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Ancient Maya Agricultural Resources in the Rio Amarillo Valley near Copán, Honduras

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ABSTRACT

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The purpose of this study was to use soil physical and chemical analyses to better understand the ancient agricultural landscape around the ancient Maya cities of Rio Amarillo and Piedras Negras, two tributary sites to Copan, Honduras. Our primary objective was to determine whether a mass erosion event around 800 A.D. occurred which could have caused crop failure and famine or if stable soil conditions persisted during the collapse of these city-states. Stable carbon isotope analysis of the humin fraction of the soils showed that much of this valley was used anciently for agriculture, including hillslopes and hilltops; however, there is no evidence of mass erosion in the soil profiles. Soil horizon development and texture is consistent with stable soil conditions in this area. The demise of these city-states was likely caused by a variety of factors including warfare and political unrest, and not solely by environmental degradation as postulated in previous studies of the valley.

Keywords: stable carbon isotopes, soil analysis, ancient agriculture, Maya agriculture, geochemistry

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INTRODUCTION

As humans we often examine past cultures and histories to improve and protect our current society. The Classic lowland Maya collapsed between C.E. 800 and C.E. 950 has been particularly intriguing as many city states fell for a variety of reasons from environmental degradation and natural catastrophes to wars and top-heavy political systems (McNeil personal communication, 2015). The Copan Valley has long been thought of as an example of a region that collapsed due to environmental exploitation and degradation (Abrams et al. 1996; Abrams and Rue 1988; Diamond 2005; Rue 1986, 1987; Webster 2002; Webster et al. 2000). Recent research has questioned this view because of a sediment core that shows stable forest conditions and a higher forest to open field ratio than in the Preclassic Period (McNeil 2006, 2009; McNeil et al. 2010). Based on this recent evidence, we believe that the Classic Period collapse was caused by other factors, and that the Maya in this time period were using sustainable agricultural practices.

The Copan Valley consists of five fertile pockets, or relatively flat valley bottoms, that occur in areas where the Copan River overtakes its tributaries and sediments provide fertile soil complexes for agriculture. These pockets are the Copan Pocket (home of the Copan Principal Group), the Santa Rita Pocket, the El Jaral Pocket, The Rio Amarillo West Pocket and the Rio Amarillo East Pocket (Figure 1). This study focuses on the soils of the Rio Amarillo East Pocket which contains the second largest Maya settlement in the region, behind Copan located 17.5 km to the southwest.

While the Maya may have begun to move into the area during the second century A.D. (Sharer 2009), there was no unifying ruler of the region until A.D 427 (Martin and Grube 2008).

By the early ninth century A.D., the city-state of Copan was in a large population decline with its last dated monument appearing in 822 A.D. (Fash 2001). The eventual collapse was manifested with a burning of the Acropolis and Late Classic palace complex (Fash et al. 2004). Originally, researchers thought the collapse was caused by a variety of factors, with environmental degradation as the main cause. It is thought that as the site grew, and there was a higher demand for food for the populace and wood for both fuel and construction resources. As the site grew during the Late Classic, more fertile land was taken up by the urban center and hillsides were deforested for fuel and agriculture. Fallow periods may also have been shortened to provide for short term agricultural needs. These combined factors would decrease soil productivity and leave the area unable to support a large population (Abrams et al. 1996, Abrams and Rue 1988; Fash 2001; Freter 2004; Rue 1986, 1987; Webster 2002; Webster et al. 2000).

The area has also been divided into three pockets: Copan, El Jaral/Sesesmil, and Rio Amarillo (Wingard 1992). In this case the El Jaral and Sesesmil pockets and the Rio Amarillo East and West pockets are combined due to proximity and relative connectedness. Of these three areas, Rio Amarillo has the greatest land area in alluvial deposits and footslopes rather than steep hillsides. The combined Rio Amarillo area is still over 50% steep hillsides. In past erosion models it was assumed that all of the land area would have been in agricultural production with varying fallow periods (Wingard 1996). Recent evidence causes us to question this assumption (McNeil, personal communication 2015).

