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The Shortcomings of Maize: Using Tipu to Assess Maize Consumption and its Impact on Stature and Limb Proportions Among the Maya

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THE SHORTCOMINGS OF MAIZE:
USING TIPU TO ASSESS MAIZE CONSUMPTION AND ITS IMPACT
ON STATURE AND LIMB PROPORTIONS AMONG THE MAYA

by

Peter Mercier

A Thesis
Submitted to the Graduate School,
the College of Arts and Sciences
and the School of Social Science and Global Studies
at The University of Southern Mississippi
in Partial Fulfillment of the Requirements
for the Degree of Master of Arts

Approved by:
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Dr. Bridget Hayden

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ABSTRACT

A reliance on maize among the ancient and modern Maya has been reasoned to cause short statures and short legs compared to overall height. The goal of this study was to test this proposition using a sample of contact period Maya from the site of Tipu in western Belize. Long bone length data from 100 individuals were compared to that from two other prehistoric maize agriculturalist societies: the Schild site in Illinois and Pecos Pueblo in New Mexico.

Four hypotheses were tested: 1) Tipu would be the shortest, 2) Tipu would have the shortest femora relative to tibiae, 3) Tipu would have the shortest femora relative to humeri, and 4) Tipu would be osteologically typical of the Maya and greater Mesoamerica. All were made with the prediction that maize consumption negatively affected limb length and stature. Hypotheses 1 and 2 were supported. Hypothesis 3 was rejected; Tipu's humerus:femur ratios were proportional compared to other groups, suggesting that short statures and legs are not specific to the Maya. Lastly, Tipu showed no significant difference compared to ancient populations from the Valley of Mexico, supporting hypothesis 4.

This study contributes a greater understanding of Mesoamerican stature by suggesting that it is not caused primarily by maize and factors such as genetics, latitude, and climate are potential contributing factors. Lastly, this study contributes to a better understanding of growth and development by suggesting that biological stress manifests not only in disproportional upper:lower body ratios but in disproportionality *within* legs.

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DEDICATION

I am an anxious person. Those who are close to me know this. This thesis seemed an insurmountable task but became a more than pleasant experience first and foremost because of Dr. Danforth, who provided much more than academic guidance during the course of this project. She was always in-tune to both my academic and mental needs and never hesitated to go above and beyond as both a mentor and a professor. Seldom will you find a professor so invested in his or her students. This is a quality I will never take for granted.

I would also like to thank my extremely supportive family, especially my mom and dad, who made higher education a possibility for me and supported my dreams every step of the way. Lastly, I would like to dedicate this thesis to my lovely southern belle, my fiancé Mary Bess, who kept me sane through all the stress and anxiety and was my support system in Mississippi. I love you with all my heart.

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VM

Valley of Mexico

CHAPTER I - INTRODUCTION

It has long been evident that external environmental pressures are catalysts for stunted growth and short adult statures among various human populations. Evidence strongly suggests that poor nutrition is a leading and direct cause of this delayed growth and short adult stature (Bogin et al. 2002; Bogin and Varela-Silva 2009; Nickens 1976). Short adult stature and delayed growth have a strong socioeconomic relationship, since people occupying more privileged social positions often have access to better living conditions and nutrition.

Short stature is especially prominent throughout Mesoamerica, where it has been observed that stature among its populations declined over the Late Classic period. This decrease in stature has typically been attributed to a variety of factors, including diet, genetics, inter-population breeding, and ecological pressures (Bogin et al. 2002; Bogin and Varela-Silva 2009; Danforth 1999; Haviland 1967; Longyear 1952; Lowe 1985; Márquez Morfín et al. 2002; Nickens 1976; Santley et al. 1986; Willey et al. 1973). The ancient Maya embody this typical stature decrease in Mesoamerica, as there has long been a suspected correlation between health, nutrition, and social status.

What is particularly intriguing about the Maya is not just that their stature decreased over time, but the unique arm to leg length ratios that appear to have been related to this decrease. Ancient Maya leg lengths were disproportionately short compared to their arm lengths and their overall adult height (del Angel 1996, 64; Márquez Morfín and del Angel 1997, 57-58). To be clear, long bone “disproportionality”, especially as it applies to the Maya, refers to long bones that are not only shorter compared to those same bones in other populations but also bones that are more similar in length to the other

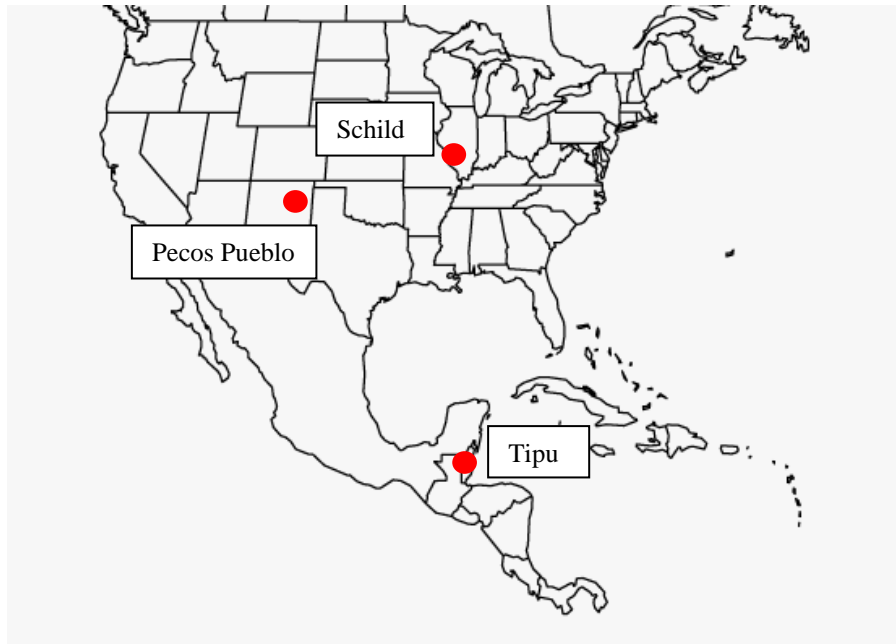
bones within that limb segment or between upper and lower body segments. The reason I refer to this as “disproportional” is because the various long bones have different average lengths (e.g., femora are longer than tibiae). Therefore, different long bones that are similar in length do not reflect what is seen in the typical human skeleton. It has often been suggested that environmental changes and their impact on health and nutrition directly influence limb proportions (Bogin and Rios 2003), but poor preservation has resulted in scarce skeletal data. Therefore, studies that have attempted to explain their specific causes and how Maya limb proportions compare to other Native American populations are lacking.

The Maya site of Tipu, located in west central Belize, offers a unique opportunity to address these issues given that the skeletal remains are relatively well preserved. Tipu is located on the western edge of Belize, and because of its landlocked location, was somewhat buffered against political pressure from the colonizing Spanish (Graham et al. 1989; Jones 1989). Of utmost importance to note is the fact that, despite Spanish colonialism and its influence in Mesoamerica’s social landscape, the Maya maintained their cultural identity and traditional lifeways, especially maize consumption (Graham 2011).

Reliance on maize as a dietary staple was not unique to the Maya of Mesoamerica, as a dependence on this staple is also observed in many other parts of North America. According to archaeological records, maize appeared in the American Bottom rather abruptly around AD 900 (Emerson et al. 2020, 255) and had long been a major subsistence strategy in the American Southwest (Spielmann et al. 1990). These regions therefore provide the opportunity for a cultural comparison with the Tipu Maya

in order to determine whether disproportionately short legs are unique to the Maya or if this pattern exists among other Native American groups. The locations of these sites are illustrated below in Figure 1.

Figure 1. Schild, Pecos Pueblo, and Tipu Site Locations



Therefore, the purpose of this project is to mount a comparison of leg bone lengths, used as a proxy for stature, between precontact populations of the Lower Illinois River Valley, the Pecos River Valley, and the Tipu Maya in order to assess whether atypically short legs and statures are unique to the Maya or common among other Native American populations. If similar ratios of tibiae to femora, suggestive of decreasing stature, are observed in both North American and Mesoamerican indigenous groups, their shared dietary reliance on maize can be isolated as the primary factor. If, however, Tipu is significantly shorter than the other groups, we must consider the importance of other underlying biological factors, such as genetics and climatic factors, in impacting adult height and leg proportions.

It is important to point out that, although Tipu, Pecos Pueblo, and Schild are comparable in many ways, there are certain ways in which they do differ that are relevant to this study. The largest of these issues is with the level of maize consumption. Maize had been a part of Tipu's and Pecos Pueblo's diets for centuries, but it was still relatively new to the inhabitants of the Schild site. Isotopic data, as opposed to botanical data, suggests that there was no major maize consumption in the Middle Woodland period at Schild (Cook 2007, 10-11; Emerson et al. 2020; Rose 2008), which would result in the late Late Woodland sample used in this study having had maize as a major staple in their cultures for only about a century. Nevertheless, the fact that Schild did eventually come to consume on maize, even if later than Tipu and Schild, makes it reasonable to compare the three groups for nutritional and skeletal variability since dietary effects would occur within the lifetime of the individual. Furthermore, the site offers a different climatic setting as well as a geographical distance from the other two sites, thereby helping to isolate maize dependency as a variable.

I tested four major hypotheses in this study. In the first hypothesis, I predicted that the Tipu Maya would be the shortest out of all three groups. In the second hypothesis, I postulated that the Tipu Maya would have femora that are relatively short compared to their tibiae, which caused their short stature. This would result in a lower ratio (i.e., a smaller difference in the lengths of the femora compared to tibia, caused by a shortening of the former). My third hypothesis is that the Tipu Maya would have humeri and femora that are similar in length, also resulting in a lower ratio and also caused by shortened femora. My fourth and final hypothesis predicts that Tipu would have long bone lengths and proportions that are typical of greater Mesoamerica and other Maya populations. All

hypotheses are centered around the idea that some external stress impacted Maya femora most directly, resulting in short stature, and that this pattern is reflected at Tipu.

CHAPTER II – LITERATURE REVIEW

Stature Decrease in Mesoamerica

A trend in stature decrease throughout ancient Mesoamerica was first observed by Stewart (1949; 1953) and Newman (1953). Stewart noticed that modern inhabitants of the Guatemalan Maya highlands were several centimeters shorter than their ancestors from the same region, particularly at the site of Zacaleu (Stewart 1949; 1953). However, it was Nickens who formalized bioarchaeological approaches in the study of secular (non-genetic) stature decrease in Mesoamerican over time. Nickens proposed that this was an adaptive response to malnutrition and noted a clear correlation between nutritional diseases and reduced body sizes during childhood, adolescent, and developmental years (Nickens 1976, 37). This argument suggests that when nutritional resources are limited throughout a community, those who can sustain themselves on lower-nutrition diets are more likely to survive and reproduce. According to this model, delayed growth and short adult statures are adaptations available for selection throughout a population's gene pool (Nickens 1976, 37). This Darwinian perspective states that short height was initially a plastic adaptation that was subsequently acted upon by natural selection to increase the frequency of "short" genes in the gene pool (Nickens 1976, 39). There must have been some external environmental stressor that made short height a favorable trait. Therefore, individuals with short heights were more likely to survive and reproduce, perpetuating stunted growth throughout Mesoamerica.

The idea of short height as an adaptive trait was formalized by Seckler in 1982 in what is known as the "Small but Healthy" hypothesis. This hypothesis proposed that small bodies are better adapted to malnutrition because they require fewer nutrients to

carry out basic biological and physiological processes (Danforth 1999, 104; Seckler 1982; Stini 1971). Like Nickens' proposition from 1976, the Small but Healthy hypothesis had an explicit genetic component in that it claims that the biological effects of malnutrition can be passed down from mother to offspring. Nickens believed that the beginnings of severe nutritional distress came with the onset of intensive agriculture, which marked a major step away from the high-protein diet of hunter-gatherers to the high-carbohydrate diet of sedentary life (Nickens 1976, 39). Nickens argued that once the human body adapted to nutritional stress, the population's average height would recover and again increase in size (Nickens 1976, 39).

