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Thin Soils and Sacbes: The Soil Resources of Uci, Yucatan, Mexico

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ABSTRACT

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The objective of this study was to use pedological evidence in conjunction with Geographic Information Systems, and soil physical and chemical analyses as means to better understand the agricultural landscape surrounding the ancient Maya city of Uci. Specifically, the query of this thesis is to determine whether there is an association between settlement density and soil resources, and what relationship if any there is between the ancient sacbe of Uci and its surrounding agricultural potential. Stable carbon isotope analysis of the humin fraction of the soil organic matter was conducted on several profiles from karst depressions known as rejolladas near the site center, and from a select number of sufficiently deep profiles along and surrounding the ancient sacbe, and from beneath ancient structures. A strong C isotopic signature of ancient C_4 crops was found in a limited number of profiles while a majority of the profiles showed no evidence, or little to inconclusive evidence due to a mixture of C_3 and C_4 plants in the natural landscape. A majority of the soils surrounding Uci are shallow to extremely shallow and many profiles sampled and studied did not allow for C isotopic analysis.

Isotopic evidence along with other soil chemical and physical characteristics suggests that settlement density was linked to soil resources, specifically in the case of the rejolladas proximity to the Uci site center. However, it does not appear that the construction and location of the sacbe was linked to its surrounding soil resources or agricultural potential even though ancient maize crops may have been cultivated sporadically close to the sacbe and nearby structures. The soil resources of Uci are not conducive to the production of large maize crops and the ancient Maya of this area likely utilized maize along with alternative crops, arboriculture, wild game and trade to sustain its population.

Key Words: stable carbon isotopes, soil analysis, humin, ancient agriculture, Maya agriculture, geochemistry

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Introduction

The Classic Maya culture occupied a geographically vast and environmentally diverse region of Mesoamerica. The ancient Maya managed to sustain significant populations in a fragile landscape, and, like all cultures, depended on natural resources, especially the soil. The northern portion of the Yucatan peninsula of Mexico is an example of one of the more harsh environments in which the Maya flourished. This region is impaired by widely varying precipitation and extreme dry seasons (Beach, 1998b; Dahlin et al., 2005; Sweetwood, 2008; Wilson et al., 2008). Shallow soils in the karst landscape of the Northern Yucatan compound the difficulties and produce incredibly low maize yields of between 0.25 to 1 Mg ha^{-1} in a good year and as low as 0.1 Mg ha^{-1} (Beach, 1998a; Whittaker et al., 2009), especially when compared with average world yields of 4.6 Mg ha^{-1} (McAnany, 2011).

The modern day inhabitants of this area experience many of the same challenges the ancient Maya faced. Despite extensive investigation of Maya sites, relatively little is understood of the agricultural methods and land use practices of the Northern Lowland Maya. To investigate questions of ancient Maya agriculture, it is important to recognize that subsistence strategies and environmental factors varied both geographically and temporally (Dunning, 1996; Turner II, 1985). Indeed "…it is dangerous to extrapolate environmental circumstances, and inferred agricultural adaptations to them, from one area of the Maya Lowlands to another" and "What is needed now are more careful examinations of specific adaptations made in the suite of microenvironments presented in the various regions of the Maya Lowlands" (Dunning, 1996;

Dunning, 2000; Dunning and Beach, 2000; Fedick, 1995). It is therefore necessary for case-by-case approaches to ancient agricultural investigations that employ a variety of tools and academic backgrounds (Dunning and Beach, 2004).

Ancient agricultural lands of the Maya rarely left visible remains such as terraces or canals, and the dense, short jungle scrub of the Yucatan peninsula often make surveying and sampling of the area difficult. In addition to traditional archaeological investigation, knowledge of Maya subsistence, agriculture, and paleoecology has been interpreted from various sources including paleolimnology (Anselmetti et al., 2007; Brenner et al., 2002), palynology (Leyden, 2002), pedology (Burnett et al., 2012a; Burnett et al., 2012b; Sweetwood et al., 2009; Wells and Terry, 2007), ethnology (Atran, 1993; Cowgill, 1962; Dunning and Timothy, 2004; Jensen et al., 2007; Nations and Nigh, 1980), historical accounts (Tozzer, 1941), epigraphy (Taube, 1992), and combinatory approaches (Beach, 1998a; Dunning et al., 1997). The use of soil science methods can be applied to similar archeological questions. Soil physical and chemical characteristics often contain clues that can reveal information about past cultivation practices and the agronomic resources that were available to the past inhabitants. Through field observation in conjunction with laboratory tests, information can be produced to understand more about the past.

In the case of Uci in Northern Yucatan, where thin soils dominate the landscape, the physical and chemical characterization and taxonomy of these soils can provide evidence of location suitability for ancient agricultural production (Fedick, 1994; Fedick, 1995; Jensen et al., 2007; Johnson et al., 2007b; Sweetwood et al., 2009; Webb et al., 2007; Webb et al., 2004). The indigenous Maya as well as the modern Maya inhabitants of the Yucatan have also long used a simple classification system known today as the Maya Reference Groups (MRG) to describe the soils of their landscape. The MRGs are based mainly on soil depth, color and clay content. These factors are influenced by organic carbon content (color), physical restrictions to root growth, water retention and drainage limitations, and profile development (Bautista and Zinck, 2010; Dunning and Beach, 2004; Weisbach et al., 2002). According to this system the two most common soil types in the northern plain are *boxlu'um (box = light black),* and *kancab lu'um (kan = yellowish, cab = clay).* These soil types formed on Late Miocene to Pliocene limestone (Pope et al., 1996). *Boxlu'um* is a shallow clay loam (Calciustolls and Haplustolls), high in carbonates, which formed in fractured cobble and gravel limestone (Beach, 1998a). *Kancab* soils (Argiustolls, Haplustolls, and Calciustolls) are higher in clay, deeper, and less stony than *boxlu'um (Beach, 1998a)*. *Kancab* soils formed from the dissolution of limestone and aeolian deposition including Saharan dust and volcanic ash (Beach, 1998a; Muhs et al., 2007). *Boxlu'um* tends to have a relatively high nutrient status, with higher organic matter and available macro- and micronutrients than *kancab* (Weisbach et al., 2002).

Yucatan soils have been taxonomically classified by the World Reference Base (WRB) system. Bautista used the WRB to describe the suite of soil types in the Yucatan, with Leptosols (Rendzinas) being the most common across the northern plain and central part of the state (Bautista and Zinck, 2010). Leptosols or Rendzinas are described as shallow dark soils, grey to black overlying calcareous substrates. Other soils described and classified within the state from regions other than the northern plains include Cambisols, Luvisols, Arenesols, Gleysols, Stagnosols, Vertisols, Nitisols and Solonchack (Bautista and Zinck, 2010; Fedick and Ford, 1990; Sedov et al., 2008; Solleiro-Rebolledo et al., 2011; Wollwage et al., 2012). In the eastern part of the state of Yucatan similar soils as those found in the northern plains are encountered on hilltops between deeper red soils in the valleys. These thin soils on hilltops were classified as Rendzinas and Calcisols (Sedov et al., 2008; Smardon, 2006; Solleiro-Rebolledo et al., 2011). On the West side of the state, shallow Leptosols are the main soil type encountered (Dahlin et al., 2005; Isphording and Wilson, 1973). West Yucatan soils near Chunchucmil have been classified by USDA taxonomy as Argiustolls, Haplustolls, and Calciustolls (Sweetwood et al., 2009).

Ancient vegetation changes related to forest clearance for ancient maize agriculture can be detected in the stable carbon (C) isotopes of soil organic matter SOM (Burnett et al., 2012a; Burnett et al., 2012b; Fernandez et al., 2005; Johnson et al., 2007b; Webb et al., 2004; Wright et al., 2009). The tree and vine species of the Yucatan scrub use a specific C_3 photosynthetic pathway, while maize and many of the grassy weeds associated with forest clearance utilize a different photosynthetic pathway known as C_4. C_3 and C_4 plants assimilate different amounts of stable but heavier ^{13}C isotope into their plant tissue as they incorporate atmospheric carbon dioxide in photosynthesis. This distinction in photosynthetic pathways results in unique carbon isotopic ratios in the plant tissue that can be quantified (Fernandez et al., 2005; Healy et al., 1983; Webb et al., 2007; Webb et al., 2004; Wright, 2007; Wright et al., 2009). These unique ratios are then transferred to the soil organic matter as surface detritus and subsurface root exudates decompose. The vegetative residues incorporated into SOM become recalcitrant humic substances that are preserved in the soil for centuries. In landscapes such as those commonly inhabited by the Maya, C_3 is the dominant photosynthetic pathway of the natural forest vegetation. A long period of agricultural clearing and C_4 plant cultivation in the natural landscape can be detected by analyzing the relative abundances of stable carbon isotopes within the humin fraction of soil organic matter from soil profiles (Webb et al., 2004). The determination of $\delta^{13}C$ levels greater than -26‰, typical of C_3 plants, is suggestive of a change in ancient vegetation to C_4 plants. A change in $\delta^{13}C$ within soil profiles of approximately 4‰ has been used as a benchmark to attribute the change to a C_3/C_4 vegetation shift as opposed to microbial fractionation of carbon isotopes during diagenesis of the SOM (Balesdent and Mariotti, 1987; Martinelli et al., 1996; Powers and Schlesinger, 2002). Maize (*Zea Mays*) is the only C_4 plant known to be cultivated by the Maya and also represented the staple crop in the Maya diet (Healy et al., 1983; Lentz, 1999; Tieszen and Fagre, 1993; Turner II and Miksicek, 1984; Webb et al., 2004). Hence, a relative enrichment of SOM in ^{13}C can reasonably be attributed to ancient maize agriculture (Burnett, 2009; Burnett et al., 2012a; Burnett et al., 2012b).

Stable carbon isotopes analysis has been used as a method of prospection for maize agriculture at several archeological sites across Mesoamerica. Many of these studies have indicated that the most likely areas for ancient maize agriculture include generally deep footslope and toeslope soils, valley bottoms (Fernandez et al., 2005; Webb et al., 2007) and other gently sloped, well drained soils (Johnson et al., 2007a). Through isotopic investigation, strong evidence of ancient maize agriculture has also been associated with toeslopes, rejolladas, seasonal bajos, and terraced hillsides (Beach et al., 2008; Webb et al., 2004; Wright, 2007; Wright et al., 2009). Since the use of this method in Maya archeology is relatively new, Webb et al. (2004) has suggested that stable carbon isotope studies be used in conjunction with soil surveys to better understand ancient agricultural dynamics, which is at the heart of this study.
In other areas of the Maya world, isotopic results and interpretations have been substantiated by lake sediment stratigraphy, pollen data, soil phosphorus and charcoal levels, soil sediment deposition and radio carbon dating (Beach et al., 2006; Beach et al., 2008; Beach et al., 2009; Beach et al., 2011; Binford et al., 1987; Brenner et al., 2003; Brenner et al., 2002; Burnett, 2009; Curtis et al., 1998; Deevey et al., 1979; Dunning et al., 1998; Rice, 1993; Rosenmeier et al., 2002a; Rosenmeier et al., 2002b; Rue et al., 2002).

At Tikal, Guatemala a computer model of specific locations predicted to have high enrichment of $\delta^{13}C$ and high potential for ancient maize agriculture was developed with Landsat imagery, AIRSAR and GIS data in conjunction with stable carbon isotopes (Balzotti, 2010; Balzotti et al., 2013). In like manner, GIS data along with satellite imagery were used to identify suitable areas for soil surveys in order to better understand the dynamics and geographic extent of Uci's agriculture and how this may have been related to settlement density and the construction of the causeway. One location within the study area identified to be of high likelihood for agricultural importance are the tightly grouped rejolladas (karst depressions) in the Uci site center at the southwest end of the causeway and in close proximity to the most monumental architecture of the site. The rejolladas are unique geologic landforms that create enhanced agronomic potential due to deeper soils with higher capacity to gather and retain moisture than the surrounding shallow soils.

Regional Background and Study Area

Compared with the climates of other major Maya population centers such as the Petén of northern Guatemala, northern Yucatan is comparatively dry much like it was during the height of the Classic Maya civilization (Brenner et al., 2003; Leyden et al., 1996). The northern Yucatan is made up of four main vegetative zones: northern karst plain, savanna, swamp and hillocks. Uci and the secondary site centers of Kancab, Ukana, and Cansahcab in the immediate periphery are part of the northern plain of the peninsula. This area consists of shallow soils, limestone outcrops, and low thorny secondary forests (6-15 m) locally referred to as *acahual* (Nations and Nigh, 1980). Currently this vegetative zone is in large part used for grazing and cultivation of maize, henequen and other crops. Extending toward the north, west and east, the northern plain transitions into the other three vegetative zones nearer the coast, including grasses and sedges in the savanna region, and mangroves and salt flats in the swamp regions and medium deciduous forests in the hillock region (Lynch, 1989).

The soil types and resources of the region have been previously identified and classified by Bautista and Zinck (2010) and Beach (1998b). The swamp and estuary zones near the coast are comprised of soil types including: Histisols, Inceptisols and Entisols, which are often covered by salts and algal detritus known as periphyton. High water tables and extremely high salinity associated with tidal flooding render these soils unusable for cultivation (Beach, 1998b). The savanna and hillock regions are ancient sea benches and swales with weathered limestone hills. During the rainy season the savannas flood due to shallow soils, case hardened limestone and poor infiltration (Hardin et al., 1999; Pope et al., 2001). The well drained hillocks provide the locations for tree growth amidst the surrounding grassy savannas.

One of the most notable differences geologically and geographically between the present northern Yucatan landscape and the way it was at the height of Uci's growth (250-500 AD) is that the present sea level is thought to be near 60 cm higher than in ancient times (Beach, 1998b; Sweetwood et al., 2009). This indicates that there could have been more agriculturally suitable land available for crop production with receded seas and lower water tables in the areas north of Uci, extending toward the coast. This difference however, would not have had a direct impact on the local agriculture of Uci, but on a larger regional scale may have been a factor in food production, trade, and transport.

The soils of the Uci region are notably shallow and in many areas consist of thin detritus or no soil at all. Approximately 55 to 80% of the northern karst plain has thin to no soil and 25 to 50% lack soil all together (Dahlin et al., 2005). In much of the Maya world thin or shallow soils are a result of erosion caused by steep slopes, forest clearance and questionable agricultural methods (Beach et al., 2008). However, in this region of the Maya lowlands as with much of the Yucatan peninsula slopes rarely exceed 1 percent and the soil parent material is almost strictly limestone. This suggests that the paucity of soils in this region is due in large part to the porous nature of the limestone bedrock and slow soil development. This geologic dynamic resulted in limestone dissolution, karst depressions and very highly weathered silicate clay as parent material for soil genesis (Beach, 1998a; Beach, 1998b; Curtis et al., 1996; Kellman and Tackaberry, 1997). In some cases rejolladas or sink holes have accumulated deeper soils through erosion of the areas immediately surrounding these depressions, and increased plant material deposition due to increased soil depth and soil water retention in these unique areas. Contemporary soil depths and conditions are likely similar to what they were in Maya times because no period of heightened soil erosion existed previously, due to the minimal slope and clayey soils of the area (Beach, 1998a; Curtis et al., 1996).

It is likely that the climate of the Northern Yucatan has varied little since the time of ancient Maya occupation (Dahlin, 1983). The semi-arid landscape is influenced greatly by unpredictable annual weather and precipitation (Beach, 1998a; Dahlin et al., 2005; Sweetwood, 2008; Wilson et al., 2008). The region experiences a dry season of approximately 4 to 5 months, which runs from January to May with the greatest temperatures in March through May (Grube, 2000). The average annual temperature of the region is 27.2C (Querejeta et al., 2007). The warm soil temperature regime is isomegathermic. The wet season is from May to September, but rainfall varies widely from year to year and even within a single year (Beach, 1998a; Dahlin, 1983; Dunning, 2000; Dunning and Beach, 2000; Sweetwood, 2008). The soil moisture regime is classified as ustic (Eswaran et al., 1997). Ustic moisture regimes are dry and except during specific time periods each year when monsoon or wet season rains provide the bulk of the annual moisture (Soil Survey Staff, 2006).

Some years, rainfall will be as much as 3 to 4 times that of dry years (Lundell, 1937). A large majority of the rainfall each year (80-90%) falls during the growing season, approximately 640-900 mm (Dahlin et al., 2005; Instituto Nacional de Estadistica, 1983; Luzzadder-Beach, 2000).

