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Evidence of Ancient Maya Agriculture in the Bajos Surrounding Tikal, Guatemala

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ABSTRACT

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Current Central American agricultural practices are environmentally and economically unsustainable, yet the ancient Maya who lived in the same region thrived for thousands of years. Archaeologists have attempted to understand the factors enabling the prolonged success and ultimate collapse of the Maya societies. Some have proposed that the karst seasonal wetlands, called *bajos*, that border many Maya sites in the region were an influential factor in the Maya's ability to flourish. For the past decade, researchers have used carbon isotope analyses to identify areas of ancient maize agriculture at Maya archaeological sites. In this study, we collected soil samples from *bajos* and upland areas at Tikal, one of the most prominent Maya sites, located in northern Guatemala, and analyzed the samples for evidence of past C_4 vegetation. Our results confirm that *bajos* were utilized by the ancient Maya for long-term maize cultivation. Additionally, they suggest that modern agricultural methods in Guatemala that strategically utilize *bajos* may improve productivity and sustainability.

Key words: sustainability, milpa, corn, Guatemala, maize, stable carbon isotope, wetlands

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I extend endless appreciation and admiration to my wife, Aubree, and our children, Forest and Felicity. I love you.

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Introduction

For nearly three millennia, the Maya thrived in the highlands of southern Guatemala and the lowlands of Northern Guatemala, Belize, and the Yucatan (Coe 2011, Sharer and Traxler 2005). From the Pre-Classic (circa 2000 B.C. to A.D. 250) to the end of the Classic period (circa A.D. 250 to 900), the Maya civilization occupied an area from what is now southeastern Mexico on the west and western Honduras on the east. The Maya region is divided by modern archaeologists into three territories based on topography: the highlands which extend from east to west along the Sierra Madre de Chiapas mountains in southern Guatemala and southern Mexico, the Southern Lowlands which include the department of Petén, Guatemala, and Belize, and the Northern Lowlands which extend north to through the Yucatán (Coe 2011, Sharer and Traxler 2005).

The topographic distinctions in the Maya region resulted in major differences in the availability of natural resources among the three areas, most especially water and cultivable land. While the highlands in the south of the Maya region consist of a temperate volcanic mountain range, across the lowlands spans a hilly landscape over limestone bedrock with only small changes in elevation. Although few lakes are found in the region, perennial wetlands appear along the Belizean coast, and seasonal wetlands, termed *bajos* by local inhabitants, dot the southern lowlands. Bajos vary by size, vegetation, and degree of inundation, but typically include any low-lying wet terrain (Dunning et al. 2015). Geologically, most are karst depressions that inundate during the rainy season and desiccate during the dry season. The largest bajos occupy tens to hundreds of square kilometers (Azúcar, Santa Fe, and La Justa) while smaller "pocket bajos" cover less than two square kilometers each and are found amid areas of higher elevation (uplands) (Balzotti et al. 2013; Dunning et al. 2015). Bajos seem to be a regular motif among Maya sites as many early permanent settlements were located near bajos, and researchers speculate whether bajos hold the key to the Mayas success in this region (Bullar 1960; Dunning et al. 2002).

For years, archaeologists had assumed that the Maya subsisted entirely on the swidden milpa system of agriculture. This system and agricultural lifestyle is employed by many of the modern inhabitants of the Petén as well as other peoples throughout the world (Baker 2007; Nigh and Diemont 2013; Sanders 1962, 1963). Farm families that practice swidden agriculture select an area for a small family farm, called a milpa, cut down the natural vegetation, and burn it to release minerals from the plant material into the soil. This added fertility enables the cultivation of corn, beans, squash, and other foods. At the end of the harvest and just before the rainy season, the previous year's residue is burned to release again the minerals into the soil for another season of cultivation. Swidden milpas typically support two to five years of cultivation before they lose productivity. A fallow period of more than ten years is then required to allow the natural vegetation to regrow and return the agricultural potential to the land (Baker 2007; Linton 1962; Roys 1972; Thompson 1954). In this time, the family must move to the next selected and prepared milpa for cultivation while the previous milpa returns to forest vegetation. Although swidden milpa agriculture may be useful at low population densities, as populations and the demand for land increase, fallow regrowth periods become shortened, depleting soil nutrients, and swidden agriculture becomes unsustainable.

As archaeological surveys uncovered evidence to support estimates of population densities in the lowlands in excess of what a system of exclusively swidden agriculture could support, critics began to abandon the swidden thesis for the "New Orthodoxy" which suggested that bajos provided a sustainable resource for intensive agriculture that would have supplemented swidden agriculture in the uplands (Baker 2007; Rice and Culbert 1990). Supporters of the New Orthodoxy propose that ancient bajo agriculture would have solved the issue of sustainably cultivable land (Folan Higgins et al. 2015). Bajos and bajo margins (the transition area between upland and bajo) could be cultivated during the dry season whereas uplands could only produce during the wet season (Baker 2007; Cowgill 1961; Reina 1967). Although some researchers still clung to the swidden thesis in their “Alternative Orthodoxy”, claiming that if wetlands were ever used for agriculture in the Maya region it would have been during the Preclassic period, evidence has been building over the past thirty years to support the New Orthodoxy of bajo utility (Bloom et al. 1983; Fedick and Ford 1990; Pohl et al. 1990; Pope and Dahlin 1989).

Studies in Bajo *Utility*

Numerous studies have unearthed evidence to support the New Orthodoxy that wetland and bajo soils were a valuable if not vital resource for ancient Maya agriculture in the lowlands, specifically as areas for intensive maize (*Zea mays*) cultivation. At Maya sites throughout Belize, the deposition of eroded upland soils and the anthropogenic creation of drained agricultural fields in the bajos offer clear evidence for theories of wetland maize cultivation (Beach et al. 2003; Beach et al. 2006; Beach et al. 2009; Beach et al. 2015; Dunning et al 1998; Dunning et al. 2002; Jacob 1995; Luzzadder-Beach and Beach 2009). Wetland agriculture is further supported by accounts of visible canals throughout drained fields in Belize (Beach et al. 2003; Sluyter 1994). Siemens and Puleston thought that they observed the same raised fields and canals in the Petén using aerial photographs and radar, but they were later shown to be mistaken by Pope and Dahlin (Pope and Dahlin 1989; Siemens and Puleston 1972; Sluyter 1994).

Nevertheless, other studies in the Petén support claims that wetlands may have been useful for agriculture in the Maya lowlands (Beach et al. 2011; Dunning et al. 1998).

Critics of the New Orthodoxy have used soil surveys as an argument against the use of bajos for maize cultivation by the ancient Maya. In 2002, Gunn et al. collected soil samples from the centers and edges of two bajos near the site of Calakmul in Campeche, Mexico (Gunn et al. 2002). Laboratory analyses of the samples revealed high levels of clay and gypsum in the soils which were classified as Vertisols according to USDA Soil Taxonomy. Due to the apparent infertility of the soils, Dunn et al. concluded that bajo soils would not have been conducive to Maya agriculture.

More recent soil surveys offer evidence to support theories of ancient Maya bajo agriculture. Using carbon isotope ratios in soil organic matter as a direct indicator of forest clearance for maize agriculture, researchers have been able to identify areas of ancient maize production at numerous sites and their surrounding locales, without having to rely on visible structures or assumptions relating to soil fertility (Balzotti et al. 2013; Burnett et al. 2012 a and b; Webb et al. 2004; Webb et al. 2007). We define maize agriculture as the clearance of most trees to allow cultivation of crops that require full sun exposure. Those crops could include maize, amaranth, and associated weeds. At the site of La Milpa in Belize, four soil pedons collected from bajos presented evidence of ancient maize cultivation (Beach et al. 2011, Table 1). Stable carbon isotope evidence of ancient maize cultivation has been reported in six bajo pedons from the Petexbatún region of the Petén (Johnson et al. 2007b, Table 2; Wright et al. 2009, Table 5). In another study, three more pedons collected from bajos at the Macabilero watershed between Piedras Negras and Yaxchilán offered evidence of ancient maize agriculture (Johnson et al. 2007, Table 3). However, while each of these studies gives validity to the New

Orthodoxy of Maya agriculture, supporting the theory of bajo utility for maize cultivation, the number of combined samples is too small to make general claims as to whether bajos were intensively cultivated in the long-term and throughout the Maya lowlands.

Although more needs to be done to establish the extent to which bajos may or may not have been utilized by the ancient Maya for maize agriculture, extensive studies seem to have verified the utility of the bajo margins and pocket bajos for agriculture (Baker 2007; Wright et al. 1959). Previous studies of the pocket bajos and the margins of the Bajo de Santa Fe and the Bajo El Grande at Tikal, studies have presented numerous pedons indicating that the seasonal wetlands were a valuable ancient agricultural resource (Burnett et al. 2012 a and b; Dunning et al. 2015). Although one of the authors conceded that the "high clay content would make [the soils] difficult to cultivate," the carbon isotope analyses reported in these three studies provided in strong evidence of maize agriculture within and along the bajo edges (Burnett et al.2012b), and within the Perdido pocket bajo near the Aguada Perdido, southwest of the site center (Dunning et al.2015). The single sample that offered strong evidence of ancient maize cultivation near the Terminos settlement, six kilometers east of the site center, collected in 2010 (Dunning et al. 2015) suggested that the Bajo de Santa Fe and other large regional bajos may have been cultivable in addition to the pocket bajos.

Balzotti et al. used a compendium soil properties and carbon isotope data from 185 soil cores and profiles collected around the site of Tikal by Burnett and colleagues in 2005 and 2006 as well as remote sensing and GIS predictor variables to extend the study of pocket bajos and larger bajo margins (Balzotti et al. 2013; Burnett et al. 2012a and b). Balzotti and colleagues developed a model for predicting the ancient agricultural potential of land areas within Tikal National Park. Acknowledging that the model was limited to park elevations between 222 m and

290 m above mean sea level (MSL) (an elevation that excludes the large regional bajos that surround Tikal), they concluded that the model predicts areas with high potential for ancient maize production along the bajo edges and on foot and toeslopes around satellite settlements. The model presented by Balzotti et al., therefore, supports the claim that bajo edges were likely generally utilized for ancient maize cultivation, but, because most of the bajo areas near Tikal are found at elevations below 222 m MSL, the model did not address maize production in the bajos. Thus, more soil sampling from large bajos is necessary to test the hypothesis that bajos were utilized by the ancient Maya for intensive maize agriculture.

Bajo *Utility*

Much of the challenge in discussing ancient agricultural potential of the bajos is the "oversimplification of the ecological variability present in the Maya Lowlands" and the failure to recognize the "substantial environmental heterogeneity that exists today within bajos…would have prevailed in ancient times" (Baker 2007; Kunen et al. 2000). The limited discussion of the vegetative variability among bajos can be traced back to Lundell's landmark studies which led to the dichotic classification of bajos as either tintal bajos or escoba bajos (Lundell 1933; Lundell 1937). According to his observations, tintal bajos, or logwood bajos, so called due to the presence of *Haematoxylum campechianum*, were typified by low-canopied, thorny scrub, making passage through the bajo extremely difficult. Escoba bajos, characterized by the dominance of palms, especially *Crysophila argentea*, displayed a slightly higher canopy and shorter periods of flooding during the rainy season than tintal bajos. Puleston's surveys along the transects of Tikal National Park followed this simple classification style, with the addition of corozal bajos, another bajo type characterized by the presence of the *corozal* palm, *Orbignya cohune*.

Kunen et al. considered this classification system too narrow, proposing instead that Landsat Thematic Mapper (TM) satellite imagery could be used to identify different bajo types. This could then be used as a guide for further archaeological investigations (Kunen et al. 2007). Although this remote sensing system for classifying bajo vegetation was not realized, Kunen introduced a number of bajo subtypes to enhance bajo vegetative classifications (Kunen 2004; Kunen et al. 2007). In addition to the *tintal bajos*, *pucteal bajos* (*Bucida buceras*), *sapamucheal bajos* (*Oreopanax guatemalense*), and *huechal bajos* (*Scleria* sp.) were presented as distinct types of scrub bajos, based on the prevalent species for which they are respectively named.

The failure to distinguish bajos by vegetation and soils and, therefore, the inappropriate comparison of data among vegetation and soil types has likely influenced the discrepancy of findings related to the ancient agricultural potential of bajos among studies (Baker 2007; Dunning and Beach 1994; Dunning et al. 2006; Fedick 1996; Kunen et al. 2000; Pope and Dahlin 1989). For example, the bajo soils that Gunn and colleagues claim to be infertile were classified as Vertisols according to USDA taxonomic classification (Gunn et al. 2002). In contrast, the bajo soils which Burnett and colleagues found displaying strong evidence of ancient maize cultivation were classified under the order Mollisols, which is accepted to be a much more agriculturally productive soil type (Beach et al. 2003; Burnett et al. 2012b). The model presented by Balzotti and colleagues included the near-infrared (NIR), Landsat 7 band 4 (0.76-0.90 µm), which is sensitive to water levels in leaves and may be an indicator for differences in vegetation. They claimed that NIR may show a connection between past land use and modern vegetation (Balzotti et al. 2013). Thus, it appears that future discussion of bajo utility for ancient maize cultivation must also consider the variety of vegetation types that exist among bajos.

Carbon Isotope Analysis for Evidence of Maize Agriculture

An understanding of the ability of soils to provide insights into ancient agricultural practices begins with knowledge of the naturally-occurring stable isotopes of carbon. An isotope is a variation of an element with a different number of neutrons. For example, carbon always has six protons in its nucleus and typically has six neutrons, giving it an atomic weight of twelve (^{12}C). A naturally occurring heavy isotope of carbon has an extra neutron, yielding an atomic weight of thirteen (^{13}C). Radioactive ^{14}C, has eight neutrons, but its unstable nucleus is subject to radioactive disintegration in the environment. This unstable property of ^{14}C allows scientists to estimate ages of natural organic products which incorporate $^{14}CO_2$ during photosynthesis. Our study is focused on the stable isotopes of carbon that exist naturally in the environment.