However, the Small but Healthy model comes with contradictions. Initially, the ubiquitous temporal decrease in stature throughout Mesoamerica seems consistent with Nickens' adaptive model and was overtly proposed as an explanation at times (e.g., Saul and Saul 1989, 300). However, if short stature were susceptible to the forces of evolution and natural selection, we would not expect such a quick recovery in stature following the cessation of environmental stress since evolutionary processes take time. Furthermore, studies have shown that small, malnourished bodies actually put the individual at a higher risk for a number of health issues (Martorell 1989). Short statures can therefore not be an adaptation since they do not offer any survival or reproductive benefit. For these reasons, the Small but Healthy hypothesis is no longer accepted in scientific circles. Moreover, this indicates that short stature and short legs among the Maya are likely not the result of genetic forces (Danforth 1999, 105-106; Vázquez-Vázquez et al. 2013). However, it is possible that the same selective pressure could favor different genes in different regions. For example, it has been suggested that brachymesophalangia (the shortening and

widening of the middle segment of a phalanx) in digit five is associated with the shortening of other appendages and thus may be adaptive in regions where malnutrition is high and natural selection favors reduced body size (Garn et al. 1967).

There also appears to be a geographic component to Mesoamerican stature. Nickens (1976) noted that stature decreases in Mexico from north to south, and he attributed this decrease to the more temperate climate of northern Mexico that was “less affected by long term food producing economies than central or southern Mexico” (33). This was similarly noted by del Angel (1996), who observed that mean stature in northern Mexico was greater than that in southern Mexico, which he attributed to factors such as climate and nutrition. Other studies (del Angel 1996; Jaén Esquivel and López Alonso 1974; Márquez Morfín and del Angel 1997) further report a gradient in stature from northeast to southwest Mesoamerica, with the shortest statures in the tropical lowlands (Márquez Morfín et al. 2002).

The Limitations of Maize

Any discussion of skeletal health and development in the Americas would be incomplete without discussing maize and therefore a brief introduction of its nutritional composition is necessary. Simply put, the nutritional value of maize is poor. Many of the amino acids essential for proper bodily function are missing from maize, including tryptophan and lysine. In addition, maize is also deficient in B-vitamins, vitamin C, iodine, and iron (Nuss and Tanumihardjo 2010, 418).

Perhaps the most glaring issue with maize consumption is its severe lack of protein. The majority of maize (72%) is pure starch (Inglett 1970, Nuss and Tanumihardjo 2010, 418), while only a meager 8.9% is protein per 100 grams (Watt and

Merrill 1975, 26), although recent studies have suggested this number is 9.42% (Kindscher et al. 2018, 217). Therefore, in order to meet basic daily nutrition requirements and energy needs, both children and adults would have to consume extremely large amounts of maize (Brown et al. 1988; Mertz 1970; Nuss and Tanumihardjo 2010, 418). This is crucial since protein is vital to proper bone growth and therefore adult stature. The relationship between dietary protein and bone growth begins in utero, during which time the skeleton grows in repeated episodes of bone deposition and resorption, which effectively allows the bone to increase in length. After birth, this process continues until adult size is achieved (Heaney et al. 2000; Parfitt 1994; Wallace 2019, 110; Weaver et al. 2016). Since bone growth is a continuous process, a steady and sufficient source of amino acids (proteins) is needed for proper bone formation, maintenance, and achievement of adult size (Wallace 2019, 107). Also worthy of mention is the fact that maternal health directly impacts bone health of children (Mitchell et al. 2015; Wallace 2019, 110). This demonstrates how dietary deficiencies are not a one-generation problem. These conditions span throughout generations of peoples and families, which is what makes them so pervasive.

The importance of protein in skeletal growth has been emphasized in studies (Graham 1990; Gunaratna 2010) in which maize was selectively modified to have higher protein content. It was found that increasing the protein content of maize resulted in more positive long bone growth in infants. This further exemplifies the fact that low-protein foods like maize “may not allow optimal height growth” (Millward 2021, 43). Yet, despite these shortcomings, maize is still the favored food source in many parts of the world, including Latin America, making it a primary culprit in malnutrition (Nuss and

Tanumihardjo 2010, 418). Maize, therefore, is of paramount relevance to inquiries regarding skeletal growth and stature among the Maya, who relied upon this food as their primary subsistence.

The Maya

Adoption of Maize

Maize has long been a part of Maya society. It has been traditionally believed that agriculture emerged in the Maya highlands in western Guatemala circa 5000 B.C. before spreading to the lowlands at a much later date (Fritz 1994; Long et al. 1989; Pohl et al. 1996, 355). However, in recent years this view has shifted. New data suggests that, while still originating in the highlands, maize was introduced in the Maya lowlands between 3000 and 3500 B.C. (Fritz 1994; Long et al. 1989; Pohl et al. 1996, 355, 368). These earlier dates are evidenced by the rapid deforestation in northern Belize around 2500 B.C., which is believed to be the result of the proliferation of maize agriculture (Pohl et al. 1996, 155). Further evidence of the spread of maize agriculture is observed in the “intensification in wetland environments” between about 1500 and 1300 B.C. (Pohl et al. 1996, 155). In addition, the Maya might have also had some early dependence on manioc, a starch grain, but its prevalence in their diet is difficult to study because it does not preserve well in the archaeological record (Cagnato and Ponce 2017, 278). This millennia-old reliance on such a nutritionally deficient food provides a potential explanation for the Maya’s short statures and leg lengths, which will be discussed in the following sections.

Maya Stature and Limb Length

Short stature throughout Mesoamerica is perhaps best exemplified by the Maya. It was once believed that the Maya's short stature was a climatic adaptation (Newman 1953; Stewart 1953, 300). This notion is rooted in Bergmann's Rule, the idea that organisms living in warmer regions have a smaller body mass in order to accommodate greater surface area, which would have a direct impact on height (i.e., a smaller body mass calls for a smaller stature) (Haviland 1967, 320). Del Angel's reported stature decrease from northern to southern latitudes seems to conform to this hypothesis, especially concerning sites like Tikal, which are closer to the equator. However, Haviland ultimately rejected this climatic model in favor of a nutritional one. The human body adapts relatively quickly to environmental pressures, but throughout Mesoamerica, changes in stature appear far more gradual over time. This slow rate of change is more akin to nutritional distress (Haviland 1967).

Complicating the issue further is the fact that sex and status may have played a role in contributing to adult height and limb lengths. This is perhaps best represented at the ancient Maya site of Tikal, Guatemala. Here, Haviland found "a marked sexual dimorphism so far as stature was concerned", which "probably reflects basic genetic factors, but a lower status for women relative to men is probably also involved" (Haviland 1967, 323). It has also been argued that sexual dimorphism becomes more extreme during times of low environmental stress and less pronounced during times of increased environmental stress, a trend attributed to female growth canalization. During times of environmental stress, such as famine, female growth remains more protected

compared to males, who grow taller during when food is plentiful and shorter during times of famine (Stini 1969; Stinson 1994).

Bioarchaeologists have recently run statistical tests regarding ancestry and status among the Yucatan Maya and have found that while having Maya ancestry does increase the likelihood of short stature, biological, socioeconomic, and environmental factors play a far more statistically significant role in determining adult height (Vázquez-Vázquez et al. 2013, 591-592). This is supported by the skeletal data at Tikal, which indicates that men buried in elite tombs had statures greater by as much as 7 cm than men in non-elite interments (Haviland 1967, 320-321). The influence of sex and status on stature is a logical consideration if we view stature to be the result of primarily nutritional factors. Access to nutritious food was directly related to sex and status in the ancient Maya culture because their society was patriarchal, exemplified by cultural practices such as later male weaning (Storey 1998). Men received more prioritized treatment over women and therefore had better and more frequent access to nutritious foods.

While these theories attempt to scientifically explain the stature patterns we see in ancient Mesoamerica, they are often inconclusive and contradict one another. For example, while studies at Tikal do show a direct correlation between higher social status and increased stature, the complete opposite is found at sites such as Monte Albán, Mexico. Here, it was observed that commoners had greater average statures than elites (Wilkinson and Norelli 1981). This is both contradictory to Haviland's study as well common sense, as we would typically expect the ruling class to have better nutritional access and thus greater statures. However, Monte Albán is by no means the defining study in ancient Mesoamerican stature patterns. It may simply reflect natural regional

variation, or it may also indicate that there are more factors that influence stature than we understand at this time.

Maya Long Bone Length Ratios

In addition to issues regarding stature, it has long been reported that the Maya have disproportional arm to leg length ratios in that their legs are disproportionately short compared to their arms and their overall stature (Bogin et al. 2002; Bogin and Varela-Silva 2009; del Angel 1996; Genoves 1967). In his groundbreaking study of the osteometrics of the modern Maya, Steggerda had noted that they "are of small height...with long arms as compared to their size" (1932, 1), and del Angel (1996) argued it also might be applied to the ancient Maya when he analyzed Genoves' (1967) ancient Mesoamerican sample from the Valley of Mexico. Using Genoves' measurements for the humerus, radius, ulna, femur, and tibia, del Angel found that leg bones became shorter than the arm bones over time. He reported a reduction in leg length (and subsequently stature) for both males and females but noted that arm lengths did not change at nearly as fast of a rate in either sex. Although the arm lengths fluctuate slightly, they maintain roughly the same length over time and space (del Angel 1996, 64).

Moreover, while overall height increases slightly during the Postclassic, femur lengths continue to decrease. Del Angel (1996) also noted that estimated stature was shorter when using the proximal bones, such as the femora compared to distal bones, such as the tibiae (64) and that there is a certain ecosensitivity of the lower body segments, especially the proximal subsegments (femora) during adolescent growth, and it is this proximal sensitivity that results in short stature (66-74). These body proportions have become a hallmark of the ancient Maya that continues to characterize them today

(Márquez Morfín and del Angel 1997, 57-58). This is much more than simply an issue of stature; even when people became taller, their legs continued to get shorter, and it appears as if the femora were most affected. The repeated cases of disproportionately short legs among the ancient Maya groups cannot be ignored.

Due to insufficient data from poor preservation, it can be difficult for bioarchaeologists to thoroughly understand limb proportion patterns in ancient societies. We can, however, attempt to understand some of these issues by studying contemporary Maya populations. In 2002, Bogin and his colleagues studied and compared modern Maya children, aged 5-12, living in Guatemala and the United States. He found that those living in the U.S. have greater statures than those living in Guatemala. Moreover, they exhibited much longer legs (Bogin et al. 2002, 760). Bogin attributes this discrepancy to differences in environmental conditions in that those residing in the U.S. experience more ready access to safe food and water as well as amenities such as healthcare (Bogin et al. 2002, 759).

In addition, other studies looking at the human body's plastic responses have confirmed how informative leg lengths and limb proportions are in determining the presence or absence of environmental stressors. Bogin and Varela-Silva (2009) found that no matter what particular leg measurement was taken, longer legs *always* corresponded with more favorable environmental circumstances, better quality nutrition, higher socioeconomic status, and better overall health (448). A 2013 study found that body proportion measurements statistically vary according to the corresponding external environmental conditions in which that individual grew up (Vázquez-Vázquez et al. 2013, 592). Therefore, the most recent research appears to confirm that these growth

patterns are not so much caused by genetics as external environmental conditions in which an individual develops.