We tested the hypothesis that ancient farmers cultivated maize on backslopes, footslopes, toeslopes, and seasonal wetland soils in the landscape of the Rio Amarillo Pocket in the Copan Valley. Ancient maize agriculture was determined by analyzing physical, chemical, and stable carbon isotope characteristics of 26 soil profiles and pedons collected along two transects between the sites of Rio Amarillo and Piedras Negras, Honduras. These data will help us understand the environmental history of the valley, and provide evidence of the role environmental degradation played in the Classic Period collapse.

Soil Resources of the Copan Area

The most agriculturally productive soils of the world fall with in the soil orders of Mollisols and Entisols. Mollisols are generally grassland soils with high organic matter in the A horizon and high base saturation which is ideal for nutrient availability. Rendolls are an important type of Mollisols that develop on limestone parent material in tropical forest environments. While not all Entisols are highly productive, those found in alluvial plains, deltas and fans are often high in nutrients and the sandy loams can be quite productive. Many of the Entisols present in the Rio Amarillo and Copan valleys formed this way. Other Entisols in the area formed on the hills and mountains in the region. Both types are and have been important for agriculture in the area (Wingard 1992, 2013).

Mollisols make up less than 10% of the Copan Valley and only occur where there is a limestone outcropping that has reach the surface. These are the only soils in the area that approach a neutral pH and are typically Rendolls (Wingard, 1992). These Mollisols are typically low in nutrients except calcium because of the limestone. The neutral pH optimizes plant uptake of the available nutrients and they are some of the most productive soils in the area. No Rendolls have been observed in the Rio Amarillo East Pocket.

Inceptisols make up a large portion of the remaining soil in the area, but they are less important agriculturally. Ustic and Lithic Dystropepts are the most common Inceptisols found in the area (Wingard, 1992). Dystropepts are Inceptisols that formed in the tropics, usually under deciduous forest or anthropic savannahs which are common in the Copan area. These soils are strongly acidic (pH = 4.7-5.5), have low base saturation and are low in available nutrients. These soils are currently not used for agriculture or are only very moderately used. Wingard (1992) proposed that in ancient times they were likely only used for timber or when the population was very large and the more productive soils were already under cultivation.

Vertisols are another important soil order found in the area, but not mentioned by Wingard. Vertisols are high shrink-swell soils that form in areas with high shrink-swell clays and have seasonal high and low water table. These soils are found in the Copan area and have been used in other Maya areas as agricultural resources (Parker, 2015). Vertisols would need to be well managed, but could provide additional land suitable for maize and other crops.

A vegetative history is recorded in the stable carbon isotopes ($^{13}C/^{12}C$)

Carbon has three naturally occurring isotopes; two of which are stable. The most common isotope is ^{12}C at a natural abundance of 98.9 atom %. Next, ^{13}C accounts for most of the rest at 1.1 atom %. There is <0.1 atom % of the unstable and radioactive ^{14}C on earth's surface. Its radioactive decay can be used for dating of organic materials. Here we will focus on applications of stable isotope ratios to understand past vegetative histories of soils. In atmospheric CO_2, there is a natural abundance ratio of ^{13}C to ^{12}C. When CO_2 is taken up by plants in photosynthesis, there is a shift in this ratio. There is a fractionation event as plant membranes and enzymes discriminate against the heavier ^{13}C. Each photosynthetic process (C_3, C_4, and CAM) has a unique isotopic ratio associated with it. C_3 plants, which make up the dominant native vegetation in the Copan Valley, leave their stomata open throughout the day and discriminate heavily against ^{13}C. Tissues of C_3 plants have a $\delta^{13}C$ of -28 to -26‰ with an average of -27‰. C_4 plants close their stomata during the hot parts of the day to retain moisture. There is less diffusion of air and as photosynthesis uses ^{12}C, the relative concentration of ^{13}C increases. More ^{13}C is used by the C_4 plants, which have less gas exchange with the ambient air. The resulting $\delta^{13}C$ of C_4 plant tissues ranges from-15 to -12‰ with an average of 14‰ (Deines 1980, Smith and Epstein, 1971).