The main objective of this project was to use pedological evidence in conjunction with geographic information systems and soil chemical analysis to better understand the agricultural landscape surrounding the ancient Maya city of Uci. Specifically the query of this research project was to determine whether there was an association between settlement density and soil resources, and what relationship if any there was between the ancient sacbe of Uci and its surrounding agricultural potential. This determination depends upon several factors including soil fertility, workability, drainage and depth (Beach, 1998a; Fedick, 1995; Sweetwood et al., 2009).

This study will determine the taxonomy and investigate the soil resources of the region surrounding Uci as well as karst depressions known as rejolladas through classification, fertility and vegetative history as reflected through stable carbon isotopes. We will examine the soil characteristics of the sample sites along the causeway while investigating the stable carbon isotope record where viable depending upon soil depth. Soil fertility will be assessed in this area by soil depth, drainage, stoniness, texture, pH and extractable nutrients P, K, and Ca. Assessing plant nutrients and soil fertility may offer some additional insight into the agronomic potential of the soil

Methods and Materials

For the scope of this study the Uci project was grouped into 3 categories or sampling schemes. Through the use of GIS maps, sampling areas and systematic sampling schemes were developed in order to sample representative areas of the general karst soil formations along the causeway, and also in and near the rejolladas. The grid sampling scheme surrounding the 21 de Abril site (Figure 1) along the causeway was constructed as a series of 46 profiles each being an equidistant 300 m from its surrounding points, setting up potential for the extrapolation of the results through a model to a wider range of the site area (Balzotti, 2010).

The first sample group consists of a grid with a North South orientation and 7 rows labeled A through G. Rows A, C, E, and G have seven samples each labeled A1 to A7 and so on for all rows. Rows B, D, and F include only 6 samples in each row and all samples in the grid are referred to by row letter and number from West to East. This study area, size and location were chosen for several reasons. The approximate center of the sampling grid was a small archeological site adjacent the sacbe (Figure 1). Since the center of the sampling grid was a point of known habitation along the sacbe, soil resources can be associated with rural habitations. Extending from this center it was possible to sample some areas that were in current agricultural use and several that were considered to be in natural or as close to natural surrounding vegetation and ground cover as possible. Since the archeological site of Uci is a currently inhabited town undisturbed areas of natural vegetation are fairly scarce. The area has been under grazing and agriculture for hundreds of years including henequen plantation as early as the late 1700's up until the present. The size of the sampling grid and distance between points was assessed with the hope of sampling several possible locations for ancient agriculture extending from the sacbe.

Along with the map view and GPS points we were able to find the sampling locations and dig profiles for analysis.

The second sampling group parallel to the ancient sacbe or road, and bisects the sampling grid from Southwest to Northeast. These points were previously surveyed in 2009, and GPS locations were used to identify sample locations approximately 300 m apart along the sacbe extending from the original sampling grid both to the East and West. The samples in this group were taken in the same manner as the samples from the grid, by digging soil pits to the bedrock and then taking a sample every 15 cm from the surface to bedrock. This sampling group was designated to provide further knowledge of the land use adjacent the sacbe and to identify any correlations between settlement density, the sacbe and agriculture (Figure 2).

The third sampling group concentrated on the soil resources of three rejolladas at the site center of Uci. These rejollada depressions within the present town of Uci. One sample came from rejollada one. From the second two rejolladas three profiles each were collected for a total of seven profiles from rejolladas. These seven profiles were opportunistically sampled from various slopes and aspects within the depressions (Figure 3).

Methods of Analysis

Physical Characterization

All samples were air dried before analysis. Both dry and moist Munsell color along with soil structure and consistence were recorded. Gravel and rock were removed and soil aggregates were crushed by mortar and pestle to pass a 2 mm sieve in preparation for physical and chemical analyses. The soil textural class was determined for each master horizon using the hydrometer method (Gee and Bauder, 1986). Slope values and aspect were derived from *in situ* data since the DEM and Landsat images revealed little variation in the relatively planar landscape. The land use capability classes were determined according to USDA land use capability class criteria. The major impediment to land use capability class was soil depth except in the rejolladas. Diagnostic horizons were assigned and USDA taxonomic classifications were determined for each profile (Soil Survey Staff, 2006).

Analysis of Chemical Properties

The pH of each surface horizon was measured in a 1:1 soil to water mixture by glass electrode. The extractable P and K levels for each surface horizon were determined using the Olsen sodium bicarbonate extraction (Olsen and Sommers, 1982). The total C and total N contents of each master horizon were determined by the use of dry combustion using a Leco elemental analyzer (Dallas, TX). The calcium carbonate equivalents (CCE) of the master horizons were measured by back titration of samples treated with an excess of hydrochloric acid (Soil Salinity Staff, 1954). The organic C content of each master horizon were determined by subtracting the carbonate-C percentage from the total C values.

Soil profiles that were at least 45 cm deep provided 3 horizon samples and allowed carbon isotope analysis. Each of these samples were sub-sampled and further ground with mortar and pestle to pass a #60 mesh, (250 μm) sieve in preparation for isotope analysis. Two grams of sample were acidified with 1 M HCl and heated in a water bath to 70° C for at least 2 hours to remove calcium and magnesium carbonates. The humic and fulvic acids were removed by alkaline pyrophosphate extraction (Webb et al., 2007; Webb et al., 2004; Wright et al., 2009) and stable carbon isotope ratios ($^{13}C/^{12}C$) of the humin fraction were determined on a Thermo Finnigan isotope ratio mass spectrometer (Waltham, MA) coupled with a Costech elemental analyzer (EAIRMS).

Results and Discussion

21 de Abril gridded profiles and sacbe soils

The configuration of the equidistant grid used in the sampling of soils surrounding the sacbe and the 21 of Abril site is an improvement upon square grid sampling schemes. The gridded profiles and the sacbe profiles totaled 55. Surface horizons of all but two of the 21 de Abril profiles were clay texture (452 to 745 g/kg clay); the remaining two were clay loam (Table 1 and 2; 343 and 410 g/kg clay). It is important to note that many of the surface horizons, especially those sampled along the sacbe and within the sampling grid, were high in gravel (49to 650 g/kg gravel), further limiting the capability of these soils. The land use capability class of the soils of the area ranged from II to VII. A few unique profiles from along the sacbe and sample grid fall under the land use capability class of II and III, limited by some stoniness and small area between poorer land use classes. Many of the profiles fall under class V due to very little erosion potential but extremely shallow soil depth. A majority of soils on the relatively flat Northern plain have little to no slope or aspect.

Uci rejollada profiles

The samples taken from within the concaved rejolladas exhibited hill slope positions and aspects. Within rejollada 3, three sequential profiles were taken with the first profile located at the toeslope within the rejollada, the second profile on the backslope and the third on the shoulder. The other profiles sampled from rejolladas were from toeslopes and footslopes. The toeslopes and footslopes of the rejolladas encompass a relatively small area of about 2 ha and the soils were classified in the land use capability class II. These rejollada soils are inhibited by high clay in the surface (481 to 745 g/kg clay) which can cause them to be sticky in the wet season and extremely hard in the dry season.

In this region, soil depth is an important agricultural resource especially with regards to maize since an unimpeded, healthy maize root system will grow 1 meter laterally and up to 2 meters in depth (Feldman, 1994). The greater volume of soil in the deeper pedons provides enhanced rooting depth and additional availability of plant nutrients and soil moisture. Over all the agricultural yields of the region are limited by low levels of macro nutrients N, P and K (Beach, 1998a; Dahlin, 2003; Dahlin et al., 2005). Even though a large portion (30-50%) of the tree species of the scrub forests of the northern Yucatan are legumes and maintain a low C/N ratio. Of the deeper profiles characterized as Argiustolls, total nitrogen was generally between 1 and 11 g/kg which would quickly become a limiting nutrient under agricultural conditions. Surface horizon concentrations of potassium and phosphorus were compared to general fertility recommendations in (Havlin et al., 2005; Tables 9-13, 9-14, and 9-16). Phosphorus ranged from

0.2 to 23.3 mg/kg (Tables 1, 2, 3, and 4) and was considered limited in many profiles and sufficient in some profiles containing higher concentrations. Potassium ranged from 1 to 278 mg/kg (Tables 1, 2, 3, and 4) with a majority of the profiles considered to be marginal when compared to the general soil fertility recommendations. The pH of the soils across the study area were fairly consistent and ranged from slightly alkaline at 7.99 to slightly acidic at 6.65 (Tables 1, 2, 3, and 4). The Calcium Carbonate Equivalents (CCE) varied widely from as low as 4.7 g/kg to as high as 735 g/kg (Tables 1, 2, 3, and 4). This was typical of soils from the Yucatan Peninsula, and most likely correlates to high cation exchange capacity and base saturation which are also characteristic of Yucatan soils (Johnson et al., 2007a; Johnson et al., 2007b). Another cause of the variability in the CCE of soils at Uci was possibly linked to occupied areas and unoccupied areas. Ancient Maya activities of construction involved limestone and lime stucco that have broken up with weathering and been incorporated into the soil. Soils on ancient residential patios and structures generally contain higher $CaCO_3$ equivalents than unoccupied areas (Solleiro-Rebolledo et al., 2011; Sweetwood et al., 2009).

Outside of the three rejolladas at the site center, the homogeneity of the surface elevation, minimal slope, and shallow soil depth limited the feasibility of modeling soil resources and ancient maize agriculture potential. Another complicating factor in affirmatively delineating ancient maize agriculture was the mix of C_3 and C_4 natural vegetation and colonial CAM photosynthetic henequen agriculture, in the study area, which makes it very difficult to affirmatively associate ancient maize cultivation with a sample site.

Mollisols is the dominant soil order of Uci area with a majority of soil profiles falling under the Argiustolls and Haplustolls great groups. A smaller number of profiles fall under the Entisols soil order and Ustorthents suborder and great group. All profiles where stable carbon 13 isotope ratios indicated ancient maize agriculture are Argiustolls. Other than depth and relatively dark soil color (7.5YR3/3 and darker), no other physical or chemical soil characteristics were unique to these profiles (Tables 1 & 2).

Carbon Isotopes

Carbon isotope ratios ($^{13}C/^{12}C$) of the humin fraction were analyzed from only 20 of the total 68 profiles sampled in the study due to insufficient soil depth. Only profiles greater than 30 cm deep allowed collection of three horizon samples for the observation of changes in $\delta^{13}C$ from the surface soil to soil at depth. Fifty five profiles were sampled from the grid surrounding the 21 de Abril archeological excavations and along the sacbe, but only 8 profiles reached a depth of greater than 30cm and none over 45cm. Of these 8 profiles the average surface $\delta^{13}C$ was -25.13‰, indicative of C_3 vegetation dominance with a slight shift toward C_4 plants probably due to some native C_4 grasses (Figure 4, Tables 1 and 2).

Profile D4 located immediately southeast and less than 300 m from the 21 de Abril excavations and on the south side of the sacbe, was the only profile exhibiting a strong shift in isotopic signature throughout the profile (Figure 5). At the surface the δ13C was -25.34‰ and became less negative at -20.37‰ at the 15 to 30cm depth. This indicated of a vegetation shift from possible ancient maize agriculture returning back to the native C_3 vegetation signature at the surface. A notable feature of this 45-cm deep profile was the isotopic shift toward C_4 soil humus in the middle of the profile and the C_3 humus at the bottom and the surface of the profile. (Webb et al., 2004) explained the distributions of C_4 and C_3 derived soil humus throughout shallow profiles. A majority of ^{13}C enriched soil humus from C_4 plants (maize) was originally deposited in the top 10cm of soil. During and after the cessation of cultivation, bioturbation and water percolation would cause the C_4 plant signal to migrate downward in the profile and the ensuing return to native C_3 vegetation would further add to the depleted ^{13}C signature in the overlying surface. Burnett et al. (2012a and 2012b) reviewed the literature that demonstrated that much of the soil carbon from maize resulted from rhizo-deposition of root exudates. However, it is also important to note the colonial period cultivation of CAM henequen within the bounds of the study area. This fact coupled with the existence of several native C_4 grasses makes it near impossible to affirm that maize was uniquely responsible for shifts in the stable carbon isotope ratios of these soils. As well, many of the profiles in this study were unique with regards to whether they have been cultivated with maize in modern times, been buried by structures in ancient times or allowed to return to native forest vegetation since ancient cultivation took place. It is therefore necessary to evaluate each sample in its context and not necessarily apply the general rule of an isotopic change of 4‰ to indicate whether ancient maize was likely present or not (Agren et al., 1996).

Carbon isotope ratios ($^{13}C/^{12}C$) of the humin fraction were analyzed from 20 of the 68 profiles that possessed sufficient soil depth to observe changes in $\delta^{13}C$ from the surface soil to soil at depth. Within the three rejolladas, six of the seven profiles were evaluated for change in $\delta^{13}C$ with depth. Rejollada 2 profile 2 was not evaluated for carbon isotopes due to shallow soil depth. Three of six rejollada profiles, demonstrated some evidence of maize agriculture (Table 3). These profiles, however, do not necessarily show a shift in vegetation type from ancient C_4 plants back to C_3 in contemporary times. Rather, throughout the profile the isotopic evidence demonstrates a vegetative history of C_4 plants being grown continuously with no significant sustained changes in vegetation from ancient times until the present as evidenced by both the $\delta^{13}C$ ratios and the observed modern maize crops.

The rejolladas are located adjacent to each other and immediately adjacent the two main site center pyramids. Within rejollada 1 only one profile was sampled and analyzed (R1P1). This sample only demonstrated a $\delta^{13}C$ shift of 1.6‰ which does not suggest a major change in vegetation type throughout the vegetative history (Figure 6). However the $\delta^{13}C$ ratio at the surface was -21.2‰ and became only slightly more negative at -22.8‰ which was indicative of strong C_4 vegetation mixed with some C_3 plants (Figure 6).

Rejollada 2 was the largest of the three karst depressions and the location where modern maize cultivation was observed. Within this rejollada profiles one and three were analyzed and found to have similar isotopic results as the profile from rejollada 1. Profile R2P1 had a $\delta^{13}C$ at the surface of -19.8‰ and shifted only 1.6‰ to -21.4‰ at depth. Profile R2P3 had a $\delta^{13}C$ of -21.6‰ at the surface and was slightly more ^{13}C enriched to -20.7‰ at depth (Figure 6, Table 3). Isotope ratios in each of these profiles demonstrated no major shift in vegetation type within this rejollada but indicated that C_4 plants (likely maize agriculture) have been the dominant contributors of soil humus for a long period of time.

Three profiles were sampled from rejollada 3 which was the smallest of the three depressions. Profile R3P1was taken from the toeslope of the rejollada, R3P2 was collected from the gradually inclined backslope and R3P3 was collected from the shoulder slope on the ruins of and ancient platform. Profile R3P1 had a $\delta^{13}C$ at the surface of -26.8‰ and a less negative ratio of -24.3‰ and the bottom of the profile. Profile R3P2 had a $\delta^{13}C$ of -25.9‰ at the surface and shifted only 1.4‰ to -24.5‰ at depth. Profile R3P3 contained the largest isotopic shift of 2.6‰ going from -25.4‰ to -22.8‰ at depth. This shift in $\delta^{13}C$ provides weak only evidence of maize agriculture within this profile (Figure 7, Table 3). All three of these profiles from rejollada 3 indicate a long standing mixture of C_3/C_4 plants with native C_3 plants representing the bulk of the soil humus additions.

Geographically, the profiles where possible evidence of ancient maize agriculture was found were located near the Uci site center in the rejolladas and also near structures and one near the sacbe extending toward the secondary sites of Ukana and Kancab (Figure 1). Even though positive results for ancient maize agriculture were only found in 3 of 62 surface profiles and 3 of 6 profiles taken from beneath structures, these findings support the hypothesis that settlement density was linked to soil resources. This theory was especially supported by the Uci site centers location immediately adjacent to the rejolladas which were the largest contiguous area of desirable agricultural soil. These profiles were of special interest due to their unique characteristic of having much deeper soils and moisture holding capacity than the surrounding areas which likely provided a critical agronomic resource for the ancient Maya. Ancient wells were located in rejolladas 2 and 3. This could be an additional reason for the Uci site center being located adjacent the rejolladas. These wells may have been used as a culinary water source as well as irrigation water for maize crops grown in the rejolladas. Since the northern Yucatan is comprised mainly of shallow soils, and an ustic moisture regime, rejolladas may have been a key feature for the ancient Maya when constructing site centers. In addition to their increased soil depth it was anticipated that these rejolladas would also exhibit buried horizons and layers of deposition which would allow for study of erosion histories. However, erosion histories were not present to offer insights into the effects of ancient and modern settlement and agriculture (Sedov et al., 2008).