These studies indicate that limb proportions are physical manifestations of an individual's health. Both Bogin's and Vázquez-Vázquez's studies show that the human body reacts to environmental stressors, but they extend this discussion to environmental pressures other than nutrition. Healthcare and medicine, for example, seem to play a role in arm to leg length ratios, which is not necessarily inherently an issue of nutrition, though there may be a close relationship. Even more importantly, these studies show that changes in stature are almost exclusively due to changes in the leg lengths. This is a particularly important notion, since bioarchaeologists can expect decreases in stature to coincide with decreases in leg length, allowing inquiries regarding limb proportions to inform questions of stature and vice versa. Although we still have much to understand, noting how the legs react so frequently and consistently to external pressures helps narrow our search for answers to this odd osteological anomaly.

Measuring Legs

One of the best ways to address how stature is affected by nutrition and the environment in bioarchaeology is to study leg length, which is made somewhat easier by the fact that leg bones are very robust and thus are recovered more frequently than others (Auerbach and Ruff 2009, 197). One potential shortcoming to using only limb length to estimate stature is that it does not take into account the contributions of the axial portions of the body, but their inclusion in stature estimation methods (e.g., Fully 1956; Raxter et al. 2007) is challenging since skeletal elements of that region of the skeleton often do not preserve well. Nonetheless, examining leg length helps researchers understand the

environmental conditions that the individual experienced during childhood and adolescent development. This is best demonstrated by studies that have found that groups living in more favorable ecological and social environments, which likely have access to better nutrition, will experience greater leg growth (Azcorra et al. 2013, 659). That leg bone growth is so sensitive to environmental pressures is what makes it the ideal metric for the present study. There is also a simple yet helpful logic to it: if we observe a population with shorter legs compared to another group—all other variables equal—we are likely observing the direct effects of negative environmental pressures.

Moreover, leg length can tell us about adolescent health because the rate at which legs grow compared to the rest of the human body plays a significant role in determining adult stature. This is highlighted by the cephalocaudal gradient, a pubescent developmental pattern that causes legs to grow at a much faster rate than the rest of the body. This is due to the fact that upper body growth is favored early in development (Azcorra et al. 2013, 659). Following birth, human legs grow at a faster rate than any other post-cranial body part because *in utero*, “the umbilical arteries carry de-oxygenated fetal blood to the placenta and this ‘short-circuits’ the blood supply to the legs... The lack of oxygen and nutrients supplied to the legs slows their growth and development compared with more cephalic regions of the body” (Bogin and Varela-Silva 2009, 442).

Because brain development is so important *in utero*, blood supply to the head is of paramount importance to the fetus, which puts the legs behind in terms of development, causing them to play catch-up after birth. This makes their immediate growth after birth crucial for adult stature and proper skeletal proportions. This also exacerbates the impact leg length has on adult stature, because if leg bones miss that crucial window of

development in early childhood, they will never develop enough for maximum potential adult stature to be achieved. Leg length therefore serves as an effective biological marker of childhood nutrition and health.

Further emphasizing the importance of adolescent growth rates is the crural index, which is the ratio of tibia to femur length. Experts have applied the crural index and found that distal limb elements grow at a faster rate relative to the rest of the body than do proximal elements (Auerbach and Sylvester 2011, 382). This means that relative to the rest of the body, the tibia grows more rapidly than the femur. Bogin et al. (2002) found exactly this in his aforementioned contemporary Maya study where he noted that “the lower limb bones increased in length more than the upper limb bones, and the distal leg bones (tibia and fibula) increased in length at a faster rate than the femur” (759). It has also been noted that high crural indices (lower tibia:femur ratios) may be associated with taller statures (Auerbach and Ruff 2010, 203), although this does not seem to apply with the Maya.

In other comparative studies, it was found that non-Maya individuals are on average taller than those of Maya ancestry, which was attributed to the formers' longer torsos and femora. Those Maya individuals who grew up in more unfavorable environmental conditions not only had shorter statures, but also had disproportionately shorter upper legs (femora) compared to lower legs (tibiae) (Vázquez-Vázquez et al. 2013, 592). In other words, whatever environmental stressors are acting on Maya children are most directly impacting the femora. This confirms that proximal body segments are more susceptible to environmental influences than distal elements such as the tibia and indicates that the environmental conditions' impact on stature is most clearly

reflected in the femora. The importance of the crural index in Maya long bone proportions cannot be understated, as it makes evident that studying limb proportions should not just be limited to metric variation *between* the limbs; we also must consider metric variation *within* the limbs.

Applying Maya Stature and Leg Length at Tipu

The above points are of special interest to bioarchaeologists studying the Maya in the Yucatan peninsula, which was home to a diverse political climate. Due to their ideal location as trading ports, coastal regions were under high Spanish scrutiny while more inland locations experienced less Spanish interference (Graham et al. 1989; Graham 2011; Jones 1989). The Maya site of Tipu, located in western Belize, provided such an inland sanctuary from coastal conflict. Tipu was a Spanish visita mission site in the 16th century, visited only on occasion by Spanish priests and their escorts (Graham 1998, 50). It existed in a so-called no-man's-land between regions occupied by the Spanish to the north and east and the Itza Maya to the west, and because of its inland location, it became a refugee site for the Yucatec Maya who were fleeing from the Spanish who were more preoccupied with the colonization of larger, more major centers (Cohen et al. 1994, 121). This is not to say that the Tipu Maya had no contact with the Spanish, however. Although at times the interim was as long as a few years, the Spanish never failed to routinely check in on the Maya community at Tipu, albeit much less than they did with centers in the more coastal areas. Largely accomplished through the mission church, Spanish presence at Tipu was enough to infiltrate ancient Maya culture and everyday life. The Maya are a syncretic people, ready to incorporate many outside beliefs into their existing culture. This resulted in a hybrid culture at Tipu in which traditional Maya practices were

maintained along with newly Spanish practices, such as Christianity, being incorporated (Graham 2011).

Despite the integration of some Spanish practices, the population at Tipu was culturally and biologically Maya. This is seen especially in terms of Tipu diet in which evidence of European dietary introductions, such as pigs, are largely absent from the faunal assemblages at Tipu (Emery 1999). Graham et al. (1989) has also noted that Tipu food refuse is consistent with traditional Maya diet, largely unchanged by European influence. Nevertheless, the sociopolitical conditions at Tipu make it clear that the Maya experience on the western edge of Belize was not like that seen on the eastern coast. Among the 550 burials recovered in the church cemetery, there is little evidence of skeletal trauma, which is consistent with the fact that the Tipu Maya were able to coexist relatively peacefully with the Spanish, although it might suggest that any rebels were buried elsewhere. In addition, there is no evidence for epidemics in the Tipu cemetery, such as hurried or mass burials (Cohen et al. 1997, 86).

Despite the fact that living conditions appear to be, overall, substantially better at Tipu than at other colonized Maya sites, the Tipu Maya stature is “at least average by available Maya data” (Cohen et al. 1994, 129), although the purpose of this statement appears to be mostly to support the conclusion of Tipu’s relatively good health and was not extensively researched. Nevertheless, this remark brings up an interesting contradiction, since we might expect to see more positive skeletal growth and longer leg lengths in regions with less negative external pressures. It is therefore reasonable to suspect that adult stature and skeletal growth at Tipu is the result of factors other than its political environment.

The American Bottom

The Adoption of Maize

The populations of the American Bottom of the Middle Mississippi Valley region are of interest in this study because their diet was also carbohydrate-based as they relied upon the maize introduced from Mesoamerican populations to the south (Simon 2017, 144). The original models of the origins of maize in the North America suggested that maize was a minor part of the American subsistence system during the first few centuries AD. According to these early models, maize was introduced around AD 100 and reached large-scale cultivation around AD 900, making the implementation of maize into the American diet a long and gradual process (Simon 2017, 142).

However, new evidence suggests a different history of maize in North America. Recent studies utilizing isotopic analysis have suggested that maize arrived in North America as recently as AD 900 (Emerson et al. 2020, 255), and it has also been suggested that the widespread use of maize in North America happened very quickly. It is now generally accepted that after its abrupt arrival in North America around AD 900, maize was quickly integrated into the existing subsistence economy of the Eastern Agricultural Complex and eventually became the primary subsistence crop in North America (Emerson et al. 2020, 255).

The American Bottom

Perhaps the best proxy of maize adoption in North America is in the American Bottom, the region of the Mississippi River's floodplain in southern Illinois. Here, the widespread use of maize dramatically increased from nearly zero percent in the Patrick phase to about 60 percent during the Dohack phase around AD 900 (Fortier and McElrath

2002, 196). Over a period of roughly 250 years, maize went from scarcely used to nearly dominating the American Bottom's subsistence (Koldehoff and Galloy 2006, 275). In fact, the most recent studies push this date up even further and suggest that maize was not the dominant crop in the American Bottom until as recently as AD 1000 (Emerson et al. 2020, 59), although its importance in the American Bottom as a staple crop also varied depending on the region (Fortier and McElrath 2002, 196).

Nevertheless, an increased reliance on maize agriculture resulted in population clustering and an increase in population density (Emerson et al. 2005, 100). This shows that, similar to Mesoamerican populations, North American populations increased their reliance on maize agriculture to support an expanding population. However, this increase in economic productivity and political expansion comes with the cost of reduced skeletal health. This may be seen in its impact on growth and development in the Lower Illinois River Valley in west central Illinois. For example, femur lengths for children under six years of age during the late Late Woodland period are shorter than the groups before them as well as the groups that succeeded them. This reflects some kind of delay in growth, especially since children's skeletons are so sensitive to nutritional and environmental stress (Cook 1984, 237-240). Of particular interest is the fact that the decrease in femur length coincides with the increase in maize consumption. However, while this is true for juvenile samples, adults show a different pattern, the latter presenting more inconsistent data, with the shortest male populations coming from the Ledders and Joe Gay sites from the Late Woodland period. It is tempting to also attribute this to the onset of maize agriculture, but these groups seem to be the exceptions, not the rule. It is, however, worth noting an apparent relationship between adult height and

status, though this does not appear to explain juvenile stature as it relates to subsistence (Cook 1984, 241-242).

Skeletal data appear to support the role of adoption of maize in influencing health patterns among indigenous groups in the region (Cook 1984; Dreizen et al. 1964; Garn et al. 1966; Kulus and Dąbrowski 2019, 1169; Murchison et al., 1984). In the Woodland sample sequence, Harris lines increase through time, peaking during the Mississippi period. A similar pattern was found for frequency of enamel defects. This indicates skeletal stress throughout the entire body, likely caused by a combination of “increased population pressure on food resources, increased reliance on carbohydrates for weaning diets, and environmental deterioration” (Cook and Buikstra 1979, 656).

Overall, the introduction of maize to the late Woodland diet caused a decrease in childhood health. In the Lower Illinois River Valley, the late Late Woodland people continued to rely on maize to a greater degree, and the Mississippian people that followed them relied upon maize even more. Yet, evidence for nutritional stress and disease among the more recent Mississippian population is largely lacking. Therefore, maize cannot be blamed entirely for the poor health of the late Late Woodland people (Cook 1984, 261). Nevertheless, we must acknowledge that stunted growth does not necessarily always associate with poor health as manifested in the skeleton. With this in mind, it is important to consider the possibility that maize affected the long bone development of the aforementioned populations without posing any real threat of death.

The onset of maize agriculture in the Illinois River Valley has been a point of contention among archaeologists in recent times. Once thought to be of far more ancient origin, it is now believed that maize arrived rather abruptly in the American Bottom

around the time of AD 900. While the importance of maize in the American Bottom grew over time, it was not until the Late Woodland period in the Lower Illinois River Valley, including the site of Schild, that maize was largely consumed, and recent evidence shows that maize abundance during this time was lower than previously believed (Fritz 2019, 63). This means that by the late Late Woodland period, Schild had only been consuming maize for about a century.

