of the main drivers of Tiwanaku's decline (Arnold et al. 2021; Bruno et al. 2021; Janusek 2004; Ortloff and Kolata 1993; Williams 2010). For instance, lake sediment analysis from Lake Orurillo revealed periods of prolonged drought in the Andean Altiplano region from 4.8ka-226 years BP (Arnold et al. 2021). Further research on Lake Wiñaymarka, a smaller lake within the Lake Titicaca watershed, also revealed fluctuating lake levels through time, with some of the lake levels becoming shallow around the dispersal of the Tiwanaku state at 0.75ka (Guédron et al. 2023). Although the disintegration of the Tiwanaku polity resulted in smaller, dispersed communities and groups in the Andean Altiplano, people still continued to occupy the highlands despite the sudden shift in climate variability and environmental changes (Langlie and Arkush 2016; McCool et al. 2021; Torres-Rouff 2020).

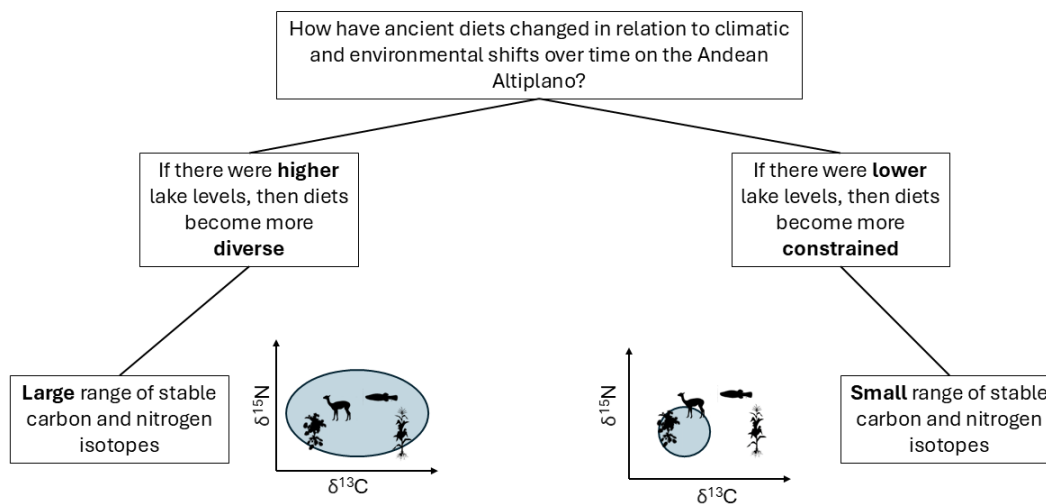
While the Post Tiwanaku Period, or Late Intermediate Period (0.75–0.38ka), is mostly characterized by violence and warfare, archaeological evidence suggests that people on the Andean Altiplano were still practicing small-scale agropastoralism and

other mixed economies (Langlie and Arkush 2016). It is likely that the diversification of diet and staple food crops, like the wide varieties of tubers, during the Late Intermediate Period helped mitigate against crop failure or other types of risk that come with agropastoralism (Langlie and Arkush 2016).

Although previous investigations have shed considerable light on the relationship between diet and climate in the Andean Altiplano, a systematic diachronic analysis remains lacking. This analysis attempts to integrate human bone isotope chemistry and paleoenvironmental data in order to rigorously assess the effect of climate on diet. This analysis specifically asks: how have ancient diets changed in relation to climatic and environmental shifts over time on the Andean Altiplano? While there are paleoclimate reconstructions of the Andean Altiplano through time, there are few studies that look at both paleoclimate in conjunction with ancient diets through time (Bruno et al. 2021; Miller et al. 2021; Wilson et al. 2022). One particular study used random foresting models to conclude that climate had a larger effect on ancient diets than population size and paleodemography (Wilson et al. 2022). However, that study observed stable carbon and nitrogen isotopes of different geographic populations that include the coast, mid-elevation, and high-elevation populations of a similar cultural timeframe. Other paleoecological and archaeological studies reveal that subsistence practices and diets were flexible and diverse based on dynamic environmental changes that are observed through lake level changes (Bruno et al. 2021). This dissertation uses stable carbon and nitrogen isotopes to observe any changes in diet through time in the same geographic region (i.e., Andean Altiplano) in conjunction with lake level changes through time.

Findings from previously published research mostly focus on the ancient diets of foragers from Soro Mik'aya Patjxa and Wilamaya Patjxa within the Andean Altiplano (Chen et al. 2024; Haas et al. 2020). This final chapter will encompass the ancient diets of people in the Andean Altiplano based on the different cultural periods and different subsistence strategies (see Table 1.0 in Introduction). In order to evaluate the hypothesis that climate affected human diets in the Andean Altiplano, this analysis investigates the relationship between paleolake level estimates and human bone chemistry. If climate was a strong driver of human diet in the region, we would expect to observe that lake-level proxies predict carbon and nitrogen isotope values in human bone. Namely, we might expect increased rainfall to not only elevate lake levels but also increase the availability of food resources, including both primary producers (plants) and consumers (small mammals and ungulates) on the highlands. This increasing food availability would in turn have enhanced human food choice, which would have tended to elevate trophic levels as predicted by optimal foraging theory (see Figure 4.0).

a)



b)

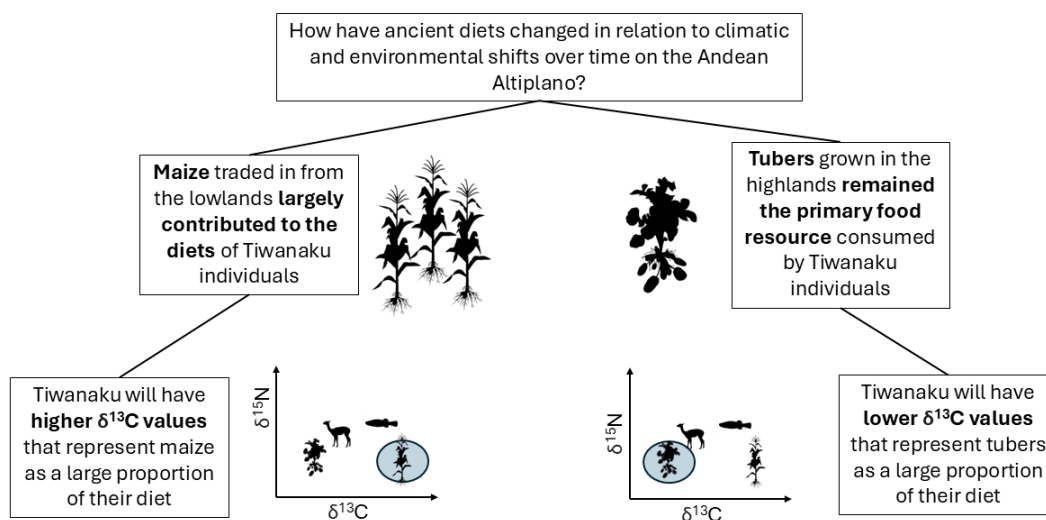


Figure 4.0. Diagrams and flowcharts of hypotheses and predictions.

MATERIALS AND METHODS

Stable carbon and nitrogen isotope values from human bone for this study are from previously published articles or dissertations that provide stable isotope results from varying archaeological sites on the Andean Altiplano (see Figure 4.1). Some isotopic values are directly from this study. Radiocarbon dates are derived from charcoal and gastropods from distinct lake sediment layers (Guédron et al. 2023).

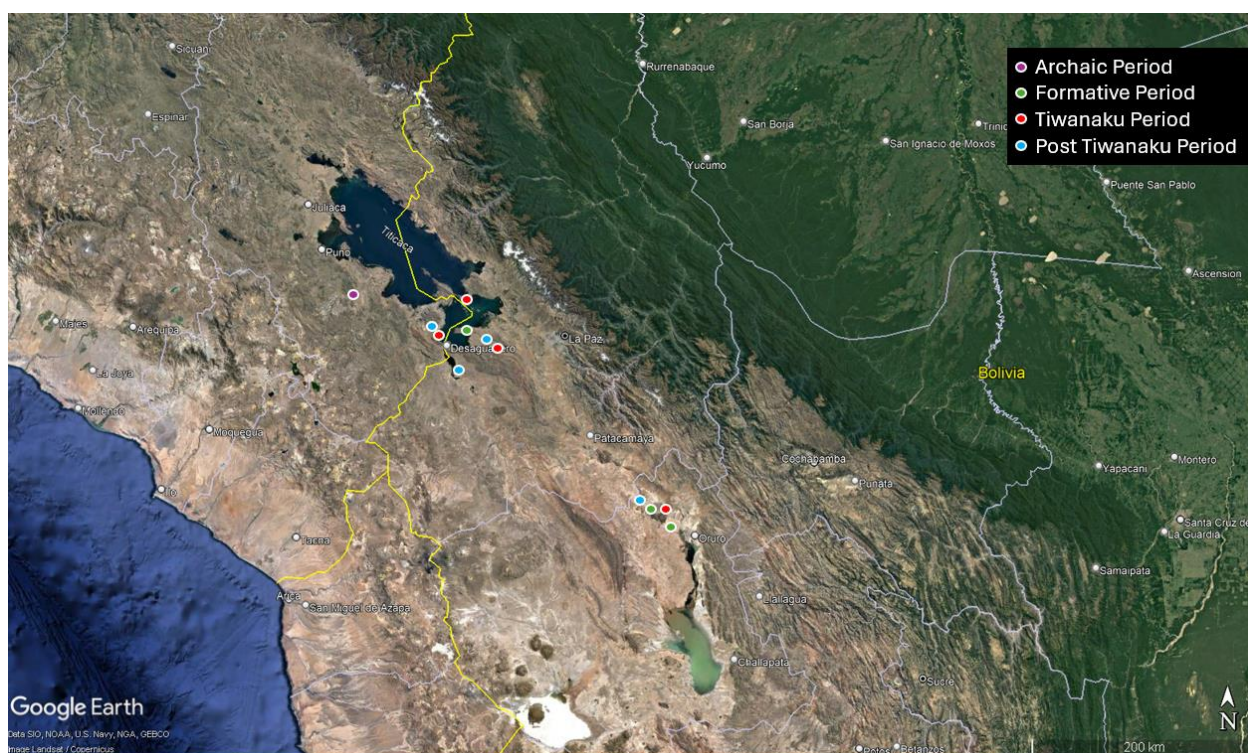


Figure 4.1. A map of the Andean Altiplano with archaeological sites from each cultural period.

Samples and Data

Datasets were gathered from previously published archaeological and paleoecological studies in the Andean Altiplano that include stable carbon and nitrogen isotope analysis of human bone (Supplementary Table 4.0), animal bone, plant materials (Table 4.0), and lake levels analysis (Berryman 2010; Bruno et al. 2021; Capriles et al. 2021; Chen et al. 2024; Grant 2016, 2017; Haas et al. 2017, 2020; Miller et al. 2010, 2021; Somerville et al. 2015; Szpak et al. 2013; Tessone et al. 2014; Weide et al. 2017). Stable carbon and nitrogen isotopes of human bone from the different cultural periods are plotted against an environmental dataset that consist of isotopes of C₃ plants, C₄ plants, large terrestrial mammals, and freshwater fish. For dietary accuracy, I have two environmental datasets—the first one consists of strictly wild resources, while the second environmental dataset consists of a mixture of wild and domesticated resources. The wild environmental dataset is only used for the population of ancient foragers from Soro Mik’aya Patjxa and Wilamaya Patjxa during the Archaic Period. The wild and domesticated environmental dataset is used for all other ancient human populations such as the Formative Period, Tiwanaku Period, and Post Tiwanaku Period.

Table 4.0. A statistical summary of baseline food resources including averages, standard deviations, and number of samples.

	$\delta^{13}\text{C}$ average (‰)	$\delta^{13}\text{C}$ standard deviation	$\delta^{15}\text{N}$ average (‰)	$\delta^{15}\text{N}$ standard deviation	n
C₃ plants	-24.64	1.87	2.68	4.32	142
C₄ plants	-9.6	2.07	4.56	4.2	56
freshwater fish	-17.1	3.25	7.11	2.2	10

large terrestrial mammal	-21.17	2.31	6.52	2.36	96
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Stable Isotopes Analysis

Stable carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) are typically used by archaeologists to recreate ancient diets (Keegan and DeNiro 1988). Stable carbon isotopes infer the different photosynthetic pathways of plants (Figure 1.1). C_3 plants such as tubers and most chenopods will have values that range from -20‰ to -37‰ while C_4 plants like maize will have values that range from -10‰ to -19‰. Stable nitrogen isotopes, on the other hand, infer the different dietary trophic levels of animals (Figure 1.1). Plants and herbivores will have generally more negative values while carnivores will have more positive values. Omnivores would have intermediary values between herbivores and carnivores or sea animals like fish and shellfish.

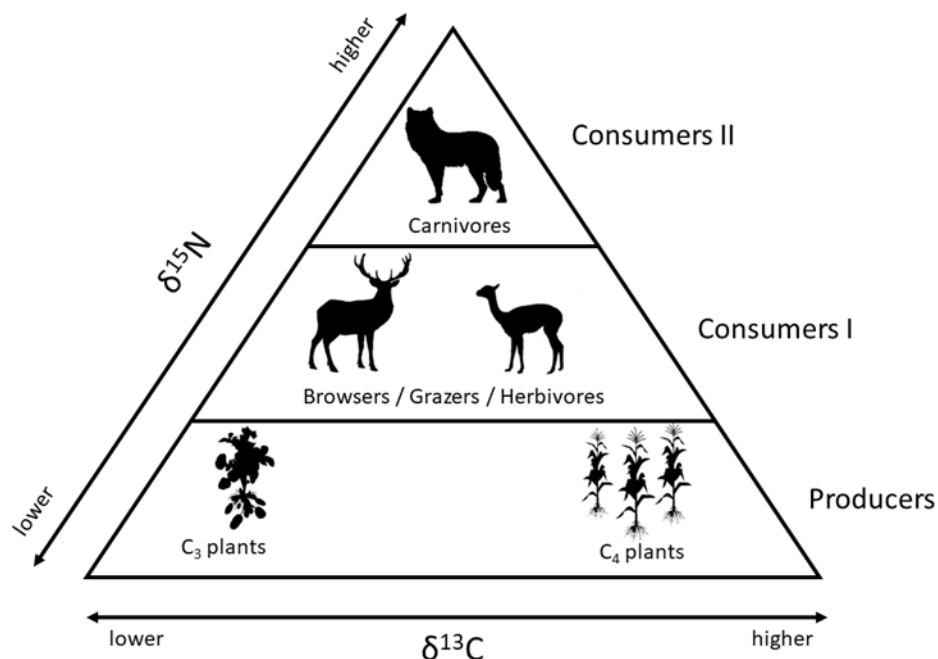


Figure 1.1. A food web graph that shows $\delta^{13}\text{C}$ on the x-axis and $\delta^{15}\text{N}$ on the y-axis with the lower tier representing producers, middle tier representing herbivores, and the top tier, or top of the food chain as carnivores.