Atmospheric carbon dioxide, CO_2 molecules contain mainly the lighter stable carbon isotope ^{12}C (98.9 atom percent) while a much smaller portion of atmospheric CO_2 contains the heaver ^{13}C isotope (1.1 atom percent) (Craig 1953, Craig 1957). Interestingly, this ratio of assimilation does not hold true for the fixation of carbon to biological matter. The cell structures and enzymes associated with photosynthesis, the process by which plants and other organisms utilize light energy to fix carbon, discriminate against the heavier $^{13}CO_2$, incorporating $^{12}CO_2$ at rates greater than 99:1 (Keeley and Rundel 2003). This phenomenon occurs because of the physiological preference of the carbon fixing molecules within a plant's chloroplasts for $^{12}CO_2$ (von Caemmerer et al 1997). Photosynthesis occurs in two general steps: the light dependent reactions take place within the thylakoids inside the chloroplasts, harnessing light energy in an electron transport chain, and the Calvin Cycle uses that energy to fix CO_2 as glucose ($C_6H_{12}O_6$) in the liquid stroma surrounding the thylakoids in the chloroplasts. For most plants, the Calvin Cycle begins with a pre-existing five-carbon molecule called ribulose bisphosphate (RuBP) that interacts with CO_2 to form two three-carbon molecules called phosphoglycerate (PGA). Plant cell membranes and RuBP naturally discriminates against the heavier $^{13}CO_2$, causing much more of the plant structure to be composed of ^{12}C. Although all photosynthesis results in the ultimate formation of the six-carbon glucose, the initial formation of the three-carbon PGA labels most plants as C_3 photosynthesizers.

Some plants, however, have developed additional steps in the photosynthetic process enabling them to better survive in their respective environments (Keeley and Rundel 2003, von Caemmerer et al 1997). Plants absorb ambient CO_2 and release the O_2 produced during photosynthesis to the atmosphere through stoma, pores located on the underside of leaves. While water inside the leaves cannot be released through the upper epidermis of the leaf, it can escape through the stoma whenever they are left open. Thus, plants in hot environments must often close their stoma during the daytime to reduce the transpiration loses of water from the leaves. When, however, plants do close the stoma to prevent a loss of water, O_2 builds up within the leaf, unable to escape to the atmosphere. Such occurrences become a severe problem to C_3 plants because RuBP in the Calvin Cycle is not selective for CO_2 and will be readily oxidized as the relative levels of O_2 rise, expending RuBP and preventing carbon fixation.

Maize, sugar cane (*Saccharum sp.*), and other tropical grasses have adapted to overcome the hot and humid environments to which they are indigenous (Keeley and Rundel 2003, von Caemmerer et al 1997). Instead of allowing cells to directly interact with the air pockets in leaves, these plants have a more restrictive leaf structure: air pockets are bordered by mesophyll cells which surround bundle sheath cell which connect to leaf veins. The distinct structure is related to the method of photosynthesis that these types of plants perform. Within the mesophyll cells, phosphoenolpyruvate (PEP), a 3-carbon molecule, initiates the process of carbon fixation by binding with CO_2 from the leaf air pockets. PEP is selective for CO_2, and will not react with O_2 despite the elevated concentrations when the plant stomata are closed. PEP and CO_2 form oxaloacetate, a 4-carbon molecule. Thus, plants that perform this step in their photosynthetic process are classified as C_4 plants.

While the RuBP that reacts with CO_2 in the Calvin Cycle to produce the first fixed carbon molecule in C_3 plants discriminates heavily against $^{13}CO_2$, PEP in C_4 plants does not discriminate as much against the heavier molecule (Craig, 1953; Craig, 1957). Thus, although both C_3 and C_4 plants have less ^{13}C in their structure than exists in the atmospheric ratio of 99:1, C_4 plants have higher levels of ^{13}C comprising their structures than C_3 plants do. The respective ratios of ^{12}C and ^{13}C found in a sample, of either organic or inorganic origin, are formally reported as the $\delta^{13}C$ in units of ‰ or per mil. The $\delta^{13}C$ of a sample is calculated according to the following formula:

$$\delta^{13}C = [\{(\text{sample } ^{13}C / ^{12}C) / (\text{standard } ^{13}C / ^{12}C)\} - 1] \times 1000$$

The standard against which samples are compared in their carbon ratios is limestone, specifically PDB, based on a Cretaceous marine fossil collected in South Carolina (Tykot, 2006). C_3 plants generally have a $\delta^{13}C$ value in the range of -35 to -20‰, while C_4 plants have values ranging from -15 to -8‰. $\delta^{13}C$ values that are less negative or closer to zero (the standard) indicate higher levels of ^{13}C.

Whenever living organisms die, microorganisms decompose the organic matter, releasing the organic carbon back into the atmosphere as CO_2. Microbial diagenesis, however, isn't usually so efficient a process, resulting in only the partial breakdown of organic molecules and the formation of many disorganized functional groups throughout the system. The product that forms in this strange, undefined process of degradation is humus, the organic compounds that comprise the soil organic matter. Humic compounds are not typically recognized by a definite structure, but are classified by their solubility and, therefore, complexity. Fulvic acids are defined by their solubility in both acidic and alkaline conditions, making them the least complex of the humic substances and considered to remain for the shortest time in soil before ultimate degradation to CO_2. Humic acids are slightly more complex than fulvic acids, and are only soluble under alkaline conditions. The humin fraction of the organic matter is the most complex of the three. It is not soluble under any conditions, and is considered to remain in the soil for the longest periods of time before degradation. Thus, it can be inferred that any evidence of ancient corn cultivation a millennium or more ago will be found in the humin fraction of the soil organic matter pertaining to the area of interest.

The rainforests of the Maya lowlands are dominated by C_3 trees and vines, and the major C_4 plant cultivated by the Maya was maize, though it is possible that other C_4 crops such as amaranth and associated weeks grew in areas (Turner and Miksicek 1984). But the $\delta^{13}C$ values of the humin fraction of the organic matter of the soils of interest are not enough to determine whether or not maize was cultivate anciently in any given area. The final factor is understanding the rate at which soil forms. Soil formation is based on five significant factors: parent material, topography, climate, biological activity, and time. In the Mesoamerican region, soil forms on average at a rate of nine to eleven centimeters per 1000 years (Fernandez et al. 2005; Webb and Schwarcz 2004). Given that the general Maya collapse took place roughly 1000 years ago, with the general occupation of the area transitioning at that time from the lowlands to the highlands, there should be no enrichment of ^{13}C in the humin fraction of the organic matter of the soils in the region due to maize cultivation in the surface soil. Changes in the $\delta^{13}C$ values of the humin fraction of the soil organic matter between surface and subsurface levels that show increasing amounts of ^{13}C deeper in the profile indicate, with some statistical level of confidence, that maize was cultivate anciently in that area. Thus, through soil analyses of Maya occupied areas, we can determine to what degree the Maya utilized that area for maize cultivation.

Effect of Microbial Diagenesis on Changes in Soil $\delta^{13}C$ Values

Although the changes in carbon isotope ratios (the $\delta^{13}C$ value) with in soils have proven to be a valid indicator past vegetation type, whether C_3 forest trees and vines or C_4 vegetation, including maize, the interpretation of $\delta^{13}C$ values is complicated due to the influence that microbial metabolism has on the isotope ratios of soil organic matter (Bai et al 2012; Freitas et al. 2001). Just as the photosynthetic pathways discriminate against $^{13}CO_2$, the membranes and enzymes of microbial respiration discriminate against organic molecules that contain ^{13}C. Thus, as greater quantities of organic ^{12}C from the soil decompose and are respired as CO_2, the isotopic ratio of $^{13}C/^{12}C$ in the soil increases causing the $\delta^{13}C$ value of the soil organic matter to increase or become less negative (tend toward zero). While this may appear to be a confounding factor in carbon isotope analyses, researchers have estimated ^{13}C enrichments in soils due to microbial diagenesis to be in the range of 2.5 to 4.0‰ (Ågren et al. 1996; Balesdent and Mariotti 1987; Boutton 1996; Cerling et al. 1997). The vegetative histories recorded in the stable carbon isotope ratios of hundreds of soil profiles and soil cores in Mesoamerica and Caribbean islands have been examined since the year 2000. Many of these soils are from land features and inundated areas where it is unlikely that maize and other C_4 vegetation could have grown.

The ideal estimate of the effects of microbial diagenesis on the $\delta^{13}C$ value of soil organic matter would be from field evidence of soils not exposed to the ^{13}C enriched carbon of C_4 plants. However, because we are attempting to observe changes in the $\delta^{13}C$ values of soils for a time period lasting over 1000 years, it is a challenge to identify study areas that have been unaffected by human activities for over a millennium. Fortunately, researchers have determined that soils collected from aguadas (ancient man-made water reservoirs) and from perennial springs that would not have supported C_4 plants are the controls we need for observing the way that $\delta^{13}C$ values change naturally over time due to microbial diagenesis in a soil environment. Aguadas and perennial springs were not used anciently for maize cultivation, so any change in $\delta^{13}C$ values between surface and subsurface horizons should entirely be due to microbial diagenesis (Burnett et al. 2012a). At the site of El Kinel in Guatemala, two pedons from aguadas revealed changes in $\delta^{13}C$ from the 15-cm to the 60-cm depth of 0.5‰ and 1.2‰, respectively (Balzotti et al 2013b, Table 1). At Tikal, two pedons from the floor of Aguada El Duende displayed changes in $\delta^{13}C$ with depth of 1.54‰ and 0.85‰ (Burnett et al. 2012b, Table 1). Diagenesis in two pedons from a perennial spring at the foot of the escarpment at Aguateca, Guatemala, was 2.2‰ and 1.8‰ at the 30 to 40-cm depth (Johnson et al. 2007, Table 2). The average change in $\delta^{13}C$ from the surface 15 cm to the 30 to 60-cm depths of these control pedons was 1.4‰. Burnett and colleagues reported on the soil properties including depth to bedrock and the change in $\delta^{13}C$ of 98 soil cores from the satellite site of Ramonal near Tikal (Burnett et al. 2012a). They reported that 70% of the pedons were from the urban center of the site and had changes in $\delta^{13}C$ of less than 2‰ from surface to depth. The properties of 11 representative pedons from the patios and spaces between the house mounds of Ramonal are listed in Table 4 of Burnett et al. (2012). The average depth to bedrock was 51 cm and the average change in $\delta^{13}C$ with pedon depth was 0.8‰. These reports allow us to revise the suggested contribution of microbial diagenesis from the estimate of 4‰ to a much lower but still conservative estimate of 2.5‰.

In this report we consider changes in $\delta^{13}C$ from the surface horizon to the modern or ancient root zone of less than 2.5‰ may be attributed to microbial diagenesis and, therefore, no evidence of ancient C_4 vegetation. Changes between 2.5‰ and 4.0‰ are considered evidence of ancient C_4 vegetation while $\delta^{13}C$ changes of 4.0‰ and greater are considered strong evidence (Balzotti et al. 2013b; Ulmer 2015).

Soil Pedon Selection

Bajos are not homogeneous; they vary by size, inundation, soil properties, and prevalent vegetation. Although researchers and locals disagree in some instances in what determines whether an area is a bajo, for this study we have characterized bajos by two principles: all are at low elevations relative to the surrounding landscape and there is an at least seasonal inundation with flood water. Plano areas are described as flat upland areas that may flood during the rainy season, and are distinguished from bajos due to their higher elevation and forest vegetation.

In their model for predicting areas used by the ancient Maya for maize cultivation at Tikal, Balzotti and colleagues reported that “the near-infrared (NIR) Landsat 7 band 4 (0.76-0.90 µm) response curve had the strongest peak between brightness values of 73 and 75,” indicating that the vegetative signature of areas within Tikal National Park may have influenced whether or not those areas were selected for ancient maize cultivation (Balzotti et al 2013). Considering the potential influence of current vegetation on ancient land use, we developed a sampling strategy for our study after reviewing Landsat 7 imagery to distinguish among regions of different vegetation. Using bands 3,4, and 5 in conjunction with an elevation map of the region, we classified major bajos at Tikal into four different Bajo Types based on moisture and biomass content (Figure 1 and 2). Areas with the lowest levels of biomass and water retention in the foliage, reflective of grasses and short growth, like the Bajo de Santa Fe located east of the site center, were classified as Bajo Type 1. Areas classified as Bajo Type 2 displayed slightly higher levels of water retention in the vegetation, including the Bajo de Chikín Tikal, which lies along the west transect between the site center and the western earthwork. Bajo Type 3 areas displayed higher levels of biomass and water retention in the vegetation and included the area surrounding the Bajo Tintal, west of the road and southwest of the site center. Areas classified as Bajo Type 4 displayed the highest levels of biomass and water retention of the bajos, similar to upland areas. Although the locals consider it to be a plano rather than a bajo, the area along the north border between the road and the north transect falls under our classification of bajo due to its very low elevation (the lowest elevation in Tikal National Park) and flooding throughout the rainy season (Figure 3).

Our purpose in this study was to determine whether bajos were utilized by the ancient Maya for maize cultivation, considering three influential factors. First, we distinguished between areas that are bajos and those that are not. Second, we differentiated among the observed types of bajo vegetation, sampling from each of the four types that we classified. Lastly, we controlled for slope, sampling progressively from the summits, backslopes, footslopes, and toeslopes of the areas of interest. Ultimately, we tested the hypothesis that bajos were utilized for maize agriculture by the ancient Maya at Tikal, if certain bajos were used while others were not based on the vegetation growing in the respective bajos, and if both or either the bajo floors (toeslopes) and/or bajo margins (footslopes) were utilized in bajo maize cultivation. As part of our continuing cooperation with local public administrative organizations and in exchange for permissions to collect soil samples, Tikal National Park and CONAP officials requested that we also collect samples from eight plots permanently designated by the park for study of long term ecological changes apart from human interference. These upland samples served as non-bajo controls for our bajo analysis.

Materials and Methods

The purpose of this study is to better understand how the Maya supported themselves for their significant period of occupation at Tikal by identifying the areas utilized for maize cultivation, the staple crop. Our hypothesis is that the Maya at Tikal utilized the large regional bajos as well as the pocket upland bajos for long-term maize cultivation. Utilizing carbon isotope analyses based on changes with depth in the $\delta^{13}C$ values of the soil organic matter in each pedon, we will determine whether the floors and the margins of large bajos were utilized for maize agriculture by the ancient Maya at Tikal and whether soil properties and observed vegetation had any influence on the types of bajos that may have been utilized. The depth of these soils and their increased capacity to retain water would have been preferential, if not necessary, for long-term sustenance of such a large population (Balzotti et al. 2013; Ford, Clarke, and Raines 2009).