Despite this, we do know that there appears to be a correlation between maize agriculture and decreases in leg length and health, but these correlations are not always strong ones. For instance, decreases in leg length with maize agriculture seems to apply mostly to juvenile populations, not adult ones. Furthermore, the full-blown agricultural Mississippian populations display better health and less nutritional distress than the slightly less maize-dependent populations that preceded them, which is counterintuitive to the fact that maize is known to cause problems in health, growth, and development. The exact effects of maize on skeletal health is evidently a tricky question and requires further inquiry.

The American Southwest

The Adoption of Maize

Maize was also an important part of the diet in the prehistoric American Southwest. There are two models that explain the advent of maize agriculture there (Merrill et al. 2009, 21019). The first model proposes that knowledge of maize agriculture was spread via diffusion without any major migrations through different foraging groups throughout the region. The second model proposes that there was a major migration of Mesoamerican farmers to the American southwest, and these Mesoamerican

migrants brought maize agriculture with them. This latter model has gained a substantial following and posits that maize arrived in the American southwest around 2100 BC, although dates as early as 6900 BC have also been proposed (Merrill et al. 2009, 21019).

The Pecos Pueblo Valley

Pecos Pueblo, a small village located in New Mexico occupied by the Pueblo culture from AD 1300 to 1846, sports a considerable amount of isotopic data that aids in our understanding of the importance of maize in the American southwest (Spielmann et al. 1990). In prehistoric times, maize played a focal role in Pecos subsistence. It was found that prehistoric farmers could meet their own caloric needs and supply enough excess maize each year for trade with plains hunter-gatherers (Spielmann 1982; Spielmann et al. 1990, 746-747). However, strontium levels of Pecos Pueblo burials after AD 1600 show a dearth in maize, which was likely due in part to Spanish demands for labor and food, which would have lessened the availability of maize to the Pecos people (Levine and LaBauve 1990, 104; Spielmann et al. 1990, 760). This decreased importance of maize in the Pecos diet is supported by isotopic data that suggests that meat, maize, or both became less important in Pecos subsistence as other plant sources were utilized (Spielmann et al. 1990, 760).

The skeletal data provided by Earnest Hooton (1930) shows similar patterns of stature and leg length decline over time. Hooton notes that while the femoral lengths stay relatively steady over time (133), the maximum tibia lengths for both males and females decline from the early to later periods (143). Hooton also realized that tibio-femoral index (the tibia:femur ratio) is slightly less in females and that the index increased over time for males but decreased for females (143). Interesting patterns are seen in the arms as well,

as both sexes experience a decrease in maximum humerus length over time (152), and the radius also tends to decrease over time, albeit to a much lesser extent (157).

All of these details, especially the leg lengths, indicate that both male and female stature declined over time, with the shortest statures being from the most recent period. Although this decline is slight—the difference in male stature over time being only 6 mm—there is a decline nonetheless (Hooton 1930, 178). This point is meaningful because this pattern parallels those trends seen in the Lower Illinois River Valley and the Yucatan peninsula. What is interesting is that it appears as if the *tibia*, not the femur, is most affected at Pecos Pueblo, the opposite of what is seen among the Maya, who tend to have extremely short femora (see previous discussion of the crural index). This is an interesting anomaly and is not yet fully explained, although it does agree with Auerbach and Ruff's (2010) observation that Pacific Northwest and Arctic populations have short statures and low crural indices (high tibia:femur ratios) caused by particularly short tibiae.

Summary

The exact causes of short stature and disproportionately short leg lengths throughout Mesoamerica are not fully understood at this time. While it is tempting to attribute this widespread pattern to genetics, we must acknowledge that the basic principles of natural selection contradict this conclusion. Further supporting the idea that short stature cannot be explained in terms of genetic adaptations is the fact that, although stature did change over time, it only took a few centuries. This is relatively quick in evolutionary terms, especially for humans, a species that does not reproduce quickly. It therefore appears that nutritional and socioeconomic explanations are much more

compelling. What we do know is that short stature, as inferred by leg length, is perhaps best exemplified by the Maya, making Tipu's complete and well-preserved collection ideal for research into nutrition and skeletal development.

The aim of this project is to isolate the primary culprit of short stature among the Maya, and the ubiquity of maize consumption in both North America and Mesoamerica provides important points of comparison and the means to test my hypothesis that maize is the main cause of the Maya's short statures and disproportionately short legs. North America's high reliance on maize as a dietary staple is comparable to that of the Maya, and it is therefore reasonable to believe these similar diets had similar impacts on skeletal health. It is for this reason that a skeletal comparison between Tipu, Pecos Pueblo, and the Lower Illinois River Valley (all of which have extensive skeletal data) should be revelatory in evaluating greater patterns of diet, health, and skeletal growth among the Maya. If leg lengths and stature are similarly short for all three populations, then maize may very well be the dominant factor affecting short adult stature during the transition from food collecting to food producing.

If, on the other hand, the Tipu Maya prove to have considerably shorter heights and legs than the North American populations, maize may only be a minor contributing factor among the Maya's particularly short adult height. Not only do I suspect the Tipu Maya to be considerably shorter than their North American counterparts, but I also hypothesize that their femora will be disproportionately shorter compared to Pecos Pueblo and Schild. There are plenty of contradictions and discrepancies in the literature regarding the relationship between maize consumption, genetics, stature, and leg length, and only after such a cross-cultural comparison has taken place can bioarchaeologists

confidently rule out factors such as genetics as an explanation for short Maya stature and leg lengths.

CHAPTER III - MATERIALS AND METHODS

This study used leg measurements (femora and tibiae) and arm measurements (humeri and radii) from three populations: the Maya site of Tipu (Belize), the Schild site from the Lower Illinois River Valley, and the Pecos Pueblo site from the American Southwest. All three of these sites were chosen because their occupants relied upon intensive maize agriculture, thereby allowing complete impact of maize on stature, limb length, and limb proportions to be observed and compared.

For the Tipu collection, an osteometric board was used to take standardized measurements of femora, tibiae, radii, and humeri with a total sample size of 100. There are two standardized femur length measurements: maximum and bicondylar. Femur maximum length is “the distance from the point in the acetabulum where the three elements meet to the deepest point on the ischial tuberosity” (White et al. 2012, 82). The femur bicondylar length is the “distance from the most superior point on the head to a plane drawn along the inferior surfaces of the distal condyles” (White et al. 2012, 82). These measurements are depicted in Figure 1 below.

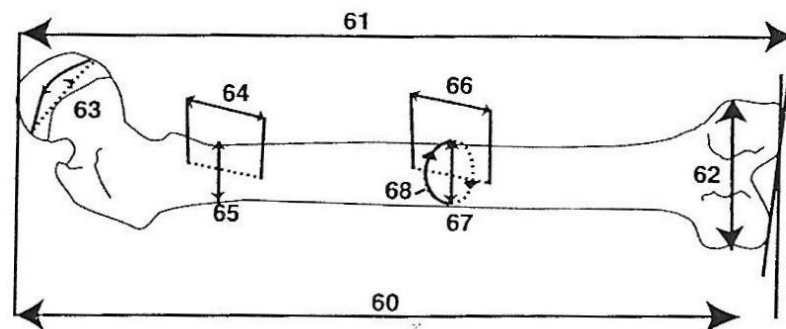


Figure 2. Femur Maximum and Bicondylar Lengths

Maximum and bicondylar femur measurements, represented by lines 61 and 60, respectively (White et al. 2012, 83) (after Moore-Jansen et al. 1994).

Two length measurements were also taken for the tibia: maximum and condylar. There is an important distinction between the two: the condylar length is defined as the “distance from the superior articular surface of the lateral condyle to the tip of the medial malleolus” (White et al. 2012, 83). This is a recognized osteometric standard often typically referred to as simply “tibia length”. Maximum length of the tibia may be defined as the distance from the most proximal tip on the articular surface of the condyle to the tip of the medial malleolus. I have added this measurement because it allowed me to measure the length of the entire tibia. The traditional measurement starts only at the condylar surface, which is not representative of total length. The tibia measurements are illustrated in Figure 2 below.

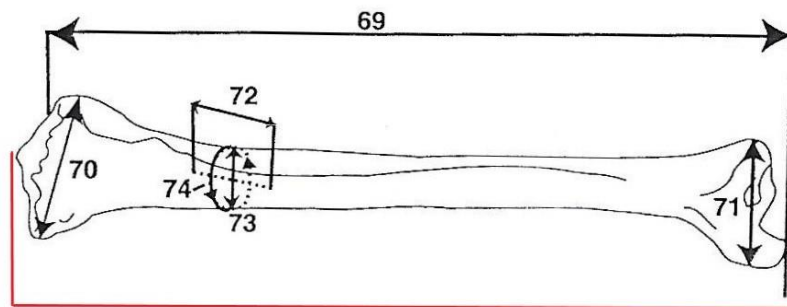


Figure 3. Tibia Maximum and Bicondylar Lengths

Maximum and bicondylar tibia lengths. Maximum length is represented by the red line, and bicondylar length is represented by line 69 (White et al. 2012, 83) (after Moore-Jansen et al. 1994).

Measuring the tibiae proved to be one of the more difficult aspects of data collection because, although “maximum length” is not a recognized osteological standard in textbooks, it is often used in studies. This inconsistency surrounding tibial measurements has long been an issue in biological anthropology. Around a century ago, it was established that the maximum length of long bones should be used in all cases,

except for the femur and tibiae, which are to both be measured in oblique positions (i.e. their bicondylar and condylar lengths, respectively). Unfortunately, this agreement not been consistently followed, especially for the tibia, for which anthropologists often measure the maximum length instead of the bicondylar length without specifying they had done so (Krogman 1978, 154). In fact, even Trotter was inconsistent with tibia measurements in applying her own descriptions, often excluding the malleolus when she herself specified it was to be included, leading to further confusion (Jantz et al. 1995; Meadows and Jantz 1995). It is for this reasons that I am including and specifying both maximum and condylar tibia measurements. Adding an additional tibia measurement will also make for more meaningful statistical analysis by increasing sample size, since often times the entire tibial condyle is not persevered. To avoid confusion between the two tibial measurements, the remainder of this study will refer to traditional tibia length as “condylar length” and my maximum measurement as “maximum length”.

Measurements for the arm bones are straightforward. The maximum length of the humerus is defined as the “direct distance from the most superior point on the head of the humerus to the most inferior point on the trochlea” (White et al. 2012, 80) (Figure 3).

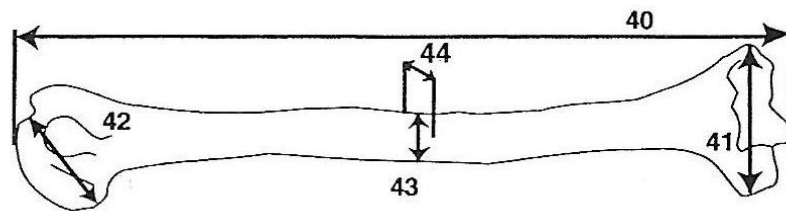


Figure 4. Maximum Humerus Length

Maximum humerus measurement, represented by line 40 (White et al. 2012, 80) (after Moore-Jansen et al. 1994).

The maximum length of the radius is defined as “the distance from the most proximally positioned point on the head of radius to the tip of the styloid process without regard to the long axis of the bone” (White et al. 2012, 80). Maximum radius length is depicted below in Figure 4.