Carbon and nitrogen isotope values are also adjusted for fractionation offsets like trophic fractionation (TEF), elevation, Suess effect for modern samples, and bone to tissue fractionation (DeNiro and Epstein 1978; Fernandes et al. 2012; O'Connell et al. 2012). This chapter will infer the ancient diets of populations from the Archaic Period, Formative Period, Tiwanaku Period, and Post Tiwanaku Period (see Table 4.1) by plotting and comparing human carbon and nitrogen isotope values with values from food resources. You are what you eat; the closer the human isotope values in black triangles are to the respective food resources' crosshairs, which represent the average of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, the more likely it is that that specific cultural period population are eating. Again,

the Archaic Period populations will only be compared to wild resources while other cultural periods that utilize some form of agropastoralism are compared to domesticated resources. Figures of each biplot are made using R, a statistical program, and a Bayesian mixing model package within R, MixSIAR, is also implemented to produce percentages of food types being consumed (Cheung and Szpak 2021; Stock et al. 2018).

Table 4.1. A simplified table derived from Watson and Haas 2017; cultural periods with associated subsistence strategy, time span in years cal. BP, and average stable carbon and nitrogen isotope values.

Cultural Period	Subsistence Strategy	Time (ka)	$\delta^{15}\text{N}$ average (‰)	$\delta^{13}\text{C}$ average (‰)
Archaic	foraging	~9.0–3.5ka	3.4	-24.19
Formative	early agropastoralism	3.5–1.5ka	4.88	-23.39
Tiwanaku	agropastoralism	1.5–0.75ka	5.22	-20.84
Post Tiwanaku/Late Intermediate Period	agropastoralism	0.75–0.38ka	7.28	-22.83

Lake Levels Analysis

Lake sediment cores were taken from the smaller lake of Lake Titicaca, Lake Wiñaymarka, where radiocarbon dates of each sediment layer were extracted from associated aquatic gastropods and charcoal (Guédron et al. 2023). Stable organic carbon isotopes and lake diatom species analyses were used to recreate past lake levels (Guédron et al. 2023). Table 4.2 below represents lake level data with the different cultural periods.

Table 4.2. Lake Wiñaymarka lake levels through time (year cal. BP) (Guédron et al.

2023) in conjunction to cultural periods.

Cultural Period	Date Range (years cal. BP)	Lake level average (masl)	Lake level standard deviation
Archaic	7950-3450	3797.8	9.77
Formative	3450-1450	3800	1.82
Tiwanaku	1450-700	3803.9	1.31
Post Tiwanaku	700-500	3803.6	0.9

Lake Levels vs. Stable Isotopes Analysis

A linear regression model was run using R to determine whether or not there was a statistically significant relationship between the fluctuating paleolake levels and ancient human diets. Lake level averages were compared to stable carbon and nitrogen isotopes for each cultural period and population in this linear model.

RESULTS

This results section will first present the stable isotopes results of ancient human diets from the Archaic Period, Formative Period, Tiwanaku Period, and the Post Tiwanaku Period. Bayesian mixing model results from MixSIAR are presented in each stable carbon and nitrogen isotope figures in the upper right corner. Results of the linear model are presented last of lake level proxies to assess the effect of paleoclimate on ancient human diets.

Archaic Period (9.0-3.5ka)

The environmental baseline dataset that is used to plot against the ancient forager population contains only wild resources—96 large mammals, 84 C₃ plants, 29 C₄ plants, and 10 fish samples. Soro Mik'aya Patjxa and Wilamaya Patjxa individuals (n=21) all cluster closely together, mostly with the 84% C₃ plants (73-92% range), 9% large terrestrial mammal like wild deer and wild camelids (0-24%), 4% freshwater fish (0-13%), and 2% C₄ plants (0-6%) (see Figure 4.2) (Chen et al. 2024).

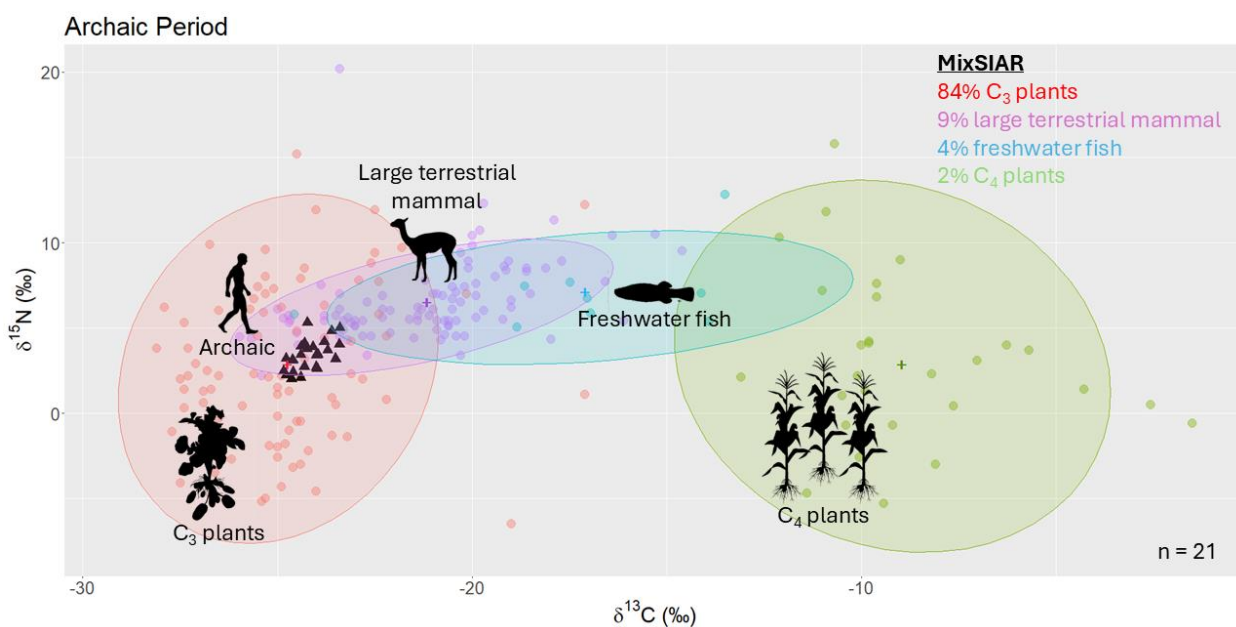


Figure 4.2. A stable carbon and nitrogen isotope biplot with Archaic foragers plotted against wild Andean resources. Crosshairs with their respective colors are $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ averages of baseline resources. MixSIAR results of consumption percentages on the upper left corner and sample size number on the bottom right corner.

Formative Period (3.5-1.5ka)

The environmental baseline dataset used in this comparison and all others following this cultural period consists of both wild and domesticated Andean resources—142 C₃ plants, 56 C₄ plants, 10 freshwater fish, and 96 large terrestrial mammals. The stable carbon and nitrogen isotope results of 40 human individuals reveal an expanding dietary breadth that consisted of 47% C₃ plants (33-63% range), 40% large terrestrial mammals (9-62%) that were most likely domesticated camelids like alpacas and llamas, 9% freshwater fish (0-29%), and 2% C₄ plants (0-8%) (see Figure 4.3).

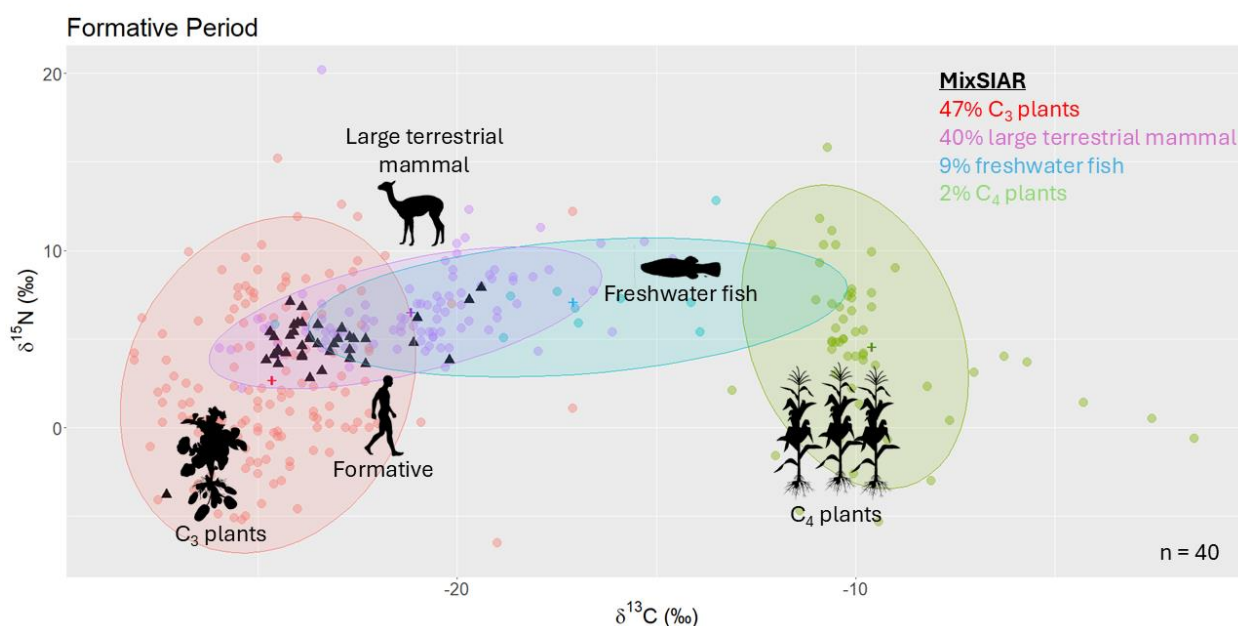


Figure 4.3. A stable carbon and nitrogen isotope biplot with Formative early agropastoralists plotted against wild and domesticated Andean resources. Crosshairs with their respective colors are $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ averages of baseline resources. MixSIAR results of consumption percentages are on the upper left corner and sample size number on the bottom right corner.

Tiwanaku Period (1.5-0.75ka)

The environmental dataset used for this comparison is a mixture of wild and domesticated Andean resources. The stable isotope results of 65 human individuals from the Tiwanaku Period show high diet diversity among the population (see Figure 4.4). MixSIAR results also reveal that while many individuals during this cultural period are still consuming C₃ plants though at 34% (21-48%), there is an addition of 20% (1-48%) of freshwater fish implemented into the diet, with 7% (0-15%) C₄ plants, and mostly large terrestrial mammals at 40% (6-64%).

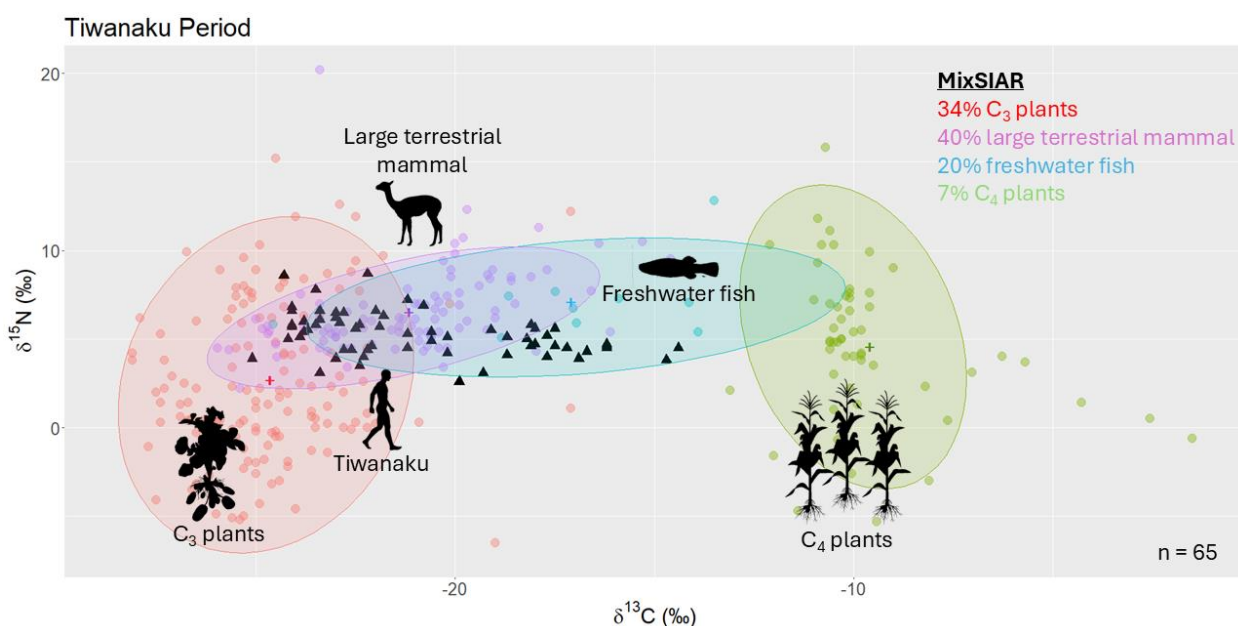


Figure 4.4. A stable carbon and nitrogen isotope biplot with Tiwanaku agropastoralists plotted against wild and domesticated Andean resources. Crosshairs with their respective colors are $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ averages of baseline resources. MixSIAR results of consumption percentages on the upper left corner and sample size number on the bottom right corner.

Post Tiwanaku Period (0.75-0.38ka)

The environmental dataset used for this comparison is a mixture of wild and domesticated Andean resources. Stable isotopes results from 16 human individuals from the Post Tiwanaku or Late Intermediate Period reflect a mostly constrained diet of C₃ plants at 16% (1-44%) of the diet, 65% (16-92%) large terrestrial mammal, 14% (1-54%) freshwater fish, and 2% (1-54%) C₄ plants (see Figure 4.5).