In situ *Collection and Laboratory Processing*

In two trips, one in May of 2014 and the other in February of 2015, we collected 366 soil samples from 70 soil cores (pedons) at Tikal National Park. Prior to collection, we removed leaf litter from the soil surface, and then cored each pedon using a bucket auger designed for soils with high clay content, appropriate for Tikal soils. We collected samples at depth increments of 15 cm until reaching depths of 150 to 195 cm or impenetrable bedrock. We sealed and stored the samples in plastic bags (Nasco Whirl-Pak) and transported them to the Brigham Young University (BYU) Environmental Analysis Laboratory in accordance with United States Department of Agriculture (USDA) permits.

At the Environmental Analysis Laboratory, we dried the soils in air and ground them by mortar and pestle to pass a #10-mesh (2 mm) sieve. We determined soil colors by hue, chroma, and value under wet and dry conditions according to the Munsell Soil Color Charts. After characterizing soils by color, we allowed the samples to equilibrate in a 1:1, soil:deionized water mixture and then measured soil pH by glass electrode. To determine the texture of each sample, we blended 40 g of soil in water with 15 mL of 1 *N* sodium hexametaphosphate, transferred it to 1 L hydrometer jar, and measured the temperature with a thermometer and suspension density with a hydrometer 30s and 2 hr after initial mixing (Gee and Bauder 1986). The sand, silt, and clay content of the soil were then calculated. To determine the Mehlich II extractable phosphorus (P), we placed two grams of each soil in 30 mL jars, treated them with 20 mL of Mehlich II extractant solution, and shook them for five minutes (Terry et al., 2000). We then filtered the suspensions through 15 cm (diam) medium fast filter paper. We diluted one mL of the filtered solution to ten mL with distilled water. We added a PhosVer 3 powder pillow packet to the solution with agitation for one minute and allowed the solutions to sit for an additional four minutes for color development. Phosphorus was then measured with a Hatch DR 850 colorimeter with a wavelength of 690 nanometers. The percent transmittance was compared to a standard curve to determine the extractable phosphorus content.

For subsequent analysis of carbon, nitrogen, and stable isotopes, we further ground 5-g portions of the samples by mortar and pestle to pass a #60-mesh (250 μm). We determined the calcium carbonate equivalent with a titration method. Samples of 0.5 to 5 grams (depending on relative carbonate content) were digested in standardized 0.5 M HCl by boiling for 5 min and cooling for 15 min. The samples were then back-titrated to a pH of 7.0 with standardized 0.25 M NaOH. Higher levels of NaOH required for titration indicated lower levels of calcium carbonate (Allison and Moode 1965). Total carbon and total nitrogen levels were determined by dry combustion with a LECO TruSpec CN Determinator (LECO Instruments, St. Joseph, Mich., USA) according to the guidelines presented by McGeegan and Naylor (1988).

Isolation of the Humin Fraction of the Soil Organic Matter

The humic and fulvic acid fractions of the soil organic matter were extracted from the samples to isolate the humin fraction for stable isotope analysis. The humin fraction is considered the oldest humic substance and offers the best evidence of ancient Maya maize production. We followed the methods adapted from Webb and Schwarz (2004) and Wright et al (2009) by weighing out two grams of each sample into plastic tubes and adding between 10 and 30 mL of 1 *M* HCl to drive off the carbonates associated with each sample. The samples were shaken in a water bath set at 70 ^{o}C for at least 2 hours. We added HCl periodically until effervescence ceased. This removed all carbonate carbon from the samples. After acidification, we transferred the samples to 50 mL Nalgene (Rochester, NY) Oakridge type centrifuge tubes, and centrifuged the samples at 9,000 rpm for thirty minutes. We disposed of the chloride-rich supernatant and then added 20 mL of distilled water to the soils. We allowed the solutions to mix for twenty-four hours on a reciprocating shaker before centrifuging them again at 9,000 rpm for thirty minutes. We then poured off and disposed of the supernatants and repeated with a second wash in distilled water to remove residual chloride ions.

After the second wash, humic and fulvic acids were extracted to isolate the humin fraction of the organic matter of the soils. The alkaline extractant solution was composed of 0.1 *M* sodium pyrophosphate ($Na_4P_2O_7$) and 0.1 *M* NaOH (Burnett et al. 2012 a and b). We added 25mL of the alkaline solution and sealed each sample with teflon-lined septum lids. We purged the headspace of the tubes with nitrogen gas (N_2) to prevent possible oxidation of the soil humin fraction in the alkaline environment. We allowed the samples to shake for twenty-four hours and then centrifuged the samples at 17,000 rpm (30,000 * *g*) for two hours and discarded the supernatant that contained the humic and fulvic acids. The extractions with alkaline pyrophosphate were repeated two additional times with the expectation that this further removed all the humic and fulvic acids from the samples.

Having isolated the humin fraction of the soil organic matter in the samples, we removed any residual alkaline solution in another wash cycle as previously described (but centrifuged at 17,000 rpm for two hours), and then neutralized the pH of the samples by adding 0.5 M phosphoric acid (H_3PO_4), allowing the samples to shake for twenty-four hours, centrifuging the samples (17,000 rpm for two hours), and pouring off the supernatant. We performed a final rinse before drying the samples in a hot water bath (70 ^{o}C). We then transferred the samples to 20 mL scintillation vials, dried them overnight in a laboratory oven (105 ^{o}C), and then ground each sample to #60-mesh (<0.025 mm) with mortar and pestle. We weighed out the prepared samples into tin capsules based on the expected organic content of each sample (5 mg for high expected organic content, 15 mg for medium, and 20 mg for low), and sent them to the University of California Davis Stable Isotope Facility (Davis, CA), where they were analyzed by continuous flow Isotope Ratio Mass Spectrometer for ^{13}C enrichment.

Changes in δ^{13}C and Soil Fertility Analysis

The δ^{13}C per mil enrichment for each horizon sample was to calculate the greatest change in δ^{13}C between the surface and subsurface levels for each soil profile. Subsurface horizon ^{13}C enrichment greater than or equal to 4.0‰ is considered strong evidence of ancient maize cultivation in that area, and ^{13}C enrichment greater than or equal to 2.5‰ indicates evidence of ancient maize cultivation. We also compared various physical and chemical properties and soil fertility factors among the bajo types for further discussion of cultivable potential. Utilizing an analysis of means (ANOVA) test, we compared mean surface pH, phosphorus, $CaCO_3$ equivalent, and surface $\delta^{13}C$ among the four different bajo types, plano, and upland regions within the park. These results were meant to supplement findings for carbon isotope values.

Results

The intent of our analyses has been to determine whether maize was cultivated anciently in the margins (footslopes) and floors (toeslopes) of large bajos at Tikal and whether the type of vegetation growing in the bajos influenced whether they were used for ancient agriculture. In this section we describe the vegetation observed in each of the Bajo Type classifications. Additionally, we report the characteristics and USDA taxonomic classifications of the soils collected in each Bajo Type. Finally, we list the number of pedons in each Bajo Type that presented evidence of ancient maize cultivation.

Landsat Bajo *Type 1*

As expected, in conjunction with the Landsat imagery used to develop the sampling plan (Figure 2), the vegetation observed in areas classified as Bajo Type 1 were very similar. As Puleston described, these areas could appropriately be described as a tintal bajo, due to the low canopy and heavy presence of tintal trees, but the density of the trees was not as high as expected (Puleston 1983). Instead, a type of sawgrass that the locals call *sacate hueche* (*Scleria* sp.) covered the bajo floor between knotted tintal trees (Figures 9 and 10). Thus, the areas might also be appropriately classified according the Kunen et al. model as *huechal bajos* (Kunen et al. 2000; Kunen 2004). Pedons collected from areas classified as Bajo Type 1 included Airstrip 1 and 2, Bajo East 1 and 2, East Brecha 1 and 2, SF 1 and 2, South Border 2 and 3, WB2 3, and West Bajo 2 and 3. The Airstrip and East Brecha pedon displayed less of this bajo uniqueness with a higher canopy due to their locations along the periphery of the bajos, but do share similar soil properties.

Soils in areas classified as Bajo Type 1 are listed in Table 1. The pedons were deep (150 cm or deeper), displaying cracks at the surface and slickensides. All surface samples were clay soils, each containing at least 55% clay by weight, and some with up to 100% clay composition. Soils in this type of bajo were typically very acidic with surface pH's ranging between 4.6 and 5.6, and subsurface pH's reaching values as low as 3.35. $CaCO_3$ was virtually non-existent in this type of bajo, with only one sample displaying percent $CaCO_3$ equivalent above 2.0%. The average surface phosphorus level was 5.66 mg/kg with minimal deviation. Soils collected in areas classified as Bajo Type 1 were typically Vertisols according to the USDA taxonomic classification system.

The average surface $\delta^{13}C$ for pedons in the Bajo Type 1 was -28.07‰. The soil organic matter was enriched in ^{13}C with depth. SF 1 and WB2 3 displayed changes in $\delta^{13}C$ values of 4.0‰ and 4.73‰, respectively, from the surface OM to the 75-cm depth (Figure 4 and 5). Both pedons were located on toeslopes, areas with minimal slope located down within the bajo, past the bajo margins, or transition zones. Similarly, Bajo East 1 and South Border 2, pedons that offered evidence of ancient maize cultivation (3.34‰ and 3.40‰, respectively), were also located in the lowest accessible points of other bajos, one in the Bajo de Santa Fe and the other in the bajo near the southwest corner of the Park. Of the thirteen pedons collected from areas classified as Bajo Type 1, five provided evidence of ancient maize cultivation (change in $\delta^{13}C$ between 2.5‰ and 4.0‰) and two provided strong evidence (change in $\delta^{13}C$ greater than 4.0‰) (Table 1).

Landsat Bajo *Type 2*

Areas classified as Bajo Type 2 were much more typical of the description that Puleston offered for the bajo tintal: low-canopy, thick with tintal trees, but differentiated from Bajo Type 1 with a slightly higher canopy and very sparse grass (Figures 2, 11, and 12). Four pedons were collected from areas classified as Bajo Type 2, including WB2 2, West Bajo 2, WT1 1, WT1 2, and WT1 3 (Table 2). Soils collected in this type of bajo were also deep (150 cm or deeper) and very high in clays (no samples were composed of less than 80% clay). Soils were very light in color, but no sample contained more than 0.78% $CaCO_3$ equivalent. Surface phosphorus values were similarly low, with an average of 4.57 mg/kg. Although still acidic, surface soil pHs were milder than Bajo Type 1, ranging between 5.83 and 6.68. Additionally, while the pH of soils of Bajo Type 1 typically decreased with depth, the pH of soils of Bajo Type 2 increased with depth. No slickensides or horizonation was observed in these soils, resulting in their classification as Entisols.

The average surface $\delta^{13}C$ for pedons in the Bajo Type 2 was -28.27‰. Of the four pedons collected from areas classified as Bajo Type 2, one presented evidence of ancient maize agriculture while two presented strong evidence with changes in $\delta^{13}C$. Pedon WT1 3, one of the two samples offering strong evidence, was located at the lowest point of the Bajo de Chikín Tikal along the west transect, while the other two samples presenting evidence of maize production (WB2 2 and WT1 2) were both located along bajo edges.

Landsat Bajo *Type 3*

Areas classified as Bajo Type 3 appropriately fall under Puleston's classification of escoba bajos, displaying higher canopies that tintal bajos and a high density of escoba palms (Figure 13). Six pedons were collected from areas classified as Bajo Type 3, including SWB 1, 2, 4, and 5 and WB1 1 and 2 (Table 3). Soils in these areas were moderately deep (usually 100 cm or deeper) but darker than soils in Bajo Types 1 or 2. Two of the pedons that demonstrated higher levels of $CaCO_3$ equivalent were classified as Mollisols while the four were labeled Entisols, due to their lack of visible horizonation. Soils were classified as clays and one sandy clay, with neutral surface pH values (between 6.26 and 7.92) and pH's that increased with depth (Figure 7). The average surface phosphorus value was 5.64 mg/kg.

The average surface $\delta^{13}C$ for pedons in the Bajo Type 3 was -27.57‰.None of the four pedons collected from the SWB area displayed changes in $\delta^{13}C$ with soil depth sufficient to provide evidence of ancient maize cultivation. WB1 1, a toeslope sample, presents evidence of maize cultivation with a change in $\delta^{13}C$ of 2.71‰, and WB1 2, a footslope sample, presented strong evidence of maize cultivation with a change in $\delta^{13}C$ of 4.31‰ (Table 3).

Landsat Bajo *Type 4*

Puleston described the area along the north border of Tikal National Park as escoba bajos (Puleston 1983). Using Landsat 7 Bands 4,5, and 3, we classified the area as Bajo Type 4, due to the apparently high levels of water retained in the vegetation (Figure 2). While collecting samples in the field from areas classified as Bajo Type 4, we observed upland style vegetation with tall canopies (Figures 14 and 15). Despite the sparse presence of escoba palms in Norte2, guides referred to both areas as plano, not even bajo due to the lack of indicative bajo vegetation. Areas in this bajo type were confirmed by guides, however, to be covered with water during the rainy season, confirming an appropriate differentiation from upland areas for comparing land use practices. Additionally, some grass was viewed growing along cleared paths, but none was observed off the brechas. Four pedons were collected from areas classified as Bajo Type 4, including NB1 1 and 2 and Norte2 2 and 3 (Table 4).

Due to weak horizonation, soils from Bajo Type 4 were classified as Entisols. All pedons were deep (greater than 100 cm), and the presence of some subsurface gleying was reflective of the seasonally aquic conditions described. Soils were very high in clay (at least 60%) with a neutral surface pH (three of the four had a surface pH greater than 7.0) that increased with depth (Table 4). $CaCO_3$ levels were very low (less than 4.0% in three of the four samples), and the average surface phosphorus level was 6.97 mg/kg.

The average surface $\delta^{13}C$ for pedons in the Bajo Type 4 was -27.92‰. Two of the four pedons presented strong carbon isotope evidence of ancient maize cultivation (Figure 8). Both NB1 1 (toeslope) and NB1 2 (footslope) displayed a change in $\delta^{13}C$ 4.35‰ within the top 75 cm of soil.