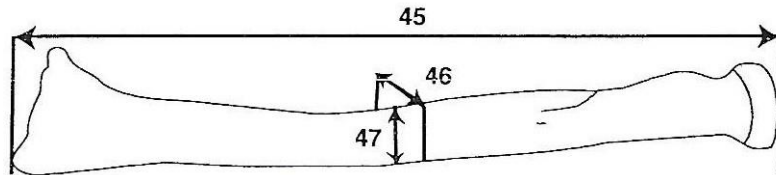


Figure 5. Maximum Radius Length

Maximum radius length, represented by line 45 (White et al. 2012, 80) (after Moore-Jansen et al. 1994).

Raw data for the Schild site was generously provided by Dr. Della Cook (Indiana University-Bloomington) and includes all the same leg and arm measurements as those from Tipu. Both condylar and maximum tibia length measurements were used. The sample size for Schild was 128. The Pecos Pueblo data was accessed from Earnest Hooton’s 1930 study “The Indians of Pecos Pueblo: A Study of their Skeletal Remains”; only descriptive summary statistics were available. The sample size for the site was 221. All of the same measurements that were used at Tipu and at Schild were utilized here except for tibia condylar length, which was not available in this dataset. Hooton (1930) only took maximum tibia measurements, not condylar measurements. In my study, therefore, only maximum tibia length was analyzed from Pecos Pueblo.

For consistency, left measurements were used when available, and right measurements were substituted when a left measurement was not available or when preservation for the right side was better and thus offered a more reliable measurement.

The means and standard deviations of each bone length were computed to determine differences in length (and thus stature). In addition, ratios between each bone were taken to determine how distal elements compared relative to proximal elements within the same limb. These ratios are as follows: tibia condylar length:femur maximum length, tibia maximum length:femur maximum length, radius maximum length:humerus maximum length, and humerus maximum length:femur maximum length. Since the Pecos Pueblo dataset is lacking tibia condylar length, this study does not include the ratio of tibia condylar length:femur maximum length.

Taking the ratios between the humeri and femora was done with the intent of observing body proportion differences between the populations, since the Maya are presumed to have very short legs compared to their arms and overall stature (Bogin and Rios 2003; del Angel 1996, 64; Márquez Morfín and del Angel 1997, 57-58). Maximum femur lengths were used in calculating ratios in favor of bicondylar femur lengths because maximum femur lengths are more reflective of overall height. Both condylar and maximum tibia lengths were used to clear up the aforementioned confusion surrounding the standardization of tibia measurements.

The statistics program SPSS was used to calculate basic descriptive statistics for Tipu and Schild. By inputting all available long bone measurements to the program, averages and standard deviations for all measured bone lengths were calculated. SPSS also calculated the averages and standard deviations for all bone length ratios. Hooton (1930) furnished summary descriptive statistics for the Pecos Pueblo population, so these values were not determined using SPSS.

To compare the statistical significance between the two populations, a two sample independent t-test as performed to compare data between Tipu and Schild and Tipu and Pecos Pueblo. SPSS was used to complete the t-test between the Tipu and Schild datasets. Testing the significance between Tipu and Pecos Pueblo was done slightly differently because the Pecos Pueblo dataset only included summary descriptive statistics and did not include individual bone lengths, and since SPSS requires individual numerical entries between all populations to complete cross-population comparisons, Pecos Pueblo data could not be included in the SPSS input. For this reason, t-scores and p-values were calculated separately for Pecos Pueblo based on Hooton's summary descriptive statistics and Tipu's summary descriptive statistics using the on-line calculator at graphpad.com. Although all measurements were run through SPSS, maximum lengths were prioritized since these best reflect total stature and are thus most relevant to this study.

Four hypotheses were addressed using these statistics: 1) the Tipu Maya would be the shortest compared to Schild and Pecos Pueblo, 2) the Tipu Maya would have lower tibia:femur ratios compared to Schild and Pecos Pueblo, 3) the Tipu Maya would have lower humerus:femur ratios compared to Schild and Pecos Pueblo, and 4) Tipu's long bone lengths and ratios would be typical of greater Mesoamerica. The results of these analyses are presented in the following chapter.

CHAPTER IV – RESULTS

In this section, I first break down the results of my analysis into three main parts. First, I outline how Pecos Pueblo and Schild long bone lengths compare to those at Tipu, with special emphasis on maximum long bone lengths, since those are most correlated with stature. Second, I outline how the body proportions (between and within the arms and legs) at Pecos Pueblo and Schild compared to those at Tipu. Last, I finish with a brief comparison of the Tipu skeletal data to that of the Valley of Mexico, as discussed by del Angel (1996) and del Angel and Serrano (1991). The purpose of this comparison is to see if Tipu skeletal lengths and proportions are typical of the Maya and cultures of the greater Mesoamerican region.

Bone Measurement Comparisons: Tipu, Schild, and Pecos Pueblo

Bone Lengths

In assessing long bone lengths, I first tested to see whether there was a difference between males and females between the sites. After confirming a meaningful difference, I chose to consider their long bone lengths separately. The differences in maximum long bone lengths by site are summarized in Table 1, and the significance values (p-values) are summarized subsequently in Table 2.

As was expected, Tipu, with few exceptions, had the shortest long bones for both sexes out of all the sites. The t-test results showed that, compared to both Pecos Pueblo and Schild, Tipu had statistically significantly shorter maximum and bicondylar femur lengths. The greatest difference between femur lengths occurred when comparing Tipu and Schild. Tipu also had statistically significantly shorter tibiae for both sexes compared to Schild. Interestingly, the maximum tibia lengths of males at Pecos Pueblo were

actually slightly shorter than those at Tipu, although this difference was not statistically significant.

Tipu also had the shortest humeri for both sexes out of all the sites with the most highly significant difference between the humerus length occurring between Tipu and Schild for both sexes. The difference in humerus length was not as large between Tipu and Pecos Pueblo, although the difference between the male humeri measurements between the two sites was statistically significant. Lastly, Tipu also had the shortest radii out of all the groups. This difference was statistically significant when comparing Tipu to Schild but not when comparing Tipu to Pecos Pueblo.

Table 1 *Mean Maximum Long Bone Lengths by Sex by Site (mm)*

Femur Maximum Length

Site	Sex	n	\bar{x}	SD
Tipu	M	41	418.65	16.55
	F	33	388.05	14.61
Schild	M	66	453.56	19.72
	F	68	423.60	18.33
Pecos Pueblo	M	140	426.71	19.85
	F	105	396.05	17.50

Femur Bicondylar Length

Site	Sex	n	\bar{x}	SD
Tipu	M	40	416.68	16.96
	F	32	384.86	14.38
Schild	M	65	450.29	19.57
	F	68	415.19	32.02
Pecos Pueblo	M	142	423.24	19.25
	F	104	393.03	17.45

Table 1 Mean Maximum Long Bone Lengths by Sex by Site (mm) (cont.)

Tibia Maximum Length

Site	Sex	n	\bar{x}	SD
Tipu	M	35	358.59	15.32
	F	24	323.46	16.18
Schild	M	62	386.05	19.88
	F	64	356.25	17.45
Pecos Pueblo	M	117	357.78	18.75
	F	81	323.83	14.90

Tibia Condylar Length

Site	Sex	n	\bar{x}	SD
Tipu	M	33	356.32	15.14
	F	20	322.80	15.66
Schild	M	62	380.95	19.42
	F	65	351.20	19.75
Pecos Pueblo	M	/	/	/
	F	/	/	/

Humerus Maximum Length

Site	Sex	n	\bar{x}	SD
Tipu	M	26	301.13	9.68
	F	19	279.95	9.33
Schild	M	58	326.26	13.04
	F	70	303.86	13.63
Pecos Pueblo	M	134	308.25	14.70
	F	87	285.06	12.30

Radius Maximum Length

Site	Sex	n	\bar{x}	SD
Tipu	M	30	236.38	10.05
	F	27	212.07	11.37
Schild	M	57	253.21	32.77
	F	64	231.31	28.76
Pecos Pueblo	M	100	238.35	13.15
	F	57	216.59	10.95

Table 2 *Summary of Significance Values for Differences in Mean Maximum Bone Length by Site Comparisons*

Length	Sites Compared	Sex	P-Value
Femur Maximum	Tipu-Schild	M	0.0000
		F	0.0000
	Tipu-Pecos Pueblo	M	0.0189
		F	0.0188
Femur Bicondylar	Tipu-Schild	M	0.0000
		F	0.0000
	Tipu-Pecos Pueblo	M	0.0525
		F	0.0174
Tibia Maximum	Tipu-Schild	M	0.0000
		F	0.0000
	Tipu-Pecos Pueblo	M	0.8159
		F	0.9168
Tibia Condylar	Tipu-Schild	M	0.0000
		F	0.0000
	Tipu-Pecos Pueblo	M	/
		F	/
Humerus Maximum	Tipu-Schild	M	0.0000
		F	0.0000
	Tipu-Pecos Pueblo	M	0.0191
		F	0.0913
Radius Maximum	Tipu-Schild	M	0.0080
		F	0.0010
	Tipu-Pecos Pueblo	M	0.4509
		F	0.0847

Forward slashes (/) represent lengths that were unavailable to use in analysis.

Bone Length Ratios

Upper:lower limb proximal bone length ratios were considered because the Maya have been argued to have disproportionate bodies in comparison to most populations in that their lower bodies are especially short compared to their upper bodies (Bogin et al. 2002; Bogin and Varela-Silva 2009; del Angel 1996; Genoves 1967). This disproportionality manifests as very short legs compared to arms (i.e., arms and legs are

more similar in length) and is important because shortened legs can potentially indicate biological stress during childhood (Bogin et al. 2002; Bogin et al. 2003, Bogin et al. 2009; del Angel 1996). In calculating these ratios, maximum femur lengths were used instead of bicondylar femur lengths since maximum femur lengths are more representative of total stature. Both tibia maximum and tibia condylar lengths were used in ratio calculations to avoid confusion of measurements (see Materials and Methods).

It was found that Tipu displayed a higher humerus:femur ratio, which means that there was a greater difference between humerus length and femur length compared to the values seen at the other sites. It actually is Pecos Pueblo that had lower humerus:femur ratios, which may indicate shortened femora at Pecos Pueblo. These results are summarized below in Table 3, and the significance values are summarized in Table 4.

Table 3 *Mean Long Bone Length Ratios by Site (mm)*

Tibia Condylar:Femur Maximum

Site	Sex	n	\bar{x}	SD
Tipu	M	25	0.85	0.02
	F	16	0.83	0.02
Schild	M	58	0.84	0.02
	F	61	0.83	0.02
Pecos Pueblo	M	/	/	/
	F	/	/	/

Tibia Maximum:Femur Maximum

Site	Sex	n	\bar{x}	SD
Tipu	M	26	0.86	0.02
	F	18	0.83	0.02
Schild	M	58	0.85	0.02
	F	60	0.84	0.02
Pecos Pueblo	M	104	0.84	0.02
	F	71	0.83	0.02

Table 3 *Mean Long Bone Length Ratios by Site (mm) (cont.)*

Radius Maximum:Humerus Maximum

Site	Sex	n	\bar{x}	SD
Tipu	M	20	0.79	0.02
	F	16	0.76	0.03
Schild	M	54	0.79	0.03
	F	62	0.76	0.09
Pecos Pueblo	M	/	0.77	/
	F	/	0.76	/

Humerus Maximum:Femur Maximum

Site	Sex	n	\bar{x}	SD
Tipu	M	21	0.72	0.02
	F	13	0.71	0.02
Schild	M	55	0.72	0.02
	F	64	0.72	0.02
Pecos Pueblo	M	116	0.73	0.02
	F	78	0.73	0.02

Forward slashes (/) are ratios that could not be calculated due to insufficient data at Pecos Pueblo.