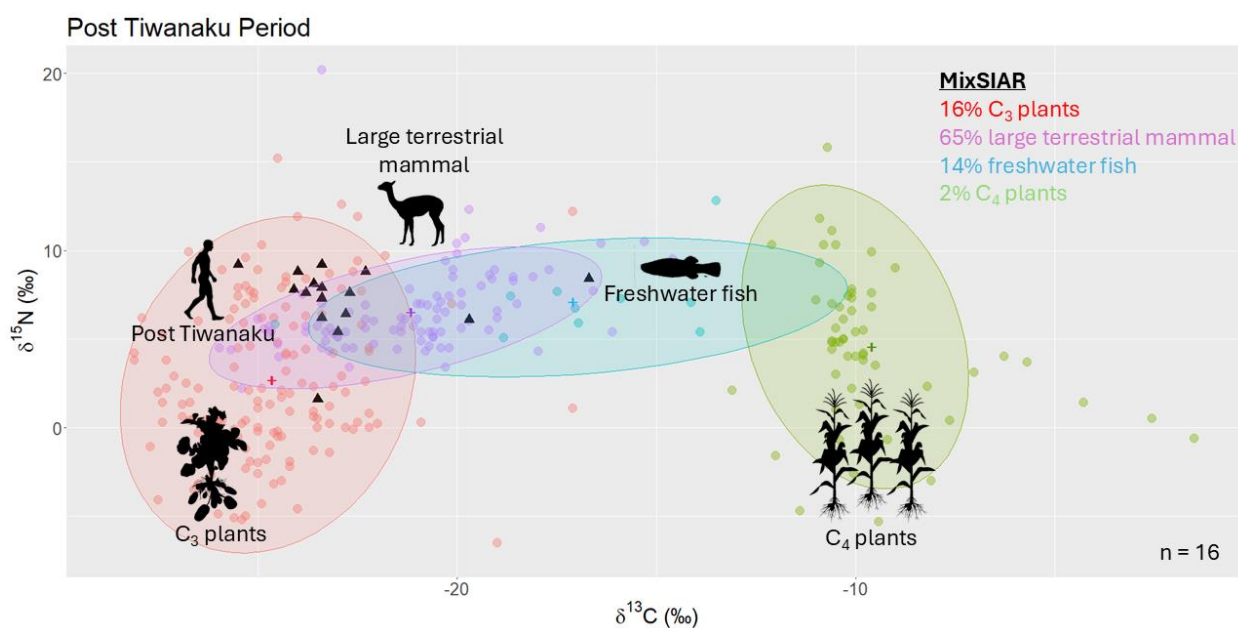


Figure 4.5. A stable carbon and nitrogen isotope biplot with Post Tiwanaku agropastoralists plotted against wild and domesticated Andean resources. Crosshairs with their respective colors are $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ averages of baseline resources. MixSIAR results of consumption percentages on the upper left corner and sample size number on the bottom right corner.

Lake Levels vs. Diet Results

Lake sediment cores from Lake Wiñaymarka reveal that lake levels fluctuated through time (Guédron et al. 2023) (see Figure 4.8). The highest lake level is 3814.1 meters above sea level while the lowest and most shallow lake level is 3783.5 meters above sea level, both during the Archaic Period. Observations of lake levels in relation to ancient diet include a second y-axis for stable nitrogen (see Figure 4.6) and stable carbon (see Figure 4.7) isotopes of each cultural periods' population. Both Archaic Period and Formative Period populations suggest relatively stable, but constrained diets based on the similar positions on Figures 4.6 and 4.7. Instead, changes to diet and diet diversity can be seen in the Tiwanaku Period and Post Tiwanaku Period populations for both stable nitrogen and carbon isotopes. Diet diversity can best be observed in the Tiwanaku Period population (Figure 4.4) where the average stable nitrogen isotopes are low (Figure 4.6), but the average stable carbon isotopes are high (Figure 4.7); the Post Tiwanaku Period population's (Figure 4.5) stable carbon and nitrogen isotopes results are reversed.

Linear regression of lake level averages and total stable carbon and nitrogen isotopes suggests that while stable nitrogen isotopes in conjunction with lake level averages were not statistically significant with a p-value of 0.3701, the stable carbon isotopes in relation to the lake level averages were, in fact, statistically significant with a p-value well below the 0.05 threshold. Although the stable nitrogen isotopes linear regression was not statistically significant, the coefficients still infer a tentative, positive relationship. However, this positive trend can be observed in the linear regression analysis of stable carbon isotopes for all individuals in their respective cultural period.

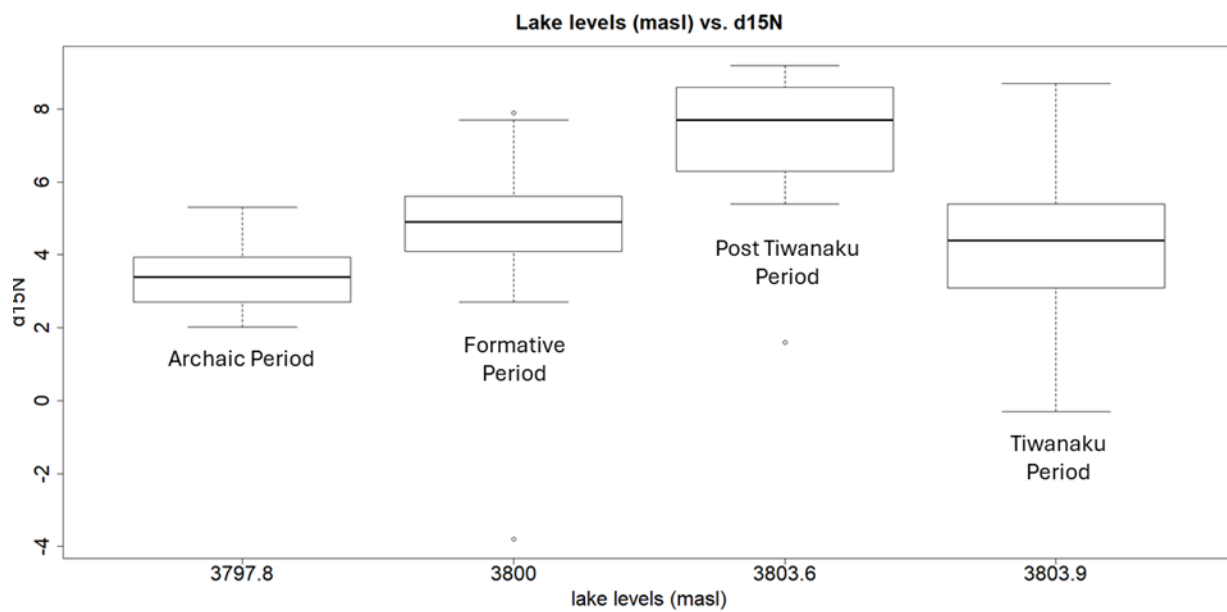


Figure 4.6. Lake level averages (x-axis) from 3783-3814 masl at Lake Wiñaymarka through time with stable nitrogen of each cultural periods' populations (y-axis).

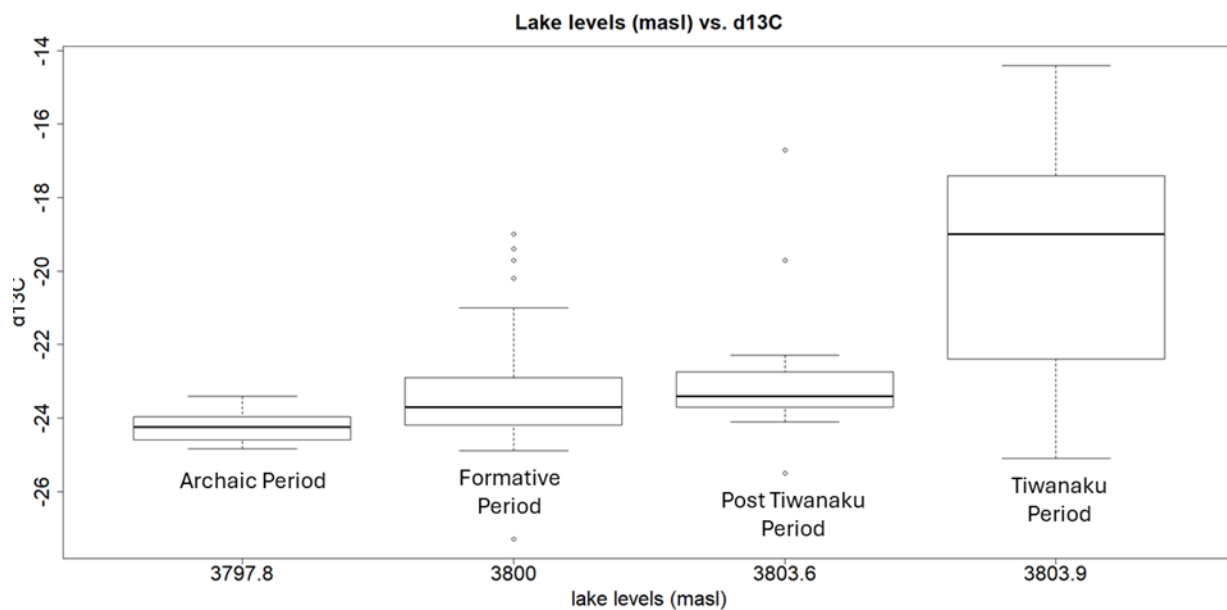


Figure 4.7. Lake level averages (x-axis) from 3783-3814 masl at Lake Wiñaymarka through time with stable carbon of each cultural periods' populations (y-axis).

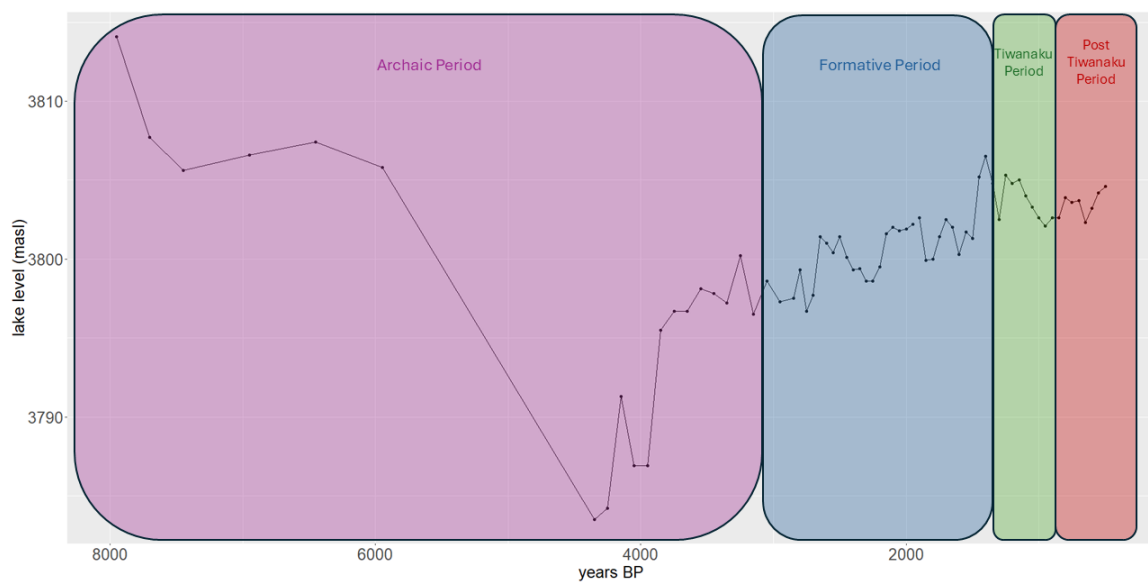


Figure 4.8. Lake Titicaca lake levels across time with data from Guédron et al. 2023 with highlighted cultural periods.

DISCUSSION

Stable isotopic evidence of subsistence strategies changed over time in the Andean Altiplano from foraging to agropastoralism. The transition from foraging to agropastoralism was made possible due to the changing climate and environment after the termination of the Younger Dryas (Kennett and Winterhalder 2006; Rankoana 2017; Savo et al. 2016). With this change in subsistence economies, some wild food resources were eventually domesticated through intensification, like tubers, chenopods, and camelids, with more stable and high lake levels (Kennett and Winterhalder 2006; Morgan 2015).

This chapter specifically explored how ancient diets changed in relation to climatic and environmental shifts over time in the Andean Altiplano. I hypothesized that not only will subsistence strategies change from foraging to agropastoralism based on climate variability and environmental changes, but diet diversity will also fluctuate based on these climatic and environmental drivers. It was predicted in this chapter that higher isotope values deriving ancient diet were a result of higher precipitation based on past lake levels from Lake Titicaca.

Archaic Period (9.0-3.5ka)

This study found a lack of diet diversity with early highland foragers during the Archaic Period despite having some of the highest lake levels during that time period. Previous archaeological and stable isotopic studies reveal that these Archaic Period foragers were permanently settled in the highlands (Haas et al. 2017). Although previous paleoecological studies on the south-central Andes reveal that the paleoenvironment and paleoclimate during the Archaic Period was semi-arid and harsh, early foragers still occupied the highlands (Baied and Wheeler 1993). Bioarchaeological research reveals that the Soro Mik'aya Patjxa and Wilamaya

Patjxa individuals did not suffer from malnutrition and that they were also mostly consuming wild tubers based on dental wear (Watson and Haas 2017). Average stable carbon and nitrogen isotopes of both Archaic Period sites suggests a consistent diet of mostly C₃ plants like tubers. Despite the higher lake levels during this time, freshwater fish did not take up a majority of their diet according to stable isotope analysis and MixSIAR results.

Formative Period (3.5-1.5ka)

Formative Period individuals' diets also mostly remained constant with the main subsistence being, again, C₃ plants like tubers, and some large terrestrial mammals. Although lake levels were at its lowest towards the end of the Archaic Period, it increased towards the start of the Formative Period where early agropastoralism began to emerge in the Andean Altiplano (Baied and Wheeler 1993; Capriles et al. 2021; Miller et al. 2010). Higher lake levels infer more precipitation in the highlands, making the environment more arable and hospitable as past humans continue to intensify specific food resources like potatoes, quinoa, and camelids (Hastorf 2008).

Tiwanaku Period (1.5-0.75ka)

We see the widest diet breadth and highest diet diversity with the Tiwanaku population during that period (Figure 4.3). The average stable carbon isotope of Tiwanaku individuals suggest the introduction of some C₄ plant like maize into the diet (Figure 4.7). Slightly lower average nitrogen isotopes of this population also suggests that freshwater fish may not have contributed much into the overall diet. However, MixSIAR dietary proportions reveal that meat, like fish and large terrestrial mammals, were dominant in the diet. Diet diversity may have

expanded during the Tiwanaku Period due to trading different food resources from the lowlands to the highlands, like maize as previously mentioned (Bandy 2004; Stanish et al. 2010). However, despite trading maize in from the lowlands, few individuals during the Tiwanaku Period seemed to have consumed maize (Figure 4.4). This may suggest that maize preparation and consumption may have been strictly for the elite or upper class, or it was consumed in small enough quantities to have not made a drastic difference isotopically.

While maize may have been limited to specific, elite individuals for liminal rituals in the Tiwanaku state, the introduction of this C₄ plant resource is still considered culturally significant even if it may not be isotopically significant. However, the introduction of maize into the overall Tiwanaku population diets was still significant enough to increase the range of $\delta^{13}\text{C}$, thus resulting in higher diet diversity when compared to other cultural periods.