A vegetative history of plant species and their respective photosynthetic processes are recorded in the stable carbon isotopes of the soil organic matter. Over time, changes in vegetation are recorded as ^{13}C values change in the soil organic matter with depth (Boutton et al. 1998). Changes in the dominant vegetation in a landscape can therefore be approximated by analyzing shifts in ^{13}C values with soil depth (Accoe et al. 2002; Bai et al. 2012; Balzotti et al. 2013; Beach et al. 2006, 2009, 2011; Biedenbender et al 2004; Bostrom et al. 2007; Boutton et al. 1998; Burnett et al 2012, Feng et al. 2003; Freitas et al. 2011; Powers et al. 2002; Schweizer et al. 1999; Stinchcomb et al 2011, 2013; Werth et al 2008). Carbon isotope ratios have been used as an ecological indicator of historic vegetation, climate, and soil condition in a region (Wynn et al. 2007). Changes in ^{13}C ratios have been used in a variety of geoarchaeological, paleoclimatological, and paleoenvironmental studies (Beach et al. 2006, 2009, 2011; Pessenda 2008; Stinchcomb et al 2013).

There are various limitations and complications to using carbon isotopes as an indicator of past environments (Bai et al. 2012; Freitas et al. 2001). One of which is diagenesis of the soil organic matter. Just as plants discriminate against the heavier ^{13}C in photosynthesis, soil microbes also discriminate against ^{13}C in decomposition of soil organic matter. Microbial membranes and enzymes discriminate against organic molecules that contain the heavier ^{13}C. As organic material is driven off from the soil as CO2, the ratio of ^{13}C to ^{12}C is increased. This causes the $\delta^{13}C$ value to increase, which is an indicator of a shift in the vegetation from C_3 to C_4. While this poses a potential confounding factor, microbial diagenesis is estimated to enrich $\delta^{13}C$ values by no more than 2.5-4.0‰ (Ågren et al. 1996; Balesdent and Mariotti 1987; Boutton 1996; Cerling et al. 1997).

Ideally, soils from the Maya region would be used as an indicator for microbial $\delta^{13}C$ enrichment in the area because climatic conditions are an important variable in SOM diagenesis (Brunn et al. 2014). Since the year 2000, numerous soil profiles from the Caribbean Islands and Mesoamerica have been analyzed for stable carbon isotopes and the local vegetative histories have been recorded (Parker, 2015). A true understanding of microbial effects on $\delta^{13}C$ enrichment would come from profiles that have not been effected by man or any C3-C4 shifts. This is quite difficult because we are looking for organic matter that is over 1,000 years old in an area that has had various occupations over thousands of years.

The best known place to acquire such a sample from the area is from a perennial spring or an aguada, neither of which would support C4 plants. Aguadas are ancient man-made water reservoirs that were used as a water source during the dry season (Dunning, 2016). Neither of these features were used to grow maize in ancient times so any change in $\delta^{13}C$ values between the surface and subsurface horizons should be the result of microbial activity and not vegetation change (Burnett et al 2012). Two profiles from aguadas at El Kinel, Guatemala showed $\delta^{13}C$ value changes of 0.5‰ and 1.2‰ (Balzotti et al 2013, Table 1). Profiles from Aguada El Duende at Tikal had $\delta^{13}C$ changes of 0.85‰ and 1.54‰ (Burnett et al. 2012b, Table 1). Perennial springs near Aguateca, Guatemala have also been used to measure diagenesis in the area. The change in

$\delta^{13}C$ from those springs was 2.2‰ and 1.8‰ at the 30 to 40-cm depth (Johnson et al. 2007, Table 2). In a study conducted at Ramonal, near Tikal, 98 soil cores were collected and analyzed for $\delta^{13}C$. Seventy percent of the cores came from the urban site center and had changes in $\delta^{13}C$ of less than 2‰. There were 11 samples taken from patios and in between house mounds. The average change in $\delta^{13}C$ for these pedons was 0.8‰ (Burnett et al 2012). These data allow us to modify the estimate of the effects of microbial activity from 4‰ to 2.5‰, which is still conservative for the area (Parker, 2015).

Here, we will attribute any changes in $\delta^{13}C$ below 2.5‰ between the surface and ancient rooting depth to microbial diagenesis. Values between 2.5‰ and 3.5‰ will be considered weak evidence of ancient C_4 vegetation and values above 3.5‰ will be considered strong evidence of ancient C_4 vegetation (Balzotti et al. 2013, Parker 2015, Ulmer 2015).