Concerning the 6 samples taken from beneath structures, all were deeper than the average soil of the surrounding area not including the rejolladas. These structures and profiles were located to the east of Uci at the other end of the sacbe at the archeological site of Kancab. Half of these buried soils exhibited evidence that ancient maize agriculture existed at those locations before construction of the overlying structure. Each of the three profiles that show evidence of ancient agriculture (TB10. TB16, TB22) exhibit a ^{13}C ratio of approximately -22.5‰ suggesting strong C_4 plant carbon input at the buried surface horizon (Table 4). With depth, the isotopic ratio of all six profiles migrates to approximately -25 ‰ and the three profiles that do not show evidence of ancient agriculture (TB1, TB6, TB13) all have an isotopic ratio of nearly -26‰ suggesting strong to almost exclusive C_3 carbon input (Figures 8 & 9). Since these soils were covered by ancient stone structures they were shielded against some of the main forces of downward soil humus migration such as bioturbation and water percolation. This was precisely why the isotopic signature for C_4 plants was still at the ancient soil surface of profiles TB10, TB16 and TB22, and has remained there since the time of construction. It was not clear however, why the ancient Maya would have taken a portion of the optimal soils of the area to build on and decrease the availability of good agricultural soil, but it may have been for the same reason that present urbanization encroaches upon and consumes agricultural lands.

Many of the soils surrounding Uci were dark in color with values that ranged from 3 to 1 (Tables 1, 2, 3 and 4). There is some thought that the ancient Maya amended their soils with black carbon in order to increase fertility (Sweetwood et al., 2009). Black carbon is a byproduct of incomplete combustion (Brodowski et al., 2005) and is made up of mostly aromatic C (Schmidt et al., 2001) that resists chemical and microbial decomposition (Dai et al., 2005; Glaser et al., 2000; Glaser et al., 2001; Taylor et al., 1998.). The decomposition and accumulation of BC is linked to levels of SOM, climate, textural properties, and soil moisture (Glaser et al., 2000). Black carbon increases soil fertility by enhancing the soils capacity to hold nutrients (Glaser et al., 2000; Glaser et al., 2001). The process of amending soils with black carbon in ancient South America has most notably been observed in the terra preta soils of the Amazon where the natural un-amended soils of the Amazon Basin are nutrient poor and light in color (Glaser et al., 2001).

At Chunchucmil, Yucatan, approximately 82 mi to the south and west of Uci, black carbon amendments and accumulations were studied (Sweetwood et al., 2009). They reported that BC concentrations decreased from profiles located on house mounds and patios to undeveloped areas. The highest concentrations of BC in dark soils at Chunchucmil were at least one order of magnitude lower than average levels reported in the Amazonian Terra Preta soils (Sweetwood et al., 2009). The relative uniformity of BC concentrations within unoccupied areas of Chunchucmil suggests that the largest source of natural BC has been the intermittent wild and milpa fires (Sweetwood et al., 2009). The darker color of *Boxlu'um* soils classified under the Maya classification system described at Chunchucmil, were most likely a result of higher retention of SOM associated with neutral pH and Ca ions rather than a result of soil amendment with BC (Sweetwood et al., 2009).

The soils collected from the north western transects from Chunchucmil exhibit very similar characteristics to those of Uci, as both areas are located on the Northern karst plain. The darker *boxlu'um* soils of Chunchucmil where no evidence of BC soil amendment was observed were nearly identical to the Argiustolls and Haplustolls soils of Uci in depth, color, texture and SOM content. It is likely that what little BC was present in the soils at Uci was a result of wild fires, burning of milpas and burning of the native scrub to clear land for cattle grazing and other agricultural needs such as henequen plantations. Due to the generally acceptable nutrient levels, high pH and $CaCO_3$ of the dark mollic epipedons of the soils of Uci, and the negative results of BC enrichment at the near-by site of Chunchucmil in similar soils, it is not likely that the ancient Maya purposely amended the soils surrounding Uci with charcoal.

Two correlation matrixes were analyzed using Jump statistical software in order to identify relationships and unique soil characteristics among the various profiles sampled (Tables 5 and 6). Table 5 is a correlation matrix which includes results from all profiles analyzed in the study and shows significance with regards to soil depth related to plant nutrients P, K and N as well as CCE levels. Table 6 is the same matrix but with the results from the rejolladas and buried profiles removed. Excluding the results of the deeper soil profiles from the rejolladas and the buried profiles there appears to be no significant or unique correlations in the surrounding landscape of relatively shallow soils. This further cements the fact that the deeper soils such as those found in the rejolladas and beneath structures at Kancab were an important agricultural resource relative to the surrounding shallow soils of the Uci area. The significance of CCE being related to the deeper soils of the rejolladas and the deeper profiles below structures is most likely two fold. First, surface and ground water flow through preferential flow channels with accumulated amounts of dissolved $CaCO_3$ from the surrounding bedrock and gathers in the karst depressions where evapotranspiration leaves the $CaCO_3$ behind. Second these areas of deeper soils were also related to settlements and human activity where construction with limestone and burnt lime stuccos were used and have since deteriorated into the soil. Examples of shallow soil profiles from the 21 of Abril sampling grid and a deeper profile R2P1 from the rejolladas can be seen in Figures 10, 11, and 12.

Conclusion

A thorough survey of the soil resources of the archeological site of Uci has revealed an extremely difficult setting in which to grow crops and thrive. It is not likely that the location of this site was chosen by the ancient Maya based on soil resources or the agricultural potential of the soil. The area is comprised of shallow clayey soils, variable rains, seasonal flooding and dry seasons, all of which would not have been conducive to large healthy populations. The rejolladas near the site center did offer enhanced fertility due to the increase in soil depth and the potential for increased surface water accumulation. However the total area (2.6 ha) and size of the rejolladas would not have been sufficient to fulfill all of the agricultural needs of a large population.

The stable C isotope evidence of the SOM from the profiles collected in this project along with the data gathered at the site about contemporary farming practices indicate that the ancient as well as the modern peoples of this area follow similar practices and deal with many of the same difficulties. Isotope evidence indicated that the rejolladas were at least in part used for the cultivation of maize as they are today (Figures 6 & 7). As well at least one profile from along the sacbe showed stable C isotope evidence of a vegetation shift from C_3 ancient forest scrub to C_4 and back again to natural contemporary C_3 vegetation (Figure 5). This was consistent with the observed small and often poorly yielding milpas scattered sparsely throughout the surrounding areas.

The site of Uci may be the perfect example that agricultural potential and actual use are not always synonymous. The decisions of land-use are rarely founded on strictly one factor, and soil fertility or depth may not be the only, or the most important variable indicating ancient agriculture (Wright, 2007). Several factors including political mandate, proximity to resources, history, or tradition may have all played a large role in the decisions to cultivate an area or to construct on an area once used for agriculture as the evidence from the samples taken near Kancab indicate. A major question at the heart of this study was whether or not there was an association between settlement density and soil resources. This question can be answered affirmatively due to the location of the Uci site center being immediately adjacent to the rejolladas which offer the highest agricultural soil potential of the immediate area. However, as discussed and demonstrated in the results and discussion of this study, other areas less suitable for maize agriculture may have also been cultivated. With poor maize yields, atypical crops such as arboriculture (Ross, 2011), game, or traded perishables from other nearby sites reasonably supplemented the Uci Maya diet, which would have also been a probable use for the prominent sacbe linking Uci with Kancab, Ukana and Cansahcab. It likely took a combination of all available resources to sustain the people of Uci since nearly all food sources and even trade would have been susceptible to the effects of poor soil, harsh climate and disastrous flooding and drought.

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Table 1. Physical and chemical properties of 46 profiles sampled at the 21 de Abril site near Uci.

Soil Profile Taxonomic Subgroup	Depth	Horizon	Structure Grade, Size, Type	Consistence Dry	Soil Color Dry	Texture Clay	Texture Class	Slope	Slope Hillslope	pH	Olsen extraction P	Olsen extraction K	Total N	Total C	Organic C	CCE	$\delta^{13}C$	Change in $\delta^{13}C$	UTM Zone 16S East	UTM Zone 16S North
	cm					g/kg		%			mg/kg	mg/kg	g/kg	g/kg	g/kg	g/kg	------ ‰ ------		m	m
A1	0	A	1,F,GR	L	7.5YR3/4	482	clay	0-2%	TS	7.6	3.3	12.8	13.0	214	203	96			267701	2339511
Haplustolls																				
A2	0	A	1,F,GR	L	7.5YR3/3	506	clay	0-2%	TS	7.7	3.9	3.8	9.4	199	171	230			268034	2339510
A2	15	C/R			7.5YR5/3	505	clay													
Ustorthents																				
A3	0	A	2,M,SBK	SH	7.5YR3/2	410	CL	0-2%	TS	7.6	3.6	67.8	13.9	304	267	306			268366	2339508
A3	15	Bw/R			7.5YR3/2	544	clay													
Argiustolls																				
A4	0	A	1,M,GR	SH	7.5YR3/1	461	clay	0-2%	TS	7.8	2.3	67.2	12.1	251	223	237			268699	2339511
Haplustolls																				
A5	0	A	1,M,GR	SH	7.5YR4/4	579	clay	0-2%	TS	7.8	2.1	43.8	11.3	184	180	34			269030	2339508
A5	15	C/R			7.5YR4/6	581	clay													
Ustorthents																				
A6	0	A	2,M,GR	SH	7.5YR3/2	481	clay	0-2%	TS	7.7	10.9	58.6	14.0	264	249	126	-25.79	-2.00	269366	2339511
A6	15	AB			7.5YR3/1	556	clay										-23.79			
A6	30	Btw/R			7.5YR4/3	638	clay										-24.78			
Argiustolls																				
A7	0	A	2,F,GR	SH	7.5YR4/4	589	clay	0-2%	TS	7.8	6.0	36.2	7.5	133	126	60	-23.96	-0.58	269696	2339507
A7	15	Btw			7.5YR4/4	664	clay										-23.77			
A7	30	C/R			7.5YR4/6	639	clay										-24.35			
Argiustolls																				
B1	0	A	2,F,GR	SH	7.5YR3/3	465	clay	0-2%	TS	7.8	3.4	38.4	20.0	243	226	138			267865	2339222
Haplustolls																				
B2	0	A	1,F,GR	L	7.5YR4/4	625	clay	0-2%	TS	7.8	2.6	173.8	9.4	183	156	224			268198	2339222
Haplustolls																				
B3	0	A	2,M,SBK	MH	7.5YR3/3	593	clay	0-2%	TS	7.9	2.2	36.8	9.3	207	194	112			268530	2339222
Haplustolls																				
B4	0	A	2,M,SBK	MH	7.5YR4/2	615	clay	0-2%	TS	8.0	3.6	37.1	7.5	180	145	290			268863	2339224
B4	15	C/R			7.5YR4/2	595	clay													
Ustorthents																				
B5	0	A	1,F,GR	L	7.5YR4/2	600	clay	0-2%	TS	8.0	3.9	34.2	7.4	201	154	390			269196	2339222
B5	15	Aw/R			7.5YR3/3	595	clay													
Ustorthents																				
B6	0	A	1,F,GR	SH	7.5YR2.5/2	532	clay	0-2%	TS	7.9	1.9	55.4	10.2	231	194	312			269530	2339222
Haplustolls																				

Table 1. (continued) Physical and chemical properties of 46 profiles sampled at the 21 de Abril site near Uci.

Soil Profile			Structure	Consistence	Soil Color	Texture		Slope			Olsen extraction		Total	Total	Organic			Change in	UTM Zone 16S	
Taxonomic Subgroup	Depth	Horizon	Grade, Size, Type	Dry	Dry	Clay	Class		Hillslope	pH	P	K	N	C	C	CCE	$\delta^{13}C$	$\delta^{13}C$	East	North
	cm					g/kg		%			mg/kg	mg/kg	g/kg	g/kg	g/kg	g/kg	------ ‰ ------		m	m
C1	0	A	2,F,GR	SH	7.5YR3/1	576	clay	0-2%	TS	7.5	8.5	163.5	13.9	233	230	28			267703	2338929
Haplustolls																				
C2	0	A	2,F,GR	SH	7.5YR3/3	674	clay	0-2%	TS	7.5	5.4	70.4	7.5	132	128	36			268034	2338932
C2	15	C/R			7.5YR4/4	650	clay													
Ustorthents																				
C3	0	A	2,M,GR	SH	7.5YR2.5/2	574	clay	0-2%	TS	7.5	5.0	59.8	13.4	238	228	81			268366	2338931
C3	15	Bw/R			7.5YR3/1	575	clay													
Argiustolls																				
C4	0	A	1,F,GR	L	7.5YR4/6	657	clay	0-2%	TS	7.8	3.9	11.5	8.4	125	120	40			268698	2338931
C4	15	A/R			7.5YR4/6	653	clay													
Haplustolls																				
C5	0	A	2,CO,SBK	MH	7.5YR4/2	553	clay	0-2%	TS	7.9	2.1	81.0	10.5	233	198	293	-24.04	-0.74	269030	2338932
C5	15	AE			7.5YR4/3	528	clay										-23.78			
C5	30	Bt/R			7.5YR5/2	576	clay										-24.78			
Argiustolls																				
C6	0	A/R	2,M,SBK	MH	7.5YR3/2	587	clay	0-2%	TS	7.8	1.7	82.9	13.7	261	243	154			269365	2338934
Haplustolls																				
C7	0	A	2,M,SBK	MH	7.5YR4/2	531	clay	0-2%	TS	7.8	3.3	34.9	11.2	207	189	146	-25.34	-0.65	269696	2338932
C7	15	Bt			7.5YR4/2	607	clay										-24.99			
C7	30	BC/R			7.5YR4/2	568	clay										-24.69			
Argiustolls																				
D1	0	A	1,F,GR	SH	7.5YR3/4	671	clay	0-2%	TS	7.9	3.7	40.0	8.1	130	115	125			267866	2338643
Haplustolls																				
D2	0	A	1,F,GR	SH	7.5YR2.5/2	423	clay	0-2%	TS	7.8	3.4	44.2	11.7	271	228	362			258199	2338643
D2	15	AB/R			7.5YR3/2	473	clay													
Argiustolls																				
D3	0	A	2,M,SBK	MH	7.5YR3/2	527	clay	0-2%	TS	7.9	1.7	46.4	8.9	225	168	472			268531	2338643
D3	15	B/R			7.5YR2.5/1	603	clay													
Argiustolls																				
D4	0	A	2,M,SBK	MH	7.5YR2.5/1	602	clay	0-2%	TS	7.8	2.6	36.2	10.6	218	191	228	-25.34	-4.96	268863	2338643
D4	15	BC			7.5YR4/1	672	clay										-20.37			
D4	30	C/R			7.5YR2.5/1	622	clay										-25.19			
Argiustolls																				
D5	0	A	2,M,GR	SH	7.5YR3/2	501	clay	0-2%	TS	7.6	4.8	92.2	12.6	237	212	207			269196	2338644
Haplustolls																				
D6	0	A	2,M,SBK	MH	7.5YR3/2	524	clay	0-2%	TS	7.7	2.9	40.3	12.7	237	223	113			269529	2338641
Haplustolls																				

Table 1. (continued) Physical and chemical properties of 46 profiles sampled at the 21 de Abril site near Uci.