Plano

The term "plano" is utilized by the locals to refer to level area, often near areas of high moisture. Plano areas do not typically inundate like bajos, but may be covered with water during some parts of the rainy season. Structures are often located near or within plano regions, supporting the idea that they may have been preferable for some type of land use. Areas that we have classified as plano in this study are differentiated by both their tall-canopy, upland style vegetation and higher comparative elevation to the bajos (Figure 2).

The average surface $\delta^{13}C$ for pedons collected from plano areas was -26.99‰. Nine pedons were collected from areas classified as plano, exemplifying a variety of soil types and conditions (Table 5). Four of the pedons were classified as Mollisols, two Inceptisols, and three Entisols. Despite the variations, all soils were high in clay (at least 46%) with an average surface phosphorus level of 5.21 mg/kg. The average surface pH was 6.81 with a range from 5.82 to

7.56. Four of the nine pedons presented strong evidence of ancient maize cultivation, and three presented evidence.

Upland

Pedons collected from throughout the park on backslopes and slope summits with upland-style vegetation with tall canopies were classified as upland samples. Upland samples present the greatest diversity and serve as a control for our analysis of bajo samples. Twenty-seven pedons were collected from the upland areas described; eleven of the samples were classified as Mollisols, two Inceptisols, and fourteen Entisols (Table 6). The samples were typically shallow (between 15 and 60 cm) and neutral in soil pH (between 6.01 and 7.78), and the average phosphorus level was 5.81 mg/kg. The average surface $\delta^{13}C$ was -26.68, but none of the upland pedons presented evidence of ancient maize cultivation.

Statistical Analysis

Simple linear regression analysis indicated that no surface soil fertility factor could significantly explain changes in $\delta^{13}C$ values of pedons with depth. R-squared values comparing the maximum change in $\delta^{13}C$ against the fertility factors of interest were 0.12 for pH, 0.056 for $CaCO_3$, 0.035 for clay percentage, 0.0009 for phosphorus, and 0.0002 for organic C. Surface $\delta^{13}C$ displayed a 0.15 R-squared value in a simple-linear regression with maximum change in $\delta^{13}C$ in the ancient maize rooting zone. However, an ANOVA comparing surface $\delta^{13}C$ of bajo soils versus upland soils reported that bajo soils (including toeslope and footslope) had a significantly lower (more negative) surface $\delta^{13}C$ value than upland soils, with a p-value of less than 0.0001. An ANOVA comparing means of surface $\delta^{13}C$ values among Bajo Types resulted in a p-value of 0.18.

Discussion

Previous studies have demonstrated how pocket bajos and bajo margins were utilized by the Maya for maize cultivation (Balzotti et al. 2013a; Burnett et al. 2012a and b). Our analysis confirms the importance of the margins of large bajos around Tikal for ancient cultivation. Additionally, our study displays that the floors of large bajos were also useful to the Maya for ancient agriculture, regardless of the types of vegetation found therein.

Bajo *Edges*

Following what has been indicated in previous studies, our results confirm the ancient use of bajo margins or transitional zones between upland areas and bajos for maize cultivation, irrespective of the vegetation that might prevail in an area (Burnett et al. 2012 and b). Strong evidence of maize production was identified in pedons classified among Bajo Types 2, 3, and 4, and multiple pedons from different areas classified as Bajo Type 1 presented evidence of ancient maize cultivation. As many researchers have postulated, these bajo margins may have been especially useful due to the depth of the soils and their proximity to surface water and high water table. Regardless of the explanation of their usage, it is evident that these areas were clearly of importance to the ancient Maya at Tikal for C_4 plant cultivation including maize.

Bajos

Our results indicate that the bajo soils were utilized by the ancient Maya at Tikal for maize agriculture. Of the fourteen pedons collected from bajo floors throughout Tikal National Park, four presented strong evidence of ancient maize cultivation, and some presented weak evidence of ancient maize cultivation. Moreover, this evidence of ancient maize cultivation is not limited to any Bajo Type classification, but evenly distributed among the four. Thus, despite the differences in soil and vegetative conditions, all types of bajos sampled were useful to the ancient Maya for maize agriculture, along the margins and down in the bajos.

The above statement is very intriguing; as the New Orthodoxy has gained popularity, the community of Maya scholars has generally accepted that drained fields found in wetlands in Belize were agriculturally productive, but scholars doubt the potential utility of the lowland bajos. Supporting this skepticism, Gunn and colleagues indicated that the high gypsum levels and acidity of bajo soil samples would have made maize cultivation in bajos impractical if not impossible (Gunn et al. 2002). Others, attempting to explain the centrality of bajos to Maya sites have suggested that tintal bajos, like the Bajo de Santa Fe at Tikal, may have functioned as an impassible defensive boundary, due to their low expected productivity. However, the soils in areas classified as Bajo Type 1, including samples collected from the Bajo de Santa Fe, matched the chemical and physical properties of those described in the study performed by Gunn et al., yet they still presented strong evidence of ancient maize cultivation. SF 1, which was collected along a toeslope from the Bajo de Santa Fe and is classified as a Vertisols and very light in color, showed a change in $\delta^{13}C$ of 4.09 at 75 cm depth from the soil surface. At WB2 3, despite a pH of 4.11 at 60 cm depth, a change in $\delta^{13}C$ of 4.73 was observed, with pH values dropping below 4.0 at lower depths. Moreover, both pedons contained levels of clay in excess of 90%. Evidently, despite what would otherwise be considered poor soil fertility conditions, the huechal and tintal bajos at Tikal, classified as Bajo Type 1, were useful to the ancient Maya for maize cultivation.

In contrast to the uninviting Vertisols of Bajo Type 1, the deep Entisols of Bajo Types 2, 3, and 4 seemed to have no impediment to agriculture in terms of soil fertility. Despite the high clay percentages prevalent in each of the three bajo types, the neutral soil pHs and high organic

C contents would have been very accommodating to cultivation. Furthermore, there is no significant difference between the surface phosphorus values and texture classification between the bajos and upland soils, and these factors associated with fertility and cultivability presented no significant influence on $\delta^{13}C$ values. Thus, it should be no surprise that tintal, escoba, and high-canopied bajos were useful to the ancient Maya for maize agriculture at Tikal, as confirmed by evidence from carbon isotope analyses.

Additionally, there appears to be no association between ancient agricultural use and the proximity of pedons to the site center of Tikal. Although the model developed by Balzotti et al. predicts a higher probability of ancient maize cultivation closer to the site center, our results show strong evidence of maize cultivation at NB1 1 (12 km from the site center) and WT1 3 (8 km from the site center) and evidence of maize cultivation at Bajo East 1 (10 km from the site center) and South Border 2 (15 km from the site center). Satellite agricultural communities may explain the evidence of ancient maize agriculture so far from the site center, but our research seems to indicate that the sizes and locations of bajos throughout the Maya Lowlands should not disqualify them from agricultural consideration. On the contrary, having confirmed positive ancient agricultural utility, future studies should attempt to determine the extent to which these resources were not only useful but perhaps necessary for providing sustenance to ancient peoples.

Defense of $\delta^{13}C$ Interpretation

Critics may question whether modern vegetation influenced $\delta^{13}C$ values, resulting in false positive evidences of ancient maize cultivation. As maize is a grass, critics may appropriately suspect that grasses in the huechal and tintal bajos artificially elevated $\delta^{13}C$ values (closer to zero) due to their use of the same C_4 photosynthetic pathway employed by maize. While our

ANOVA did indicate that the mean surface $\delta^{13}C$ value of bajo soils was significantly different from the mean surface $\delta^{13}C$ value of upland soils, the test determined that the mean surface $\delta^{13}C$ value of bajo soils was lower (more negative) or less influenced by C_4 photosynthesis or microbial diagenesis than upland soils. Thus, modern vegetation was not shown to be a confounding factor resulting false positives of evidence of ancient maize cultivation.

Numerous studies performed by Beach and others at Blue Creek and similar sites in Belize have illustrated how land management practices performed by the Pre-Classic and Classic Maya resulted in severe erosive events in which massive amounts of soil from upland hills were deposited in what are now perennial wetlands (Beach et al. 2003; Beach et al. 2006; Beach et al. 2009; Beach et al. 2015; Dunning et al. 1998; Dunning et al. 2002; Jacob 1995; Luzzadder-Beach and Beach 2009). Critics may argue that as swidden agricultural soils from upland backslopes were exposed to erosive forces with the loss of their natural vegetative cover, they would have aggraded in the bajos and contributed the $\delta^{13}C$ signatures perceived as evidence of ancient maize cultivation within the bajos. Simple visual verification may be used in place of a quantitative statistical test to discount this challenge. If a large erosive event worthy to confound our results were to have occurred, leading to the aggradation of upland soils in the bajo, we would expect our graphs of the depth of each pedon to display some sudden change in $\delta^{13}C$, in which values suddenly became much more or much less negative. However, as is repeatedly observed in the included figures, the $\delta^{13}C$ value in the pedons progressively increased from the soil surface through the extent of what would have been the root zone of ancient maize (75 cm to 1 m in depth). Although the $\delta^{13}C$ trends varied among pedons at depths below the root zone, no large and irregular changes were observed that could be attributed to major erosion events. Moreover, it is unlikely that the entire meter of soil that presents our evidence of maize cultivation would have been aggraded from upland sources, especially when observing the clean progression of $\delta^{13}C$ values with depth, clearly in contrast with the evidences of erosion observed in $\delta^{13}C$ values by Ulmer (2015). We affirm that the evidence of maize cultivation by the ancient Maya in the bajos surrounding Tikal is a result of cultivation practices within the bajos themselves and not from eroded agricultural upland soils.

Conclusions

Seasonal wetland bajos were an important aspect of Maya maize cultivation at Tikal and throughout the Maya lowlands. Carbon isotope analyses of soil samples displayed that both the margins and the floors of large regional bajos were utilized for ancient maize cultivation. The bajos that were used for agriculture were not selected based on the type of vegetation growing, and high clay and sulfate contents were not a deterrent from cultivation. We recommend that future studies evaluate the use of bajos for ancient maize agriculture throughout the Maya lowlands and explore the potential productivity and duration of fertility of bajos after extensive cultivation through modern experimental agriculture.

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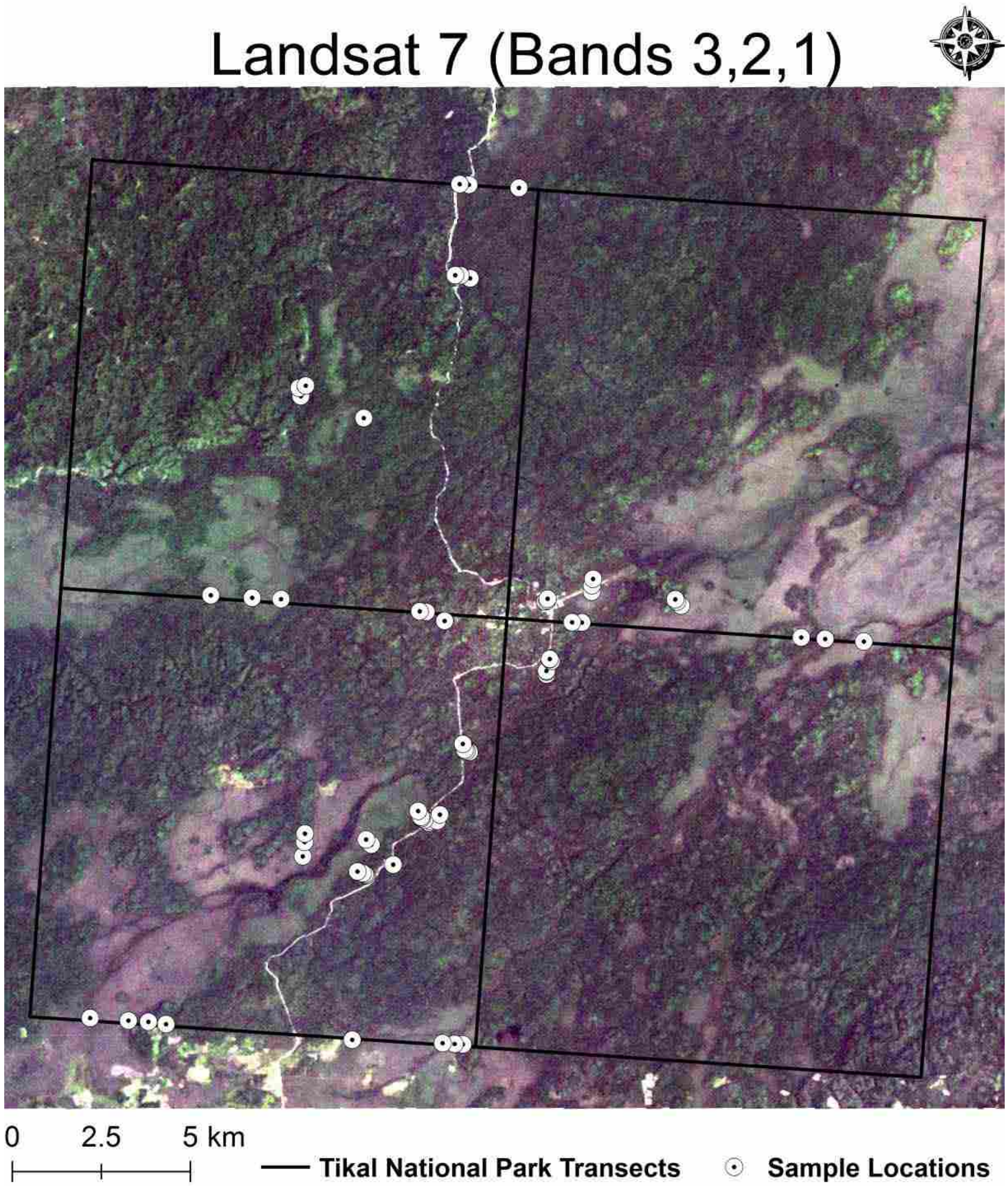

Figure 1. Landsat 7 (Bands 3,2,1) image of Tikal National Park.