Table 4 *Summary of Long Bone Length Ratio Significance Values*

Ratio	Sites Compared	Sex	P-Value
Tibia Maximum:Femur Maximum	Tipu-Schild	M	0.0590
		F	0.4580
	Tipu-Pecos Pueblo	M	0.0010
		F	1.0000
Tibia Condylar:Femur Maximum	Tipu-Schild	M	0.0030
		F	0.9740
	Tipu-Pecos Pueblo	M	/
		F	/
Humerus Maximum:Femur Maximum	Tipu-Schild	M	0.5970
		F	0.7220
	Tipu-Pecos Pueblo	M	0.0368
		F	0.0012
Radius Maximum:Humerus Maximum	Tipu-Schild	M	0.9380
		F	0.9060
	Tipu-Pecos Pueblo	M	/
		F	/

Forward slashes (/) are ratios that could not be calculated due to missing measurements at Pecos Pueblo.

The proximal:distal long bone segment ratios were also analyzed within each limb because they have been argued to be a good health indicator since proximal segments are more directly impacted by biological stress (Vázquez-Vázquez et al. 2013, 592). It was found that Tipu had lower tibia:femur ratios compared to the other sites—that is, there was a smaller difference in length between the tibiae and femora, although males showed a greater length difference within their leg segments than did females. The most significant statistical differences occurred between the Tipu males' tibia maximum:femur maximum ratios when compared to Pecos Pueblo and Schild and the Tipu males' tibia condylar:femur maximum ratios when compared to Schild. This indicated a shortening of the femur (since the femur is a longer bone and is closer in length to the tibia) and that Tipu individuals therefore underwent more stress during growth. What was interesting was that the tibiae in the Pecos Pueblo and Tipu populations were nearly identical in length, further suggesting that shortened femora at Tipu caused this low ratio (i.e. less discrepancy) between leg bone lengths.

In summary, the residents of Tipu were the shortest out of the three populations. The largest and most statistically significant differences in height occurred between Tipu and Schild, and while some differences in height between Tipu and Pecos Pueblo were significant, those differences were smaller than those between Tipu and Schild. Tipu skeletons also revealed low tibia:femur ratios, indicating femora that were relatively shorter and therefore closer in length to the tibiae. This supported the idea that short femora at Tipu contributed to short stature and reflected biological stress. However, Pecos Pueblo did have greater disproportionality between upper and lower body

segments, which indicates that shortened femora were a phenomenon that occurred in North America as well.

Bone Measurement Comparisons: Tipu and Other Mesoamerican Populations

In order to determine whether Tipu displayed a pattern of bone measurements that is one broadly seen in much of Mesoamerica, it was necessary to compare skeletal data from the site with the Valley of Mexico data compiled and analyzed by del Angel and Serrano (1991). This aggregated sample was composed of 346 individuals from 12 Preclassic sites (n=207) and 5 Postclassic sites (n=139). Tipu data was compared to del Angel and Serrano's (1991) Postclassic data since they were temporally more similar.

Overall, Tipu was slightly shorter than the Mesoamerican sample (del Angel and Serrano 1991). Tipu had slightly shorter femora, humeri, and radii for both sexes. Tipu females also had shorter tibiae, but males had slightly longer tibiae, although the difference is a minuscule 2 mm. However, these differences are small, and the only statistical difference was in the female tibiae. All other leg bone values between the groups were not statistically significant and indicate that the Tipu Maya stature was not substantially different in stature and limb length than other Mesoamerican groups. A statistical analysis could not be performed on the long bone ratios between Tipu and the Valley of Mexico because del Angel and Serrano (1991) did not provide the standard deviations for the long bone ratios and thus a statistical comparison to the Tipu data was not appropriate. However, manual calculations of the long bone ratios from the Valley of Mexico show that they do not differ from those ratios at Tipu. In addition, the long bone ratios and long bone lengths of Schild and Pecos Pueblo also did not differ significantly from those of the Valley of Mexico, although Schild was slightly taller than the Valley of

Mexico populations. This pattern also shows a decrease in stature going from northern to southern latitudes.

In summary, there appears to be no substantial difference between the long bone lengths and proportions of the Tipu Maya compared to the Mesoamerican population of the Valley of Mexico. These results are summarized below in Tables 5, 6, and 7.

Table 5 *Tipu and Postclassic Valley of Mexico (VM) Mean Long Bone Lengths (mm)*

Femur Maximum Length

Site	Sex	n	\bar{x}	SD
Tipu	M	41	418.65	16.55
	F	33	388.05	14.61
VM	M	107	423.75	21.06
	F	75	394.48	23.93

Tibia Maximum Length

Site	Sex	n	\bar{x}	SD
Tipu	M	35	358.59	15.32
	F	24	323.46	16.18
VM	M	65	356.88	18.89
	F	61	330.93	13.38

Humerus Maximum Length

Site	Sex	n	\bar{x}	SD
Tipu	M	26	301.13	9.68
	F	19	279.95	9.33
VM	M	86	308.63	23.85
	F	61	285.08	11.74

Radius Maximum Length

Site	Sex	n	\bar{x}	SD
Tipu	M	30	236.38	10.05
	F	27	212.07	11.37
VM	M	47	243.13	15.15
	F	43	219.17	9.99

Measurements from the Valley of Mexico are after del Angel and Serrano (1991).

Table 6 *Tipu and the Postclassic Valley of Mexico (VM) Mean Leg Bone Length Comparison Significance Values*

Length	Sex	P-Value
Femur Max	M	0.1656
	F	0.1560
Tibia Max	M	0.6466
	F	0.0320

Table 7 *Tipu and Postclassic Valley of Mexico (VM) Mean Long Bone Ratios*

Tibia Maximum:Femur Maximum

Site	Sex	\bar{x}
Tipu	M	0.86
	F	0.83
VM	M	0.84
	F	0.84

Radius Maximum:Humerus Maximum

Site	Sex	\bar{x}
Tipu	M	0.79
	F	0.76
VM	M	0.79
	F	0.77

Humerus Maximum:Femur Maximum

Site	Sex	\bar{x}
Tipu	M	0.72
	F	0.71
VM	M	0.73
	F	0.72

Summary

Tipu had the shortest stature of the three primary maize-based populations analyzed in this study. All long bones tested—humeri, radii, tibiae, and femora—were shortest for the Tipu Maya. This is consistent with the well-documented trend that the Maya are notoriously short by global standards (Bogin et al. 2002; Bogin and Varela-

Silva 2009; Danforth 1999; Haviland 1967; Longyear 1952; Lowe 1985; Márquez Morfín et al. 2002; Nickens 1976; Santley et al. 1986; Willey et al. 1973). However, compared to other Mesoamerican populations, stature at Tipu was generally very comparable, and Pecos Pueblo was not substantially taller than Tipu. Among the groups considered, arguably the most salient observation is that those from Schild were quite tall, and it is worth noting that stature appeared to decrease from northern to southern latitudes, with Schild being the tallest and northernmost population and Tipu being the shortest and southernmost population.

The tibia:femur ratios were particularly low at Tipu, which reflects little difference between tibia and femur lengths. This is perhaps best explained by extremely short femora among the Tipu Maya. Interestingly, Pecos Pueblo exhibited greater disproportionality between their upper and lower bodies, indicated by humeri and femora that were closer in length. Both Tipu's long bone lengths and proportions appeared within the range of published values for the Valley of Mexico data as well. Given this information, Tipu—both as a site and as a proxy for the Maya—did not seem to have unusual long bone proportions.

Analysis of Hypotheses

The results of the testing of the four main hypotheses are addressed individually below.

Hypothesis 1

The first hypothesis stated that the Tipu Maya would have the smallest stature among the three populations considered. My data analysis supported this hypothesis. Based on the analysis of leg lengths seen at Tipu, Schild, and Pecos Pueblo, it appears

that the Maya were the shortest of the three populations. Tipu had statistically significantly shorter tibiae and femora compared to Schild and Pecos Pueblo for both males and females. The biggest and most statistically significant height difference occurred between Schild and Tipu, while Tipu and Pecos Pueblo were similar in stature, seen especially in the female long bone lengths.

The fact that Tipu was the shortest compared to Schild and Pecos Pueblo was expected since stature decreased in Mesoamerica from the Preclassic to Postclassic periods (del Angel 1996; Haviland 1967; Longyear 1952; Lowe 1985; Márquez Morfín et al. 2002; Nickens 1976; Santley et al. 1986; Willey et al. 1973) and the Maya are notorious for their short statures (Bogin et al. 2002; Bogin and Varela-Silva 2009; Márquez Morfín and del Angel 1997). Given the fact that Pecos Pueblo is close behind Tipu in terms of stature, it may be that extremely short statures are not a Maya-specific phenomenon. Instead, this may suggest a regional correlation between stature and latitude since Schild (the northernmost population) is tallest, followed by Pecos Pueblo, then by Tipu, which is the shortest and southernmost population.

Hypothesis 2

The second hypothesis was based on del Angel's argument about tibia:femur ratios that characterized populations in the Valley of Mexico, namely that Mesoamerican populations showed femora that were relatively short compared to the tibiae (1996). I predicted that the Tipu Maya would show a similar pattern, and based on my data, this hypothesis was also supported. Out of the three groups tested, Tipu had lower tibia:femur ratios, and the most statistically significant differences occurred when comparing the males from Tipu to the males at both Pecos Pueblo and Schild, although the differences

between Tipu and Pecos Pueblo were more statistically significant. In other words, Tipu had overall less discrepancy between the leg bone segment lengths. Since it was argued that the femur growth is most affected by negative external influences (del Angel 1996, 66-74; Vázquez-Vázquez et al. 2013, 592), these ratios at Tipu likely meant that the Maya underwent greater stress during childhood than those at Schild and Pecos Pueblo.

However, these patterns were not quite so clear cut, and there are some subtleties than must be mentioned. Although Tipu's leg segment lengths exhibited less discrepancy in relationship to each other, these differences were not very large. For the tibia condylar:femur maximum ratio, in fact, the females from Tipu and Pecos Pueblo had the exact same value, and the males differed by only 1%. For the tibia maximum:femur maximum ratio, both males and females varied slightly, but again, this difference was small. The largest ratio difference was 2%, and this occurred between males of Tipu and Pecos Pueblo. While there was a strong statistical significance between these two sites, the actual difference in the ratio value itself was somewhat small. The tibia condylar:femur maximum ratio for Schild compared to Tipu was also statistically significant, but to a lesser degree than that of Pecos Pueblo compared to Tipu. This suggests that, although the greatest difference in long bone lengths occurred between Tipu and Schild, Tipu and Schild were more similar in terms of leg segment ratios.

This pattern is also interesting because it seemingly disagrees with Auerbach and Ruff's 2010 suggestion that higher crural indices due to shortened *tibiae* (lower tibia:femur ratios) are associated with taller statures. My data suggests that Tipu was the shortest compared to Schild and Pecos pueblo, and this is likely due to higher crural indices caused to shortened *femora*. Perhaps, then, the patterns between my observations

and Auerbach and Ruff's observations do not totally disagree. It is true that the stature patterns between Auerbach and Ruff's data and my data differ, but this might be because differences in stature were caused primarily by different leg segments (tibiae in the former, femora in the latter).

Hypothesis 3

In the third hypothesis I predicted that the Tipu Maya would have lower humerus:femur ratios, that is, the humerus and femur would be more similar in length because environmental factors were depressing femoral growth. I did not observe this pattern in the Tipu sample; therefore Hypothesis 3 is rejected. My data showed that Tipu had significantly higher humerus:femur ratios (a greater difference between the lengths of the two bones) compared to Pecos Pueblo, with greater statistical significance occurring for females. I found that Pecos Pueblo had lower humerus:femur ratios compared to Tipu, indicating that the humerus and femur were closer in length and caused by shortened femora at Pecos Pueblo. The humerus:femur ratios at Schild were not statistically different from Tipu, once again suggesting that Tipu and Schild were more similar in body proportions even though they had greater differences in height. Moreover, the fact that Tipu had a higher humerus:femur ratio compared to Pecos Pueblo suggests that perhaps the femora are not as severely shortened at Tipu as was expected. In fact, based on the high humerus:femur ratio at Pecos Pueblo, one could argue that Pecos Pueblo was more biologically stressed compared to Tipu.