Post Tiwanaku Period (0.75-0.38ka)

After the disintegration of the Tiwanaku state into smaller, competing polities in the Andean Altiplano, diet diversity was constrained with few outliers. While small-scale agropastoralism was still practiced during this period, trade between the lowlands and highlands seemed to have halted. This also suggests that maize is an even smaller percentage of the overall Post Tiwanaku diet. The average stable carbon isotopes of the Post Tiwanaku Period individuals dropped, while the average stable nitrogen isotopes are some of the highest. Lake levels during this period appear stable, potentially making freshwater fish and other edible aquatic resources a staple food source. However, the majority of the diet during this period consists of mostly large terrestrial mammals that were likely domesticated camelids with few individual outliers consuming C₃ plants and freshwater fish.

Overall Dietary Changes Through Time on the Andean Altiplano

Instead of seeing a progression of one food resource to another throughout the different cultural periods as many food resources were domesticated, we see that all populations were mostly consuming a variety of food resources regardless of lake levels through time like C₃ plants like tubers, large terrestrial mammals like camelids, freshwater fish from the lake, and C₄ plants like maize or kiwicha through time from the Archaic Period to the Post Tiwanaku Period. Recent paleoecological evidence from another study suggests that there were brief periods of dryness that suggested difficulties in continuing agropastoral practices (Arnold et al. 2021). This climatic and environmental mechanism resulted in the decline of the Tiwanaku polity where the main population of this initial state formation dispersed into smaller, competing groups.

However, lake levels do not appear to drastically change throughout time except between the Archaic Period and Formative Period where lake levels are at their lowest and diet breadth is slowly diversifying. Recent paleoclimate studies on precipitation and drought in the Andean Altiplano suggest that prolonged aridity can be tolerated without cultural changes (Ortloff and Kolata 1993; Rigsby et al. 2003). While many archaeological studies state that prolonged periods of drought resulted in the decline of the Tiwanaku state, some paleoecological studies counter that there were other sociopolitical mechanisms that ultimately resulted in the decline of the state (Arnold et al. 2021; Baied and Wheeler 1993; Guédron et al. 2023). Despite the decline of Tiwanaku, Post Tiwanaku Period populations were still consuming diverse foods with their main diet being large terrestrial mammals—likely camelids.

Previous archaeometric studies suggests the importance of C₃ plants, like tubers and geophytes, to heavily contribute to the diets of Archaic Period individuals (Chen et al. 2024). However, other archaeometric studies observing other cultural periods on the Altiplano suggest a more diverse range of diet of the food groups from this study (e.g. C₃ plants, large terrestrial

mammals, freshwater fish, and C₄ plants). This diachronic study reveals the gradual importance of meat in ancient diets over time. Stable isotopes and Bayesian mixing models reveal a preference for meat at higher percentages, more specifically, camelids, beginning in the Formative Period and onwards.

C₃ plants like tubers have paved the way for the intensification of a variety of other food resources, including large terrestrial mammals like camelids. While tubers and geophytes have dietary significance across time in the Andean Altiplano, camelids also have cultural significance. Many archaeological investigations have revealed an abundance of camelid motifs throughout the Altiplano ranging from mass camelid sacrifices to small, carved camelid figurines found in culturally significant underwater sites in Lake Titicaca (Baitzel and Trigo Rodríguez 2019; Delaere et al. 2019; Delaere and Capriles 2020; Dufour et al. 2020).

The findings from this investigation reveal that despite precipitation changes and possible brief dry spells on the Altiplano, diet remains mostly unaffected. Although there were significant dietary changes through time, there is no statistical correlation between diet and lake level changes. However, sample sizes remain small for each cultural period population, potentially affecting the statistical significance of diet and lake level changes. Future directions to improve our understanding of climate-diet interactions in the Andean Altiplano may include larger sample size of ancient humans from all cultural periods, including the Inca, and possibly a finer grain resolution of the changing lake levels.

Chapter 5

OVERALL CONCLUSIONS

The role that food and cuisine played on the highlands has a deep, rich, and complex history within Andean archaeology and ethnography. More specifically, wild and eventually domesticated geophytes played a crucial role in the sociopolitical dynamics of the south central Andean Altiplano. Stable carbon and nitrogen isotope analyses of human remains and Andean food resources gives us insight into some of the earliest interactions of people and the high altitude environment. Human behavioral ecology and some of its models provide an even greater insight into predicting what early humans on the Andean Altiplano were eating.

The first chapter of this dissertation offers new perspectives for this traditional narrative of meat-heavy diets as well as chenopod-camelid co-evolutionary dynamics. Rather, some C3 plants in the Andes, like tubers and other geophytes, played a significant role in early forager diets. Bioarchaeological evidence of ancient foragers from Soro Mik'aya Patjxa and Wilamaya Patjxa reveal regular tuber processing from wear on the lingual surface attrition of the maxillary anterior teeth (LSAMAT) (Watson and Haas 2017). While large terrestrial mammals like camelids and taruca were still being hunted based on the abundance of stone tools found associated with different individuals and the presence of burnt zooarchaeological remains, their contribution to overall diet seem little when compared to C3 plants from stable carbon and nitrogen isotope analyses. Instead of a chenopod-camelid domestication mutualism, there should also be a tuber-camelid mutualism narrative for the eve of agropastoralism on the Andean Altiplano.

Further insight into the same ancient foragers at Soro Mik'aya Patjxa and Wilamaya Patjxa also reveals overall longer breastfeeding times and later weaning as discussed in the

second chapter. While it is still unknown whether or not individuals from these archaeological sites have already genetically adapted to highland living, there is some clarity from stable nitrogen isotopes of first molar serial sections that infant and childhood diets of these individuals relied on prolonged breastfeeding and delayed weaning. Even early anthropological studies on contemporary Indigenous highland communities shows later weaning times between 3 to 4 years old when compared to their lowland counterparts at 1 to 2 years old (Halcrow et al. 2017; Sellen 2009; Vitzthum 2013, 1992). One particular study investigated the “weaning food availability” hypothesis which states that if proper weaning foods were readily available, then mothers would choose to begin the weaning process earlier rather than prolong breastfeeding (Sellen and Smay 2001). However, many studies on breastfeeding and weaning times in harsh environments like living in high-altitude show the preference, and perhaps necessity, of prolonging breastfeeding despite having weaning foods available (King et al. 2018; Ugwu 2009; Vitzthum 2013, 1992).

Although there are little studies done on weaning foods in the high Andes, one could claim the importance of tubers in the diets of individuals at any age (Ugwu 2009). In this dissertation, the first paper reveals the unexpected importance of tubers through stable isotope analysis, bioarchaeological evidence, and paleoethnobotanical evidence as well. It is possible that Archaic Period individuals from Soro Mik’aya Patjxa and Wilamaya Patjxa were prolonging breastfeeding while also very slowly weaning their offspring on wild, cooked, mashed tubers.

However, it is also important to note that while these Archaic Period individuals have permanently occupied the highlands, the harsh high-altitude still proves to be challenging according to early childhood diets and late weaning times. When comparing the ancient Andean populations to contemporary Quechua and Aymara groups, individuals from the Archaic Period sites weaned their offspring off breastmilk at even later ages (i.e., ~5-6 years old). Later weaning during the Archaic Period could have been a cultural adaptation to high-altitude living, ensuring infant survivability through prolonged breastfeeding. While the first paper of this dissertation

makes broad, general observations and interpretations on early highland forager diets before the domestication process, the second paper reveals prolonged breastfeeding times to ensure infant survivability and also implies tubers as possible weaning food.

The third paper of this dissertation investigates ancient diet through time on the Andean Altiplano in conjunction with lake levels from Lake Titicaca inferring past precipitation. Results from this study suggest that lake levels of Lake Titicaca have been generally stable throughout time with higher lake level average during the Tiwanaku Period and lower lake level average during the Archaic Period. While the overall diet from different cultural periods were variable, especially during the Tiwanaku Period, there seemed to be a heavy reliance on C3 plants in the earlier periods and a heavy reliance on large terrestrial mammals, likely camelids, in the later periods based on Bayesian mixing models.

The Archaic Period reveals a relatively strict diet that mostly consists of C3 plants and some wild, large terrestrial mammal according to stable carbon and nitrogen isotopes, zooarchaeological analyses, and paleoethnobotanical analyses. Although lake levels were at their lowest during the Archaic Period, ancient forager diets remained fairly consistent with C3 plants. The Formative Period individuals exhibited some diversity in diet with the intensification of camelids and surprisingly some freshwater fish based on recovered zooarchaeological fish remains despite low lake levels (Capriles et al. 2008, 2014). The Tiwanaku Period, while temporally short compared to other cultural periods, exhibited the highest diet diversity and diet breadth with the highest lake level average. While many food resources on the Andean Altiplano are domesticated at this point, domesticated food resources from the lowlands are also being traded and brought up to the Altiplano like maize (Berryman 2010; Browman 1981). Although much archaeological research focuses on the importance of maize during the Tiwanaku Period, Bayesian mixing models suggest that maize may not be an important contribution to most individuals' diets. Instead, maize brought up into the highlands may have been used to brew

chicha—a fermented maize beer—that is most likely consumed during ritual ceremonies for elite members of the Tiwanaku state (Goldstein and Coleman 2004).

Despite the high diversity in diet during the Tiwanaku Period, many other archaeological or paleoecological studies observing lake sediment cores revealed prolonged periods of drought that eventually led to a cultural transition and the dispersal of the Tiwanaku state (Arnold et al. 2021; Bruno et al. 2021; Janusek 2004; Ortloff and Kolata 1993; Weide et al. 2017; Williams 2010). However, this dissertation observed minimal changes to lake levels during the Tiwanaku Period going into the Post Tiwanaku Period. A lack of lake level changes may not necessarily suggest prolonged drought. One study suggests sociocomplexity and population demographics to be other major drivers of the decline of state formations like Tiwanaku (Lima et al. 2023).

Cultural transitions, shifts, or cultural dispersals in other areas of the world, like the classic Maya state in Central America, is often associated with climatic instability or climatic extremes (e.g., drought, floods) (Budja 2015; Douglas et al. 2016; Drysdale et al. 2006). Perhaps more frequent climatic instability towards the end of the Tiwanaku Period also suggested sociopolitical instability that continued on during the Post Tiwanaku Period, or the Late Intermediate Period.

The Post Tiwanaku Period individuals reveal mostly large terrestrial mammal diet. The lack of C4 plants, like maize, in the overall diet of the Post Tiwanaku Period population may insinuate that trade between the highlands and lowlands had halted after the dispersal of the Tiwanaku state. Despite this stability in lake levels during the Post Tiwanaku Period, archaeological evidence from other studies suggest this cultural period have been filled with warfare and violence (Langlie and Arkush 2016; Torres-Rouff 2020). Many human burials associated with the Post Tiwanaku Period, or Late Intermediate Period, have an abundance of injuries like blunt force trauma to the skull (Arkush et al. 2023; McCool et al. 2021). Daily violence and warfare during this cultural period could also explain the unusually high stable

nitrogen isotopic values. While stable carbon and nitrogen isotopes show that camelids may have been the main diet of these individuals, contemporary studies on daily fasting or starvation could also result in slightly higher overall nitrogen (Doi et al. 2017). On the contrary, high nitrogen could also be the result of mostly consuming nitrogen-fixing beans, or the use of camelid dung as fertilizer for crops. Alternatively, a combination of the explanations above in Post Tiwanaku individuals could also result in high nitrogen too.

In this dissertation, I explored the ancient diets of pre-Hispanic populations on the Andean Altiplano and asked several questions: How were early ancient foragers on the highlands interacting with food resources (Chapter 1)? When were ancient highland foragers weaning their offspring off breastmilk and permanently onto solid foods (Chapter 2)? How have ancient diets changed in relation to climatic and environmental shifts over time on the Andean Altiplano (Chapter 3)?

Despite the variable paleoclimate and harsh semi-arid environment on the Andean Altiplano, early foragers who have permanently occupied the highlands have thrived through cultural adaptations like prolonged breastfeeding and having later weaning times, and eventual genetic adaptations like higher hemoglobin count (Aldenderfer 2003; Beall 2006, 2007; Bigham et al. 2013; Moore et al. 2011). Through time on the Andean Altiplano, ancient peoples intensified, consumed, and eventually domesticated several species native to the Andes that include potatoes, alpacas, llamas, quinoa, and beans. Many of these food resources that were domesticated are also considered drought-resistant resources, allowing people to continue shaping their surrounding environment despite highly variable or extreme climate conditions. Early climate-diet dynamics in the ancient Andes are only recently being studied using quantitative methods like stable carbon, nitrogen isotopes and lake level observations (Lima et al. 2023; Wilson et al. 2022). Further studies on these past interactions and dynamics can also provide beneficial knowledge for contemporary Indigenous communities, like the Quechua and Aymara,

where recent climate change have lowered lake levels and have affected agropastoral subsistence practices (Lozano-Povis et al. 2021).

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Appendix A

Supplementary Materials for Chapter 2

See Chen et al. 2024 for supplementary materials in supporting information section of published paper.

Appendix B

Supplementary Materials for Chapter 3

Supplemental Table 3.0. Serial sections of adult first molars with stable carbon and nitrogen isotope values per section. Some teeth sections had to be combined in order to meet weight requirements.