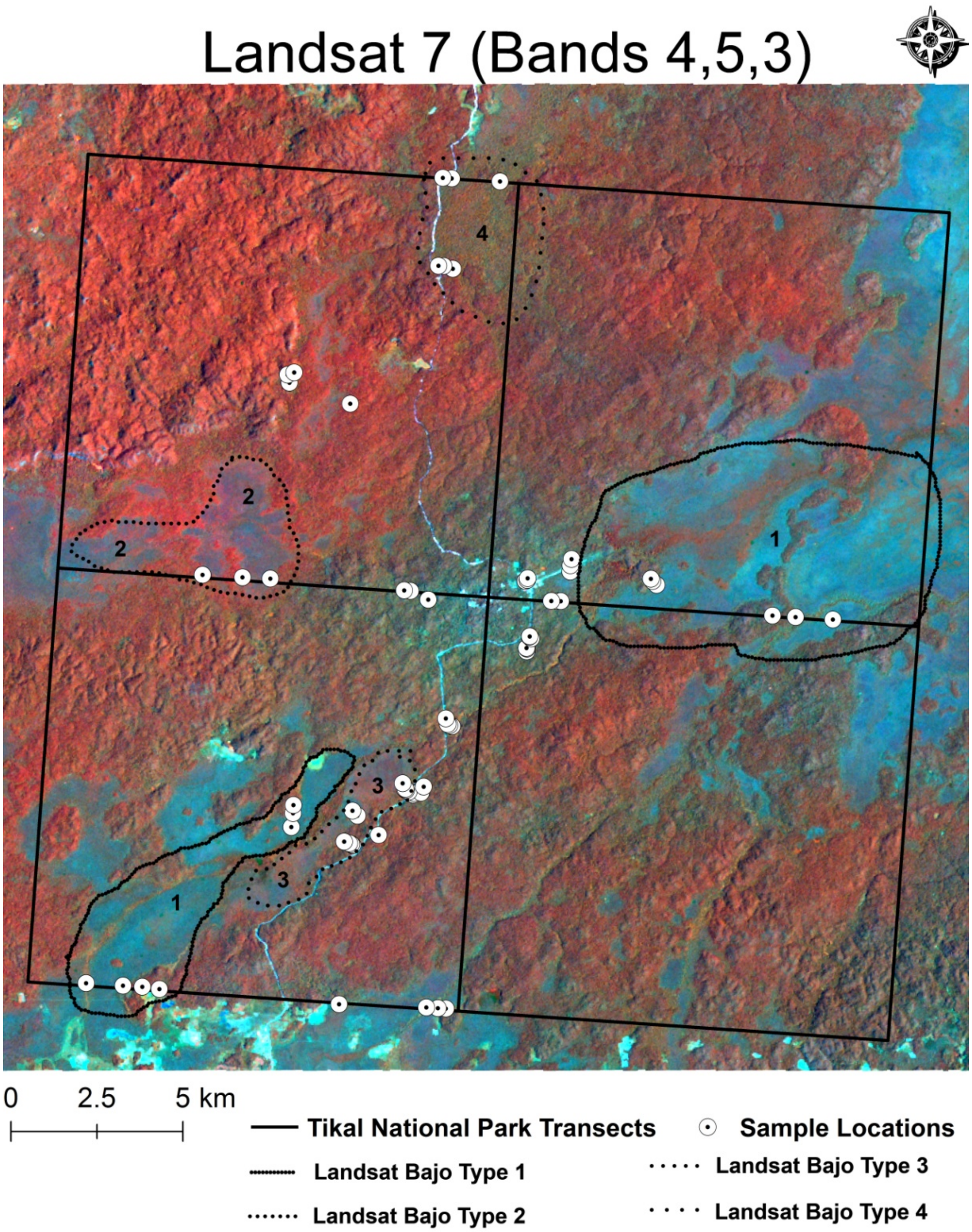

Figure 2. Landsat 7 (Bands 4,5,3) image of Tikal National Park**.** Blue areas are interpreted to have vegetation that retains less water in the foliage. Red areas are interpreted to have vegetation that retains more water in the foliage. The sample locations and bajo types are outlined on the map.

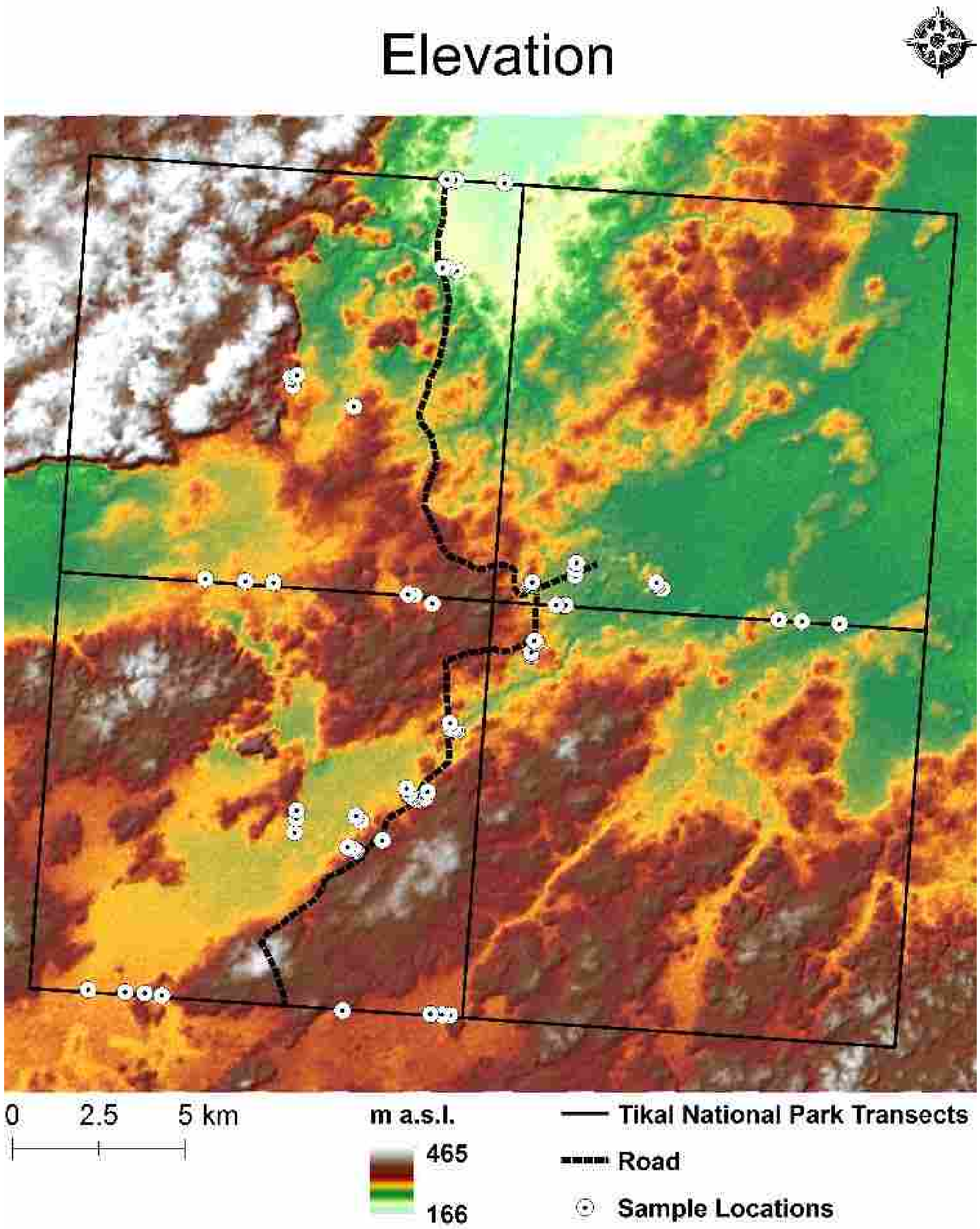

Figure 3. Elevation map of Tikal National Park.

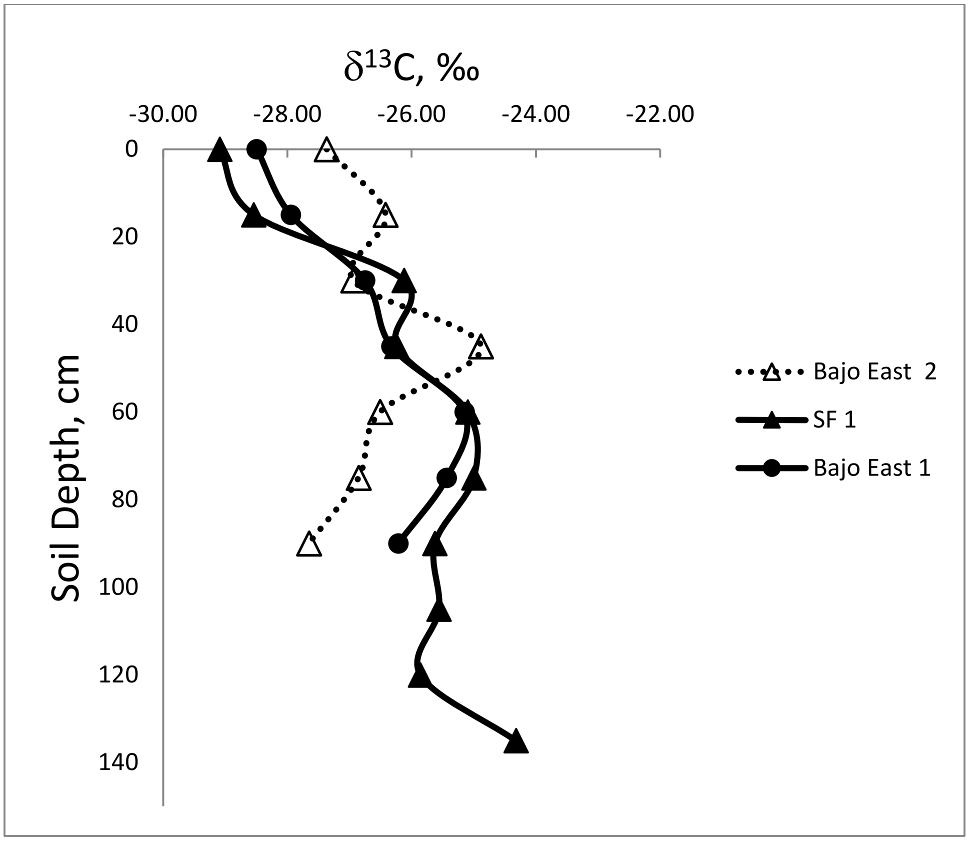

Figure 4. The changes in δ13C vs Soil Depth for selected pedons collected in areas classified as Landsat Bajo Type 1. Pedons SF1 and Bajo East 1 displayed evidence of C_4 vegetation with a change in $\delta^{13}C$ in the top 90 cm of 4.09‰ and 3.34‰, respectively. Bajo East 2 did not display evidence of C_4 vegetation.

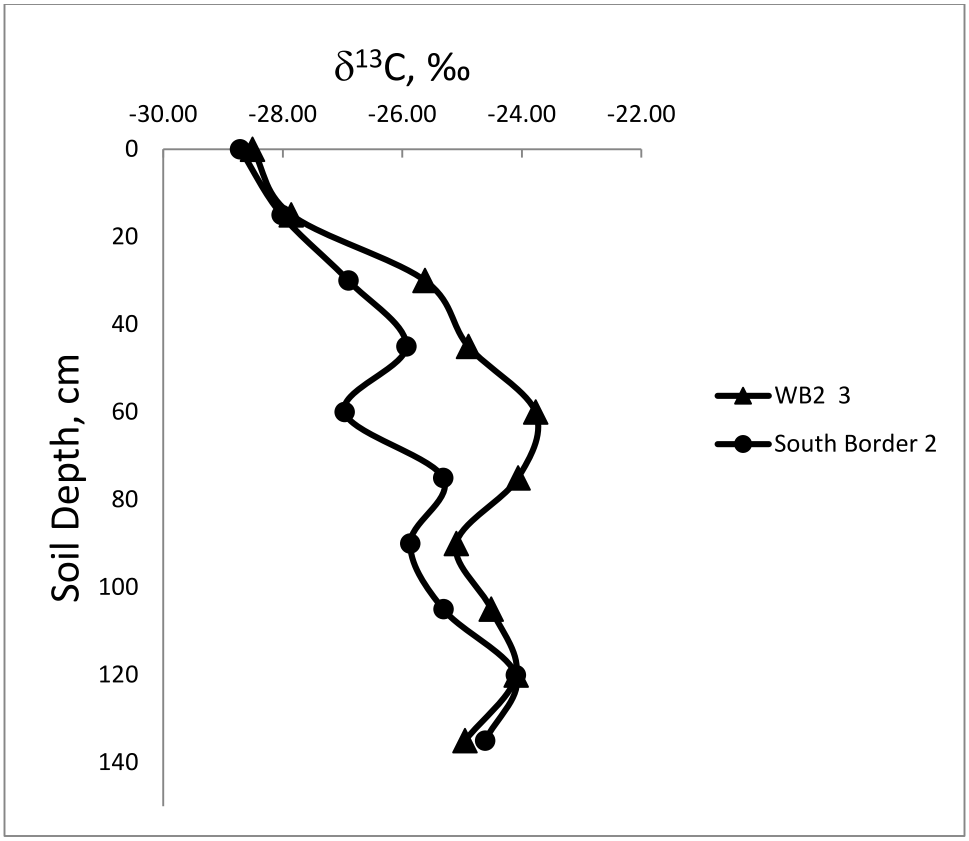

Figure 5. The changes in δ13C vs Soil Depth for selected pedons collected in areas classified as Landsat Bajo Type 1. Pedons WB2 3 and South Border 2 displayed evidence of C_4 vegetation with a change in $\delta^{13}C$ in the top 90 cm of 4.73‰ and 3.40‰, respectively.