Hypothesis 4

Hypothesis 4 predicted that the Tipu Maya were typical of the Maya and other Mesoamerican groups in terms of stature and long bone proportions. In comparing del

Angel and Serrano's (1991) data to Tipu, I found that while Tipu was slightly shorter, this difference in stature was not significant. Furthermore, the variation in long bone proportions between Tipu and the Valley of Mexico dataset was minimal. Once again, the males exhibited more variation than the females, but the biggest difference between the males of Tipu and the Valley of Mexico occurred in the tibia maximum:femur maximum ratios, and this was only a 2% difference. Due to these similarities between Tipu and the Valley of Mexico, hypothesis 4 was supported.

I would be remiss not to point out that there is also a 2% difference in tibia maximum:femur maximum ratios between the males of Tipu and Pecos Pueblo, and this difference was statistically significant. Moreover, the tibia condylar:femur max ratios between the males of Tipu and Pecos Pueblo exhibited a 1% difference that was also statistically significant. So, it is possible that the 2% difference in tibia maximum:femur maximum ratios between the males of Tipu and the Valley of Mexico is meaningful. However, without being able to perform a formal statistical analysis on these data, it is hard to definitively determine that a 2% ratio difference between Tipu and the Valley of Mexico is meaningful. Nevertheless, regardless of whether there is a statistically significant difference between these values, the tibia maximum:femur maximum ratios from the Valley of Mexico indicate that their femora was also shortened relative to their tibiae.

The commonalities between the Valley of Mexico and Tipu is noteworthy because it suggests that, while a reduction in leg length and stature is common among the Maya, this pattern is not specific to the Maya. The Maya's short statures and long bone ratios appear to be rather typical of the region, which indicates that this pattern is more

ubiquitous and widespread throughout Mesoamerica and not a Maya-specific phenomenon.

CHAPTER V – DISCUSSION

In this study, Maya long bone lengths from the site of Tipu, Belize, were assessed in order to determine if maize consumption had an impact on adult Maya height and long bone proportions and to determine if Tipu had statures and long bone proportions reflective of the greater Maya population throughout Mesoamerica.

The Impact of Maize on Growth

The populations examined from Tipu, Schild, and Pecos Pueblo were all relatively short by today's height standards in developed countries (Peñuelas et al. 2017). This can be explained, at least in part, by maize consumption. All three populations relied as a major food staple, and in doing so, they consumed lots of starchy carbohydrates but not nearly enough protein, iron, and B-vitamins (Nuss and Tanumihardjo 2010, 418). This diet was therefore highly unbalanced, and individuals in these regions were not receiving the proper nutrition, especially protein, required to reach maximum potential adult height.

The fact that the Tipu Maya were still shorter than the other two maize-consuming populations is telling. The Maya consumed relatively equal amounts of maize compared to Schild and Pecos Pueblo, yet they were still shorter by a statistically significant amount. However, it is worth noting the nuance within these patterns. First, the males appeared more affected by external pressures, which was especially evidenced by greater differences within the males' leg segment ratios. In addition, the greatest difference in height occurred between Tipu and Schild. So, while Tipu was the shortest compared to Pecos Pueblo and Schild, Pecos Pueblo was much closer to Tipu in terms of stature than Schild. Nevertheless, the fact that Tipu was the shortest indicates that high

maize consumption plays only a partial role in the Maya's short adult stature, and while the exact magnitude of this is unclear at this time, this study suggested that maize was not the primary culprit of short stature among the Maya. It might be *a* factor, but it was not the *only* factor.

Even though short stature and short legs might be a more common phenomena than expected, studying these skeletal data was still helpful in revealing patterns of health, growth, and development. This was perhaps best demonstrated by Bogin et al.'s work (2002; 2003; 2009), which, as the reader will recall, found correlations between short statures, reduced leg lengths, and negative external pressures in modern Maya communities.

It is also possible that Maya long bone proportions have been over-interpreted. My data showed that the Tipu Maya's femora did appear to be particularly short relative to the rest of their body, but their upper-lower body ratios were not unique as has been suggested. Recall that the Maya have been believed to have disproportionately short legs compared to arms (del Angel 1996, 64; Márquez and del Angel 1997, 57-58). However, my data showed that this pattern was seen in North America as well. It was Pecos Pueblo, from the American Southwest, that showed the greatest upper:lower body disproportionality (i.e., shortened legs relative to arms). This further emphasizes the point that these patterns may very well be phenomena seen throughout all of the Americas and not unique to the Maya.

Yet, it is intriguing that, despite similar bone proportions between Tipu and greater Mesoamerica, Tipu appeared to be slightly shorter in stature compared to the del Angel and Serrano (1991) sample. This is a very curious observation, especially since we

might have expected Tipu to be taller than other Mesoamerican groups because of their otherwise good health (Cohen et al. 1994; Danforth et al. 1997). However, the skeletal data from Tipu might not be entirely representative of total health in the population. It is possible that health at Tipu was slightly worse than previously believed (Danforth et al. 1997) and that particularly unhealthy individuals died before pathological effects could manifest in their skeletons, a phenomenon that is part of the osteological paradox (Wood et al. 1992).

Another potential explanation for short stature at Tipu compared to the Valley of Mexico is the fact that the del Angel talked about Mesoamerican stature decrease *over time* caused by factors such as climatic conditions, interbreeding, nutritional deficiencies, and increased population density (del Angel 1996, 56). Given that Tipu was a colonial site that was compared to del Angel's Postclassic sample could potentially account for Tipu's shorter stature, since Tipu are the more recent group and therefore would have presumably undergone the aforementioned short stature inducing conditions for a longer period of time. However, this too comes with its own set of problems. While the effects of short stature and short leg lengths had been around for a long time, these effects could have been mitigated rather quickly with cultural change, given that short stature and leg bones are not rooted in genetics. Furthermore, while some of these effects, such as climate and nutrition, could have persisted through time, factors such as population density would have theoretically decreased over time. In addition, if interbreeding were a real issue, as del Angel (1996) has suggested, then we might expect this intermixing of genes to result in taller statures and leg bones, not shorter ones, through the effects of heterosis.

Nevertheless, it is important to point out that, although Tipu was slightly shorter than the greater Mesoamerican sample, the differences were small, and only one of those differences were statistically significant. In addition, the body proportions of Tipu compared to the Valley of Mexico were about the same. Overall, the differences between Tipu and the Valley of Mexico were not large enough to allow the conclusion that the Tipu Maya were osteologically unique compared to their surrounding region. For this reason, we can confidently conclude that Tipu statures and long bone lengths were rather typical of the Maya.

Other Potential Considerations in Mesoamerican Stature Patterns

What, then, explains why the Maya are so much shorter than their northern American counterparts? All three populations seemed stressed on some level, and while maize might have played a part in biological stress, it likely was not solely responsible for the Maya's short stature. My data does indicate that there might be a strong regional component at play, as was proposed first by Jaén Esquivel and López Alonso (1974) and then by del Angel (1996). It is clear from the numbers that the average leg bone lengths, and therefore statures, got progressively shorter as latitudes got lower. This pattern is congruent with earlier claims that there was a decline in stature in Mesoamerica from north to south. Similarly, del Angel's data from Mesoamerica suggested that the people in northern Mesoamerica were taller than those groups in more southern regions (1996, 58). My findings not only verified this pattern but also suggested that this pattern extended into more northern latitudes, as evidenced by comparatively tall statures at Schild, the northernmost of the three sites in this study.

As discussed earlier, decrease in stature from northern to southern latitudes might have been related to the basic human biological principles of Bergmann's Rule, which states that organisms living in hotter regions will have smaller body masses to assist in heat regulation (Foster and Collard 2013). Out of all three populations studied here, the Tipu Maya existed farthest south by a substantial distance, a region with a climate which is hotter and more humid than those at the sites of Pecos Pueblo and Schild. These results suggested that we should not completely rule out the fact that short Maya stature was a warm weather adaptation. Yet we must be careful with this conclusion, as the reader will remember that there does not appear to have been any selective or adaptive advantage to the Maya's small size because it does not help in survival and reproduction (Martorell 1989). Regardless, it was possible that the low-latitude climate influenced Maya stature and long bone length in some capacity, even if it was not in the adaptive sense.

However, recent studies have suggested that Bergmann's Rule as it applies to humans is a more complex issue than previously believed, being most valid when "there are major differences in latitude and temperature among groups" (Foster and Collard 2013, 1). According to this study, there must be a geographic difference of greater than 50 degrees latitude and a temperature difference of greater than 30 degrees Celsius for Bergmann's Rule to apply meaningfully to human populations (Foster and Collard 2013, 1). This point is intriguing because it does not appear to apply neatly to Tipu, Pecos Pueblo, and Schild; the distance between the northernmost site, Schild (approximately 40 degrees North) and southernmost site, Tipu (approximately 17 degrees North) does not appear to have been great enough to explain stature differences in terms of Bergmann's Rule. Moreover, Schild's location in Illinois has an average annual temperature of 3.5 –

15 degrees Celsius, while Tipu's location in Belize has an annual temperature of about 22 – 30 degrees Celsius. Even though Tipu is much warmer, the difference is not greater than 30 degrees Celsius, and thus should not have a strong enough correlation with Bergmann's Rule for it to significantly impact human body dimensions.

More recent studies have shown that the exact ways in which Bergmann's Rule applies to humans is still relatively poorly understood at this time. Wells et al. (2019) suggest that Bergmann's Rule is likely an oversimplified explanation for the complicated and multifaceted issue of human body morphology. They suggest that Bergmann's Rule is not simply explained only by thermodynamic regulation by showing that average precipitation and temperature volatility (i.e., floods, droughts, and rapid and drastic changes in temperature) in a region also have an impact on human body dimensions (Wells et al. 2019, 82). In other words, overall climatic instability seems to play a role in an individual's size. For example, it was found children born in Peru during the time of ENSO floods "had reduced height and lean mass compared to unexposed peers, but similar fat mass" (Danysh et al. 2014; Wells et al. 2019, 84). Examples such as this remind us that we must keep in mind quick, short-term events and their impact on body size as well.

Allen's Rule may be another potential explanation for the Maya's stature and limb lengths. Allen's Rule says that in warmer climates organisms will have longer appendages to help dissipate body heat, while individuals in colder regions will have shorter appendages to help retain body heat (Tilkens et al. 2007). The issue here is that the opposite pattern was seen in this study; the Tipu Maya, who were the furthest south, had shorter limbs than the inhabitants of Schild, who were the furthest north. We might

have expected to see shorter limbs at Schild since their more northern location gives them a cooler climate than that of the Yucatan Maya. Clearly, although Bergmann's and Allen's Rules might have played a partial role in explaining short stature among the Maya, they were by no means a complete explanation.

Perhaps a simpler explanation is that, at some point in ancient history, the ancestral Maya populations underwent a genetic bottleneck event. It could be that the Maya's short stature *is* explained in terms of genetics, but this explanation did not entail an adaptive explanation. It could just be that, by random mutations and chance, a small group of ancient Maya ancestors had genes for short stature and propagated these traits throughout the landscape, passing them down for generations. In this evolutionary model, this genetic trait for short stature might not have been evolutionarily relevant enough for natural selection to act on it, and short stature among the Maya was neutral trait under very little, if any, selective pressure.