Tooth	Section	Year	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	%C	%N	C:N ratio
WMP 1 LM1	H 1mm crown	1.169106	-19.01	8.38	15.22	5.36	3.311361
WMP 1 LM1	G 1mm	2.75	-19.39	7.94	11.21	3.85	3.395483
WMP 1 LM1	F 1mm	3.827882	-19.25	8.54	7.1	2.42	3.421367
WMP 1 LM1	E 1mm	4.905765	-19.59	7.34	3.99	1.18	*3.94318858842671
WMP 1 LM1	D 1mm	5.983647	-19.46	7.71	6.98	2.41	3.377498
WMP 1 LM1	C 1mm	7.061529	NA	NA	NA	NA	NA
WMP 1 LM1	B 1mm	8.139412	NA	NA	NA	NA	NA
WMP 1 LM1	A 1mm root	9.217294	-18.78	7.9	13.82	4.69	3.436306
WMP 4 RM1	E 2mm crown	0.038386	-18.55	11.91	20.35	7.04	3.37092
WMP 4 RM1	D 1mm	1.394193	-18.77	11.41	19.31	6.45	3.491236
WMP 4 RM1	C 1mm	2.75	-18.74	10.1	22.94	7.88	3.394876
WMP 4 RM1	B 1mm	5.020795	-18.73	9.62	15.22	5.32	3.336258

WMP 4 RM1	A 1mm root	7.291591	-19.1	9.31	11.49	3.9	3.435675
WMP 6 RM1	H 1mm crown	0.035424	-18.49	9.98	16.39	5.6	3.413089
WMP 6 RM1	G 1mm	1.392712	-18.84	9.49	10.94	3.73	3.420307
WMP 6 RM1	F 1mm	2.75	-18.79	9.66	14.37	4.87	3.440998
WMP 6 RM1	E 1mm	3.983054	-18.46	10.76	36.83	12.09	3.552484
WMP 6 RM1	D 1mm	5.00931	-18.81	9.86	11.42	3.78	3.523149
WMP 6 RM1	C 1mm	6.138966	-19.72	7.58	7.43	2.47	3.507911
WMP 6 RM1	B 1mm	7.268621	NA	NA	NA	NA	NA
WMP 6 RM1	A 1mm root	8.398276	-19.12	9.91	16.65	5.38	3.609014
WMP 8 RM1	F 2mm crown	1.63734	-18.6	11.03	17.13	5.65	3.53562
WMP 8 RM1	E 1mm	2.75	-19.02	9.47	11.24	3.84	3.413436
WMP 8 RM1	D 1mm	4.241587	-18.7	10.8	14.74	5.06	3.397063
WMP 8 RM1	C 1mm	5.733174	-19.56	8.26	7.45	2.5	3.475145
WMP 8 RM1	B 1mm	7.22476	NA	NA	NA	NA	NA
WMP 8 RM1	A 1mm root	8.716347	-19.2	8.63	11.79	4.09	3.361609
WMP 9 LM1	I 3mm crown	2.006789	-18.16	11.33	32.29	11.4	3.303086
WMP 9 LM1	H 1mm	2.75	-19.01	10.63	7.88	2.73	3.366047
WMP 9 LM1	G 1mm	3.675153	-18.94	10.17	13.13	4.53	3.38005
WMP 9 LM1	F 1mm	4.600306	-18.85	9.21	7.05	2.45	3.355673
WMP 9 LM1	E 1mm	5.52546	-19.01	9.35	9.16	3.18	3.359116
WMP 9 LM1	D 1mm	6.450613	-19.11	9.29	8.28	2.86	3.376144
WMP 9 LM1	C 1mm	7.375766	-18.97	7.73	8.16	2.96	3.214808
WMP 9 LM1	B 1mm	8.300919	-18.55	8.91	11.33	4.1	3.222573
WMP 9 LM1	A 1mm root	9.226073	-18.97	7.7	12.43	4.46	3.250072

SMP 4 RM1	F 2mm crown	1.320865	-18.72	9.96	25.8	9.37	3.210974
SMP 4 RM1	E 1mm	2.75	-19.11	9.05	8.93	3.15	3.30596
SMP 4 RM1	D 1mm	4.079909	-19.32	8	7.93	2.8	3.30272
SMP 4 RM1	C 1mm	5.409818	-19.72	8.37	6.96	2.41	3.36782
SMP 4 RM1	B 1mm	6.739727	-19.2	9.05	13.93	4.89	3.321995
SMP 4 RM1	A 1mm root	8.069636	-19.28	8.67	16.6	5.81	3.331874
SMP 7 RM1	H 1mm crown	0.811744	-18.3	9.79	NA	NA	NA
SMP 7 RM1	G 1mm	1.780872	NA	NA	NA	NA	NA
SMP 7 RM1	F 1mm	2.75	-17.98	9.51	16.83	6.17	3.180941
SMP 7 RM1	E 1mm	4.056648	-18.02	7.37	11.26	4.15	3.164076
SMP 7 RM1	D 1mm	5.363296	-18.04	8.07	10.93	4.01	3.178575
SMP 7 RM1	C 1mm	6.669944	NA	NA	NA	NA	NA
SMP 7 RM1	B 1mm	7.976592	NA	NA	NA	NA	NA
SMP 7 RM1	A 1mm root	9.283239	-18.01	8.34	16.42	6.04	3.170245
SMP 8 LM1	K 2mm crown	2.75	-18.91	9.11	15.21	5.54	3.201667
SMP 8 LM1	J 1mm	3.390043	-19.02	8.5	13.97	5.05	3.22598
SMP 8 LM1	I 1mm	4.030086	-18.91	9.04	17.27	6.19	3.253556
SMP 8 LM1	H 1mm	4.670129	-19.4	7.53	7.03	2.48	3.305676
SMP 8 LM1	G 1mm	5.310173	-19.61	7.84	4.76	1.63	3.405462
SMP 8 LM1	F 1mm	5.950216	-19.49	7.23	8.66	3.05	3.311118
SMP 8 LM1	E 1mm	6.590259	-19.53	7.61	11.52	4.05	3.317066
SMP 8 LM1	D 1mm	7.230302	-19.44	7.63	9.29	3.28	3.302924
SMP 8 LM1	C 1mm	7.870345	-19.49	8.2	12.01	4.23	3.311001
SMP 8 LM1	B 1mm	8.510388	NA	NA	NA	NA	NA

SMP 8 LM1	A 1mm root	9.150431	-19.85	8.42	10.01	3.41	3.423232
SMP 11 RM1	K 1mm crown	0.04194	-19.04	8.37	26.26	9.34	3.278721
SMP 11 RM1	J 1mm	0.944627	-19.08	9.39	29.47	10.31	3.333329
SMP 11 RM1	I 1mm	1.847313	-19.06	9.06	32.68	11.74	3.246165
SMP 11 RM1	H 1mm	2.75	-19.2	8.95	19.21	6.75	3.318794
SMP 11 RM1	G 1mm	3.598291	-19.2	9.4	18.16	6.34	3.340283
SMP 11 RM1	F 1mm	4.446582	-19.3	9.76	22.28	7.83	3.318257
SMP 11 RM1	E 1mm	5.294873	-19.38	10.15	13.87	4.66	3.470941
SMP 11 RM1	D 1mm	6.143164	-19.03	10.04	30.72	11.35	3.156327
SMP 11 RM1	C 1mm	6.991455	-18.99	10.49	36.22	13.48	3.133395
SMP 11 RM1	B 1mm	7.839745	-18.87	10.48	32.37	11.62	3.248577
SMP 11 RM1	A 1mm root	8.688036	-19.17	10.73	38.51	13.23	3.394457
SMP 12 RM1	L 2mm crown	1.60235	-18.28	8.35	21.13	7.65	3.22103
SMP 12 RM1	K 1mm	2.75	-18.39	8.13	19.9	7.11	3.263925
SMP 12 RM1	J 1mm	3.681723	-18.67	8.09	15.2	5.48	3.234593
SMP 12 RM1	I 1mm	4.318362	-18.89	7.75	15.14	5.44	3.245515
SMP 12 RM1	H 1mm	5.102543	-19.07	7.81	7	2.55	3.201213
SMP 12 RM1	G 1mm	5.886723	-19	7.18	5.61	2.03	3.222727
SMP 12 RM1	F 1mm	6.670904	-18.74	6.77	6.56	2.38	3.214279
SMP 12 RM1	E 1mm	7.455085	-18.44	9.38	9.9	3.44	3.356089
SMP 12 RM1	D 1mm	8.239266	-18.3	9.14	7.83	2.78	3.284533
SMP 12 RM1	C 1mm	9.023447	-18.26	9.65	13.7	4.83	3.30773
SMP 12 RM1	B 1mm	9.807628	-18.35	8.47	12.13	4.41	3.20759
SMP 12 RM1	A 1m root	10.59181	-18.57	9.63	14.13	4.82	3.418628

Code Used for Analyses

R Code. The following code replicates the stable carbon and nitrogen isotopes analyses of Chapter 3 on breastfeeding and weaning times of Archaic Period individuals from Soro Mik'aya Patjxa and Wilamaya Patjxa.

```

---
title: "S3_RCode"
author: "Jennifer Chen"
date: "2024-09-30"
output: word_document
---

###SMP11 RM1 (anomaly)
SMP11RM1<-read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/Patjxa
Teeth/SMP11 RM1.csv")
SMP11RM1
names(SMP11RM1)[1]<-"tooth"
names(SMP11RM1)[5]<-"d15N"
SMP11RM1

#graphing teeth by nitrogen
library(ggplot2)
SMP11RM1N<-ggplot(data=SMP11RM1, aes(x=year, y=d15N, group=1))
SMP11RM1N
SMP11RM1nitrogen<-ggplot(data=SMP11RM1, aes(x=year, y=d15N,
group=1))+
  geom_point(size=5)+
  labs(title="SMP11 RM1 Nitrogen")+
  theme(axis.text = element_text(size = 25))+
  geom_vline(xintercept=2.75, color="chartreuse4")+
  geom_errorbar(aes(xmax=6.34, xmin=2.5, y=9.71),
color="chartreuse4")+
  geom_hline(yintercept=9.43, color="purple")+
  geom_smooth(method="lm", se=FALSE, fill=NA,
              formula=y~poly(x, 4), color="deepskyblue")
SMP11RM1nitrogen
#graphing teeth by carbon
SMP11RM1C<-ggplot(data=SMP11RM1, aes(x=year, y=d13C, group=1))
SMP11RM1carbon<-SMP11RM1C+
  geom_point()+
  geom_line()+
  labs(title="SMP 11 RM1 Carbon")
SMP11RM1carbon
ggarrange(SMP11RM1nitrogen, SMP11RM1carbon)

###WMP8 RM1

```

```

WMP8RM1<-read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/Patxja
Teeth/WMP8 RM1.csv")
WMP8RM1
names(WMP8RM1)[1]<-"tooth"
WMP8RM1
#graphing by nitrogen
library(ggplot2)
WMP8RM1N<-ggplot(data=WMP8RM1[!is.na(WMP8RM1$d15N)],,
                 aes(x=year, y=d15N, group=1, na.rm=FALSE))
WMP8RM1nitrogen<-WMP8RM1N+
  geom_point(na.rm=TRUE, size=5)+
  labs(title="WMP8 RM1 Nitrogen")+
  theme(axis.text = element_text(size = 25))+
  geom_errorbar(aes(xmax=7.88, xmin=2.23, y=9.64),
color="chartreuse4")+
  geom_vline(xintercept=7.537, color="red")+
  geom_vline(xintercept=5.73, color="chartreuse4")+
  geom_smooth(method="lm", se=FALSE, fill=NA,
              formula=y~poly(x, 4), color="deepskyblue")
WMP8RM1nitrogen
#graphing by carbon
WMP8RM1C<-ggplot(data=WMP8RM1[!is.na(WMP8RM1$d13C)],,
                 aes(x=year, y=d13C, group=1, na.rm=FALSE))
WMP8RM1carbon<-WMP8RM1C+
  geom_point()+
  geom_line()+
  labs(title="WMP8 RM1 Carbon")
ggarrange(WMP8RM1nitrogen, WMP8RM1carbon)

###WMP6 RM1
WMP6RM1<-read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/Patxja
Teeth/WMP6 RM1.csv")
WMP6RM1
#graphing by nitrogen
library(ggplot2)
WMP6RM1N<-ggplot(data=WMP6RM1[!is.na(WMP6RM1$d15N)],,
                 aes(x=year, y=d15N, group=1, na.rm=FALSE))
WMP6RM1nitrogen<-WMP6RM1N+
  geom_point(na.rm=TRUE, size=5)+
  labs(title="WMP6 RM1 Nitrogen")+
  theme(axis.text = element_text(size = 25))+
  geom_errorbar(aes(xmax=6.79, xmin=1.95, y=9.61),
color="chartreuse4")+
  geom_vline(xintercept=7.135, color="red")+
  geom_vline(xintercept=6.14, color="chartreuse4")+
  geom_hline(yintercept=8.10, color="purple")+
  geom_smooth(method="lm", se=FALSE, fill=NA,
              formula=y~poly(x, 4), color="deepskyblue")
WMP6RM1nitrogen
#graphing by carbon
WMP6RM1C<-ggplot(data=WMP6RM1[!is.na(WMP6RM1$d13C)],,
                 aes(x=year, y=d13C, group=1, na.rm=FALSE))

```

```

WMP6RM1carbon<-WMP6RM1C+
  geom_point(na.rm=TRUE)+
  geom_line(na.rm=TRUE)+
  labs(title="WMP6 RM1 Carbon")
ggarrange(WMP6RM1nitrogen, WMP6RM1carbon)

###SMP12 RM1 (anomaly)
SMP12RM1<-read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/Patxja
Teeth/SMP12 RM1.csv")
SMP12RM1
#graphing by nitrogen
SMP12RM1N<-ggplot(data=SMP12RM1,
  aes(x=year, y=d15N, group=1, na.rm=FALSE))
SMP12RM1nitrogen<-SMP12RM1N+
  geom_point(na.rm=TRUE, size=5)+
  labs(title="SMP12 RM1 Nitrogen")+
  theme(axis.text = element_text(size = 25))+
  geom_errorbar(aes(xmax=8.08, xmin=4.44, y=8.36),
color="chartreuse4")+
  geom_vline(xintercept=5.702, color="red")+
  geom_vline(xintercept=5.10, color="chartreuse4")+
  geom_hline(yintercept=9.09, color="purple")+
  geom_smooth(method="lm", se=FALSE, fill=NA,
  formula=y~poly(x, 4), color="deepskyblue")
SMP12RM1nitrogen
#graphing by carbon
SMP12RM1C<-ggplot(data=SMP12RM1,
  aes(x=year, y=d13C, group=1, na.rm=FALSE))
SMP12RM1carbon<-SMP12RM1C+
  geom_point(na.rm=TRUE)+
  geom_line(na.rm=TRUE)+
  labs(title="SMP12 RM1 Carbon")
ggarrange(SMP12RM1nitrogen, SMP12RM1carbon)

###SMP8 LM1
SMP8LM1<-read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/Patxja
Teeth/SMP8 LM1.csv")
SMP8LM1
#graphing by nitrogen
SMP8LM1N<-ggplot(data=SMP8LM1,
  aes(x=year, y=d15N, group=1, na.rm=FALSE))
SMP8LM1nitrogen<-ggplot(data=SMP8LM1,
  aes(x=year, y=d15N, group=1, na.rm=FALSE))+
  geom_point(na.rm=TRUE, size=5)+
  labs(title="SMP8 LM1 Nitrogen")+
  geom_errorbar(aes(xmax=7.38, xmin=4.52, y=8.11),
color="chartreuse4")+
  theme(axis.text = element_text(size = 25))+
  geom_vline(xintercept=5.95, color="red")+
  geom_vline(xintercept=4.67, color="chartreuse4")+
  geom_hline(yintercept=8.47, color="purple")+
  geom_smooth(method="lm", se=FALSE, fill=NA,