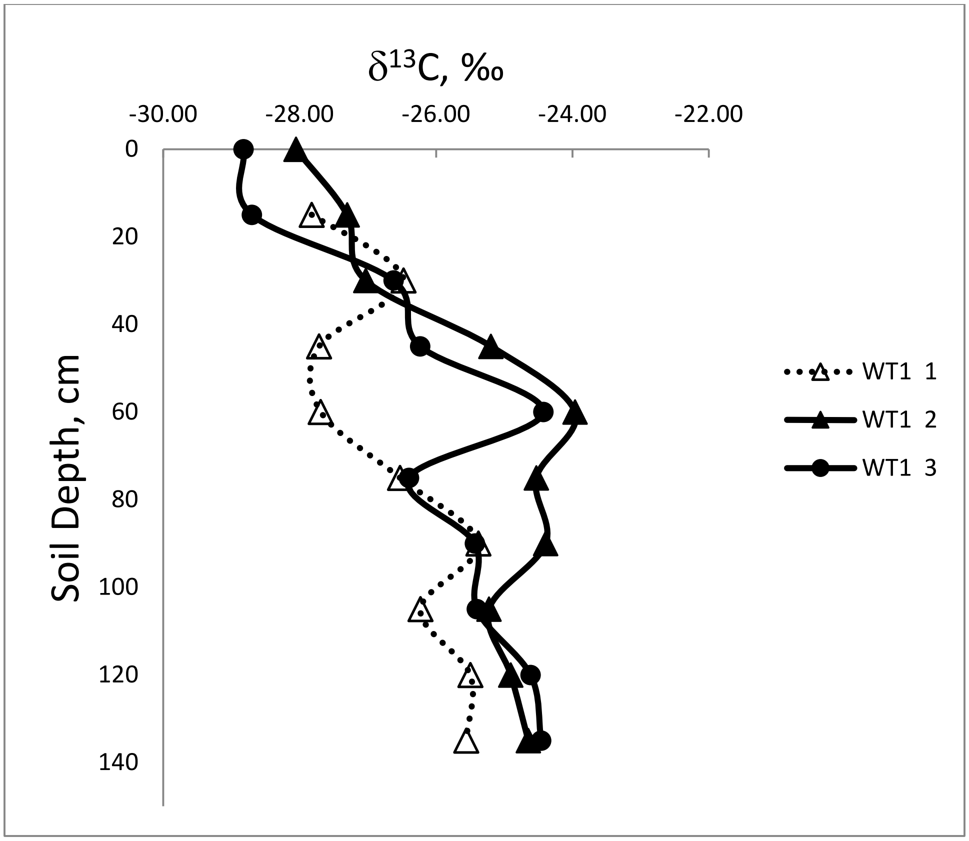

Figure 6. The changes in δ13C vs Soil Depth for selected pedons collected in areas classified as Landsat Bajo Type 2. Pedons WT1 2 and WT1 3 displayed evidence of C_4 vegetation with a change in $\delta^{13}C$ in the top 90 cm of 4.09‰ and 4.39‰, respectively. WT1 1 did not display evidence of C_4 vegetation.

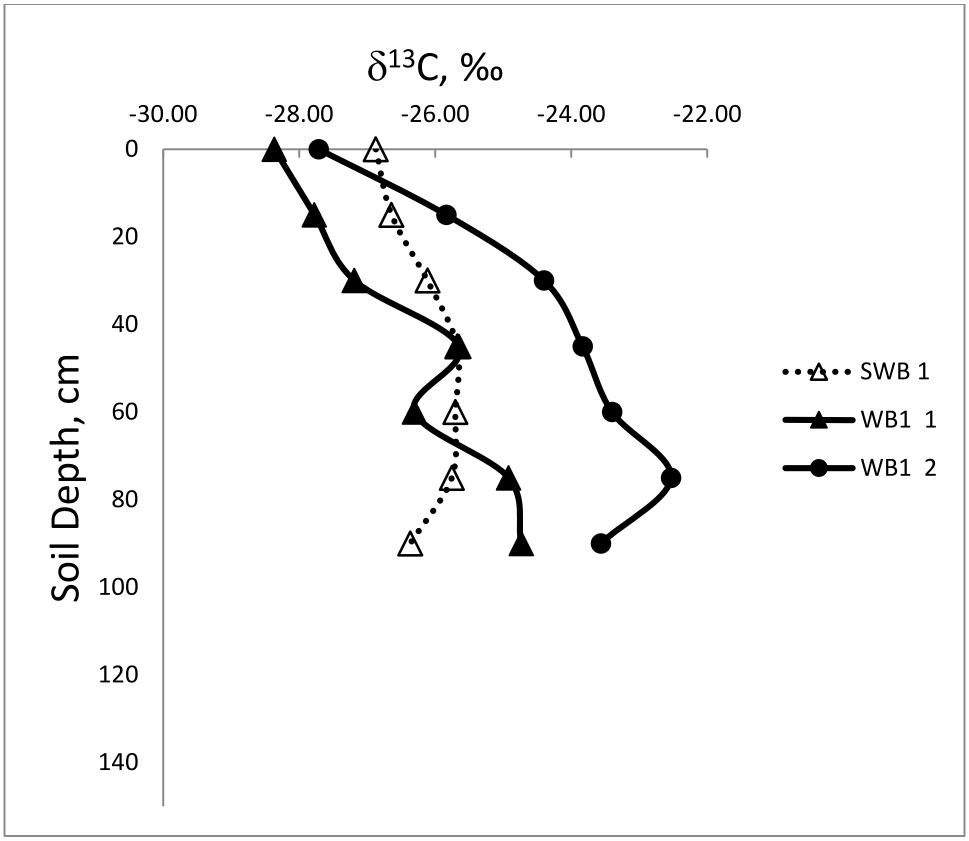

Figure 7. The changes in δ13C vs Soil Depth for selected pedons collected in areas classified as Landsat Bajo Type 3. Pedons WB1 1 and WB1 2 displayed evidence of C_4 vegetation with a change in $\delta^{13}C$ in the top 90 cm of 2.71‰ and 4.31‰, respectively. SWB1 did not display evidence of C_4 vegetation.

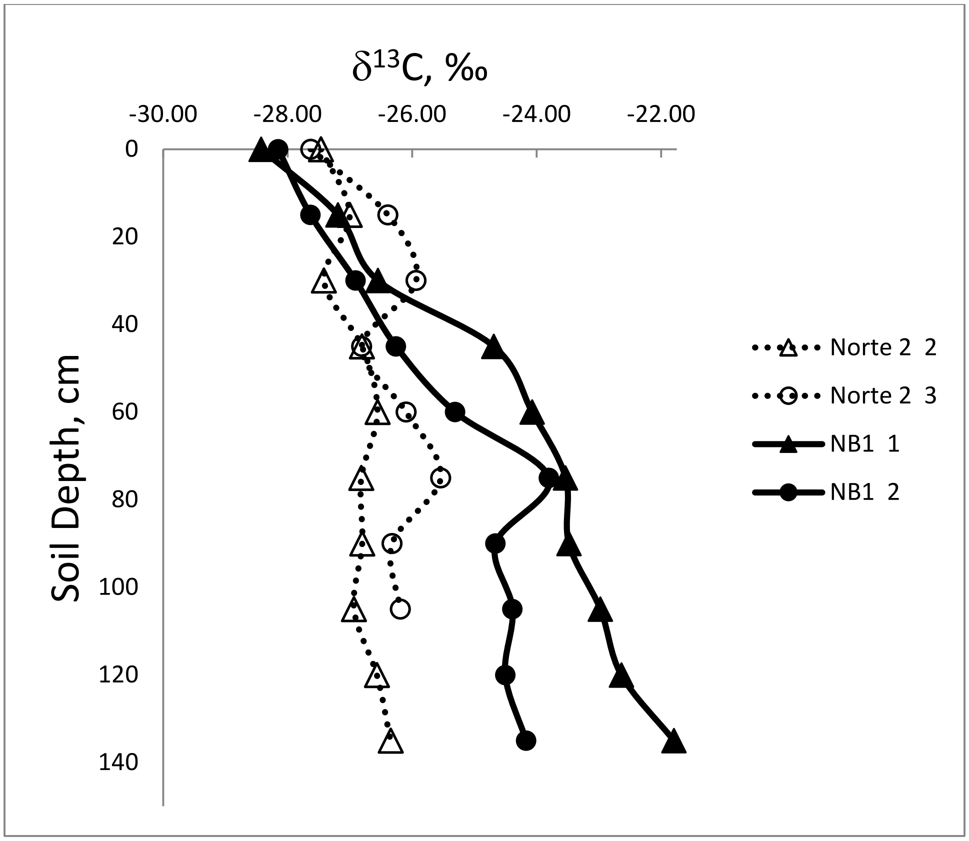

Figure 8. The changes in δ13C vs Soil Depth for selected pedons collected in areas classified as Landsat Bajo Type 4. Pedons NB1 1 and NB1 2 displayed evidence of C_4 vegetation with a change in $\delta^{13}C$ in the top 90 cm of 4.35‰ for both. Norte2 2 and Norte2 3 did not display evidence of C_4 vegetation.

Figure 9. Vegetation observed in areas classified as Landsat *Bajo* Type 1. Photograph taken near Airstrip 1. Puleston described this area as *tintal bajo*. There is a dominant presence of *tintal* trees, but, due to the abundant *sacate hueche*, the area could similarly be described as a *huechal bajo*, according to Kunen's classifications.

Figure 10. Vegetation observed in areas classified as Landsat *Bajo* Type 1. Photograph taken near WB2 3. Puleston described this area as *tintal bajo*. There is a dominant presence of *tintal* trees, but, due to the abundant *sacate hueche*, the area could similarly be described as a *huechal bajo*, according to Kunen's classifications.

Figure 11. Vegetation observed in areas classified as Landsat *Bajo* Type 2. Photograph taken near WT1. Vegetation is reflective of the *tintal bajos* described by Puleston.

Figure 12. Vegetation observed in areas classified as Landsat *Bajo* Type 2. Photograph taken near WT2. Vegetation is reflective of the *tintal bajos* described by Puleston. There is an abundant presence of *tintal* trees and minimal *sacate hueche*.

Figure 13. Vegetation observed in areas classified as Landsat *Bajo* Type 3. Photograph taken near SWB 5. Vegetation is reflective of the *escoba bajos* described by Puleston.

Figure 14. Vegetation observed in areas classified as Landsat *Bajo* Type 4. Photograph taken near NB1. Puleston described this area as *escoba bajo*. Although there is some *escoba* palm present, they are not as prevalent as in areas classified as Landsat *Bajo* Type 3. Additionally, the general canopy is observed to be taller than in areas classified as Landsat *Bajo* Type 3.

Figure 15. Vegetation observed in areas classified as Landsat *Bajo* Type 4. Photograph taken near NB1. Puleston described this area as *escoba bajo*. Although there is some *escoba* palm present, they are not as prevalent as in areas classified as Landsat *Bajo* Type 3. Additionally, the general canopy is observed to be taller than in areas classified as Landsat *Bajo* Type 3.

Table 1
Soil physical and chemical properties of pedons collected from areas classified as Landsat Bajo Type 1.

Pedon Great Group	Hillslope	Depth	Horizon	Soil Color Dry	Texture Clay	Texture Sand	Texture Class	pH	P	Total N	Total C	Organic C	CCE	$\delta^{13}C$	Change in $\delta^{13}C$	UTM Zone 16 East	UTM Zone 16 North
					------%------				mg/kg	------------------%------------------				------‰------		m	m
Airstrip 1	TS	0 - 15	A							0.24	2.69	2.49	1.64	-28.65	1.70	223355	1907065
Hapluderts		15 - 30		10YR 5/1	83	11	C	5.20						-27.92			
		30 - 45	Bss	5Y 6/1	100	0	C	5.66						-26.95			
		45 - 60	C	10YR 5/1				6.33						-27.76			
		60 - 75		5Y 6/1				6.91						-27.24			
		75 - 90	C	10YR 7/1				6.97						-27.10			
Airstrip 2	TS	0 - 15	A	2.5Y 6/1	90	0	C	6.87	6.87	0.19	2.68	1.78	7.51	-28.29	1.31	223323	1906888
Hapluderts		15 - 30		2.5Y 6/1				6.67						-27.56			
		30 - 45	AC	10YR 7/1	93	1	C	6.74						-26.75			
		45 - 60	C	5Y 6/1				7.03						-27.20			
		60 - 75		5Y 6/1				7.30						-26.97			
Bajo East 1	TS	0 - 15	A	10YR 6/2	83	6	C	4.65	5.03	0.17	1.65	1.61	0.32	-28.49	3.34	230600	1905222
Hapluderts		15 - 30		2.5Y 6/3	100	5	C	4.30						-27.95			
		30 - 45	C	2.5Y 6/2				3.93						-26.75			
		45 - 60		2.5Y 7/2				3.87						-26.33			
		60 - 75		2.5Y 7/1				3.85						-25.15			
		75 - 90		2.5Y 6/2				3.95						-25.43			
		90 - 105		2.5Y 7/2				4.97						-26.22			
Bajo East 2	FS	0 - 15	A1	2.5Y 5/1	86	6	C	6.23	6.38	0.41	3.75	3.57	1.54	-27.37	2.48	229564	1905307
Humaquepts		15 - 30	A2	5Y 6/1				6.93						-26.42			
		30 - 45	Bw	5Y 6/1	54	39	C	7.00						-26.94			
		45 - 60	C	5Y 6/1				6.87						-24.88			
		60 - 75		5Y 6/1				6.91						-26.51			
		75 - 90		5Y 7/1				7.00						-26.85			
		90 - 105		5Y 8/1				7.04						-27.65			
East Brecha 1	TS	0 - 15	A	2.5Y 4/1	100	0	C	5.09	5.12	0.32	3.09	2.94	1.28	-26.70	2.75	222937	1905853
Endoaquerts		15 - 30	Bss	10YR 5/1				4.97						-25.86			
		30 - 45		10YR 5/1	100	0	C	5.40						-24.93			
		45 - 60		2.5Y 6/1				6.18						-25.55			
		60 - 75		5Y 6/1				6.76						-23.95			
		75 - 90		10YR 6/1				6.91						-24.63			
		90 - 105		5Y 6/1				7.04						-24.32			
East Brecha 2	TS	0 - 15	A	10YR 5/1	58	37	C	5.39	3.88	0.24	2.27	2.11	1.35	-27.14	0.88	223041	1905855
Endoaquerts		15 - 30		5Y 6/1				5.40						-27.45			
		30 - 45		5Y 6/1	70	27	C	6.08						-27.45			
		45 - 60		5Y 6/1				5.84						-26.26			
		60 - 75		5Y 6/1				6.67						-26.36			
		75 - 90		5Y 7/1				6.81						-27.27			
SF1	TS	0 - 15	A	2.5Y 6/2	96	0	C	5.58	5.05	0.26	2.77	2.53	1.98	-29.09	4.09	225710	1906290
Endoaquerts		15 - 30		2.5Y 6/2				6.52						-28.54			
		30 - 45	E	2.5Y 7/3				5.59						-26.12			
		45 - 60		5Y 7/2				4.79						-26.24			
		60 - 75	Bss	2.5Y 6/1				4.57						-25.10			
		75 - 90		2.5Y 7/2				4.79						-25.00			

Table 1, continued.