In past studies in the Usumacinta River Region, slope position played a large role in isotopic signature (Fernandez et al. 2005, Johnson et al. 2006). Near Piedras Negras, Guatemala, moderate signature was found in some foot- and backslope profiles, but the profiles were quite shallow. Additionally, only the A and B horizons (where present) were analyzed for stable carbon isotopes (Fernandez et al 2005). In the “breadbasket” area near Laguneta Lacandón, similar results were found in the soils of the foot- and backslopes (Johnson et al. 2006). In both studies, the moderate to weak signature is accounted for by erosion of the soil and associated organic matter to the lower toeslopes.

In the Maya region, large city centers often did not produce enough food in the immediate surrounding area to sustain the large population. There were smaller agricultural communities with vast areas under maize production that likely supported the large sites. Such was the case at Tikal, with Ramonal being one of the agricultural communities (Burnett et al

2012). It also appears to be the case in The Usumacinta region with Piedras Negras and El Kinel, Guatemala (Balzotti et al. 2012). It is hypothesized that Rio Amarillo and Piedras Negras, Honduras provided additional crops to Copan.

Enrichment in ^{13}C has been found in alluvial, lacustrine, and wetland sediments; however, the interpretation typically requires further pollen, phytolith, or archaeological evidence of agriculture or maize production (Beach et al. 2011; Fernandez et al. 2005; Lane et al. 2004). In the Birds of Paradise, Belize wetland fields studied by Beach et al (2011) there are strong shifts in the ^{13}C isotope ratios in seven of nine of the wetland cores. The surface samples from each profile indicate current vegetation dominated by C_3 plants with a strong shift towards mixed vegetation during the Classic Maya occupation of the area. In the Usumacinta River sediments there is strong C_3 signature in the top 60 cm where there are also no artifacts. Below 60 cm, there are pot sherds and other markers of ancient Maya activity that match up with a shift in carbon isotope ratios to mixed vegetation (Fernandez et al. 2005). The ratio of ^{13}C was also enriched at Laguna Zoncho and Machita swamp, Costa Rica and maize cultivation was confirmed by pollen in the same cores (Lane et al. 2004). Because maize pollen is larger and heavier than most other pollen, its presence in these cores indicates that it was likely grown close to the water. If maize pollen is not found in sediments, it does not necessarily mean that the signature does not come from maize, the pollen may not have been transported as far as the SOM that carried the signature.

Many ancient Maya political centers and permanent settlements were located in close proximity to bajos, which are a type of wetland depression (Bullard, 1960; Dunning et al. 2002). Near the site of Tikal, Guatemala, the bajo edges had some of the highest potential for ancient maize production based on a model that used soil data, elevation, slope, and Landsat imagery to predict $\delta^{13}C$ enrichment (Balzotti et al. 2013). In Belize, several studies have shown evidence of wetland agriculture through drained fields, some of which include visible canals (Beach et al. 2003; Beach et al. 2006; Beach et al. 2009; Beach et al. 2015; Dunning et al 1998; Dunning et al. 2002; Jacob 1995; Luzzadder-Beach and Beach 2009; Sluyter 1994). This evidence has led to a "New Orthodoxy" (Rice and Culbert, 1990) that these wetland and bajo soils were an important agricultural resource for maize (*Zea mays*) production. However, not all wetlands and bajos seem to have been used. Siemens and Puleston believed there were raised fields and canals in the Petén based on aerial photographs and radar, but they were later shown to have been mistaken (Pope and Dahlin 1989; Siemens and Puleston 1972; Sluyter 1994). While Siemens and Puleston were mistaken, a recent study has shown that the bajos surrounding Tikal may have been used for maize agriculture (Parker, 2015).

The primary objective of this study was to determine whether a mass soil erosion event around 800 A.D. occurred which could have caused crop failure and famine or if stable soil conditions persisted in the Rio Amarillo East Pocket during the Classic Maya collapse. Our specific objectives were to examine the soil chemical and physical properties and to determine the ancient vegetative histories of soils used in maize agriculture.