Soil Profile			Structure	Consistence	Soil Color	Texture		Slope			Olsen extraction		Total	Total	Organic			Change in	UTM Zone 16S	
Taxonomic Subgroup	Depth	Horizon	Grade, Size, Type	Dry	Dry	Clay	Class		Hillslope	pH	P	K	N	C	C	CCE	$\delta^{13}C$	$\delta^{13}C$	East	North
	cm					g/kg		%			mg/kg	mg/kg	g/kg	g/kg	g/kg	g/kg	------ ‰ ------		m	m
E1	0	A	1,F,GR	SH	7.5YR4/4	456	clay	0-2%	TS	7.8	2.2	17.6	7.8	220	170	417			267705	2338352
Haplustolls																				
E2	0	A	1,F,GR	L	7.5YR4/4	647	clay	0-2%	TS	7.9	1.0	46.7	7.3	116	111	41	-25.17	-0.72	268033	2338353
E2	15	AB			7.5YR4/6	721	clay										-24.45			
E2	30	Btw/R			7.5YR4/6	742	clay										-24.85			
Argiustolls																				
E3	0	A	2,M,SBK	MH	7.5YR3/1	593	clay	0-2%	TS	7.6	1.5	10.2	9.4	215	178	309			268365	2338353
E3	15	AB/R			7.5YR3/1	622	clay													
Argiustolls																				
E4	0	A	2,M,SBK	MH	7.5YR3/3	652	clay	0-2%	TS	7.8	3.9	6.7	9.7	156	153	26			268699	2338354
E4	15	Btw/R			7.5YR4/4	694	clay													
Argiustolls																				
E5	0	A	2,M,SBK	MH	7.5YR4/6	739	clay	0-2%	TS	7.8	0.2	9.6	7.5	115	114	11			269032	2338353
E5	15	A/R			7.5YR4/6	565	clay													
Haplustolls																				
E6	0	A	2,CO,SBK	H	7.5YR4/2	664	clay	0-2%	TS	7.6	3.2	30.1	10.3	248	203	376			269362	2338354
Haplustolls																				
E7	0	A	2,M,SBK	MH	7.5YR4/6	692	clay	0-2%	TS	7.5	4.6	6.1	7.6	126	119	56			269696	2338353
E7	15	A/R			7.5YR3/3	697	clay													
Haplustolls																				
F1	0	A	1,F,GR	SH	7.5YR3/2	653	clay	0-2%	TS	7.9	2.7	62.4	11.5	212	196	133			267866	2338065
Haplustolls																				
F2	0	A	2,F,GR	SH	7.5YR2/1	343	lay loa	0-2%	TS	7.5	3.2	278.1	19.5	374	349	211			268198	2338063
Haplustolls																				
F3	0	A	2,F,GR	SH	7.5YR3/2	534	clay	0-2%	TS	7.6	3.5	48.0	10.5	239	198	345	-26.22	-0.79	268531	2338063
F3	15	AB			7.5YR3/2	561	clay										-25.43			
F3	30	BC/R			7.5YR5/3	636	clay										-25.51			
Argiustolls																				
F4	0	A	2,CO,SBK	MH	7.5YR3/1	610	clay	0-2%	TS	7.5	2.0	44.2	10.4	179	171	68			268863	2338062
Haplustolls																				
F5	0	A	2,M,SBK	MH	7.5YR4/6	645	clay	0-2%	TS	7.8	1.5	41.0	9.4	151	147	35			269198	2338062
Haplustolls																				
F6	0	A	2,CO,SBK	H	7.5YR3/2	536	clay	0-2%	TS	7.8	4.5	99.5	12.9	241	227	121			269530	2338062
F6	15	Bt/R			7.5YR3/3	601	clay													
Argiustolls																				

Table 1. (continued) Physical and chemical properties of 46 profiles sampled at the 21 de Abril site near Uci.

Soil Profile			Structure	Consistence	Soil Color	Texture		Slope			Olsen extraction		Total	Total	Organic			Change in	UTM Zone 16S	
Taxonomic Subgroup	Depth	Horizon	Grade, Size, Type	Dry	Dry	Clay	Class		Hillslope	pH	P	K	N	C	C	CCE	$\delta^{13}C$	$\delta^{13}C$	East	North
	cm					g/kg		%			mg/kg	mg/kg	g/kg	g/kg	g/kg	g/kg	------ ‰ ------		m	m
G1	0	A	2,CO,SBK	MH	7.5YR4/6	626	clay	0-2%	TS	7.8	2.9	6.1	7.6	122	115	56			267701	2337777
G1	15	A/R			7.5YR4/6	628	clay													
Ustorthents																				
G2	0	A	2,M,SBK	MH	7.5YR4/6	652	clay	0-2%	TS	7.8	1.0	9.0	9.1	142	137	41			268031	2337777
G2	15	ABt/R			7.5YR4/6	684	clay													
Argiustolls																				
G3	0	A	2,M,GR	SH	7.5YR3/2	452	clay	0-2%	TS	7.7	3.0	145.3	14.0	299	285	113			268366	2337776
Haplustolls																				
G4	0	A	2,M,GR	SH	7.5YR2.5/2	562	clay	0-2%	TS	7.7	2.8	65.9	6.7	233	188	378			268699	2337777
G4	15	C/R			7.5YR4/3	539	clay													
Ustorthents																				
G5	0	A	2,M,SBK	MH	7.5YR4/4	613	clay	0-2%	TS	7.9	5.6	1.9	7.9	170	167	25			269031	2337776
G5	15	AC/R			7.5YR4/3	615	clay													
Ustorthents																				
G6	0	A	2,CO,SBK	MH	7.5YR3/4	649	clay	0-2%	TS	7.9	3.7	15.0	5.9	145	144	5			269364	2337776
G6	15	AB/R			7.5YR3/4	666	clay													
Argiustolls																				
G7	0	A	2,M,SBK	MH	7.5YR4/4	645	clay	0-2%	TS	7.8	5.2	31.4	7.0	162	158	37			269692	2337768
G7	15	AB/R			7.5YR4/4	710	clay													
Argiustolls																				

Texture	Structure Grade	Structure Size	Structure Type	Consistence	Slope Position		
CL = Clay Loam	0 = Structureless	VF = Very Fine	GR = Granular	L = Loose	SU = Summit	**$\delta^{13}C$†**	$\delta^{13}C$ of the surface horizon
	1 = Weak	F = Fine	ABK = Angular Blocky	SH = Slightly Hard	SH = Shoulder		
	2 = Moderate	M = Medium	SBK = Subangular Blocky	MH = Moderately Hard	BS = Backslope	**$\delta^{13}C$‡**	The change in $\delta^{13}C$ from surface horizon to a horizon at depth
	3 = Strong	CO = Coarse	PL = Platy	HA = Hard	FS = Footslope		
		VC = Very Coarse	SGR = Single Grain	VH = Very Hard	TS = Toeslope		
		TK = Thick	MA = Massive	EH = Extremely Hard		CCE = Calcium carbonate equivalent	

Table 2. Physical and chemical properties of 8 profiles sampled along the Uci Sacbe.

Soil Profile Taxonomic Subgroup	Depth	Horizon	Structure Grade, Size, Type	Consistence Dry	Soil Color Dry	Texture Clay	Texture Class	Slope	Slope Hillslope	pH	Olsen extraction P	Olsen extraction K	Total N	Total C	Organic C	CCE	$\delta^{13}C$	Change in $\delta^{13}C$	UTM Zone 16S East	UTM Zone 16S North
	cm					g/kg		%			mg/kg	mg/kg	g/kg	g/kg	g/kg	g/kg	------ ‰ ------		m	m
P22	0	A	2,CO,SBK		7.5YR2/1	711	clay	0-2%	TS	6.8	6.8	55.4	6.8	162	158	34			267199	2338219
P22	15	AC/R			7.5YR2/1	635	clay													
Ustorthents																				
P24	0	A	2,CO,SBK	MH	7.5YR3/2	635	clay	0-2%	TS	7.0	5.2	2.2	6.5	182	161	174			267384	2338288
Haplustolls																				
P26	0	A	2,M,SBK	SH	7.5YR4/3	691	clay	0-2%	TS	7.0	4.9	92.5	7.3	174	171	28			267575	2338358
P26	15	Bt			7.5YR3/3	739	clay													
P26	30	C/R			7.5YR4/3	659	clay													
Argiustolls																				
Sacbe P 1200	0	A	2,M,SBK	MH	7.5YR3/3	596	clay	0-2%	TS	7.0	3.4	93.4	7.7	184	180	37			266245	2337921
Sacbe P 1200	15	Bt/R			7.5YR3/4	733	clay													
Argiustolls																				
SACBE P 1600	0	A	2,M,SBK	SH	7.5YR3/3	633	clay	0-2%	TS	7.0	0.8	39.4	7.7	177	173	37			266626	2338039
Haplustolls																				
Sacbe P 1800	0	A	2,CO,SBK	MH	7.5YR3/4	657	clay	0-2%	TS	6.7	0.1	89.9	4.4	121	120	10	-25.66	-1.54	266819	2338095
Sacbe P 1800	15	A/B			7.5YR4/6	683	clay										-24.12			
Sacbe P 1800	30	Btw/R			7.5YR4/6	710	clay										-24.47			
Argiustolls																				
Sacbe P 200	0	A	2,CO,SBK	MH	7.5YR3/4	659	clay	0-2%	TS	6.7	1.1	32.3	5.7	138	134	35			265275	2337680
Sacbe P 200	15	Bt/R			7.5YR3/4	735	clay													
Argiustolls																				
Sacbe P 2000	0	A	2,CO,SBK	MH	7.5YR3/3	745	clay	0-2%	TS	6.8	0.9	20.8	4.3	111	108	28			267011	2338154
Sacbe P 2000	15	A/C/R			7.5YR3/3	688	clay													
Ustorthents																				
Sacbe P 900	0	A	2,CO,SBK	MH	7.5YR3/3	694	clay	0-2%	TS	7.1	3.2	23.7	6.6	172	167	38			265953	2337842
Sacbe P 900	15	A/R			7.5YR3/3	685	clay													
Haplustolls																				

Texture	Structure Grade	Structure Size	Structure Type	Consistence	Slope Position		
CL = Clay Loam	0 = Structureless	VF = Very Fine	GR = Granular	L = Loose	SU = Summit	**$\delta^{13}C$†**	$\delta^{13}C$ of the surface horizon
	1 = Weak	F = Fine	ABK = Angular Blocky	SH = Slightly Hard	SH = Shoulder		
	2 = Moderate	M = Medium	SBK = Subangular Blocky	MH = Moderately Hard	BS = Backslope	**$\delta^{13}C$‡**	The change in $\delta^{13}C$ from surface horizon to a horizon at depth
	3 = Strong	CO = Coarse	PL = Platy	HA = Hard	FS = Footslope		
		VC = Very Coarse	SGR = Single Grain	VH = Very Hard	TS = Toeslope		
		TK = Thick	MA = Massive	EH = Extremely Hard		CCE = Calcium carbonate equivalent	

Table 3. Physical and chemical properties of 7 profiles sampled from rejolladas near the Uci site center.

Soil Profile			Structure	Consistence	Soil Color	Texture		Slope			Olsen extraction		Total	Total	Organic			Change in	UTM Zone 16S	
Taxonomic Subgroup	Depth	Horizon	Grade, Size, Type	Dry	Dry	Clay	Class		Hillslope	pH	P	K	N	C	C	CCE	$\delta^{13}C$	$\delta^{13}C$	East	North
	cm					g/kg		%			mg/kg	mg/kg	g/kg	g/kg	g/kg	g/kg	------ ‰	------	m	m
Rejollada 1 P1	0	A	2,CO,SBK	MH	7.5YR3/3	735	clay	0-2%	TS	7.0	11.5	10.9	4.2	167	136	262	-21.24	-1.64	263897	2337301
Rejollada 1 P1	15	C			7.5YR4/2	694	clay										-22.22			
Rejollada 1 P1	30	C			7.5YR4/3	685	clay										-22.88			
Rejollada 1 P1	45	C/R			7.5YR4/2	633	clay										-22.76			
Ustorthents																				
Rejollada 2 P1	0	A	2,CO,SBK	MH	7.5YR5/3	657	clay	0-2%	TS	7.1	23.3	221.4	1.3	172	111	509	-19.78	-1.62	263978	2337411
Rejollada 2 P1	15	AB			7.5YR5/4	683	clay										-21.40			
Rejollada 2 P1	30	Btw/R			7.5YR4/3	710	clay										-20.69			
Argiustolls																				
Rejollada 2 P2	0	A	2,M,SBK	SH	7.5YR3/3	745	clay	0-2%	TS	7.2	12.8	35.2	2.3	158	117	346			263980	2337410
Rejollada 2 P2	15	C/R			7.5YR4/3	688	clay													
Ustorthents																				
Rejollada 2 P3	0	A1	2,M,SBK	SH	7.5YR3/3	688	clay	0-2%	TS	7.1	9.9	46.7	4.1	151	128	190	-21.62	-0.88	264029	2337495
Rejollada 2 P3	15	AE			7.5YR4/3	596	clay										-21.22			
Rejollada 2 P3	30	B			7.5YR4/3	721	clay										-20.80			
Rejollada 2 P3	45	BC			7.5YR5/4	721	clay										-21.27			
Rejollada 2 P3	60	C/R			7.5YR4/6	699	clay										-20.74			
Argiustolls																				
Rejollada 3 P1	0	A	2,M,SBK	SH	7.5YR3/2	574	clay	0-2%	TS	7.0	16.9	309.8	2.9	204	155	411	-26.79	-2.27	264021	2337322
Rejollada 3 P1	15	AE			7.5YR4/2	482	clay										-25.04			
Rejollada 3 P1	30	EB			7.5YR4/2	629	clay										-24.91			
Rejollada 3 P1	45	B1			7.5YR4/2	660	clay										-24.77			
Rejollada 3 P1	60	B2			7.5YR4/2	628	clay										-24.52			
Rejollada 3 P1	75	Bt/R			7.5YR4/4	703	clay										-24.30			
Argiustolls																				
Rejollada 3 P2	0	A	2,CO,SBK	MH	7.5YR4/2	481	clay	3%	FS	7.1	12.3	146.2	2.1	221	136	708	-25.90	-1.36	264031	2337327
Rejollada 3 P2	15	AB			7.5YR4/2	515	clay										-24.59			
Rejollada 3 P2	30	BwC			7.5YR4/2	477	clay										-25.29			
Rejollada 3 P2	45	C			7.5YR5/2	463	clay										-24.54			
Rejollada 3 P2	60	C			7.5YR5/3	488	clay										-24.55			
Rejollada 3 P2	75	C/R			7.5YR5/4	539	clay										-24.63			
Argiustolls																				

Table 3. (continued) Physical and chemical properties of 7 profiles sampled from rejolladas near the Uci site center.

Soil Profile Taxonomic Subgroup	Depth	Horizon	Structure Grade, Size, Type	Consistence Dry	Soil Color Dry	Texture Clay	Texture Class	Slope	Hillslope	pH	Olsen extraction P	Olsen extraction K	Total N	Total C	Organic C	CCE	$\delta^{13}C$	Change in $\delta^{13}C$	UTM Zone 16S East	UTM Zone 16S North
	cm					g/kg		%			mg/kg	mg/kg	g/kg	g/kg	g/kg	g/kg	------ ‰ ------		m	m
Rejollada 3 P3	0	A1	2,VC,SBK	HA	7.5YR3/2	492	clay	3%	SH	7.1	8.3	199.4	3.0	235	147	735	-24.64	-1.42	264042	2337334
Rejollada 3 P3	7	A2			7.5YR 3/3	670	clay										-25.44			
Rejollada 3 P3	15	ABt			7.5YR4/2	546	clay										-24.70			
Rejollada 3 P3	30	BC			7.5YR4/2	516	clay										-24.02			
Rejollada 3 P3	45	C			7.5YR5/2	354	CL										-24.18			
Rejollada 3 P3	60	C/R			7.5YR5/2	405	CL													
Argiustolls																				

Texture
CL = Clay Loam

Structure Grade
0 = Structureless
1 = Weak
2 = Moderate
3 = Strong

Structure Size
VF = Very Fine
F = Fine
M = Medium
CO = Coarse
VC = Very Coarse
TK = Thick

Structure Type
GR = Granular
ABK = Angular Blocky
SBK = Subangular Blocky
PL = Platy
SGR = Single Grain
MA = Massive

Consistence
L = Loose
SH = Slightly Hard
MH = Moderately Hard
HA = Hard
VH = Very Hard
EH = Extremely Hard

Slope Position
SU = Summit
SH = Shoulder
BS = Backslope
FS = Footslope
TS = Toeslope

$\delta^{13}C$† $\delta^{13}C$ of the surface horizon

$\delta^{13}C$‡ The change in $\delta^{13}C$ from surface horizon to a horizon at depth

CCE = Calcium carbonate equivalent

Table 4. Physical and chemical properties of 6 profiles sampled from beneath structures at the Kancab archeological site.