Pedon Great Group	Hillslope	Depth	Horizon	Soil Color Dry	Texture Clay	 Sand	 Class	pH	P	Total N	Total C	Organic C	CCE	δ13C	Change in δ13C	UTM Zone 16 East	 North
		90 - 105	C	2.5Y 8/1				4.87						-25.63			
		105 - 120		5Y 8/2				5.78						-25.56			
		120 - 135		5Y 7/2				6.47						-25.86			
		135 - 150		2.5Y 7/3				7.23						-24.32			
SF2	FS	0 - 15	A	5Y 4/1	90	3	C	6.82	10.56	0.67	5.53	5.36	1.43	-27.43	2.28	225604	1906400
Endoaquerts		15 - 30		7.5YR 4/1				7.63						-26.64			
		30 - 45	Bss	2.5Y 6/1				7.49						-26.42			
		45 - 60		10YR 7/1				7.57						-26.40			
		60 - 75		5Y 7/1				8.10						-25.15			
		75 - 90		5Y 7/1				7.90						-26.31			
		90 - 105		5Y 7/1				8.14						-25.17			
		105 - 120		2.5Y 7/1				7.97						-25.26			
		120 - 135		2.5Y 7/1				8.03						-25.00			
		135 - 150		2.5Y 7/1				7.74						-23.22			
		150 - 165		5Y 7/2				7.61						-24.60			
		165 - 180		5Y 8/1				7.59						-26.10			
		180 - 195		5Y 8/2				7.58						-25.11			
South Border 2	TS	0 - 15	A	10YR 5/1	55	40	C	5.43	3.69	0.42	3.97	3.89	0.69	-28.71	3.40	209681	1894990
Hapluderts		15 - 30		10YR 5/1				5.46						-28.02			
		30 - 45	Bss	10YR 5/2				5.36						-26.90			
		45 - 60		10YR 5/2				4.88						-25.93			
		60 - 75		10YR 5/1				4.17						-26.97			
		75 - 90		10YR 6/2	100	0	C	4.06						-25.32			
		90 - 105		10YR 6/2				3.80						-25.87			
		105 - 120		10YR 6/2				3.78						-25.31			
		120 - 135		10YR 6/2				4.05						-24.10			
		135 - 150		7.5YR 7/2				3.84						-24.61			
South Border 3	FS	0 - 15	A	10YR 6/2				4.71	4.74	0.29	2.47	2.44	0.29	-28.40	2.88	210709	1894902
Dystruderts		15 - 30		10YR 6/2				4.28						-27.06			
		30 - 45	Bss	2.5Y 6/2	98	0	C	3.90						-26.48			
		45 - 60		2.5Y 6/2				3.78						-26.12			
		60 - 75		2.5Y 6/2				3.58						-26.13			
		75 - 90		2.5Y 7/2				3.41						-25.53			
		90 - 105	C	2.5Y 7/1				3.42						-25.15			
WB2 3	TS	0 - 15	A	2.5Y 6/2	91	7	C	5.52	5.22	0.38	3.30	3.30	0.00	-28.50	4.73	215458	1899424
Endoaquents		15 - 30		2.5Y 6/3				4.82						-27.86			
		30 - 45		2.5Y 7/3				4.55						-25.62			
		45 - 60		2.5Y 7/3				4.18						-24.89			
		60 - 75		10YR 7/3				4.11						-23.77			
		75 - 90		10YR 7/2				3.84						-24.06			
		90 - 105		2.5Y 7/3				3.46						-25.10			
		105 - 120		10Y 7/2				3.35						-24.51			
		120 - 135		10YR 8/2				3.40						-24.10			
		135 - 150		5Y 7/2				3.75						-24.95			

Slope Position: SU, summit; BS, backslope; FS, footslope; TS, toeslope.
Texture Class: SCL, sandy clay loam; SC, silty clay; CL, clay loam; C, clay.

$CaCO_3$: $CaCO_3$ Equivalent
Change in $\delta^{13}C$: The maximum change in $\delta^{13}C$ between 0 and 90 cm.

Table 2
Soil physical and chemical properties of pedons collected from areas classified as Landsat *Bajo* Type 2.

Pedon Great Group	Hillslope	Depth	Horizon	Soil Color Dry	Texture Clay	Sand	Class	pH	P	Total N	Total C	Organic C	CCE	$\delta^{13}C$	Change in $\delta^{13}C$	UTM Zone 16 East	North
					------%------				mg/kg	------------------%------------------				------‰------		m	m
WB2 2	FS	0 - 15	A	10YR 5/2	81	10	C	6.68	4.64	0.51	5.27	5.22	0.44	-27.36	2.85	215507	1899823
Endoaquents		15 - 30		2.5Y 6/1				7.20						-26.56			
		30 - 45		5Y 7/2				7.69						-25.67			
		45 - 60		5Y 7/2				7.79						-25.40			
		60 - 75		5Y 7/2				7.72						-24.51			
		75 - 90		5Y 7/2				7.73						-25.69			
		90 - 105		2.5Y 7/2				8.03						-24.90			
		105 - 120		5Y 7/2				7.87						-24.24			
		120 - 135		10YR 8/2				7.85						-23.31			
		135 - 150		10YR 8/2				7.85						-23.58			
West Bajo 2	TS	0 - 15	A	10YR 5/1	94	0	C	5.30	4.12	0.41	4.52	4.45	0.62	-28.86	3.15	217165	1899871
Udorthents		15 - 30	AC	2.5Y 7/2	96	0	C	4.56						-27.42			
		30 - 45	C	5Y 7/2				3.89						-26.82			
		45 - 60		5Y 8/2				3.56						-25.72			
WT1 1	FS	0 - 15	A	2.5Y 5/1	91	5	C	6.28	4.54	0.37	4.03	4.03	0.00		1.29	214968	1906615
Endoaquents		15 - 30		10YR 6/1				6.50						-27.82			
		30 - 45		5Y 6/1				6.97						-26.47			
		45 - 60		5Y 6/1				7.38						-27.71			
		60 - 75		5Y 7/1				7.90						-27.69			
		75 - 90		5Y 7/1				7.54						-26.53			
		90 - 105		10YR 7/1				7.72						-25.38			
		105 - 120		5Y 7/1				8.16						-26.23			
		120 - 135		5Y 7/1				8.28						-25.50			
		135 - 150		5Y 7/1				8.16						-25.56			
WT1 2	FS	0 - 15	A	2.5Y 6/1	89	7	C	5.83	5.20	0.32	2.69	2.69	0.00	-28.05	4.09	213088	1906755
Endoaquents		15 - 30		2.5Y 6/1				6.08						-27.30			
		30 - 45		2.5Y 6/1				5.98						-27.03			
		45 - 60		10YR 7/1	100	1	C	6.31	5.71	0.08	0.49	0.49	0.00	-25.19			
		60 - 75		2.5Y 5/1	95	1	C	7.55	4.87	0.08	0.86	0.70	1.35	-23.96			
		75 - 90		5Y 6/1				7.45						-24.53			
		90 - 105		2.5Y 6/1				7.70						-24.39			
		105 - 120		5Y 6/1				7.46						-25.22			
		120 - 135		5Y 6/1				7.57						-24.90			
		135 - 150		5Y 7/1				7.65						-24.65			
WT1 3	TS	0 - 15	A	10YR 5/2	86	7	C	5.98	4.36	0.39	5.03	4.94	0.78	-28.82	4.39	214197	1906668
Endoaquents		15 - 30	C	2.5Y 7/1				5.85						-28.70			
		30 - 45		2.5Y 7/1				7.69						-26.62			
		45 - 60		10YR 7/1				7.62						-26.23			
		60 - 75		5Y 6/1				8.12						-24.43			
		75 - 90		2.5Y 6/1				7.87						-26.40			
		90 - 105		5Y 6/1				8.27						-25.43			
		105 - 120		5Y 6/1				8.03						-25.40			
		120 - 135		7.5YR 6/1				7.74						-24.61			

Slope Position: SU, summit; BS, backslope; FS, footslope; TS, toeslope.
Texture Class: SCL, sandy clay loam; SC, silty clay; CL, clay loam; C, clay.
$CaCO_3$: $CaCO_3$ Equivalent
Change in $\delta^{13}C$: The maximum change in $\delta^{13}C$ between 0 and 90 cm.

Table 3
Soil physical and chemical properties of pedons collected from areas classified as Landsat *Bajo* Type 3.

Pedon Great Group	Hillslope	Depth	Horizon	Soil Color Dry	Texture Clay	Texture Sand	Texture Class	pH	P	Total N	Total C	Organic C	CCE	$\delta^{13}C$	Change in $\delta^{13}C$	UTM Zone 16 East	UTM Zone 16 North
					------%------				mg/kg	------------------%------------------				------‰------		m	m
SWB 1	TS	0 - 15	A	10YR 4/1	81	7	C	6.96	6.53	0.77	6.07	4.98	9.09	-26.88	1.20	216919	1898982
Dystrudepts		15 - 30	E	10YR 5/1				7.47						-26.64			
		30 - 45	Bw	2.5Y 4/1				7.84						-26.12			
		45 - 60	C	2.5Y 6/1				7.77						-25.68			
		60 - 75		2.5Y 7/1				7.78						-25.70			
		75 - 90		5Y 7/1				7.87						-25.76			
		90 - 105		2.5Y 7/1				7.87						-26.37			
SWB 2	FS	0 - 15	A	2.5Y 5/2	47	13	SC	7.92	4.02	0.51	9.38	2.60	56.50	-26.89	0.91	217062	1898931
Haprendolls		15 - 30	C	2.5Y 6/1				7.85						-26.08			
		45 - 60		2.5Y 6/1				7.97						-25.98			
SWB 4	BS	0 - 15	A	7.5YR 4/1	58	14	C	7.22	7.08	0.60	9.11	3.41	47.50	-27.10	0.89	217119	1898904
Haprendolls		15 - 30	C	2.5Y 6/1				8.20						-26.21			
SWB 5	FS	0 - 15	A	2.5Y 4/1	84	6	C	7.65	5.41	0.46	3.87	3.12	6.21	-27.47	2.18	217152	1898873
Endoaquents		15 - 30	C	2.5Y 7/1				7.86						-26.28			
		30 - 45		10YR 7/1				7.79						-26.65			
		45 - 60		2.5Y 7/1				7.99						-26.52			
		60 - 75		10YR 6/1				7.76						-25.29			
		75 - 90		2.5Y 6/1				7.54						-25.97			
WB1 1	TS	0 - 15	A	2.5Y 5/2	86	10	C	6.26	6.12	0.48	4.93	4.70	1.93	-28.37	2.71	218571	1900646
Endoaquents		15 - 30		2.5Y 5/2				5.68						-27.78			
		30 - 45		2.5Y 5/1				5.64						-27.19			
		45 - 60		2.5Y 6/1				6.18						-25.65			
		60 - 75		5Y 6/1				7.63						-26.31			
		75 - 90		2.5Y 5/1				7.59						-24.92			
		90 - 105		2.5Y 5/1				7.72						-24.74			
WB1 2	FS	0 - 15	A	2.5Y 4/1	85	9	C	7.29	6.75	0.65	5.99	5.49	4.19	-27.71	4.31	218645	1900482
Endoaquents		15 - 30		2.5Y 5/1				7.64						-25.84			
		30 - 45		5Y 6/1				8.01						-24.40			
		45 - 60		2.5Y 6/1				7.96						-23.83			
		60 - 75		2.5Y 5/1				7.96						-23.40			
		75 - 90		5Y 6/1				8.13						-22.53			
		90 - 105		5Y 7/2				7.99						-23.56			
West Bajo 1	FS	0 - 15	A	10YR 6/2	100	0	C	5.22	3.57	0.26	2.82	2.76	0.51	-28.56	2.32	217300	1899729
Udorthents		15 - 30	C1	2.5Y 7/1	100	0	C	4.16						-27.37			
		30 - 45	C2	5Y 6/2				4.00						-26.24			
		45 - 60		5Y 7/2				3.82						-27.21			
		60 - 75		5Y 8/2				3.78						-26.77			

Slope Position: SU, summit; BS, backslope; FS, footslope; TS, toeslope.
Texture Class: SCL, sandy clay loam; SC, silty clay; CL, clay loam; C, clay.
$CaCO_3$: $CaCO_3$ Equivalent
Change in $\delta^{13}C$: The maximum change in $\delta^{13}C$ between 0 and 90 cm.

Table 4
Soil physical and chemical properties of pedons collected from areas classified as Landsat *Bajo* Type 4.