MATERIALS AND METHODS

Sampling

Soil samples were collected from a major transect that started at the terraced ruins at Rio Amarillo and extended North through the Rio Amarillo valley to the far side of Piedras Negras and from a minor transect running between groups of house mounds in an adjacent wetland. Soils were sampled at 15 cm depth increments from profiles already exposed from airport construction or by bucket auger when no exposed profile was available. Samples were taken to the depth of bedrock, 2m, or where high water table impeded the ability to take an uncontaminated sample, whichever occurred first.

Preparation

All samples were air dried and aggregates were crushed to pass through a 10 mesh (2mm) sieve. Additionally, 5g subsamples were ground to pass through a 60 mesh (0.25mm) sieve.

Analyses

Taxonomy

All soil profiles were analyzed and classified to the great group by the USDA Keys to Soil Taxonomy (2015) classification method.

Carbon Isotopes

All soil samples were analyzed for delta ^{13}C and classified for "C4 strength according to the Johnson et al. method (2007). The humin fractions of the soil organic matter is the most sensitive to ancient vegetation changes so the humic and fulvic acids were extracted by the Webb et al. method (2004) as adapted by Wright et al. (2009).

Particle Size with Blendtek Blenders

All samples were analyzed for texture using the hydrometer method (Gee and Bauber, 1986). 50g of soil were weighed out and poured in a blender jar. 25 mL of 1 N sodium hexametaphosphate and 500 mL of water were added. Each sample was blended for one minute, three times with a five minute resting period between each blend. The resting period prevents the suspension from heating and provides more time for the sodium to bind to sites on the soil particles. After blending, the suspension was poured into a 1L Bouyouocos cylinder and brought up to volume. The cylinder was stoppered and inverted for 20 seconds. A hydrometer was placed in the suspension and the hydrometer and temperature readings were taken 40s and 2hr after the inversion. The hydrometer reading was corrected with the temperature reading as indicated in the Gee and Bauber (1986) method.

DTPA Extractable Metals

Metallic ions (Fe, Mn, Pb, Cu, and Zn) were extracted using DTPA (diethylenetriaminepentaacetic acid) chelate extractant (Lindsay and Norvell, 1978). Ten grams of soil were placed in 50 mL Oak Ridge type centrifuge tubes with 20 mL of 0.005M DTPA which was buffered at pH 7.3. Each sample was shaken for 2 hours, and then centrifuged for 20 minutes at 9,000 rpm. The supernatant was filtered into a clean vial and analyzed by ICP-AES (inductively coupled plasma - atomic emission spectrometer).

Mehlich II Phosphorus

Phosphorus levels were determined using the Mehlich II extraction method (Terry et al. 2000). 2 grams of crushed soil (10 mesh) were added to vials with 20 mL of Mehlich II extractant and shaken for 5 minutes. All samples were filtered, and 1 mL was then pipetted into a colorimeter vial and brought to 10 mL with deionized water. PhosVer 3 Reagent (Hach Company, Loveland, CO) was added and the solution was shaken for one minute. Each sample sat for 4 minutes to allow color development. Samples were analyzed with a Hach DR/850 Colorimeter. The percent transmittance function at a wavelength of 690 nm was measured by the instrument. A standard curve was produced by analyzing standard solutions with known phosphorus concentrations.

Soil Color

Soil color was evaluated using Munsell Color charts on wet and dry soils. Colors were obtained for redoximorphic features found in the soil. Measurements were taken by one individual in shaded natural light. Soil color was determined on sunny days in the late spring and early summer for consistent light.

Soil pH

Soils were saturated by adding equal parts by mass of water to the soil and thoroughly mixing which created a 1:1 ratio of soil to water by mass. The mixture was allowed to sit for one hour; then the pH was determined with a glass electrode and pH meter.

Total Carbon and Nitrogen

Total carbon and nitrogen was determined on a LECO C and N determinator by the BYU Environmental Analytical Laboratory. Soil samples were weighed out into tin foil pouches and loaded into an auto-dispenser. When each sample was dispensed, the combustion chamber was purged to remove any atmospheric CO_2 and N_2. The sample was then combusted and amounts of CO_2 and N_2 generated were analyzed and used to determine the total amounts of carbon and nitrogen in the sample.