Soil Profile			Structure	Consistence	Soil Color	Texture		Slope			Olsen extraction		Total	Total	Organic			Change in	UTM Zone 16S	
Taxonomic Subgroup	Depth	Horizon	Grade, Size, Type	Dry	Dry	Clay	Class		Hillslope	pH	P	K	N	C	C	CCE	$\delta^{13}C$	$\delta^{13}C$	East	North
	cm					g/kg		%			mg/kg	mg/kg	g/kg	g/kg	g/kg	g/kg	------ ‰ ------		m	m
TB01	2	Ab	1,F,GR	L	7.5YR3/2	506	clay	NA		6.9	3.2	125.1	6.7	268	204	536	-26.29	-1.89	271309	2339705
TB02	20	AB			7.5YR3/2	533	clay										-25.37			
TB03	35	C			7.5YR4/2	607	clay										-24.40			
TB04	60	C			7.5YR4/2	609	clay										-24.94			
TB05	75	C/R			7.5YR4/2	623	clay										-24.63			
Argiustolls																				
TB06	5	Ab	1,F,GR	SH	7.5YR3/2	541	clay	NA		6.9	1.7	123.5	6.5	265	201	530	-26.55	-1.63	271325	2339699
TB07	40	AB			7.5YR4/2	559	clay										-24.94			
TB08	60	B			7.5YR5/2	662	clay										-25.33			
TB09	70	C/R			7.5YR6/2	661	clay										-24.91			
Argiustolls																				
TB10	2	Ab	1,F,GR	SH	7.5YR3/1	461	clay	NA		7.0	0.1	99.5	10.9	350	319	260	-22.82	-2.25	268968	2338833
TB11	20	B1			7.5YR3/3	611	clay										-23.84			
TB12	30	B2/R			7.5YR4/3	690	clay										-25.07			
Argiustolls																				
TB13	5	Ab	1,M,GR	SH	7.5YR3/1	560	clay	NA		7.1	0.3	158.4	7.7	281	216	538	-25.71	-1.11	268700	2338733
TB14	20	B			7.5YR4/2	589	clay										-24.97			
TB15	30	BC/R			7.5YR5/2	613	clay										-24.60			
Argiustolls																				
TB16	10	Ab	1,F,GR	SH	7.5YR3/1	515	clay	NA		7.2	45.6	493.8	3.1	229	152	640	-22.39	-2.29	271938	2339895
TB17	20	ABw			7.5YR4/1	490	clay										-23.53			
TB18	30	B			7.5YR4/2	527	clay										-23.76			
TB19	40	C			7.5YR4/2	421	clay										-23.78			
TB20	56	C			7.5YR4/1	416	clay										-23.96			
TB21	100	Ct/R			7.5YR4/2	565	clay										-24.68			
Argiustolls																				

Table 4. (continued) Physical and chemical properties of 6 profiles sampled from beneath structures at the Kancab archeological site.

Soil Profile			Structure	Consistence	Soil Color	Texture		Slope			Olsen extraction		Total	Total	Organic			Change in	UTM Zone 16S	
Taxonomic Subgroup	Depth	Horizon	Grade, Size, Type	Dry	Dry	Clay	Class		Hillslope	pH	P	K	N	C	C	CCE	$\delta^{13}C$	$\delta^{13}C$	East	North
	cm					g/kg		%			mg/kg	mg/kg	g/kg	g/kg	g/kg	g/kg	------ ‰ ------		m	m
TB22	5	Ab	1,F,GR	SH	7.5YR4/2	562	clay	NA		7.2	4.3	293.8	3.1	241	154	722	-22.82	-1.57	1271909	2339911
TB23	20	Bw			7.5YR5/2	539	clay										-24.11			
TB24	40	C1			7.5YR5/2	607	clay										-24.39			
TB25	50	C2			7.5YR5/2	568	clay										-23.99			
TB26	70	Ct			7.5YR7/2	671	clay										-23.98			
TB27	90	C/R			7.5YR6/2	423	clay										-23.78			
Argiustolls																				

Texture	Structure Grade	Structure Size	Structure Type	Consistence	Slope Position		
CL = Clay Loam	0 = Structureless	VF = Very Fine	GR = Granular	L = Loose	SU = Summit	**$\delta^{13}C$†**	$\delta^{13}C$ of the surface horizon
	1 = Weak	F = Fine	ABK = Angular Blocky	SH = Slightly Hard	SH = Shoulder		
	2 = Moderate	M = Medium	SBK = Subangular Blocky	MH = Moderately Hard	BS = Backslope	**$\delta^{13}C$‡**	The change in $\delta^{13}C$ from surface horizon to a horizon at depth
	3 = Strong	CO = Coarse	PL = Platy	HA = Hard	FS = Footslope		
		VC = Very Coarse	SGR = Single Grain	VH = Very Hard	TS = Toeslope		
		TK = Thick	MA = Massive	EH = Extremely Hard		CCE = Calcium carbonate equivalent	

Table 5. Correlation matrix for all 68 profiles. Significant correlations are marked as follows: *= P<.05, **=P<.01. Highly significant correlations between soil depth, plant nutrients P, K and N and CCE are evident when the deeper profiles of the rejolladas and buried profiles are included in the correlation matrix.

Correlation Matrix for all Profiles Sampled

	Value Dry	Clay	pH	P	K	N	Org C	CCE
Depth	0.08	-0.062	-0.474**	0.571**	0.58**	-0.576**	-0.214	0.607**
	ValueDry	0.268*	0.234*	0.057	-0.07	-0.301*	-0.46	0.025
		Clay	-0.195	-0.01	-0.337**	-0.537**	-0.743**	-0.412**
			pH	-0.24*	-0.326**	0.504**	0.118	-0.206
				P	0.66**	-0.384**	-0.183	0.388**
					K	-0.179	0.188	0.566**
						N	0.762**	-0.341**
							Org C	0.075
								CCE

Table 6. Correlation matrix for 46 profiles in the 21 de Abril sampling grid. Significant correlations are marked as follows: * = P<.05, ** = P<.01. This table shows no unique correlations among soil depth, plant nutrients P, K and N and CCE with the deeper rejolladas and buried profiles removed.

Correlation Matrix for the 21 de Abril Sample Grid and Sacbe Profiles

	Value Dry	Clay	pH	P	K	N	Org C	CCE
Depth	0.238	0.143	0.15	0.198	-0.303*	-0.324*	-0.281	-0.008
	Value Dry	0.51**	0.358*	-0.112	-0.385**	-0.522**	-0.624**	-0.208
		Clay	0.213	-0.126	-0.447**	-0.685**	-0.801**	-0.451**
			pH	-0.291*	-0.307*	-0.381**	-0.367*	0.103
				P	0.144	0.165	0.183	-0.205
					K	0.567**	0.654**	0.098
						N	0.851**	0.035
							Org C	0.274
								CCE

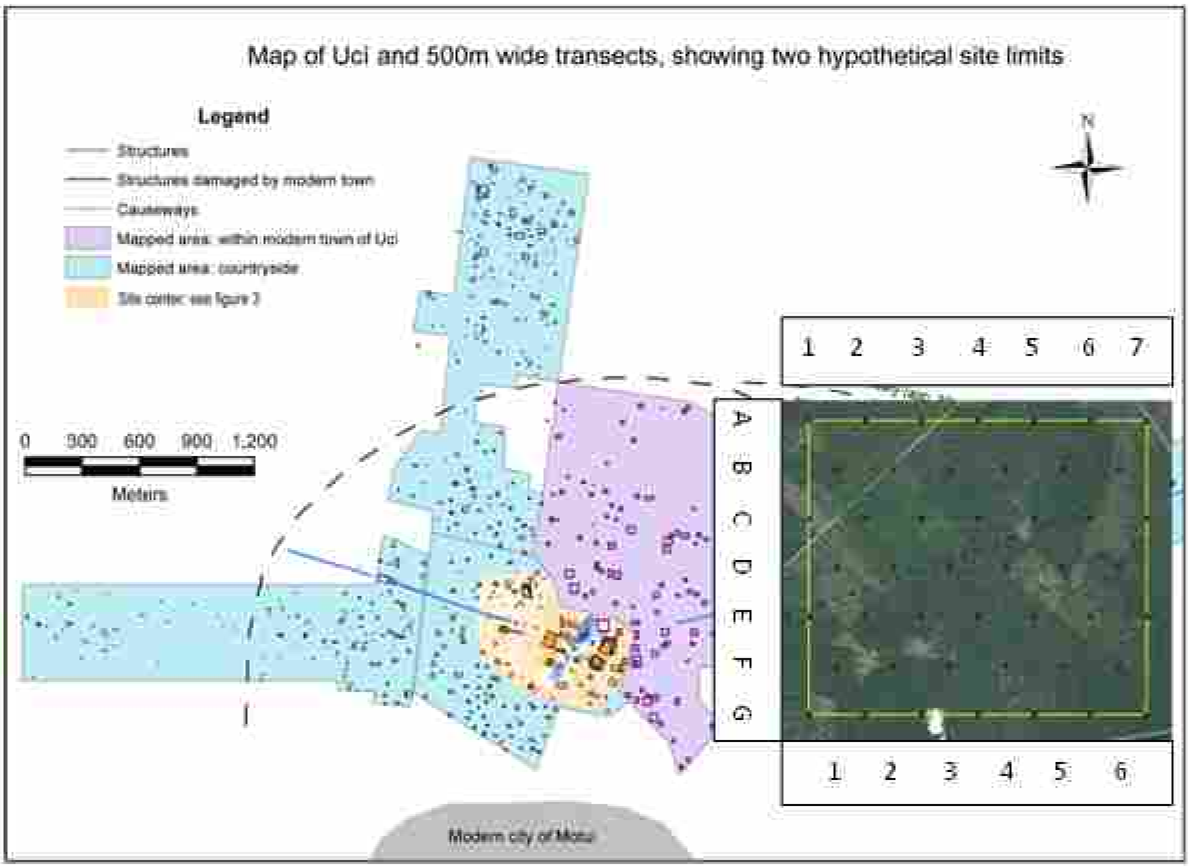


Figure 1. The yellow square is the boundary of the 21 de Abril sampling grid where 46 profiles were sampled. The red profile locations are identified by rows A through G and numbered horizontally 1 through 6 or 1 through 7 depending on the row. The small green point in the center of the sampling grid is the location of the 21 de Abril excavation. The purple points bisecting the sampling grid were surveyed sample locations along the sacbe. The rejolladas appear as dark blue areas near the main structures within the site center. This map is adapted from (Hutson, 2010), as well as Google Earth images and Geographic Information Systems.

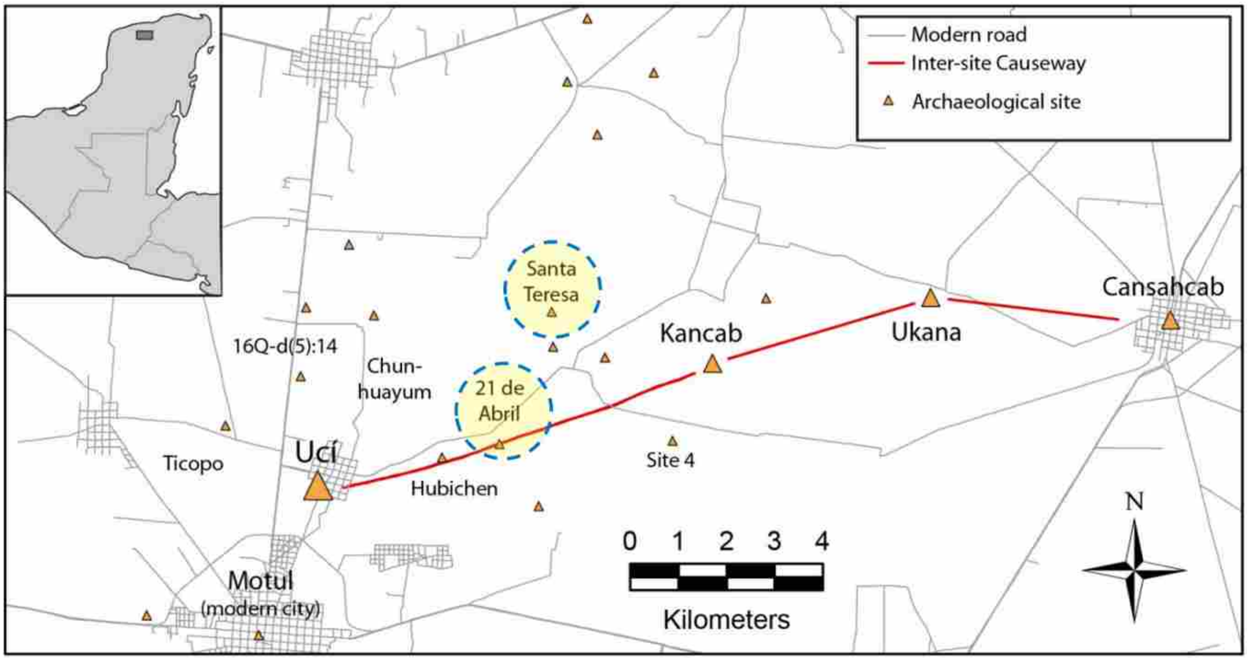


Figure 2. Map of the Project area. Samples were taken from the periphery of the 21 de Abril site, along the Inter-site causeway between Uci and Kancab, from the Kancab site, and from the rejolladas near the Uci site center. The second sampling group is located along the causeway shown in red between Uci and the 21 de Abril site. This map is adapted from (Hutson, 2010).

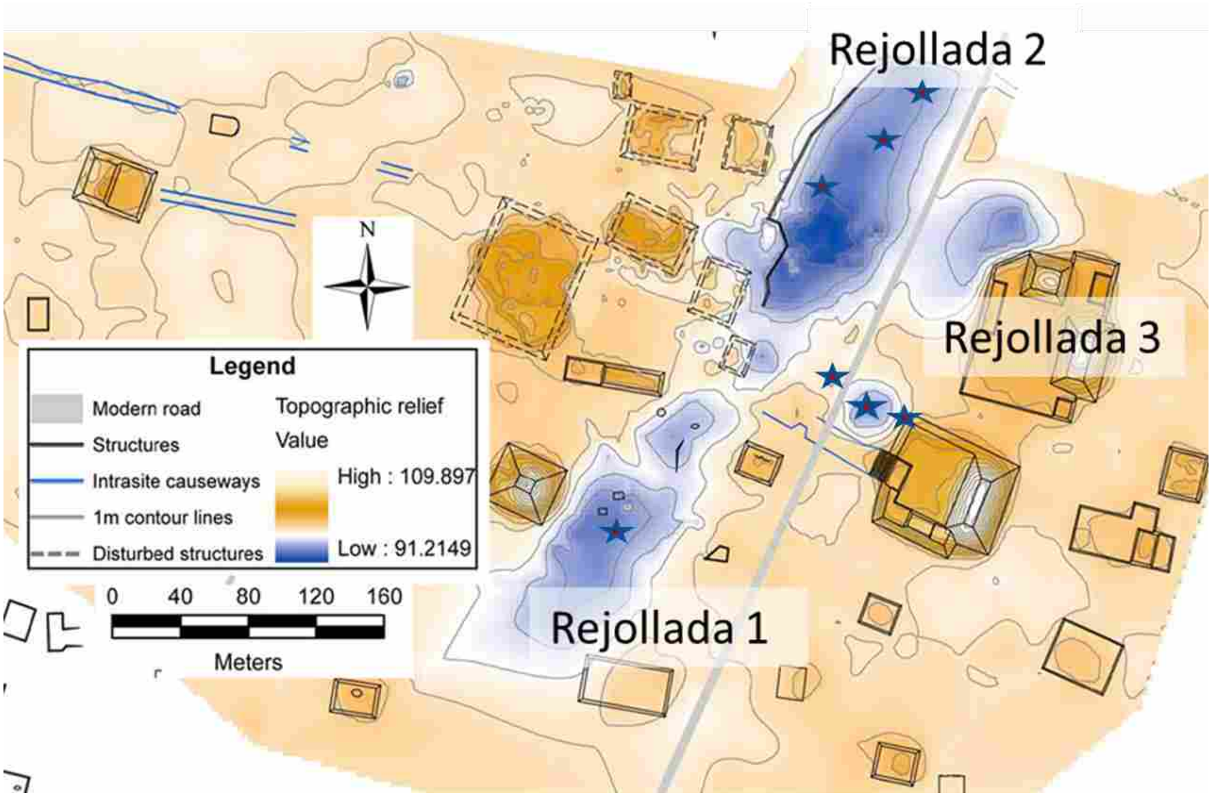


Figure 3. Map showing the Uci site center and the 3 main rejolladas with starts indicating the relative locations where profiles were sampled. Some evidence of ancient maize agriculture was encountered in each rejollada. This map is adapted from (Hutson, 2010).