Pedon Great Group	Hillslope	Depth	Horizon	Soil Color Dry	Texture Clay	Sand	Class	pH	P	Total N	Total C	Organic C	CCE	$\delta^{13}C$	Change in $\delta^{13}C$	UTM Zone 16 East	North
					------%------				mg/kg	------------------%------------------				------‰------		m	m
NB1 1	TS	0 - 15	A	10YR 4/1	94	2	C	7.29	6.04	0.42	4.03	3.98	0.44	-28.42	4.35	221514	1918013
Endoaquents		15 - 30	Bg	GLEY1 5/N				6.59						-27.19			
		30 - 45		GLEY1 5/N				7.62						-26.55			
		45 - 60		GLEY1 5/N				7.97						-24.69			
		60 - 75		10YR 5/1				8.04						-24.07			
		75 - 90	C	10YR 7/1				7.93						-23.54			
		90 - 105		5Y 6/1				8.17						-23.48			
		105 - 120		2.5Y 6/1				8.50						-22.98			
		120 - 135		2.5Y 6/1				8.05						-22.64			
		135 - 150		5Y 6/1				8.07						-21.79			
NB1 2	FS	0 - 15	A	2.5Y 6/2	96	0	C	5.60	7.86	0.37	3.12	3.08	0.31	-28.15	4.35	220173	1918122
Endoaquents		15 - 30		5Y 5/1				6.07						-27.64			
		30 - 45		5Y 6/1				6.95						-26.91			
		45 - 60		10YR 7/1				7.44						-26.26			
		60 - 75		10YR 7/1				7.80						-25.31			
		75 - 90		5Y 6/1				7.65						-23.81			
		90 - 105		5Y 6/1				7.91						-24.66			
		105 - 120		5Y 7/1				8.16						-24.39			
		120 - 135		10YR 7/1				8.26						-24.51			
		135 - 150		10YR 7/1				8.29						-24.17			
Norte2 2	TS	0 - 15	A	2.5Y 5/1	60	13	C	7.76	6.54	0.60	11.20	3.74	62.19	-27.46	0.91	220171	1915505
Endoaquents		15 - 30	C	5Y 7/1				7.68						-27.00			
		30 - 45		10YR 7/1				7.86						-27.42			
		45 - 60		2.5Y 8/1				7.82						-26.81			
		60 - 75		2.5Y 8/1				8.17						-26.56			
		75 - 90		2.5Y 8/1				7.96						-26.82			
		90 - 105		2.5Y 8/1				8.09						-26.80			
		105 - 120		2.5Y 8/1				7.96						-26.93			
		120 - 135		5Y 8/1				8.35						-26.57			
		135 - 150		5Y 8/1				8.07						-26.35			
Norte2 3	FS	0 - 15	A	10YR 4/1	85	5	C	7.34	7.45	0.76	6.29	5.85	3.71	-27.63	1.53	219913	1915591
Endoaquents		15 - 30		2.5Y 5/1				7.40						-26.39			
		30 - 45		2.5Y 6/1				7.79						-25.94			
		45 - 60		10YR 6/1				7.70						-26.81			
		60 - 75		10YR 6/1				7.85						-26.10			
		75 - 90		5Y 7/1				7.93						-25.54			
		90 - 105		5Y 8/1				7.75						-26.32			
		105 - 120		2.5Y 8/1				7.84						-26.19			

Slope Position: SU, summit; BS, backslope; FS, footslope; TS, toeslope.
Texture Class: SCL, sandy clay loam; SC, silty clay; CL, clay loam; C, clay.

$CaCO_3$: $CaCO_3$ Equivalent
Change in $\delta^{13}C$: The maximum change in $\delta^{13}C$ between 0 and 90 cm.

Table 5
Soil physical and chemical properties of pedons collected from planos.

Pedon				Soil Color	Texture					Total	Total	Organic			Change	UTM Zone 16	
Great Group	Hillslope	Depth	Horizon	Dry	Clay	Sand	Class	pH	P	N	C	C	CCE	$\delta^{13}C$	in $\delta^{13}C$	East	North
					------%------				mg/kg	------------------%------------------				------‰------		m	m
Airstrip 3	TS	0 - 15	A	5Y 6/1	62	37	C	6.60	6.05	0.15	1.56	0.47	9.11	-28.86	4.12	223314	1906708
Dystrudepts		15 - 30	C	10YR 7/1				6.80	4.42	0.07	0.92	0.00	7.91	-27.82			
		30 - 45	Ab	2.5Y 5/1	61	35	C	6.98						-24.74			
		45 - 60		2.5Y 5/1				6.92						-25.41			
		60 - 75		2.5Y 6/1	88	7	C	7.18						-25.46			
		75 - 90	C	2.5Y 7/1				7.23						-26.47			
CONAP 1 1	BS	0 - 15	A	2.5Y 4/1	62	12	C	6.99	4.74	0.42	9.85	2.31	62.80	-26.18	1.31	222068	1904513
Haprendolls		15 - 30	Ckk	5Y 7/1	50	17	C	7.15						-25.35			
		30 - 45		10YR 8/1				7.23						-24.87			
		45 - 60		2.5Y 8/1				7.38						-25.54			
CONAP 1 2	BS	0 - 15	A	5Y 5/1	46	18	C	7.10	5.27	0.44	11.30	2.42	73.97	-26.76	3.97	222078	1904494
Calciudolls		15 - 30		10YR 5/1				6.88						-24.53			
		30 - 45	Bk	10YR 7/1	44	25	C	6.93						-22.79			
		45 - 60	C	10YR 6/1				6.99						-24.64			
CONAP 2 1	SU	0 - 10	A1	10YR 5/1	51	14	C	6.84	5.49	0.61	12.30	3.93	69.74	-26.48	5.34	222158	1904838
Argiudolls		10 - 20	A2	5Y 4/1				6.87						-24.66			
		20 - 30		2.5Y 4/1				6.88						-22.72			
		30 - 45	Bt	2.5Y 5/1	58	16	C	6.98						-21.14			
		45 - 60		5Y 5/1				7.03						-21.63			
CONAP 7 3	FS	0 - 15	A1	10YR 4/1	77	6	C	7.05	4.86	0.68	7.15	5.00	17.91	-26.77	2.84	219079	1900367
Endoaquents		15 - 30		10YR 4/1				6.98						-25.56			
		30 - 45	A2	10YR 5/1				7.11						-23.93			
CONAP 7 4	TS	0 - 15	A1	5Y 4/1	88	1	C	6.98	3.55	0.36	5.10	1.78	27.71	-27.18	2.49	219152	1900542
Endoaquents		15 - 30		2.5Y 4/1				6.87						-25.94			
		30 - 45		10YR 4/1	93	2	C	7.01						-25.13			
		45 - 60	A2	10YR 5/1				7.16						-24.69			
CONAP 2 2	FS	0 - 15	A	2.5Y 4/1	67	17	C	7.56	5.74	0.63	8.91	5.50	28.40	-25.45	4.31	222205	1904785
Haprendolls		15 - 30		5Y 4/1				7.55						-24.16			
		30 - 45		2.5Y 5/1				7.77						-22.33			
		45 - 60	Ckk	2.5Y 7/1				7.88						-21.14			
		60 - 75		5Y 7/2				7.64						-23.22			
WT2 1	TS	0 - 15	A	10YR 4/1	94	2	C	5.82	4.60	0.42	3.97	3.97	0.00	-27.30	3.56	218687	1906227
Endoaquents		15 - 30		2.5Y 5/1				6.66						-25.62			
		30 - 45		10YR 5/1				5.92						-24.69			
		45 - 60		10YR 6/1				6.82						-25.58			
		60 - 75		2.5Y 6/1				7.68						-23.74			
		75 - 90		5Y 6/1				7.87						-24.57			
		90 - 105		10YR 6/1				7.52						-24.63			
		105 - 120		5Y 7/1	99	0	C	7.66	5.18	0.08	0.44	0.44	0.00	-25.17			
		120 - 135		2.5Y 6/1				7.57						-22.87			
		135 - 150		2.5Y 5/1	99	0	C	7.86	4.21	0.10	1.01	0.95	0.49	-22.67			
		150 - 165		2.5Y 5/1				7.57						-23.13			
		165 - 180		10YR 7/1				7.62						-23.52			

Slope Position: SU, summit; BS, backslope; FS, footslope; TS, toeslope.
Texture Class: SCL, sandy clay loam; SC, silty clay; CL, clay loam; C, clay.
$CaCO_3$: $CaCO_3$ Equivalent
Change in $\delta^{13}C$: The maximum change in $\delta^{13}C$ between 0 and 90 cm.

Table 6
Soil physical and chemical properties of pedons collected from uplands.

Pedon Great Group	Hillslope	Depth	Horizon	Soil Color Dry	Texture Clay	Sand	Class	pH	P	Total N	Total C	Organic C	CCE	$\delta^{13}C$	Change in $\delta^{13}C$	UTM Zone 16 East	North
					------%------				mg/kg	------------------%------------------				------‰------		m	m
Bajo East 3	BS	0 - 15	A	2.5Y 5/1	50	21	C	6.83	5.87	0.58	10.80	3.80	58.35	-27.45		228922	1905360
Haprendolls																	
CONAP 3 1	BS	0 - 15	A	5Y 3/1	53	28	C	6.92	3.90	0.70	11.90	4.79	59.23	-27.53		222160	1904846
Haprendolls																	
CONAP 4 1	BS	0 - 15	A	5Y 3/1	86	0	C	6.84	4.00	0.64	6.17	5.00	9.73	-26.80	0.33	219850	1902342
Udorthents		15 - 30		2.5Y 5/1				6.94						-26.46			
CONAP 4 2	BS	0 - 15	A	5Y 6/1	55	23	C	7.08	4.58	0.86	13.10	5.77	61.06	-27.64		219897	1902306
Hapludolls																	
CONAP 4 3	SU	0 - 15	A	10YR 6/1	40	21	C	6.86	5.83	0.78	15.00	6.38	71.82	-27.54		219967	1902279
Hapludolls																	
CONAP 5 1	BS	0 - 15	A	2.5Y 4/1	34	54	SCL	6.99	6.56	1.17	14.40	10.54	32.20	-27.47			
Udorthents																	
CONAP 6 1	BS	0 - 15	A	10YR 4/1	38	43	CL	7.02	6.73	1.09	12.80	9.39	28.46	-27.06		217882	1899162
Udorthents																	
CONAP 7 1	BS	0 - 15	A	2.5Y 4/1	28	56	SCL	6.97	3.90	0.75	12.70	4.95	64.60	-25.62		218886	1900359
Haprendolls																	
CONAP 7 2	SU	0 - 15	A	2.5Y 5/1	50	19	C	6.93	6.54	0.60	13.00	3.68	77.68	-23.66		218861	1900317
Haprendolls																	
CONAP 8 1	BS	0 - 15	A	2.5Y 4/1	53	29	C	7.20	5.23	0.55	11.90	3.29	71.71	-24.60		218736	1900400
Haprendolls																	
CONAP 8 2	FS	0 - 15	A	2.5Y 4/1	84	5	C	7.10	6.14	0.69	8.28	6.19	17.44	-27.03	1.42	218662	1900445
Dystrudepts		15 - 30	Bw	10YR 4/1				7.14						-25.61			
		30 - 45		10YR 5/1	73	14	C	7.30						-27.29			
CONAP 8 3	TS	0 - 15	A1	10YR 4/1	96	0	C	6.01	5.64	0.51	5.13	4.95	1.50	-27.80	1.42	218625	1900477
Humaquepts		15 - 30	A2	10YR 5/1				6.09						-27.06			
		30 - 45	Bw	5Y 6/1	98	2	C	6.76						-26.45			
		45 - 60	BC	10YR 7/1				6.97						-26.38			
East Brecha 3	SU	0 - 15	A	2.5Y 3/2	53	15	C	6.86	5.48	0.77	14.40	5.92	70.69	-27.77		222776	1905865
Haprendolls																	
Headquarters 1	BS	0 - 15	A	5Y 5/1	35	41	CL	7.56	7.10	0.73	13.30	6.50	56.66	-27.19		222062	1906456
Haprendolls																	
Headquarters 2	SU	0 - 15	A1	5Y 4/1	71	17	C	7.64	6.68	0.67	7.76	5.88	15.65	-24.94	1.95	222115	1906483
Udorthents		15 - 30	A2	10YR 3/1				7.58						-23.72			
		30 - 45		5Y 5/2				7.93						-22.99			
		45 - 50	C	7.5YR 7/2				7.74						-23.00			
Headquarters 3	FS	0 - 15	A	2.5Y 3/1	53	32	C	7.53	5.65	0.73	10.10	6.13	33.11	-24.41	0.21	222128	1906532
Udorthents		15 - 30		5Y 3/1				7.73						-24.62			
NB 1 3	BS	0 - 15	A	5Y 5/1	60	25	C	7.76	4.75	0.87	11.00	7.32	30.70	-26.69		219924	1918143
Udorthents																	
Norte 2 1	BS	0 - 15	A	10YR 6/1	42	22	C	7.76	5.01	0.67	12.80	4.90	65.82	-27.10		219769	1915598
Udorthents																	
SF 3	BS	0 - 15	A	5Y 4/1	51	28	C	7.78	9.88	0.87	12.50	5.83	55.55	-27.46	0.20	225553	1906469
Haprendolls		15 - 30	C	2.5Y 6/1				7.75						-27.26			
South Border 4	BS	0 - 15	A	2.5Y 3/1	70	10	C	6.83	5.97	0.95	11.10	8.31	23.26	-27.44		211243	1894864
Udorthents																	

Table 6, continued.

Pedon				Soil Color	Texture					Total	Total	Organic			Change	UTM Zone 16	
Great Group	**Hillslope**	**Depth**	**Horizon**	**Dry**	**Clay**	**Sand**	**Class**	**pH**	**P**	**N**	**C**	**C**	**CCE**	**δ13C**	**in δ13C**	**East**	**North**
WB2 1	FS	0 - 15	A	5Y 4/1	61	20	C	7.62	5.37	0.94	11.30	7.98	27.69	-26.54	1.03	215524	1900057
Udorthents		15 - 30	C	5Y 6/1				7.62						-26.18			
		30 - 45		5Y 6/1				7.98						-25.92			
		45 - 60		5Y 7/1				7.79						-25.51			
WT2 2	BS	0 - 15	A	2.5Y 7/2	34	27	CL	7.66	8.39	0.52	12.10	4.05	67.11	-27.03	0.82	219355	1905950
Udorthents		15 - 30		2.5Y 7/1				8.40						-25.68			
		30 - 45		10YR 8/2				8.61						-26.21			
WT2 3	FS	0 - 15	A	5Y 5/1	59	19	C	7.58	5.70	0.80	10.60	6.83	31.39	-25.89	2.08	218864	1906209
Udorthents		15 - 30	C	5Y 7/1				7.55						-25.30			
		30 - 45		5Y 7/1				7.93						-23.81			
		45 - 55		5Y 6/1				7.74						-26.12			

Slope Position: SU, summit; BS, backslope; FS, footslope; TS, toeslope.
Texture Class: SCL, sandy clay loam; SC, silty clay; CL, clay loam; C, clay.

$CaCO_3$: $CaCO_3$ Equivalent
Change in $\delta^{13}C$: The maximum change in $\delta^{13}C$ between 0 and 90 cm.