RESULTS

In this study, 26 soil profiles from the Rio Amarillo Pocket of the Copan Valley, Honduras were analyzed to gain further insight into ancient Maya agriculture and their soil resources. The physical and chemical characteristics of these soils are shown in Tables 1, 2, and 3. As part of this endeavor, all soil profiles were classified according to the USDA soil taxonomic system. The carbon isotope record was also analyzed to determine where vegetation shifts occurred. In these agricultural systems there is evidence of a shift from forest to cleared agricultural land, and then a shift back to forest after the collapse of the Classic Maya. Nineteen of the profiles were collected on a North-South transect between the sites of Rio Amarillo and Piedras Negras. Five additional profiles were taken from a transect that runs from south to north between groups of house mounds in a field to the east of the transect between Rio Amarillo and Piedras Negras, and the final profile was taken near the bank of the Rio Blanco approximately 0.5 km northwest of Piedras Negras. Profiles from the transect between Rio Amarillo and Piedras Negras will be referred to as RA 0-19 and the profiles from the East Transect will be referred to as ET 1-5 (see Figure 2). Both transects were oriented in a north - south direction.

The acidic soil resources in this area are not ideal for agricultural production, but manageable. The average pH of surface soil horizons was 4.8. Selected soil physical and chemical properties of the soils are listed in Tables 1, 2, and 3. The soils in this region are very clayey, with textural classes ranging from Sandy Clay Loam to Clay. The clay content ranges from 23% to 87% with an average of 58%. The Mehlich II extractable phosphorus ranges from 5.97 ppm to 12.43 mg/kg with an average of 7.14 mg/kg. Soil organic matter ranges from 0.15% to 9.58% with an average of 4.45%.

Inceptisols and Entisols make up the bulk of the soil profiles in the region with 11 and 7 profiles respectively being of these orders. Five profiles were Vertisols and three were Ultisols. While the Inceptisols and Entisols have more available resources for crop production, all five of the Vertisols profiles show evidence of ancient maize agriculture.

In the Rio Amarillo East Pocket, 9 of the 26 profiles showed no carbon isotope evidence of an ancient change in vegetation from C_3 forest plants to C4 vegetation associated with maize agriculture. The average $\delta^{13}C$ change from the surface to the ancient root zone of about 30 to 45 cm deep in these 9 profiles was 1.12‰. Four profiles showed weak evidence of a C_4 vegetation change with an average $\delta^{13}C$ change of 3.13‰. The remaining 13 profiles showed strong evidence of ancient maize cultivation with an average $\delta^{13}C$ change of 5.90‰.

The amount of carbon from C_4 vegetation can be calculated from isotopic data by rearranging the Nordt equation (2001) which has the form of a mixing line and is as follows:

$$C_{C4} = ({}^{13}C_{SOM} - {}^{13}C_{C3})/({}^{13}C_{C4} - {}^{13}C_{C3})$$

From the data derived from this calculation, we notice some interesting trends in the profiles. Firstly, all profiles show at least 18% C from C_4 plants in the ancient maize rooting zone depths (45-60cm). This indicates mixed vegetation and presents a potentially confounding factor. This may mask C_4 signature, but is unlikely to produce a false positive because of the shift of 2.5 ‰ $\delta^{13}C$ necessary to indicate C_4 agriculture. The profiles taken near the river banks contain sediments from the watershed that likely provide an estimate of the average C from combined C_3 and C_4 plants in the area. On average 33.5% of C contained in the SOM of these two profiles was derived from C_4 plants. The SOM of profiles of profiles RA10-RA19 (or the profiles closer to Piedras Negras contained an average of 56.3% of organic C derived from C_4 plants while profiles RA0-RA9 contained an average of 38.9% carbon from C_4 plants.