```

```

        formula=y~poly(x, 4), color="deepskyblue")
SMP8LM1nitrogen
#graph by carbon
SMP8LM1C<-ggplot(data=SMP8LM1,
                 aes(x=year, y=d13C, group=1, na.rm=FALSE))
SMP8LM1carbon<-SMP8LM1C+
  geom_point(na.rm=TRUE)+
  geom_line(data=SMP8LM1[!is.na(SMP8LM1$d13C),], na.rm=TRUE)+
  labs(title="SMP8 LM1 Carbon")+
  theme(axis.text = element_text(size = 25))
SMP8LM1carbon
ggarrange(SMP8LM1nitrogen, SMP8LM1carbon)

###WMP9 LM1
WMP9LM1<-read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/Patxja
Teeth/WMP9 LM1.csv")
WMP9LM1
#graphing by nitrogen
library(ggplot2)
WMP9LM1N<-ggplot(data=WMP9LM1,
                 aes(x=year, y=d15N, group=1, na.rm=FALSE))
WMP9LM1nitrogen<-WMP9LM1N+
  geom_point(na.rm=TRUE, size=5)+
  labs(title="WMP9 LM1 Nitrogen")+
  theme(axis.text = element_text(size = 25))+
  geom_errorbar(aes(xmax=7.47, xmin=3.62, y=9.37),
               color="chartreuse4")+
  geom_vline(xintercept=7.38, color="chartreuse4")+
  geom_hline(yintercept=8.70, color="purple")+
  geom_smooth(method="lm", se=FALSE, fill=NA,
             formula=y~poly(x, 4), color="deepskyblue")
WMP9LM1nitrogen
#graphing by carbon
WMP9LM1C<-ggplot(data=WMP9LM1,
                 aes(x=year, y=d13C, group=1, na.rm=FALSE))
WMP9LM1carbon<-WMP9LM1C+
  geom_point(na.rm=TRUE)+
  geom_line(data=WMP9LM1[!is.na(WMP9LM1$d13C),], na.rm=TRUE)+
  labs(title="WMP9 LM1 Carbon")+
  theme(axis.text = element_text(size = 25))
WMP9LM1carbon
ggarrange(WMP9LM1nitrogen, WMP9LM1carbon)

###SMP4 RM1
SMP4RM1<-read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/Patxja
Teeth/SMP4 RM1.csv")
SMP4RM1
#graphing by nitrogen
library(ggplot2)
SMP4RM1N<-ggplot(data=SMP4RM1,
                 aes(x=year, y=d15N, group=1, na.rm=FALSE))
SMP4RM1nitrogen<-SMP4RM1N+

```

```

geom_point(na.rm=TRUE, size=5)+
labs(title="SMP4 RM1 Nitrogen")+
theme(axis.text = element_text(size = 25))+
geom_errorbar(aes(xmax=7.37, xmin=2.09, y=8.85),
color="chartreuse4")+
geom_vline(xintercept=4.221, color="red")+
geom_vline(xintercept=4.08, color="chartreuse4")+
geom_hline(yintercept=8.23, color="purple")+
geom_smooth(method="lm", se=FALSE, fill=NA,
             formula=y~poly(x, 4), color="deepskyblue")
SMP4RM1nitrogen

SMP4RM1nitrogennoline<-SMP4RM1N+
  geom_point(na.rm=TRUE)+
  geom_line(na.rm=TRUE)+
  labs(title="Chen SMP4 Nitrogen")+
  theme(axis.text = element_text(size = 25))
SMP4RM1nitrogennoline

#Canale results
Canale_SMP4RM1<-read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/Patxja
Teeth/Canale_SMP4_Tooth.csv")
Canale_SMP4RM1
Canale_SMP4RM1N<-ggplot(data=Canale_SMP4RM1,
  aes(x=year, y=d15N, group=1, na.rm=FALSE))
CanaleSMP4RM1Nitrogen<-Canale_SMP4RM1N+geom_point(na.rm=TRUE)+
  geom_line(na.rm=TRUE)+
  labs(title="Canale SMP4 Nitrogen")+
  theme(axis.text=element_text(size=25))

ggarrange(CanaleSMP4RM1Nitrogen, SMP4RM1nitrogennoline)

#graph by carbon
SMP4RM1C<-ggplot(data=SMP4RM1,
  aes(x=year, y=d13C, group=1, na.rm=FALSE))
SMP4RM1carbon<-SMP4RM1C+
  geom_point(na.rm=TRUE)+
  geom_line(na.rm=TRUE)+
  labs(title="SMP4 RM1 Carbon")+
  theme(axis.text = element_text(size = 25))
ggarrange(SMP4RM1nitrogen, SMP4RM1carbon)

###WMP4 RM1
WMP4RM1<-read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/Patxja
Teeth/WMP4 RM1.csv")
WMP4RM1
#graph by nitrogen
WMP4RM1N<-ggplot(data=WMP4RM1,
  aes(x=year, y=d15N, group=1, na.rm=FALSE))
WMP4RM1nitrogen<-WMP4RM1N+
  geom_point(na.rm=TRUE, size=5)+
  labs(title="WMP4 RM1 Nitrogen")+

```

```

    theme(axis.text=element_text(size=25))+
    geom_errorbar(aes(xmax=6.89, xmin=0.29, y=10.47),
color="chartreuse4")+
    geom_vline(xintercept=4, color="chartreuse4")+
    geom_hline(yintercept=9.45, color="purple")+
    geom_smooth(method="lm", se=FALSE, fill=NA,
                formula=y~poly(x, 4), color="deepskyblue")
WMP4RM1nitrogen
#graph by carbon
WMP4RM1C<-ggplot(data=WMP4RM1,
                aes(x=year, y=d13C, group=1, na.rm=FALSE))
WMP4RM1carbon<-WMP4RM1C+
    geom_point(na.rm=TRUE)+
    geom_line(data=WMP4RM1[!is.na(WMP4RM1$d13C),], na.rm=TRUE)+
    labs(title="WMP4 RM1 Carbon")+
    theme(axis.text=element_text(size=25))
WMP4RM1carbon
ggarrange(WMP4RM1nitrogen, WMP4RM1carbon)

###SMP7 RM1
SMP7RM1<-read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/Patxja
Teeth/SMP7 RM1.csv")
SMP7RM1
#graph by nitrogen
SMP7RM1N<-ggplot(data=SMP7RM1,
                aes(x=year, y=d15N, group=1, na.rm=FALSE))
SMP7RM1nitrogen<-SMP7RM1N+
    geom_point(na.rm=TRUE, size=5)+
    labs(title="SMP7 RM1 Nitrogen")+
    theme(axis.text=element_text(size=25))+
    geom_errorbar(aes(xmax=7.36, xmin=2.31, y=8.62),
color="chartreuse4")+
    geom_vline(xintercept=4.312, color="red")+
    geom_vline(xintercept=4.06, color="chartreuse4")+
    geom_hline(yintercept=8.02, color="purple")+
    geom_smooth(method="lm", se=FALSE, fill=NA,
                formula=y~poly(x, 4), color="deepskyblue")
SMP7RM1nitrogen
#graph by carbon
SMP7RM1C<-ggplot(data=SMP7RM1,
                aes(x=year, y=d13C, group=1, na.rm=FALSE))
SMP7RM1carbon<-SMP7RM1C+
    geom_point(na.rm=TRUE)+
    geom_line(data=SMP7RM1[!is.na(SMP7RM1$d13C),], na.rm=TRUE)+
    labs(title="SMP7 RM1 Carbon")+
    theme(axis.text=element_text(size=25))
SMP7RM1carbon
ggarrange(SMP7RM1nitrogen, SMP7RM1carbon)

###WMP1 LM1
WMP1LM1<-read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/Patxja
Teeth/WMP1 LM1.csv")

```



```

WMP1LM1
#graph by nitrogen
WMP1LM1N<-ggplot(data=WMP1LM1,
                 aes(x=year, y=d15N, group=1))
WMP1LM1nitrogen<-ggplot(data=WMP1LM1,
                        aes(x=year, y=d15N, group=1))+
  geom_point(na.rm=TRUE, size=5)+
  labs(title="WMP1 LM1 Nitrogen")+
  theme(axis.text=element_text(size=25))+
  geom_vline(xintercept=7.17, color="red")+
  geom_vline(xintercept=4.91, color="chartreuse4")+
  geom_errorbar(aes(xmax=7.68, xmin=3.09, y=7.97),
               color="chartreuse4")+
  geom_hline(yintercept=9.90, color="purple")+
  geom_smooth(method="lm", se=FALSE, fill=NA,
             formula=y~poly(x, 4), color="deepskyblue")
WMP1LM1nitrogen
#graph by carbon
WMP1LM1C<-ggplot(data=WMP1LM1,
                 aes(x=year, y=d13C, group=1, na.rm=FALSE))
WMP1LM1carbon<-WMP1LM1C+
  geom_point(na.rm=TRUE)+
  geom_line(data=WMP1LM1[!is.na(WMP1LM1$d13C)],, na.rm=TRUE)+
  labs(title="WMP1 LM1 Carbon")+
  theme(axis.text=element_text(size=25))
WMP1LM1carbon
ggarrange(WMP1LM1nitrogen, WMP1LM1carbon)

###plotting all graphs together in one figure
install.packages("gridExtra")
library(gridExtra)
install.packages("ggpubr")
library(ggpubr)

ggarrange(SMP4RM1nitrogen, SMP7RM1nitrogen, SMP8LM1nitrogen,
          SMP11RM1nitrogen,
          SMP12RM1nitrogen, WMP1LM1nitrogen, WMP4RM1nitrogen,
          WMP6RM1nitrogen,
          WMP9LM1nitrogen, WMP8RM1nitrogen)

```

Appendix C

Supplementary Materials for Chapter 4

Supplemental Table 4.0. A table containing human bone isotope samples, trophic fractionation offsets, and dietary isotopic values.

date	specimen	sex	age	d13C_collagen	d13C_TEF	d13C_diet	d15N_collagen	d15N_TEF	d15N_diet	source
Archaic	SMP 1	NA	child	-18.11	-5.5	-23.61	10.82	-6	4.82	Haas et al. 2017
Archaic	SMP 2	M	adult	-18.89	-5.5	-24.39	9.93	-6	3.93	Haas et al. 2017
Archaic	SMP 3	F	adult	-18.01	-5.5	-23.51	9.19	-6	3.19	Haas et al. 2017
Archaic	SMP 4	NA	adolescent	-19.28	-5.5	-24.78	8.23	-6	2.23	Haas et al. 2017
Archaic	SMP 5	M	adult	-18.73	-5.5	-24.23	11.31	-6	5.31	Haas et al. 2017
Archaic	SMP 6	F	adult	-19.28	-5.5	-24.78	9.22	-6	3.22	Haas et al. 2017
Archaic	SMP 7	F	adolescent	-19.14	-5.5	-24.64	8.02	-6	2.02	Haas et al. 2017
Archaic	SMP 8	F	adult	-19.34	-5.5	-24.84	8.47	-6	2.47	Haas et al. 2017
Archaic	SMP 9	M	adult	-18.48	-5.5	-23.98	8.61	-6	2.61	Haas et al. 2017
Archaic	SMP 10	F	adult	-18.21	-5.5	-23.71	9.7	-6	3.7	Haas et al. 2017
Archaic	SMP 11	F	adult	-18.9	-5.5	-24.4	9.43	-6	3.43	Haas et al. 2017
Archaic	SMP 12	M	adult	-19.12	-5.5	-24.62	9.09	-6	3.09	Haas et al. 2017
Archaic	SMP 13	NA	child	-17.9	-5.5	-23.4	11.01	-6	5.01	Haas et al. 2017
Archaic	SMP 14	F	NA	NA	-5.5	NA	NA	-6	NA	Haas et al. 2017
Archaic	SMP 15	F	adult	-18.81	-5.5	-24.31	8.74	-6	2.74	Haas et al. 2017
Archaic	SMP 16	M	adult	-18.81	-5.5	-24.31	10.11	-6	4.11	Haas et al. 2017
Archaic	WMP 1	M	adult	-18.59	-5.5	-24.09	9.9	-6	3.9	Haas et al. 2020
Archaic	WMP 2	M	adult	-17.91	-5.5	-23.41	10.04	-6	4.04	self
Archaic	WMP 3	M	adult	-19.11	-5.5	-24.61	9.15	-6	3.15	self

Archaic	WMP 4	NA	NA	-18.46	-5.5	-23.96	9.45	-6	3.45	self
Archaic	WMP 5	NA	adult	-18.5	-5.5	-24	9.4	-6	3.4	self
Archaic	WMP 6	F	adolescent	-18.9	-5.5	-24.4	8.1	-6	2.1	Haas et al. 2020
Archaic	WMP 7	NA	adult	-19.1	-5.5	-24.6	8.4	-6	2.4	self
Archaic	WMP 8	NA	adolescent	-18.73	-5.5	-24.25	9.76	-6	3.76	self
Archaic	WMP 9	NA	child	-18.5	-5.5	-24	8.7	-6	2.7	self
Archaic	WMP 10	NA	child	-18.3	-5.5	-23.8	10.2	-6	4.2	self
Formative	NA	M	adult	-21.8	-5.5	-27.3	2.2	-6	-3.8	Capriles et al. 2021
Formative	NA	M	adult	-17.2	-5.5	-22.7	10.4	-6	4.4	Capriles et al. 2021
Formative	NA	F	adult	-14.2	-5.5	-19.7	13.2	-6	7.2	Capriles et al. 2021
Formative	NA	F	adolescent	-13.5	-5.5	-19	13.6	-6	7.6	Capriles et al. 2021
Formative	NA	M	adult	-15.5	-5.5	-21	12.2	-6	6.2	Capriles et al. 2021
Formative	NA	F	adult	-18.2	-5.5	-23.7	8.8	-6	2.8	Capriles et al. 2021
Formative	NA	F	adolescent	-17.7	-5.5	-23.2	10.9	-6	4.9	Capriles et al. 2021
Formative	NA	F	adult	-16.8	-5.5	-22.3	9.6	-6	3.6	Capriles et al. 2021
Formative	NA	NA	adult	-17.7	-5.5	-23.2	10.3	-6	4.3	Capriles et al. 2021
Formative	NA	NA	child	-17.8	-5.5	-23.3	8.7	-6	2.7	Capriles et al. 2021
Formative	NA	M	adult	-16.8	-5.5	-22.3	11	-6	5	Capriles et al. 2021
Formative	NA	M	adult	-17.9	-5.5	-23.4	9.2	-6	3.2	Capriles et al. 2021
Formative	NA	NA	child	-16.8	-5.5	-22.3	11	-6	5	Capriles et al. 2021
Formative	NA	F	adult	-15.6	-5.5	-21.1	10.8	-6	4.8	Capriles et al. 2021
Formative	NA	M	adult	-17.1	-5.5	-22.6	11	-6	5	Capriles et al. 2021
Formative	NA	NA	adult	-17.2	-5.5	-22.7	9.9	-6	3.9	Capriles et al. 2021
Formative	NA	F	adult	-13.9	-5.5	-19.4	13.9	-6	7.9	Capriles et al. 2021
Formative	NA	NA	child	-18.2	-5.5	-23.7	13.4	-6	7.4	Capriles et al. 2021
Formative	NA	NA	child	-18.6	-5.5	-24.1	10.7	-6	4.7	Capriles et al. 2021
Formative	NA	F	child	-18.5	-5.5	-24	12.7	-6	6.7	Capriles et al. 2021
Formative	NA	F	child	-19	-5.5	-24.5	10	-6	4	Capriles et al. 2021
Formative	NA	F	adult	-18.4	-5.5	-23.9	10	-6	4	Capriles et al. 2021
Formative	NA	F	adult	-18.2	-5.5	-23.7	11.1	-6	5.1	Miller et al. 2021