Settlement data suggests that in Belize, from 7000 to 2000 BC, people lived in small kin groups of 25 to 30 people at the most (Weaver 2019). This is particularly interesting since groups this small would certainly make genetic bottleneck events plausible. However, for a genetic bottleneck to occur, the groups would also have to be isolated from one another, and while Maya were often found in pockets throughout the early Mesoamerican landscape (Ford and Fedick 1992; Rice 1976), there is no evidence that these groups were isolated from one another. Furthermore, there appears to be no cultural explanations for these genetic differences. For example, if elites distanced themselves from commoners and interbred only with members of the upper class, we would expect more variation in stature between sites. However, no such pattern is overtly

evident. On the contrary, my data suggests that the Maya's short statures and limb lengths were rather typical of the Mesoamerican region, and a few genetic bottleneck events would not have been sufficient to account for the scope and scale of short statures and limb lengths in the Mesoamerican region. Yet, once again, we must note potential regional differences for genetic variability. One such example is Klippel-Feil Syndrome, a condition resulting in short necks (and potentially shortened statures) due to the fusion of vertebrae (Merbs 2004, 248). This has been observed at the site of Tancah in Mexico (Saul 1982) as well as a few individuals at Tipu.

It is possible that other cultural factors are at play in this issue. Although maize was the Maya's primary form of subsistence, they also consumed animal foods such as dogs and turkeys, both of which increased in popularity into the Postclassic Period (Emery 2004, 47-48). The issue here is that animal foods are high in protein, so we would not expect their consumption to negatively impact adult stature and leg length. In addition, the Maya consumed a fair amount of beans to complement their maize consumption. Beans are rich in tryptophan, amino acids, proteins, and calcium, which should help with bone growth (Bressani et al. 1958; Bressani and Scrimshaw 1958; Katz et al. 1974; Wright and White 1996, 151-152). In fact, it has been argued that the Maya's maize diet, when complemented with sufficient bean consumption, was enough to sustain the proper health of an adult. However, this would not have been sufficient for children, as this diet still lacked the levels of iron necessary for proper growth and development (Wright and White 1996, 152). This reinforces the fact that short adult stature was an issue that began in childhood, with its effects lasting for life (Bogin and Varela-Silva 2009, 442).

Further exacerbating this issue is the fact that, even when there is sufficient food available, children often do not eat enough food because of respiratory and intestinal infections (Behar 1977; Mata and Salas 1984; Wright and White 1996, 152). This is an interesting and valid point; since stunted growth is a childhood issue, inadequate food consumption due to disease would have likely impacted the Maya on some level. It can be argued that there are more infectious agents in tropical settings, so perhaps childhood health *would* be more impacted in regions like Mesoamerica. One recent study of two Mesoamerican sites suggests that groups near the coast have shorter statures than more inland groups because parasites and other infectious agents are found in higher abundance near water (Morales Ríos 2011, 102). While Tipu is an inland site, they were still closer to the water than Pecos Pueblo and Schild and thus would have had presumably more exposure to tropical infectious agents, such as parasites, through trade and travelers. This is a particularly intriguing idea, especially since Tipu was a colonial site that was visited by the Spanish (Graham 1998; Graham 2011; Graham et al. 1989). When thought of in these terms, perhaps disease did play a more substantial role in Tipu's short stature, potentially explaining in part why they were shorter than Pecos Pueblo and Schild.

The social organization of Maya society might have also played a partial role in the Maya's short stature and leg lengths. Maya society was extremely hierarchical and stratified, meaning that there were clear distinctions between social classes. What is interesting is that it has been noted that in the Copan Valley "the elite are members of social groups that also contain people of lower rank, possibly even commoners" (Hendon 1991, 913). By this account, social stratification permeated even deeper levels of Maya society, with rank also presenting *within* social classes, not just between them. It is

possible that this would have made it more difficult for people in each social class to acquire sufficient resources for proper nutrition. While this is certainly possible, it is still difficult to say at this time to what extent this would have impacted typical Maya skeletal growth. Besides, rank within social classes is not necessarily a social pattern unique to Maya society, which fails to fully explain why the Maya were still so short compared to other groups. Even more, Tipu did not have a great deal of social stratification compared to larger Maya sites (Cohen et al. 1994), so factors such as population density and commoner suppression by the elite would have been relatively low. This provides further evidence that the Maya's socioeconomic system was not a prerequisite for malnutrition and short stature.

In considering food consumption, we also must consider the Maya's economic distribution system. The ancient Maya had sophisticated systems of paying tributes (Speal 2014, 77) taxes, and fulfilling work debts (Speal 2014, 80). They also had extensive trade and distribution of cacao, cloth, jade, obsidian, and chert, much of which continued even with Spanish arrival (Speal 2014, 94). This extensive trade system extended to foodstuff as well. Even the Maya who lived in areas where maize was not grown, such as the coastal Belizean site of Marco Gonzalez, showed evidence for maize in their diets, which means that this domesticate was imported to this region (Staller et al. 2006, 153). Those Maya who lived on the fringes of trade routes likely intensified their own food production so as to become self-reliant and self-subsisting (Freidel and Scarborough 1982). In other words, it does not appear as if one region of the Maya landscape was getting significantly more food than the other. It is not as if the Maya had less efficient ways of distributing food across the landscape since they clearly had no

problems moving resources around. Their resource distribution systems were quite complex and sophisticated, which suggests that they are not to blame for food shortages, subsequent malnutrition, and short stature.

Summary

My analysis showed that the Tipu Maya were the shortest population compared to Schild and Pecos Pueblo. The Tipu Maya also displayed shortened femora relative to tibiae compared to Schild and Pecos Pueblo, suggesting that they were under more stress than Schild and Pecos Pueblo. However, it was Pecos Pueblo that had lower humerus:femur ratios, which showed that its inhabitants were experiencing stress that caused their femora to shorten as well. This suggests that short statures and limb lengths were a problem more widespread throughout the Americas and not a phenomenon unique to the Maya. My data also indicate that statures and limb proportions at Tipu were rather typical of the greater Mesoamerican region.

The exact reasons for short statures and limb lengths among the Maya are still not completely clear, but what we do know at this point is that maize consumption is not solely responsible for these body dimensions. The sites of Schild, Pecos Pueblo, and Tipu all consumed maize, yet Tipu was still the shortest of the groups, although Pecos Pueblo was not far behind. This suggests a possible regional component to stature and limb length, potentially explained by Bergmann's and Allen's Rules, although this explanation seems insufficient. Other Maya cultural traits, such as strong social stratification as well as infectious agents present in their tropical environment, may have contributed to short stature in some capacity. Therefore, short stature among the ancient Maya is, at this point,

best explained by a combination of many variables, and future studies should look to other contributing factors and their synergistic interactions.

CHAPTER VI – CONCLUSIONS

Maize has long been regarded as a poor source of nutrition. Its high carbohydrate content is offset by a severe deficiency of protein, and a diet dominated by this foodstuff presents fundamental problems for healthy bone development. For these reasons, it has long been suspected that the Maya's high maize reliance was the cause of their notoriously short statures and disproportionate limb lengths, the latter of which has been characterized by short legs compared to arms and overall stature. The excavation of the Maya site of Tipu recovered an extensive and relatively complete skeletal collection, and despite being a contact period site, most traditional Maya ways of life, especially subsistence, persisted (Graham 2011). Together, these factors made Tipu an ideal proxy for greater patterns of Maya stature throughout Mesoamerica.

The sites of Schild, located in the Lower Illinois River Valley, and Pecos Pueblo, located in the American Southwest, were also maize agriculturalist societies. The similar diets shared between all three sites made a cross-cultural comparison of stature and limb proportions possible. The goal of this project was to isolate maize as a test variable to determine if it was the primary culprit of short stature among the Maya. The expectation was that if Tipu was still the shortest out of all three groups, there must be other factors influencing the Maya's extremely short statures.

Divided on the basis of sex, the long bone measurements and ratios of Tipu were compared to Schild and Pecos Pueblo using SPSS to test for statistical differences between the means of each group. Four hypotheses were tested: Hypothesis 1 predicted that the Tipu Maya would be the shortest compared to Schild and Pecos Pueblo. This hypothesis was supported based on Tipu having the shortest femora compared to the

other groups. Hypothesis 2 predicted that Tipu would have relatively short femora compared to tibiae and this hypothesis was also supported. Hypothesis 3 posited that Tipu would have the lowest humerus:femur ratios caused by shorted femora. This hypothesis was not supported, as it was actually Pecos Pueblo that exhibited shorter femora compared to humeri, suggesting that short statures and leg lengths are not unique to the Maya. Lastly, Hypothesis 4 stated that the long bone lengths and proportions of the Tipu Maya would be typical of the greater Mesoamerican region. Due to the fact that Tipu's long bone lengths and ratios were similar to populations throughout the Valley of Mexico, it was concluded that Tipu is osteologically typical of the region, and hypothesis 4 was supported.

The fact that Tipu was shorter than Schild and Pecos Pueblo, even though all three groups were maize agriculturalists, suggests that maize, even with its low protein content, was not the primary reason for short stature and reduced leg lengths among the Maya. There was, however, an interesting decline in stature going from northern to southern latitudes, suggesting a possible geographical component as an underlying factor in short stature among the Maya. While there is a clear north to south gradient, from Schild to Pecos Pueblo to Tipu, this still does not explain *why* this gradient occurs. Bergmann's Rule might partially explain this pattern, but it is unlikely since the expected physiological responses require greater temperature and distance differences than are seen between the two sites.

It is also possible that estimation while measuring was a source of bias. Poor preservation often resulted in small portions of bone missing, and to address this issue, careful estimations were made as to where that measurement point would have been had

the bone been fully intact. Although it is possible that this slightly influenced results, I do not believe this bias was a factor. If the estimations were inaccurate, they were only so by a very small amount—not by an amount enough to influence results in any major way. Concern regarding accuracy of estimation would be much larger if the results were paradigm-shifting and grossly went against the existing literature.

This study opens many avenues for future research. Future studies are encouraged to look at variables other than maize that might contribute to the Maya's short stature. For example, it may be useful to look at genetics among the Maya and other Mesoamerican populations to determine if there is a genomic predisposition for short stature in the region. It is also encouraged to look at populations further north into North America and further south in Mesoamerica, below the Yucatan Peninsula, perhaps even looking at South American populations. Theoretically, people closer to the equator will be even shorter than the Maya, and it will be interesting to see if the patterns of increased height in North America are mirrored in South America. In these studies, I would also encourage the inclusion of standard deviations for all relevant metric data so that other bioarchaeologists may perform their own thorough statistical analyses in the future.

Shortened femora likely indicate childhood biological stress, and since this was seen at Tipu, future studies will benefit from looking at correlations between short femora and other markers of childhood health, such as linear enamel hypoplasias. Since both shortened femora and linear enamel hypoplasia are forms of early growth disruptions, they might share underlying causes. Acquiring a better understanding of their correlations with one another can help identify these underlying causes.

This project contributes to a greater understanding of Mesoamerican bioarchaeology and osteology by showing that maize consumption alone does not explain the Maya's short stature and leg lengths. This project also provides a greater regional understanding of short stature and leg length by suggesting that short stature as a result of biological stress extends into regions north of Mesoamerica. This opens many avenues of research by encouraging similar questions to be addressed over larger geographical spans both north and south of Mesoamerica. This study also contributes to future studies of growth and development by encouraging bioarchaeologists to not only look at upper:lower body ratios but to also focus on long bone lengths *within* the leg segments. Lastly, this study highlights the complexity and multicausality of stature, growth, and development and encourages the bioarchaeologist to probe factors other than nutrition that may contribute to short statures in the Americas.

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