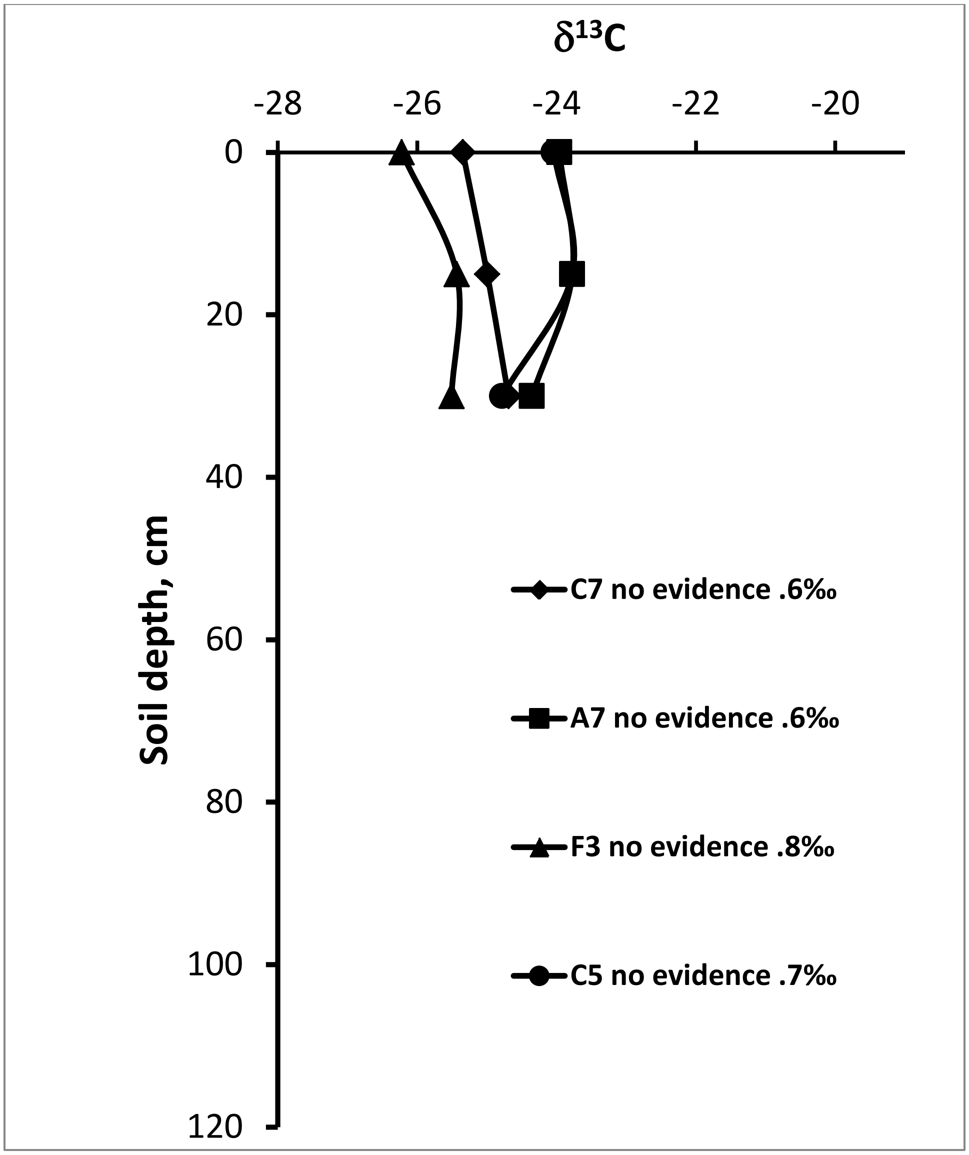


Figure 4. Each of these four profiles came from the sampling grid near the 21 de Abril site and sacbe. The $\delta^{13}C$ ratio of these soils is reflective of the native mixed C_3 and C_4 vegetation, with ^{13}C ratios of between -26‰ and -24‰ and no significant positive shift to indicate ancient maize agriculture.

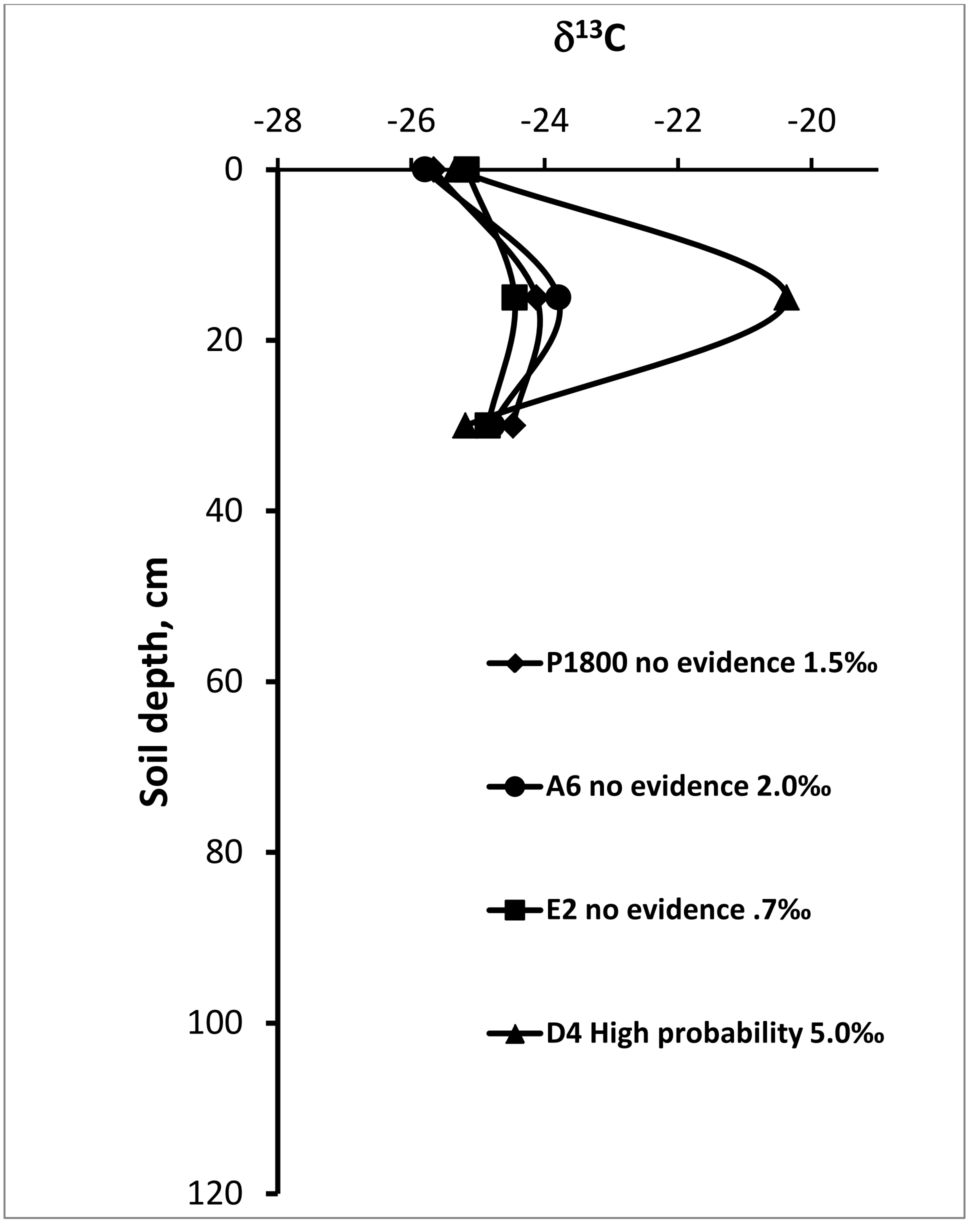


Figure 5. Each of these four profiles came from the 21 de Abril sampling grid or along the sacbe. Profile D4 is the only one which exhibits a significant isotopic shift in the $\delta^{13}C$ ratio indicating high probability that ancient maize agriculture took place at that location.

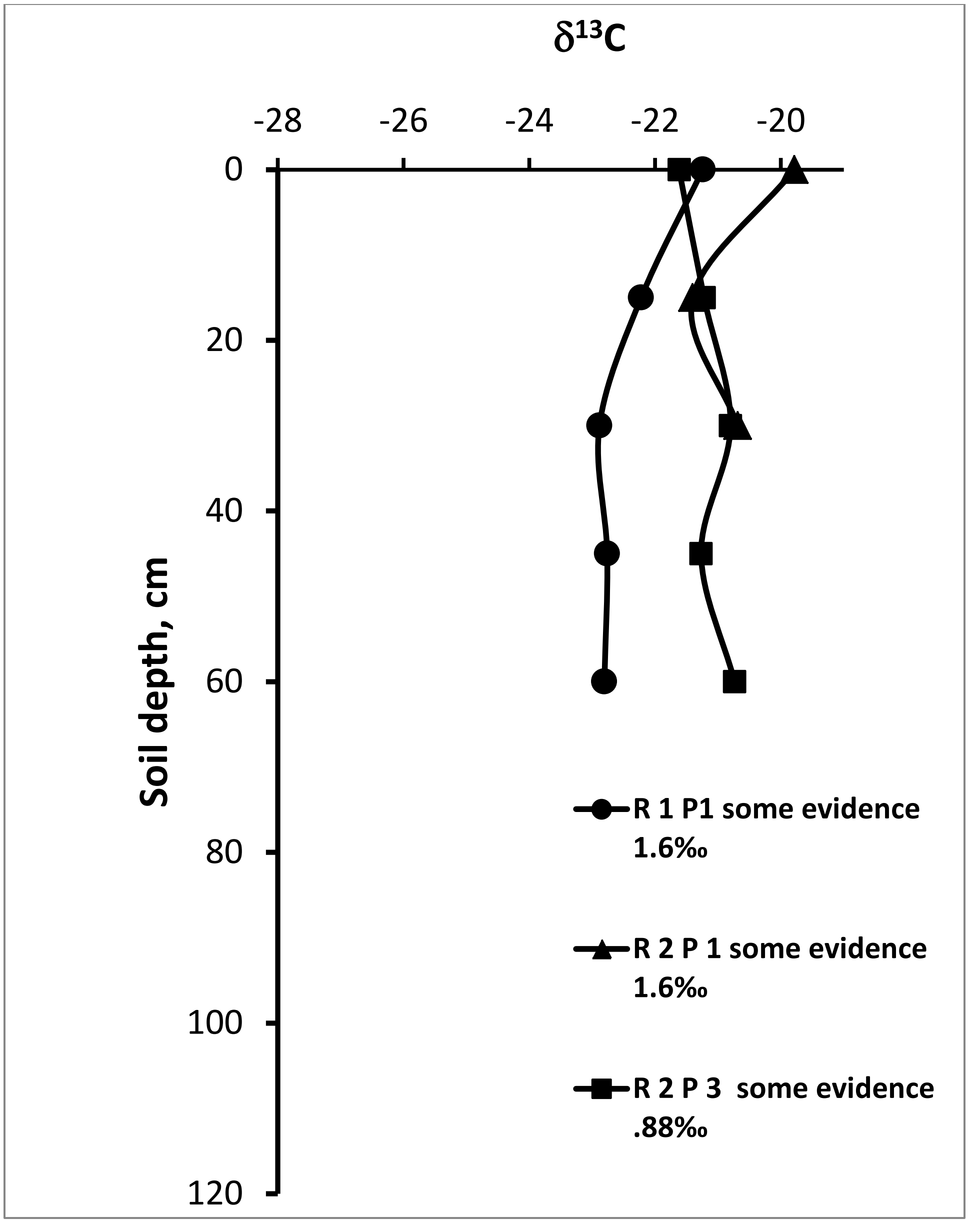


Figure 6. These profiles sampled from within the rejolladas do not show a strong isotopic shift within the profile, but do however show a shift when compared to the $\delta^{13}C$ ratio of the surrounding areas. $\delta^{13}C$ ratios of -22‰ to -20‰ indicate a dominant influence from C_4 plants. At the surface, contemporary maize was observed growing in the rejolladas which reflects the surface $\delta^{13}C$ ratio.

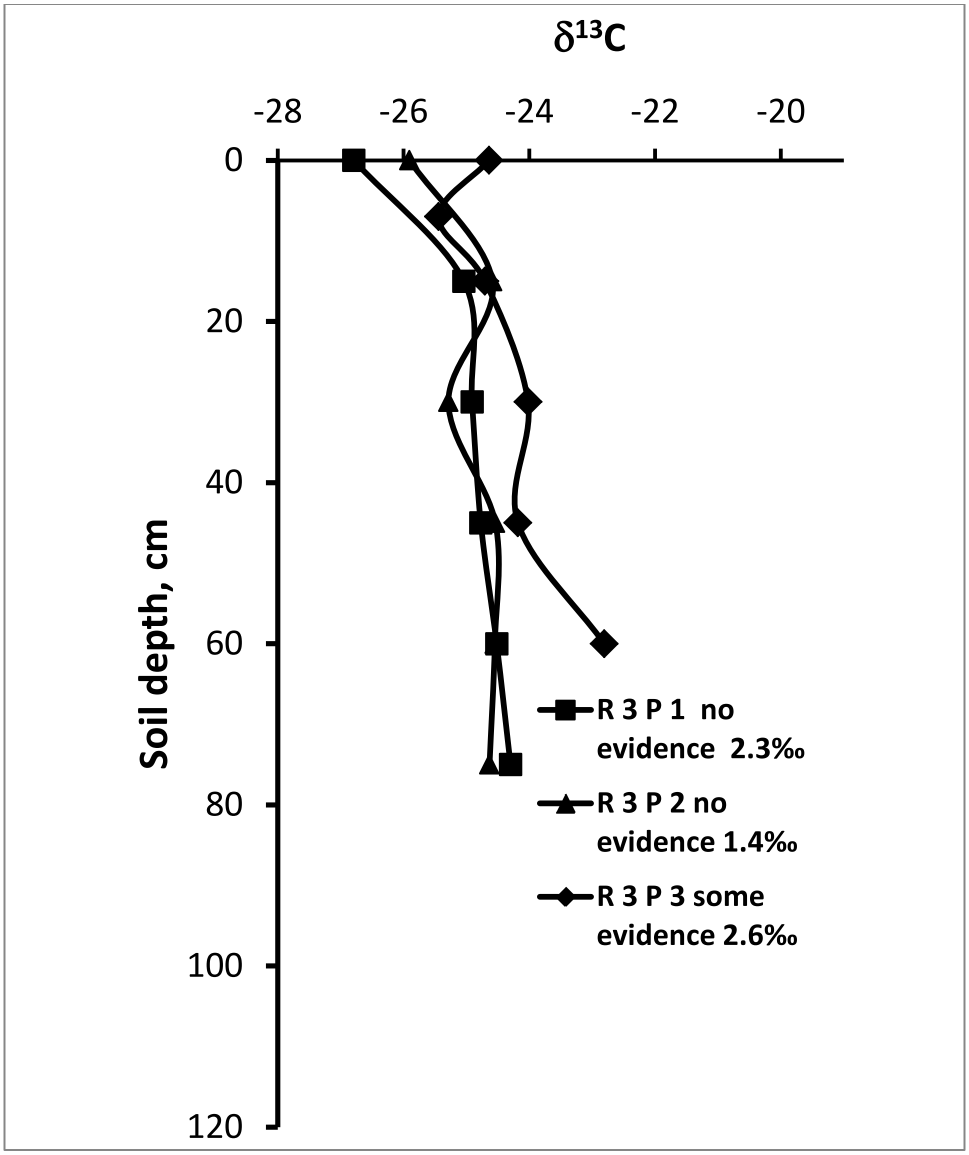


Figure 7. Of these rejollada profiles only profile R3P3 shows some evidence of ancient maize agriculture. Rejollada 3 is the smallest of the three rejolladas sampled.