Formative	NA	M	adult	-19	-5.5	-24.5	10.4	-6	4.4	Miller et al. 2021
Formative	NA	M	adult	-18.7	-5.5	-24.2	11.2	-6	5.2	Miller et al. 2021
Formative	NA	NA	adult	-18	-5.5	-23.5	11.8	-6	5.8	Miller et al. 2021
Formative	NA	NA	adolescent	-17.5	-5.5	-23	12.1	-6	6.1	Miller et al. 2021
Formative	NA	NA	adult	-18.4	-5.5	-23.9	12.8	-6	6.8	Miller et al. 2021
Formative	NA	NA	adolescent	-18.1	-5.5	-23.6	10.9	-6	4.9	Miller et al. 2021
Formative	NA	F	adult	-18.4	-5.5	-23.9	11.9	-6	5.9	Miller et al. 2021
Formative	NA	NA	adolescent	-17.6	-5.5	-23.1	11.6	-6	5.6	Miller et al. 2021
Formative	NA	NA	child	-17.2	-5.5	-22.7	11.3	-6	5.3	Miller et al. 2021
Formative	NA	NA	child	-18.7	-5.5	-24.2	10.3	-6	4.3	Miller et al. 2021
Formative	NA	NA	child	-18.9	-5.5	-24.4	10.1	-6	4.1	Miller et al. 2021
Formative	NA	NA	child	-18.6	-5.5	-24.1	10.8	-6	4.8	Miller et al. 2021
Formative	NA	NA	child	-19.1	-5.5	-24.6	9.8	-6	3.8	Miller et al. 2021
Formative	NA	NA	child	-18.9	-5.5	-24.4	9.7	-6	3.7	Miller et al. 2021
Formative	NA	NA	child	-19.4	-5.5	-24.9	10.8	-6	4.8	Miller et al. 2021
Formative	NA	NA	child	-16.4	-5.5	-21.9	13.7	-6	7.7	Miller et al. 2021
Formative	NA	NA	adolescent	-17.8	-5.5	-23.3	12	-6	6	Miller et al. 2021
Formative	NA	M	adult	-19.1	-5.5	-24.6	10.1	-6	4.1	Miller et al. 2021
Formative	NA	NA	adult	-18.4	-5.5	-23.9	10.6	-6	4.6	Miller et al. 2021
Formative	NA	NA	adult	-18.5	-5.5	-24	11.9	-6	5.9	Miller et al. 2021
Formative	NA	NA	adult	-19.1	-5.5	-24.6	11.1	-6	5.1	Miller et al. 2021
Formative	NA	NA	adult	-18.6	-5.5	-24.1	11.4	-6	5.4	Miller et al. 2021
Formative	NA	NA	adult	-19	-5.5	-24.5	10.3	-6	4.3	Miller et al. 2021
Formative	NA	NA	adult	-17.2	-5.5	-22.7	11.1	-6	5.1	Berryman diss. 2010
Formative	NA	NA	adult	-17.5	-5.5	-23	11	-6	5	Berryman diss. 2010
Formative	NA	M	adult	-18	-5.5	-23.5	10.7	-6	4.7	Berryman diss. 2010
Formative	NA	NA	adult	-17.4	-5.5	-22.9	11.6	-6	5.6	Berryman diss. 2010
Formative	NA	M	adult	-18.6	-5.5	-24.1	11.8	-6	5.8	Berryman diss. 2010
Formative	NA	F	adult	-18.2	-5.5	-23.7	11	-6	5	Berryman diss. 2010
Formative	NA	F	adult	-14.7	-5.5	-20.2	9.8	-6	3.8	Berryman diss. 2010

Formative	NA	F	adult	-19.2	-5.5	-24.7	11.4	-6	5.4	Berryman diss. 2010
Formative	NA	M	adolescent	-18.8	-5.5	-24.3	10.5	-6	4.5	Berryman diss. 2010
Formative	NA	F	adult	-19.3	-5.5	-24.8	9.8	-6	3.8	Berryman diss. 2010
Formative	NA	M	adult	-18.4	-5.5	-23.9	10.1	-6	4.1	Berryman diss. 2010
Formative	NA	M	adult	-18.7	-5.5	-24.2	13.1	-6	7.1	Berryman diss. 2010
Formative	NA	NA	adult	-18.8	-5.5	-24.3	10.2	-6	4.2	Berryman diss. 2010
Formative	NA	NA	adult	-17.6	-5.5	-23.1	10.7	-6	4.7	Berryman diss. 2010
Formative	NA	M	adult	-19	-5.5	-24.5	9.6	-6	3.6	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-15.7	-5.5	-21.2	13.2	-6	7.2	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-15.3	-5.5	-20.8	12.9	-6	6.9	Berryman diss. 2010
Tiwanaku	NA	F	adult	-10.7	-5.5	-16.2	10.5	-6	4.5	Berryman diss. 2010
Tiwanaku	NA	F	adult	-16.7	-5.5	-22.2	10.4	-6	4.4	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-12.2	-5.5	-17.7	10	-6	4	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-11.7	-5.5	-17.2	10.5	-6	4.5	Berryman diss. 2010
Tiwanaku	NA	F	adult	-16.8	-5.5	-22.3	10	-6	4	Berryman diss. 2010
Tiwanaku	NA	M	adult	-16.6	-5.5	-22.1	10.6	-6	4.6	Berryman diss. 2010
Tiwanaku	NA	M	adult	-14.7	-5.5	-20.2	10.2	-6	4.2	Berryman diss. 2010
Tiwanaku	NA	M	adult	-19.6	-5.5	-25.1	9.9	-6	3.9	Berryman diss. 2010
Tiwanaku	NA	F	adult	-18.6	-5.5	-24.1	11.7	-6	5.7	Berryman diss. 2010
Tiwanaku	NA	M	adult	-12.5	-5.5	-18	10.7	-6	4.7	Berryman diss. 2010
Tiwanaku	NA	F	adult	-13.2	-5.5	-18.7	11.1	-6	5.1	Berryman diss. 2010
Tiwanaku	NA	F	adult	-17.9	-5.5	-23.4	12.1	-6	6.1	Berryman diss. 2010
Tiwanaku	NA	F	adult	-18	-5.5	-23.5	11.8	-6	5.8	Berryman diss. 2010
Tiwanaku	NA	M	adult	-18	-5.5	-23.5	13.8	-6	7.8	Berryman diss. 2010
Tiwanaku	NA	M	adult	-16.5	-5.5	-22	12.6	-6	6.6	Berryman diss. 2010
Tiwanaku	NA	F	adult	-17.9	-5.5	-23.4	9.1	-6	3.1	Berryman diss. 2010
Tiwanaku	NA	F	adult	-18.3	-5.5	-23.8	12	-6	6	Berryman diss. 2010
Tiwanaku	NA	M	adult	-13.2	-5.5	-18.7	10.1	-6	4.1	Berryman diss. 2010
Tiwanaku	NA	M	adult	-15.1	-5.5	-20.6	10.9	-6	4.9	Berryman diss. 2010
Tiwanaku	NA	M	adult	-10.7	-5.5	-16.2	10.6	-6	4.6	Berryman diss. 2010

Tiwanaku	NA	F	adult	-11.2	-5.5	-16.7	10.3	-6	4.3	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-18.7	-5.5	-24.2	11	-6	5	Berryman diss. 2010
Tiwanaku	NA	F	adult	-15.7	-5.5	-21.2	11.3	-6	5.3	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-12.7	-5.5	-18.2	11	-6	5	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-16.9	-5.5	-22.4	11.8	-6	5.8	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-12	-5.5	-17.5	11.6	-6	5.6	Berryman diss. 2010
Tiwanaku	NA	F	adult	-11.4	-5.5	-16.9	9.9	-6	3.9	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-10.7	-5.5	-16.2	10.5	-6	4.5	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-18.8	-5.5	-24.3	14.6	-6	8.6	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-9.2	-5.5	-14.7	9.8	-6	3.8	Berryman diss. 2010
Tiwanaku	NA	M	adult	-8.9	-5.5	-14.4	10.5	-6	4.5	Berryman diss. 2010
Tiwanaku	NA	F	adult	-12.5	-5.5	-18	11.6	-6	5.6	Berryman diss. 2010
Tiwanaku	NA	M	adult	-12.6	-5.5	-18.1	11.8	-6	5.8	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-15.1	-5.5	-20.6	11.4	-6	5.4	Berryman diss. 2010
Tiwanaku	NA	F	adult	-12.2	-5.5	-17.7	11.2	-6	5.2	Berryman diss. 2010
Tiwanaku	NA	M	adult	-17.3	-5.5	-22.8	12.5	-6	6.5	Berryman diss. 2010
Tiwanaku	NA	M	adult	-16.4	-5.5	-21.9	11.7	-6	5.7	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-18.6	-5.5	-24.1	12.8	-6	6.8	Berryman diss. 2010
Tiwanaku	NA	F	adult	-18.6	-5.5	-24.1	11.8	-6	5.8	Berryman diss. 2010
Tiwanaku	NA	F	adult	-18.3	-5.5	-23.8	11.4	-6	5.4	Berryman diss. 2010
Tiwanaku	NA	NA	adult	-17.4	-5.5	-22.9	11.9	-6	5.9	Berryman diss. 2010
Tiwanaku	NA	F	adult	-18.6	-5.5	-24.1	12.6	-6	6.6	Berryman diss. 2010
Tiwanaku	NA	M	adult	-10.7	-5.5	-16.2	10.7	-6	4.7	Berryman diss. 2010
Tiwanaku	NA	M	adult	-13.6	-5.5	-19.1	11.5	-6	5.5	Berryman diss. 2010
Tiwanaku	NA	F	adult	-17.5	-5.5	-23	9.9	-6	3.9	Berryman diss. 2010
Tiwanaku	NA	M	adult	-18.4	-5.5	-23.9	11.1	-6	5.1	Berryman diss. 2010
Tiwanaku	NA	M	adult	-13.8	-5.5	-19.3	9.1	-6	3.1	Berryman diss. 2010
Tiwanaku	NA	F	adult	-16.9	-5.5	-22.4	9.5	-6	3.5	Berryman diss. 2010
Tiwanaku	NA	M	adult	-12.6	-5.5	-18.1	10.6	-6	4.6	Berryman diss. 2010
Tiwanaku	NA	F	adult	-17.1	-5.5	-22.6	10.4	-6	4.4	Berryman diss. 2010

Tiwanaku	NA	F	adult	-12	-5.5	-17.5	10.6	-6	4.6	Berryman diss. 2010
Tiwanaku	NA	F	adult	-16.3	-5.5	-21.8	12.3	-6	6.3	Berryman diss. 2010
Tiwanaku	NA	M	adult	-14.4	-5.5	-19.9	8.6	-6	2.6	Berryman diss. 2010
Tiwanaku	NA	M	adult	-17	-5.5	-22.5	11.6	-6	5.6	Berryman diss. 2010
Tiwanaku	NA	M	NA	-9.6	-5.5	-15.1	9.7	-6	3.7	Somerville et al. 2015
Tiwanaku	NA	M	NA	-11.9	-5.5	-17.4	8.9	-6	2.9	Somerville et al. 2015
Tiwanaku	NA	M	NA	-13	-5.5	-18.5	10.2	-6	4.2	Somerville et al. 2015
Tiwanaku	NA	F	NA	-13.9	-5.5	-19.4	6.8	-6	0.8	Somerville et al. 2015
Tiwanaku	NA	M	NA	-13.9	-5.5	-19.4	6.7	-6	0.7	Somerville et al. 2015
Tiwanaku	NA	F	NA	-12.8	-5.5	-18.3	8	-6	2	Somerville et al. 2015
Tiwanaku	NA	M	NA	-11.2	-5.5	-16.7	8.8	-6	2.8	Somerville et al. 2015
Tiwanaku	NA	F	NA	-14.5	-5.5	-20	10.5	-6	4.5	Somerville et al. 2015
Tiwanaku	NA	M	NA	-12	-5.5	-17.5	6.8	-6	0.8	Somerville et al. 2015
Tiwanaku	NA	F	NA	-14.7	-5.5	-20.2	5.7	-6	-0.3	Somerville et al. 2015
Tiwanaku	NA	NA	child	-13.5	-5.5	-19	5.9	-6	-0.1	Somerville et al. 2015
Tiwanaku	NA	M	adult	-12.6	-5.5	-18.1	6.3	-6	0.3	Somerville et al. 2015
Tiwanaku	NA	M	adult	-13	-5.5	-18.5	6.2	-6	0.2	Somerville et al. 2015
Tiwanaku	NA	NA	child	-10.9	-5.5	-16.4	10.7	-6	4.7	Somerville et al. 2015
Tiwanaku	NA	NA	child	-13.8	-5.5	-19.3	5.7	-6	-0.3	Somerville et al. 2015
Tiwanaku	NA	M	adult	-13.5	-5.5	-19	7.7	-6	1.7	Somerville et al. 2015
Tiwanaku	NA	NA	adolescent	-12.6	-5.5	-18.1	8.6	-6	2.6	Somerville et al. 2015
Tiwanaku	NA	M	adult	-11.8	-5.5	-17.3	9.2	-6	3.2	Somerville et al. 2015
Tiwanaku	NA	F	adult	-12.2	-5.5	-17.7	6.4	-6	0.4	Somerville et al. 2015
Tiwanaku	NA	M	adult	-10.3	-5.5	-15.8	9.7	-6	3.7	Somerville et al. 2015
Tiwanaku	NA	NA	adult	-11	-5.5	-16.5	8.5	-6	2.5	Somerville et al. 2015
Tiwanaku	NA	NA	adolescent	-13	-5.5	-18.5	6.2	-6	0.2	Somerville et al. 2015
Tiwanaku	NA	M	adult	-11.5	-5.5	-17	10.6	-6	4.6	Somerville et al. 2015
Tiwanaku	NA	M	adult	-9.7	-5.5	-15.2	8.6	-6	2.6	Somerville et al. 2015
Tiwanaku	NA	M	adult	-11.6	-5.5	-17.1	6.1	-6	0.1	Somerville et al. 2015
Tiwanaku	NA	NA	adolescent	-14.9	-5.5	-20.4	8.4	-6	2.4	Somerville et al. 2015