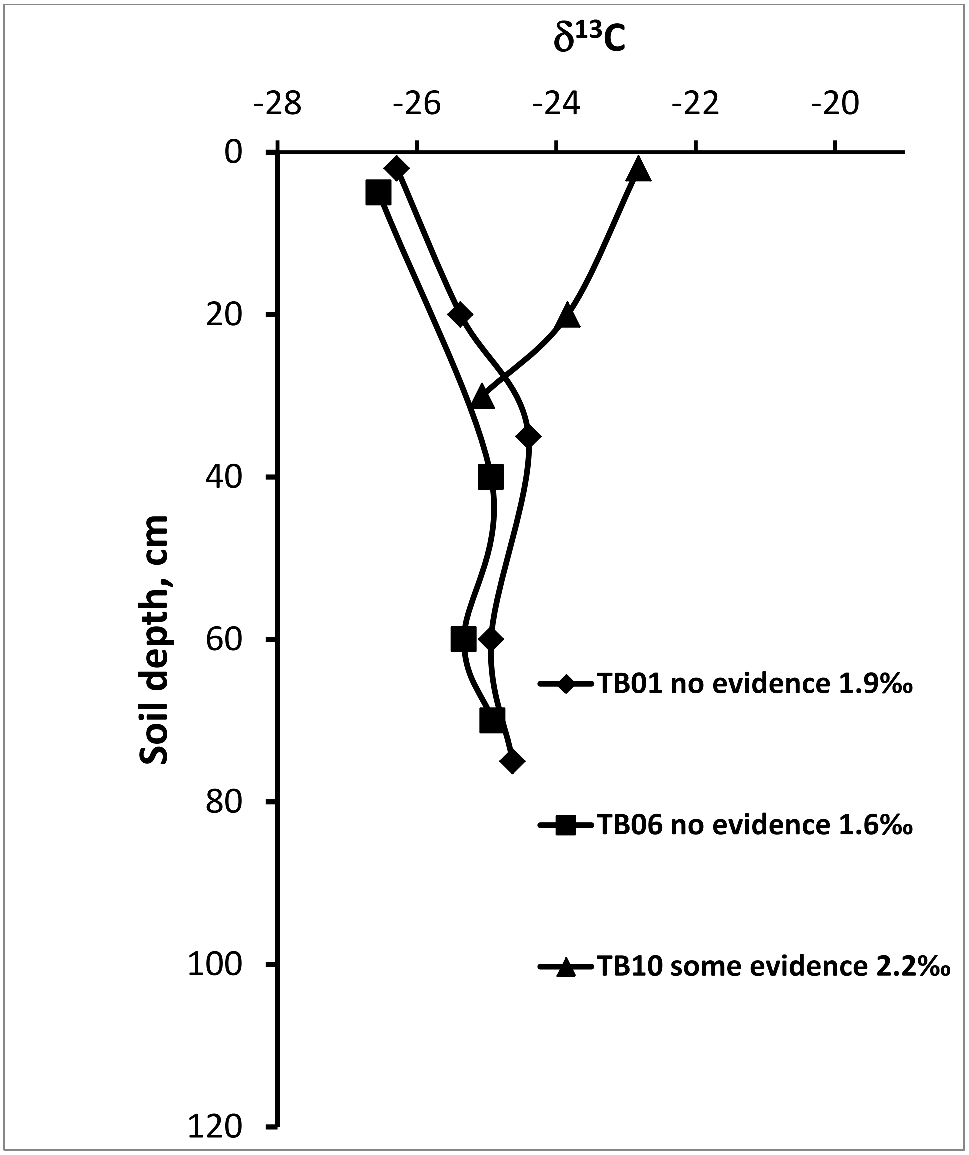


Figure 8. These samples were buried beneath structure walls near the site of Kancab along the ancient sacbe. The overlying structures preserved the isotopic signature that was in present at the time of construction preventing the downward migration of the isotopic signature. Profile TB10 shows some evidence that ancient maize agriculture was present immediately prior to construction. The isotopic signature of profiles TB01, TB06 were indicative of the natural soil $\delta^{13}C$ ratio derived from the natural forest vegetation.

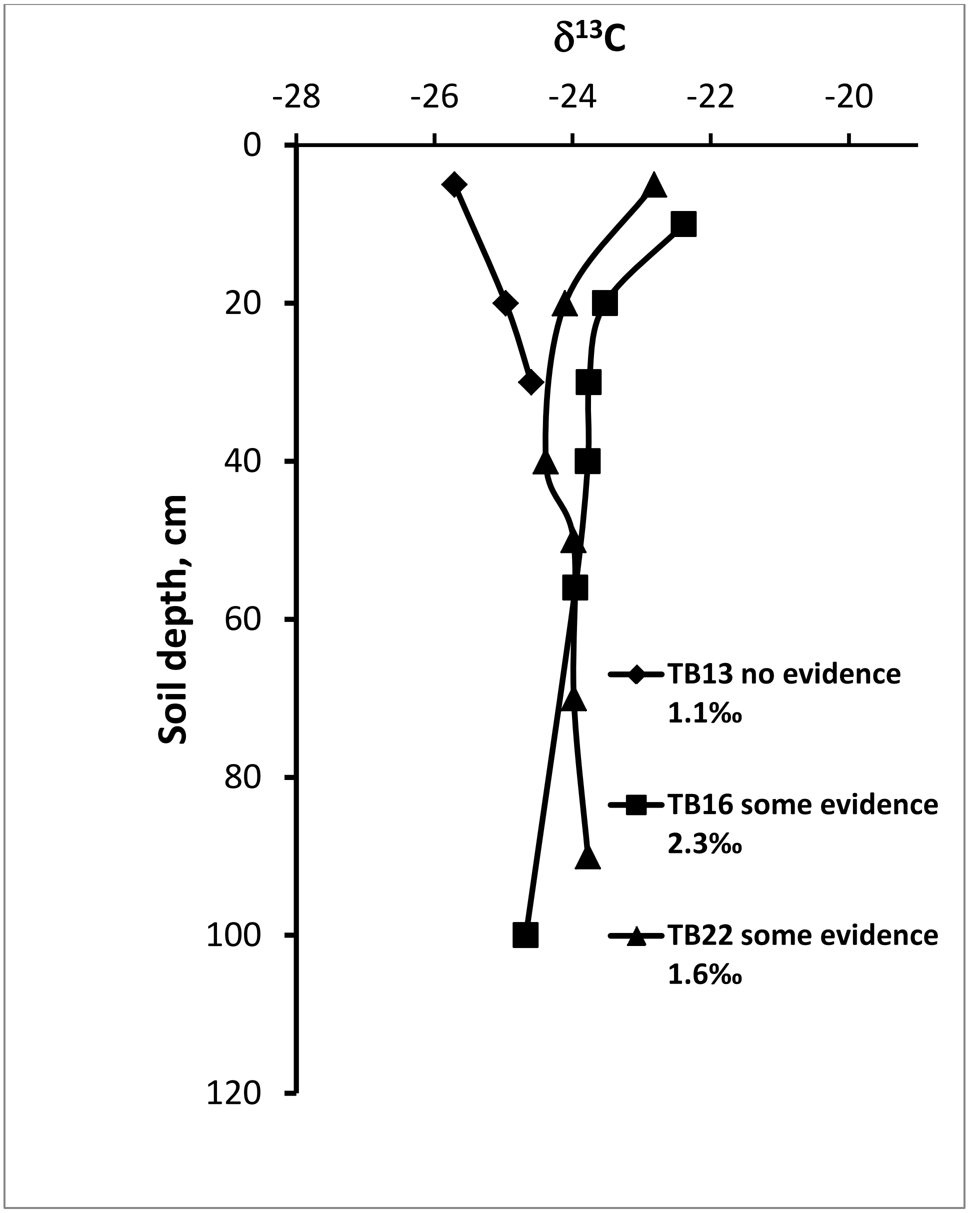


Figure 9. These profiles were located beneath structure walls at the site of Kancab. TB16 and TB22 show some evidence that ancient maize agriculture was present immediately prior to construction. Profile TB13 is indicative of the natural soil $\delta^{13}C$ ratio derived from the natural forest vegetation.

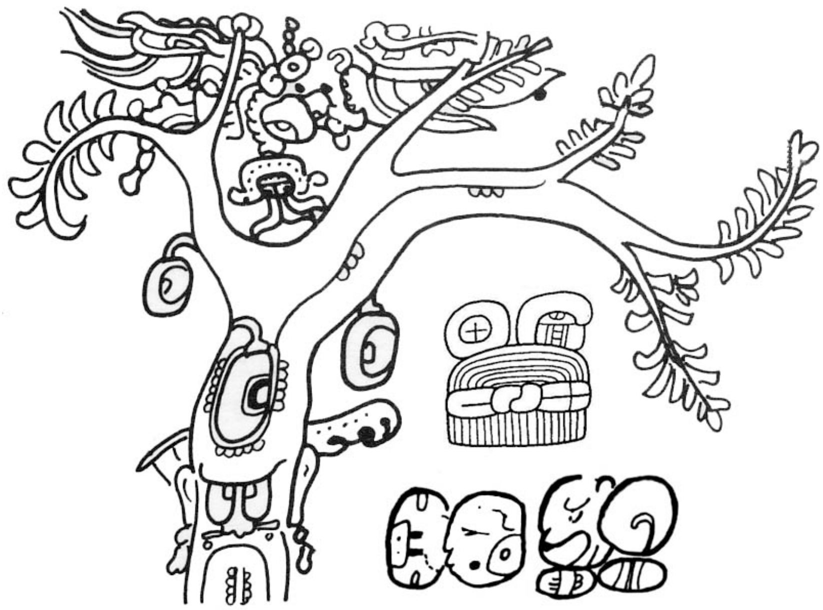
Figure 10. Haplustoll, profile F2 from the 21 de Abril sampling grid was only 10 cm deep. This is a typical shallow soil profiles from the Uci region.

Figure 11. Argiustoll, profile C5 from the 21 de Abril sampling grid. This profile was analyzed for $\delta^{13}C$ and found to have no evidence of ancient maize agriculture (Figure 4).

Figure 12. Argiustoll, profile R2P1 from the rejollada sampling group. R2P1 showed some evidence of ancient maize agriculture as well as contemporary maize being grown in this rejollada (Figure 6).

APPENDIX

Life on the Edge: Tikal in a Bajo Landscape



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Chapter 5 -- Life on the Edge: Tikal in a Bajo Landscape

Introduction

Changes in the ratios of stable carbon isotopes in the soil organic matter have been used to determine the vegetative histories of soils that have changed from predominantly C_3 forest vegetation to C_4 plants associated with ancient maize agriculture (Burnett, et al., 2012, Burnett, et al., n.d., Fernandez, et al., 2005, Lane, et al., 2004, Lane, et al., 2008, Webb, et al., 2007, Webb, et al., 2004, Wright, et al., 2009). Tree and vine species common to the Petén forest of Central America utilize a C_3 photosynthetic pathway while maize and some other tropical grasses utilize a more efficient C_4 pathway. As CO_2 diffuses into stomata and through cell membranes and biochemical pathways, there is isotopic discrimination against the heavier $^{13}CO_2$, thus all plant tissues are depleted of ^{13}C in comparison to its natural abundance in atmospheric CO_2. The $\delta^{13}C$ of C_3 plants is near -27‰. C_4 plants are much less discriminatory toward the heavier $^{13}CO_2$ and exhibit a $\delta^{13}C$ closer to -12‰. Soil humus of both surface and root-zone soil contains the decayed remains of all types of vegetation that grew for thousands of years, therefore, a vegetative history of the soil is recorded in the carbon isotope ratios of humic substances (Boutton, 1996, Boutton, et al., 1998, Webb, et al., 2004). The cultivation of ancient C_4 maize can be observed by a greater portion of ^{13}C in the humus against a background of ^{13}C depleted humus derived from native C_3 forest vegetation (Ehleringer, 1991, Liu, et al., 1997). An important factor in the interpretation of soil $\delta^{13}C$ values deals with the naturally occurring soil microbial diagenesis of soil organic matter (SOM) which results in moderate isotopic fractionation (Blair, et al., 1985). The metabolic pathways of soil microbial decomposition can cause increases in $\delta^{13}C$ of 1-2.5 ‰ in deeper soil horizons (Ágren, et al., 1996, Balesdent and Mariotti, 1987, Boutton, 1996, Cerri, et al., 1985). Certain soil conditions in tropical regions produce increased microbial activity which can induce increases in as high as 3or 4‰ (Martinelli, et al., 1996). Hence, an isotope enrichment of 4‰ or greater within a pedon has been set as a benchmark for definitive C_4 plant growth against natural C_3 isotopic ratios (Burnett, et al., 2012, Fernandez, et al., 2005, Johnson, et al., 2007b, Johnson, et al., 2007a, Lane, et al., 2004, Webb, et al., 2004, Wright, et al., 2009)

Burnett et al (2012) reported finding isotopic signatures of ancient C_4 vegetation in the pedons sampled in the margins of the Bajo de Santa Fe near Tikal. The soil al lower elevation beyond the bajo margins have not been samples and subjected to carbon isotope analysis and their use in ancient agriculture at Tikal remains unknown.

We used the Puleston survey maps (Puleston, 1983) and the (Carr and Hazard, 1960) maps to establish two separate soil survey transects spanning the summit, back-, foot-, and toeslopes of two bajo areas. The objectives of this study were to expand our knowledge of agricultural resources and to discover evidence in the SOM of ancient vegetation shifts from C_3 forest vegetation to cleared fields associated with ancient maize agriculture and then the return of native forest vegetation following collapse of the local Maya civilization about 1200 years ago.

Methods & Materials

Soil cores were collected at Tikal National Park in Petén, Guatemala using a clay specific bucket auger (AMS, American Falls, ID). Two sampling transects were designated (figure map). The first followed a portion of the East Transect established by Puleston (Puleston, 1983) near the Terminos reservoir. This transect is at the edge of the Bajo de Santa Fe about 6 km east of the site center of Tikal (Figure map). The second transect was associated with rural household groups about 0.5 km south of Perdido Reservoir (Figure map). This transect extended east to west from patio group C7 across a pocket bajo. The Terminos and Perdido transects were positioned to enable sampling of upland summits and backslopes as well as the footslopes and toeslopes of the bajos and bajo margins.

Each core was partitioned in 15-cm depth intervals. The samples were transported to the BYU Soil and Plant Analysis laboratory. Samples were dried in air and aggregates were crushed by mortar and pestle to pass a 2 mm (10 mesh) sieve. The soil textural class of each surface horizon was determined by the hydrometer method (Gee and Bauder., 1986). General taxonomic designations were determined according to the USDA taxonomic classification system.

For each 15-cm depth interval throughout the pedon an analysis of the stable carbon isotope ratio was conducted. Each sample was thoroughly mixed and a 5-g subsample was further ground by mortar and pestle to pass through a 250 micron (60 mesh) sieve in preparation for carbon, nitrogen and isotope analyses. Carbonates were removed from 3-g samples by acidification with 1.0 *M* HCl in a water bath at 70 C for 2 hours. Excess HCl was added until effervescence ceased. Humic and Fulvic acid fractions of the soil organic matter were extracted (Webb, et al., 2004, Wright, et al., 2009) leaving the humin fraction for isotope analysis. The humin fraction is considered to contain the oldest carbon in the soil (Bender, 1968). The stable C isotope ratios of the humin fraction of the SOM of each soil horizon were then determined with the use of an isotope ratio mass spectrometer (Thermo Finnigan, Waltham, MA) coupled with an elemental analyzer (EAIRMS) (Costech, Valencia, CA). The ensuing results were plotted on excel scatter plots to facilitate visual analysis and reported as $\delta^{13}C$ in per mil notation (‰).

Results and Discussion

The 16 pedons fall under the Mollisols soil order (Staff, 2006). The shallow (<45 cm) summit and backslope pedons were Rendolls while the deeper soils exhibited vertic and aquic properties. The color range is from 7.5 YR 5/1 to 10 YR 7/1, with the A horizons being generally dark and high in organic matter, and the subsurface B and C horizons exhibiting argillo-turbation with both dark and light soil intermixing with visible slickensides. Several of the sub surface intermixed C and B horizons displayed gleying and iron and manganese concretions as a result of the aquic properties of the bajos. The pedon depths vary from 20 to 180 cm, limestone bedrock was encountered in pedons less than 50 cm deep.

The typical $\delta^{13}C$ values of surface horizons ranged from -26‰ to -30 ‰, reflecting the current C_3 forest vegetation. A shift in the $\delta^{13}C$ of near 4‰ or greater between the surface horizon and soil of the ancient root zone was deemed sufficient evidence of a one-time C_4 plant dominated landscape associated with maize production.

Perdido pedons 1 through 4 were approximately 15 cm deep over limestone (Figure 1). These shallow Rendolls were sampled within patios and near household structures of Group C7. The change in $\delta^{13}C$ between surface and root zone horizons of the pedons ranged from 0.8 to 1.6 ‰ reflective of both ancient and current C_3 forest vegetation (Table 1). There was no carbon isotope evidence of ancient maize production within the household group. Pedons 5 and 6 were located at the edge of the pocket bajo just south of the Perdido reservoir. The cores were collected to depths of 105 and 90 cm, respectively. The change in $\delta^{13}C$ from the surface horizon to horizons below 45 cm show 3.3 and 6 ‰ shifts, respectively (Figure 1). Pedon 5 was closest to household structures and the shift in $\delta^{13}C$ provided some evidence of ancient C_4 vegetation but

Pedon 6 located further into the pocket bajo exhibited strong isotopic evidence of ancient C_4 vegetation associated with forest clearing and maize agriculture. Perdido Pedon 7 was only 45 cm deep and had a $\delta^{13}C$ shift of 2.7‰ which is inconclusive evidence for the presence of C-4 plants. Pedon 8 was sampled to a depth of 195 cm and it exhibited two peak shifts in $\delta^{13}C$ of 4.3 at the 30-cm depth and 4.7‰ at the 75 cm depth. This pattern in the carbon isotope data suggested two separate periods of C_4 dominated plant cover associated with ancient maize agriculture.

Of the eight Perdido pedons, number 6 contained a $\delta^{13}C$ enrichment of 6.05‰, and pedon 8 exhibited an enrichment of 4.7‰. This is significant in that such levels of ^{13}C enrichment indicate that C_4 plants (likely maize) were grown within the Perdido bajo and its margin. The $\delta^{13}C$ results from the 8 Terminos pedons sampled along a portion of the East Transect mimic those from the Perdido bajo. The Terminos transect starts on the west with pedons 1, 2 and 3 in the patios of the ancient Terminos rural settlement (Figure 2). The soil sampling transect continues toward the east into the edge of the seasonal bajo. Pedons 4 and 8 were at backslope locations near rural household groups. Pedons 5 through 7 were sampled at foot and toeslope locations.

Terminos Pedons 1 through 4 were collected on the summit and backslopes within the ancient Terminos settlement located on a limestone hill at the edge of the bajo (Figure 2). These pedons were less than 75 cm deep and the change in $\delta^{13}C$ with depth was less than 1.82‰. The vegetative history contained in these four pedons is an indication that maize was not grown long-term on the hill or among the household structures. Terminos Pedons 5 and 6 exhibited $\delta^{13}C$ shifts of 3.8 and 5.66‰, respectively. These two profiles were more than 90 cm deep and contained isotopic evidence of an ancient C_4 vegetative history suggesting ancient forest clearance and agricultural production. Pedons 7 and 8 were located at the edge of another limestone hill that also contained rural housemounds. Pedon 7 was a deeper than 90 cm and exhibited a $\delta^{13}C$ shift of 2.2 ‰. Pedon 8 was a shallow backslope soil with a $\delta^{13}C$ shift of 0.8 ‰. These two pedons at the edge of the rural settlement lacked evidence of ancient maize agriculture.

Three Perdido pedons and two Terminos pedons from bajo toeslopes exhibited weak to strong evidence of ancient C_4 maize agriculture. The soil horizons with the greatest enrichment in $\delta^{13}C$ were located at depths of 30 to 75 cm. These soil depths represent the ancient rooting zone. Soil scientists have reported that a large portion of the carbon photosynthesized by maize is converted to SOM through rhizodeposition of root tissues and root exudates (Balesdent and Balabane, 1996; Bolinder et al., 1999; Molina et al., 2001). The deposition of detritus from the C_3 forest vegetation that replaced ancient C_4 crops and weeds has deposited 13C depleted carbon at the surface. From the results of the isotope ratio analysis, 4 of the 16 pedons show strong evidence of ancient maize agriculture. One pedon showed weak evidence with a shift of 3.3‰.The weak isotopic signature could be attributed to a briefer period of maize agriculture or possibly even a transition area between ancient native forest and ancient agricultural fields. Even though the soils of the Tikal Bajos fall under the soil order of Mollisols, one of the most fertile of the 12 soil orders, significant limitations exist with these soils. The high clay content and poor drainage cause these soils to be extremely sticky and muddy in the wet season and extremely hard in the dry season. It is probable the large amounts of labor and management would have been needed to benefit from the potential fertility of these soils. It is important to note the location of the pedons along each transect in conjunction with the map and in situ information. The results of these two separate locations of very similar soil, landscape and slope provided consistent results indicating that the results are accurate and can be predictive of similar areas within the region (Wright, et al., 2009). All of the pedons indicating ancient maize agriculture are within the karst depressions and their margins which supports the hypothesis of this study. However, the slopes near the bajos and bajo margins include greater slopes including back and shoulder slopes which under ancient agricultural conditions could have posed a highly erodible landscape, which caused isotopic evidence within the soil to be lost.

In 2005, Richard Burnett conducted a similar study at the site of Ramonal near Tikal, Guatemala. In his research various other soil pedons were sampled and analyzed for stable carbon isotopes, including pedons located on the foot and toes slopes of karst depressions. Due to the homogeneity of the Tikal geologic landscape significant similarities exist between the results of that project and the results obtained in this study. When comparing soil physical and chemical characteristics between bajo soils of the two studies it is clear that the pedons fall within the same taxonomic classification of Argiudolls and Hapludolls. In Burnett's study the comparative bajo soils exhibited low to medium phosphorus levels according to generalized fertility recommendations, and total N levels slightly higher than those soil pedon taken from the Terminos and Perdido transects. Regardless, the most important commonality between the samples taken near Ramonal in 2005 and those samples taken near Tikal in 2010 is the location of the pedons where significant $\delta^{13}C$ signatures were present. The consistency of finding significant shifts in $\delta^{13}C$ in pedons from bajos and bajo margins between various sites and locations gives strong insight into the agricultural practices and subsistence methods used by the Maya. Between the several pedons sampled and tested amongst various sites in Mesoamerica and the consistent results reported, little dispute should exist over the importance of seasonal wetland bajos and their margins to Maya subsistence and agriculture. However, a larger analysis of the area on a grid basis would need to be conducted to determine the size and shape of the maize fields and to make inferences about proprietorship and societal systems of distribution.

Conclusions

Based on the results of the study, the karst depressions (seasonal wetland bajos) and depression margins not only constituted a viable agronomic resource for maize production especially during the dry season, but karst depressions were a resource that was used extensively as demonstrated by the isotopic evidence culminated in the study. There are many conclusions and implications that come from determining that these karst depressions were in fact an important and widely used resource in food production, as well as greater insight into the depth of agronomic understanding possessed by the Maya. It is possible due to this study to better understand how such large populations were able to grow in number and sustain themselves in their harsh environment. The results and information from this study will be incorporated into statistical GIS and remote sensing models to predict areas most likely to have potential for ancient maize agriculture and settlement. Much information related to karst depressions is still lacking with regards to predicting the existence of ancient agriculture through remote sensing. While this study has helped to incorporate an expanded geographic area to the existing models predicting maize agriculture, more soil research and ^{13}C isotope evidence is needed to enhance and extend the geographic capabilities of the predictive models both in the heart of the larger karst depressions and also in the high elevations of Tikal (Balzotti, et al., 2013). Similar studies performed in these un-samples areas would potentially complete the model and provide a complete view of the total geographic agricultural resources available to the ancient Maya in the Tikal region.

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Pedon Table. Tikal 2010 soil Pedon characteristics

Pedon	Easting m	Northing m	Depth cm	Slope position	Clay %	Texture class	pH	P mg/kg	K mg/kg	Total N %	Total C %	$CO_3^{=}C$ %	Org C %	Surface $\delta^{13}C$ ‰	Change ‰
Perdido 1	220185	1905099	30	Summit	30.8	Clay	6.8	5.11	66.56	0.36	13.60	10.23	3.37	-27.94	0.80
Perdido 2	220233	1905096	30	back	38.3	Clay	6.9	5.88	67.84	0.33	12.92	9.11	3.81	-27.17	1.18
Perdido 3	220276	1905090	15	back	47.9	Clay	7.0	5.70	99.52	0.36	11.58	8.01	3.57	-25.94	0.00
Perdido 4	220139	1905101	30	back	52.6	Clay	7.0	4.11	50.56	0.50	11.90	6.60	5.29	-26.63	1.63
Perdido 5	220058	1905099	105	foot	92.6	Clay	6.0	2.40	69.76	0.36	4.71	0.81	3.90	-26.19	3.32
Perdido 6	219972	1905112	90	foot	82.7	Clay	7.1	4.05	63.68	0.46	6.69	1.48	5.21	-27.65	6.05
Perdido 7	219877	1905116	45	toe	85.8	Clay	7.3	2.79	45.12	0.15	3.00	0.46	2.54	-27.71	2.71
Perdido 8	219656	1905104	195	toe	87.8	Clay	5.6	2.85	41.28	0.24	3.24	0.42	2.82	-27.80	4.33
Terminos 1	226503	1905532	60	summit	55.2	Clay	7.1	5.88	47.04	0.73	16.17	8.01	8.15	-28.51	0.70
Terminos 2	226448	1905563	45	summit	57.8	Clay	6.7	2.91	19.20	0.53	10.80	6.31	4.49	-27.93	1.10
Terminos 3	226679	1905784	15	back	42.8	Clay	7.6	2.23	0.96	0.26	10.84	9.17	1.67	-28.25	0.00
Terminos 4	226711	1905521	75	back	80.1	Clay	5.8	0.57	0.96	0.32	4.25	0.44	3.80	-29.47	1.82
Terminos 5	226778	1905518	90	foot	85.3	Clay	5.3	0.63	18.88	0.10	1.79	0.00	1.79	-29.91	3.80
Terminos 6	227321	1905476	90	toe	92.7	Clay	5.8	0.19	0.32	0.04	0.36	0.46	0.00	-28.67	5.66
Terminos 7	227717	1905444	90	toe	92.8	Clay	5.2	0.25	0.64	0.08	1.07	0.44	0.63	-28.41	2.22
Terminos 8	228000	1905430	60	back	93.1	Clay	5.7	0.30	2.88	0.11	1.29	0.44	0.85	-27.11	0.83

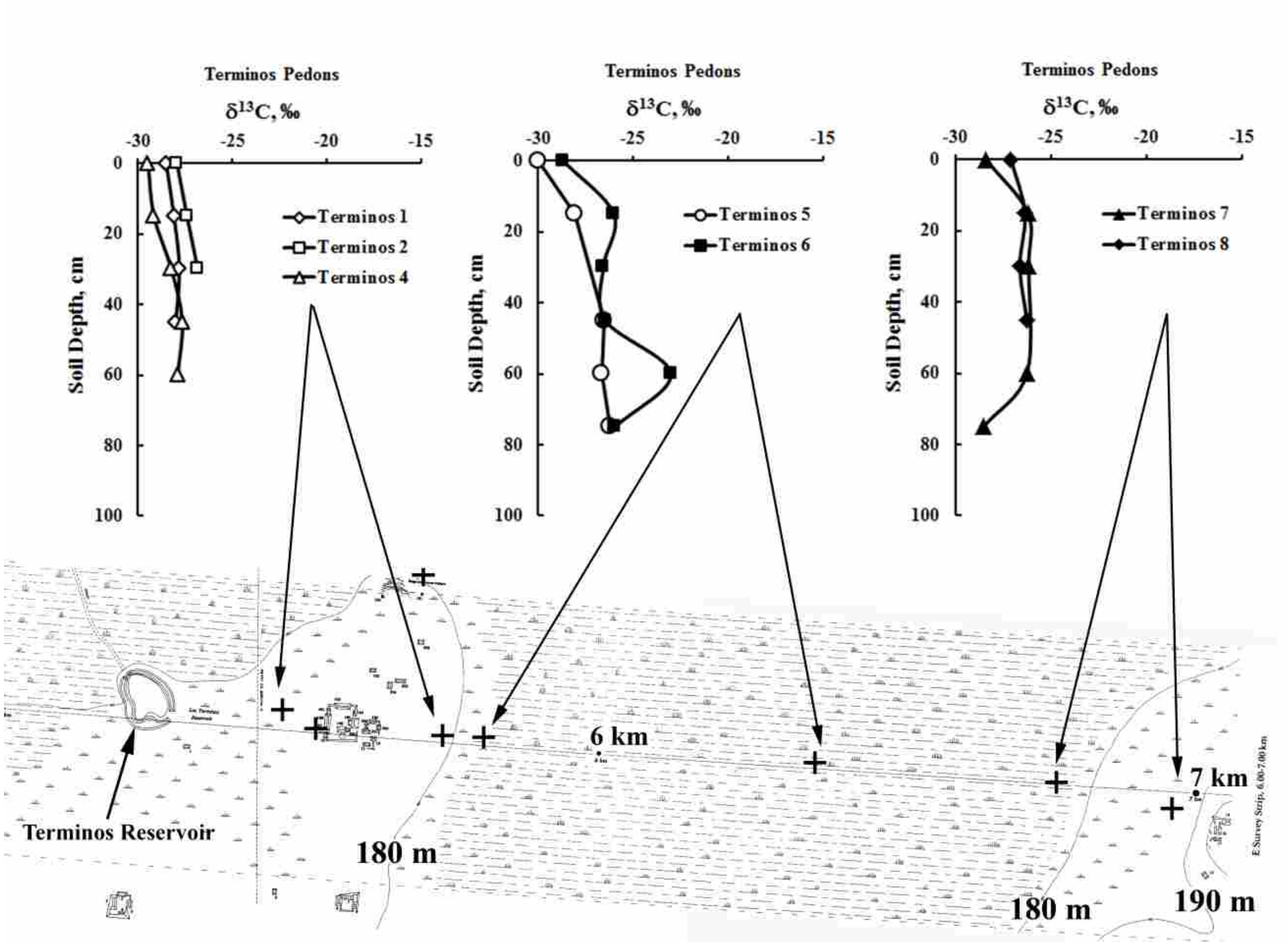

Figure 1. Terminos soil pedon locations and carbon isotope profiles.

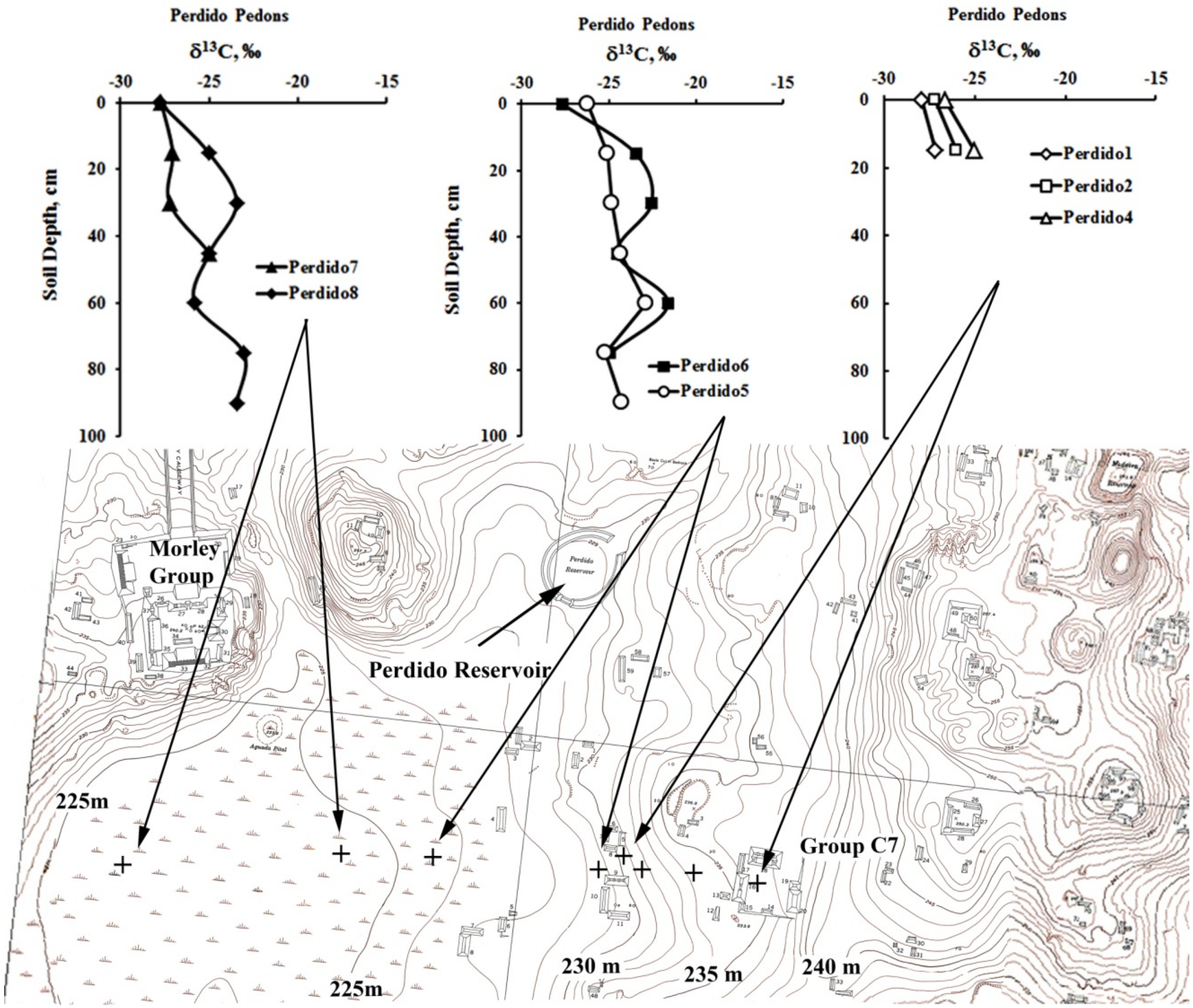

Figure 2. Perdido soil pedon locations and carbon isotope profiles.