Tiwanaku	NA	M	adult	-12.3	-5.5	-17.8	9	-6	3	Somerville et al. 2015
Tiwanaku	NA	F	adult	-12.5	-5.5	-18	7.8	-6	1.8	Somerville et al. 2015
Tiwanaku	NA	M	adult	-9.7	-5.5	-15.2	9.4	-6	3.4	Somerville et al. 2015
Tiwanaku	NA	M	adult	-13.2	-5.5	-18.7	10.6	-6	4.6	Somerville et al. 2015
Tiwanaku	NA	F	adult	-11.3	-5.5	-16.8	10.4	-6	4.4	Somerville et al. 2015
Tiwanaku	NA	F	adult	-13.2	-5.5	-18.7	9.8	-6	3.8	Somerville et al. 2015
Tiwanaku	NA	F	adult	-16	-5.5	-21.5	9.7	-6	3.7	Somerville et al. 2015
Tiwanaku	NA	NA	child	-13.3	-5.5	-18.8	5.9	-6	-0.1	Somerville et al. 2015
Tiwanaku	NA	F	adult	-11.9	-5.5	-17.4	8	-6	2	Somerville et al. 2015
Tiwanaku	NA	NA	child	-10.4	-5.5	-15.9	10.2	-6	4.2	Somerville et al. 2015
Tiwanaku	NA	NA	child	-10.9	-5.5	-16.4	9.8	-6	3.8	Somerville et al. 2015
Tiwanaku	NA	NA	child	-13.4	-5.5	-18.9	5.9	-6	-0.1	Somerville et al. 2015
Tiwanaku	NA	M	adult	-11.8	-5.5	-17.3	10.2	-6	4.2	Somerville et al. 2015
Tiwanaku	NA	F	adult	-11.6	-5.5	-17.1	8.6	-6	2.6	Somerville et al. 2015
Tiwanaku	NA	M	adult	-10.3	-5.5	-15.8	9.7	-6	3.7	Somerville et al. 2015
Tiwanaku	NA	M	adult	-10.3	-5.5	-15.8	9.6	-6	3.6	Somerville et al. 2015
Tiwanaku	NA	F	adult	-13.4	-5.5	-18.9	9.2	-6	3.2	Somerville et al. 2015
Tiwanaku	NA	M	adult	-16.7	-5.5	-22.2	14.7	-6	8.7	Capriles et al. 2021
Tiwanaku	NA	F	adult	-17.5	-5.5	-23	12.2	-6	6.2	Capriles et al. 2021
Tiwanaku	NA	M	adult	-18.2	-5.5	-23.7	11.5	-6	5.5	Capriles et al. 2021
Tiwanaku	NA	M	adult	-17.5	-5.5	-23	12.5	-6	6.5	Capriles et al. 2021
Tiwanaku	NA	NA	adult	-17.9	-5.5	-23.4	12.6	-6	6.6	Miller et al. 2021
Tiwanaku	NA	M	adult	-15.7	-5.5	-21.2	10.5	-6	4.5	Miller et al. 2021
Tiwanaku	NA	NA	child	-17.1	-5.5	-22.6	11.1	-6	5.1	Miller et al. 2021
Tiwanaku	NA	NA	adult	-17.3	-5.5	-22.8	10.4	-6	4.4	Miller et al. 2021
Tiwanaku	NA	NA	child	-15.9	-5.5	-21.4	11.2	-6	5.2	Miller et al. 2021
Tiwanaku	NA	M	adult	-14.7	-5.5	-20.2	11.1	-6	5.1	Miller et al. 2021
Tiwanaku	NA	F	adult	-17.3	-5.5	-22.8	10.4	-6	4.4	Miller et al. 2021
Post Tiwanaku	NA	M	adult	-17.5	-5.5	-23	11.4	-6	5.4	Berryman diss. 2010

Post Tiwanaku	NA	F	adult	-18	-5.5	-23.5	7.6	-6	1.6	Berryman diss. 2010
Post Tiwanaku	NA	NA	adult	-17.9	-5.5	-23.4	12.2	-6	6.2	Berryman diss. 2010
Post Tiwanaku	NA	M	adult	-14.2	-5.5	-19.7	12.1	-6	6.1	Berryman diss. 2010
Post Tiwanaku	NA	F	adult	-18.5	-5.5	-24	14.8	-6	8.8	Berryman diss. 2010
Post Tiwanaku	NA	M	adult	-18.3	-5.5	-23.8	13.6	-6	7.6	Berryman diss. 2010
Post Tiwanaku	NA	NA	adult	-16.8	-5.5	-22.3	14.8	-6	8.8	Berryman diss. 2010
Post Tiwanaku	NA	F	adult	-17.3	-5.5	-22.8	12.4	-6	6.4	Berryman diss. 2010
Post Tiwanaku	NA	M	adult	-17.9	-5.5	-23.4	13.3	-6	7.3	Berryman diss. 2010
Post Tiwanaku	NA	M	adult	-18.6	-5.5	-24.1	13.8	-6	7.8	Berryman diss. 2010
Post Tiwanaku	NA	M	adult	-17.2	-5.5	-22.7	13.6	-6	7.6	Berryman diss. 2010
Post Tiwanaku	NA	M	adult	-17.9	-5.5	-23.4	13.9	-6	7.9	Berryman diss. 2010
Post Tiwanaku	NA	M	adult	-18.1	-5.5	-23.6	14.1	-6	8.1	Berryman diss. 2010
Post Tiwanaku	NA	M	adult	-17.9	-5.5	-23.4	15.2	-6	9.2	Berryman diss. 2010
Post Tiwanaku	NA	NA	adult	-20	-5.5	-25.5	15.2	-6	9.2	Berryman diss. 2010
Post Tiwanaku	NA	NA	adult	-11.2	-5.5	-16.7	14.4	-6	8.4	Capriles et al. 2021

Code Used for Analyses

R Code. The following code replicates the stable carbon and nitrogen isotopes analyses of Chapter 4 on diets across the Andean Altiplano through diachronic time—Archaic Period, Formative Period, Tiwanaku Period, and Post Tiwanaku Period.

```

---
title: "S4_RCode"
author: "Jennifer Chen"
date: "2024-09-30"
output: word_document
---
library(MixSIAR)
library(remotes)
library(R2jags)
library(coda)
library(rjags)

###ARCHAIC PERIOD MIXSIAR
source("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3
Supplement/cnmix.R")
source("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3
Supplement/cnisospace.R")
setwd("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3 Supplement")

Arch<-cnmix(consumer="Archaic_nochildren.csv", source="sources.csv",
run.length="test")
Arch$summary

  #weight--highest number is going to be best result

##creates nicer plots
cnisospace(consumer="Archaic_nochildren.csv",
source="Master_BaselineSummary.csv", run.length="test")

###FORMATIVE PERIOD MIXSIAR

source("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3
Supplement/cnmix.R")
source("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3
Supplement/cnisospace.R")

```

```
setwd("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3 Supplement")
```

```
Form<-cnmix(consumer="Formative_nochildren.csv",
source="Master_BaselineSummary.csv", run.length="long")
Form$summary
```

```
###TIWANAKU PERIOD MIXSIAR
source("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3
Supplement/cnmix.R")
source("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3
Supplement/cnisospace.R")
setwd("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3 Supplement")
```

```
Tiw<-cnmix(consumer="Tiwanaku_noMo_nochildren.csv",
source="Master_BaselineSummary.csv", run.length="long")
Tiw$summary
```

```
###POST TIWANAKU PERIOD MIXSIAR
source("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3
Supplement/cnmix.R")
source("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3
Supplement/cnisospace.R")
setwd("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3 Supplement")
```

```
Post<-cnmix(consumer="PostTiwanaku_nochildren.csv",
source="Master_BaselineSummary.csv", run.length="long")
Post$summary
```

```
####BIPLOTS FOR ALL PERIODS####
```

```
###BASELINE DATASET WITH WILD & CULTIVATED PLANTS
baseline<-
read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/Master_Baselinesummary.csv")
head(baseline)
names(baseline) [12]<-'d13C'
names(baseline) [15]<-'d15N'
```

```
###ARCHAIC W/ ONLY WILD SOURCES
wildbaseline<-
read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/ChenEtAl2023_SupplementTable.csv")
```

```

head(wildbaseline)
names(wildbaseline)[12]<-'d13C'
names(wildbaseline)[15]<-'d15N'

Archaic<-
read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/Archaic_nolabels.csv")
head(Archaic)

library(ggplot2)
Arch<-ggplot(data=wildbaseline, aes(x=d13C, y=d15N, color=type))+
  geom_point(data=wildbaseline, aes(x=d13C, y=d15N, color=type,
size=2), alpha=0.4)+
  geom_point(data=Archaic, aes(x=d13C, y=d15N, size=2),
color="black", pch=17, lwd=2)+
  geom_point(data=wildbaseline, aes(x=-24.74, y=2.87), color="red",
pch='+', lwd=2, size=7)+
  geom_point(data=wildbaseline, aes(x=-8.96, y=2.88),
color="chartreuse4", pch='+', lwd=2, size=7)+
  geom_point(data=wildbaseline, aes(x=-21.17, y=6.52),
color="purple", pch='+', lwd=2, size=7)+
  geom_point(data=wildbaseline, aes(x=-17.10, y=7.11),
color="deepskyblue", pch='+', lwd=2, size=7)
Arch
Arch+stat_ellipse(data=wildbaseline, geom="polygon", aes(fill=type),
alpha=0.15)+
  theme(text=element_text(size=25))+
  labs(x=expression(paste(delta^13,"C (\u2030)")))+
  labs(y=expression(paste(delta^15,"N (\u2030)")))+
  guides(size=FALSE)+
  theme(legend.position="none")+
  labs(title="Archaic Period")

setwd("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3 Supplement")
Formative<-read.csv("Formative_nochildren_TEF.csv")
head(Formative)

library(ggplot2)
Form<-ggplot(data=baseline, aes(x=d13C, y=d15N, color=type))+
  geom_point(data=baseline, aes(x=d13C, y=d15N, color=type, size=2),
alpha=0.4)+
  geom_point(data=Formative, aes(x=d13C, y=d15N, size=2),
color="black", pch=17, lwd=2)+
  geom_point(data=baseline, aes(x=-24.64, y=2.68), color="red",
pch='+', lwd=2, size=7)+
  geom_point(data=baseline, aes(x=-9.60, y=4.56),
color="chartreuse4", pch='+', lwd=2, size=7)+
  geom_point(data=baseline, aes(x=-21.17, y=6.52), color="purple",
pch='+', lwd=2, size=7)+
  geom_point(data=baseline, aes(x=-17.10, y=7.11),
color="deepskyblue", pch='+', lwd=2, size=7)
Form

```

```

Form+stat_ellipse(data=baseline, geom="polygon", aes(fill=type),
alpha=0.15)+
  theme(text = element_text(size = 25))+
  labs(x=expression(paste(delta^13,"C (\u2030)")))+
  labs(y=expression(paste(delta^15,"N (\u2030)")))+
  guides(size=FALSE)+
  theme(legend.position="none")+
  labs(title="Formative Period")

###TIWANAKU
Tiwanaku<-read.csv("C:/Users/jencc/OneDrive/Desktop/PSU 2023-
2024/Dissertation/Supplementary Materials/Paper 3
Supplement/Tiwanaku_noMo_nochildren_TEF.csv")
head(Tiwanaku)
names(Tiwanaku)[1]<-'type'

library(ggplot2)

Tiw<-ggplot(data=baseline, aes(x=d13C, y=d15N, color=type))+
  geom_point(data=baseline, aes(x=d13C, y=d15N, color=type, size=2),
alpha=0.4)+
  geom_point(data=Tiwanaku, aes(x=d13C, y=d15N, size=2),
color="black", pch=17, lwd=2)+
  geom_point(data=baseline, aes(x=-24.64, y=2.68), color="red",
pch='+', lwd=2, size=7)+
  geom_point(data=baseline, aes(x=-9.60, y=4.56),
color="chartreuse4", pch='+', lwd=2, size=7)+
  geom_point(data=baseline, aes(x=-21.17, y=6.52), color="purple",
pch='+', lwd=2, size=7)+
  geom_point(data=baseline, aes(x=-17.10, y=7.11),
color="deepskyblue", pch='+', lwd=2, size=7)
Tiw
Tiw+stat_ellipse(data=baseline, geom="polygon", aes(fill=type),
alpha=0.15)+
  theme(text = element_text(size = 25))+
  labs(x=expression(paste(delta^13,"C (\u2030)")))+
  labs(y=expression(paste(delta^15,"N (\u2030)")))+
  guides(size="none")+
  theme(legend.position="none")+
  labs(title="Tiwanaku Period")

###POST TIWANAKU
PostTiwanaku<-
read.csv("C:/Users/jencc/OneDrive/Desktop/SMP/PostTiwanaku.csv")
head(PostTiwanaku)
names(PostTiwanaku)[1]<-'type'

Post<-ggplot(data=baseline, aes(x=d13C, y=d15N, color=type))+
  geom_point(data=baseline, aes(x=d13C, y=d15N, color=type, size=2),
alpha=0.4)+

```

```
geom_point(data=PostTiwanaku, aes(x=d13C, y=d15N, size=2),
color="black", pch=17, lwd=2)+
geom_point(data=baseline, aes(x=-24.64, y=2.68), color="red",
pch='+', lwd=2, size=7)+
geom_point(data=baseline, aes(x=-9.60, y=4.56),
color="chartreuse4", pch='+', lwd=2, size=7)+
geom_point(data=baseline, aes(x=-21.17, y=6.52), color="purple",
pch='+', lwd=2, size=7)+
geom_point(data=baseline, aes(x=-17.10, y=7.11),
color="deepskyblue", pch='+', lwd=2, size=7)
Post
Post+stat_ellipse(data=baseline, geom="polygon", aes(fill=type),
alpha=0.15)+
theme(text = element_text(size = 25))+
labs(x=expression(paste(delta^13,"C (\u2030)")))+
labs(y=expression(paste(delta^15,"N (\u2030)")))+
guides(size=FALSE)+
theme(legend.position="none")+
labs(title="Post Tiwanaku Period")
```

VITA

Jennifer C. Chen

EDUCATION

- 2019–present The Pennsylvania State University
Anthropology M.A. (Spring 2022)
Anthropology and Climate Science Ph.D. (December 2024)
- 2016–2018 University of California, Davis
Anthropology B.A. (Highest Honors), English B.A. (High Honors)
- 2014–2016 University of California, Merced
English Major

PUBLICATIONS

- 2024 *Stable isotope chemistry reveals plant-dominant diet among early foragers on the Andean Altiplano, 9.0–6.5 cal. ka. PLOS ONE.* **Chen, Jennifer C.**, Mark Aldenderfer, Jelmer W. Eerkens, BrieAnna S. Langlie, Carlos Viviano Llave, James T. Watson, Randall Haas
- 2020 *Female hunters of the early Americas. Science Advances.* Haas, Randall, James Watson, Tammy Buonasera, John Southon, **Jennifer C. Chen**, Sarah Noe, Kevin Smith, Carlos Viviano Llave, Jelmer Eerkens, Glendon Parker

AWARDS AND HONORS

- 2017–2018 UC Davis Outstanding Senior Award
- Winter 2018 UC Davis Dean's Honors List
- Spring 2017 UC Davis Dean's Honors List
- Spring 2016 UC Merced Chancellor's Honors List
- Fall 2015 UC Merced Dean's Honors List
- Spring 2015 UC Merced Chancellor's Honors List
- Fall 2014 UC Merced Dean's Honors List