Rio Amarillo Terrace

RA 0 was examined and collected at the site of Rio Amarillo from an elevated terrace. The terrace was built in ancient times and was under native vegetation until the land was cleared a few years ago to plant coffee. It is too small of an area to have grown a staple food crop for the site. The plants grown here may have been used for ceremonies in the site center. The soil is over 2m deep and is mostly homogeneous in color. The top 75 cm are 5 YR with a value of 4 and chroma of 3. From 75-205 cm, the soil is 5 YR with a value of 5 and chroma of 4. The color change is associated with the increased average clay content from 41.6% in the A and AB horizons to 55.5% in the Bt horizon (see Table 1 for all texture data). The pH is consistent throughout the profile with an average of 4.64. The soil is classified as Ultisols in the USDA classification system because of the deep argillic horizon, low base saturation and low shrink-swell clay.

The change in $\delta^{13}C$ from the surface to the ancient rooting depth (45-60 cm) is 0.89‰ (see Figure 3). The terrace was almost certainly not used to grow ceremonial maize, but may have been used to grow fruit or vegetable crops. Further soil testing for additional biomarkers could be done to determine the use of this peculiar terrace above the site center.

Wetland Soils

According to the EPA, "wetlands are areas where water covers the soil, or is present either at or near the surface of the soil all year or for varying periods of time during the year, including during the growing season". By this definition, profiles RA4, RA10, RA14, RA15, RA17, ET2, and ET3 are all from wetlands. All seven profiles exhibited mottling and were wet at the time of sampling. They are all covered in wetland vegetation, and locals said that those areas are often flooded during the rainy season. The pH of these soils ranges from 4.03 to 5.79 from the surface through the ancient rooting zone to a depth of about 60cm. Individual pH values are listed in Table 2. The wetland soils are very clayey with textural classes ranging from sandy clay to clay. These soils have an average clay content of 59%.

All of the wetland profiles showed strong evidence of vegetation change from C_3 to C_4 plants associated with ancient maize cultivation (see Figures 4 and 5). The change in $\delta^{13}C$ with depth in these profiles ranges from 4.28‰ to 7.85‰ (see Table 2) with an average of 5.79‰. Within the root zone of 45 to 60 cm, approximately 47% of the organic C was derived from C_4 plants. This would indicate that anciently, these wetlands were used for C_4 plant cultivation, including maize, during at least part of the year. Seasonal flooding may affect the growing season for wetland fields, but other studies have discussed the likelihood that the bajos and other wetlands were used for maize cultivation. This suggests multiple croppings would have been used as the wetlands would have been flooded during the normal upland growing season. The wetland soils would only have been used during the dry season. (Beach et al. 2003; Beach et al. 2006; Beach et al. 2009; Beach et al. 2015; Dunning et al. 1998; Dunning et al. 2002; Jacob 1995; Luzzadder-Beach and Beach 2009; Parker 2015).

Hillslope Soils

Profiles RA11 and RA19 were taken from footslopes of hillsides in the transect from Rio Amarillo to Piedras Negras. Profile RA12 was taken from the shoulder of the same hill as RA11. Profile RA16 from was taken from the backslope of a hillside. Profile 0 was taken from the backslope of the hill at the site of Rio Amarillo and was previously discussed. Profiles RA11, RA16, and RA19 all have a depth of greater than 165 cm, which would indicate that they have not been severely eroded in the past 1200 years (Table 1). Profile RA12 only extends to 75 cm and likely experienced mild erosion during the rainy season due to the steep slopes. Profiles RA11 and RA16 are clayey throughout their A and B horizons. Profiles RA12 and RA19 range from clay loam to clay. Although these soils are highly sloped and susceptible to erosion, they have a very high percent clay. The pH of these soils is acidic like the surrounding soils with an average of 4.3. The SOM ranges from 2.4% to 7.7% with an average of 4.86%. Profiles RA11, RA16, and RA19 were all classified as Inceptisols, and RA12 was classified as an Entisols.

The changes in $\delta^{13}C$ for profiles RA11, RA16, and RA19 were 6.94‰, 6.17‰, and 6.48‰ respectively (Table 1). These soils also have 64%, 39%, and 52% C from C_4 plants respectively. All three footslope profiles exhibited strong evidence of ancient maize cultivation and may have been used during both the Preclassic and Classic occupations. For profiles RA11 and RA19, the slope is less than 10% and the soils are well developed which indicates that these soils were well managed when under production. RA16 has a slope of 20%, but is still well developed with a Bt horizon. The soil extends over 2m in depth. There was no visible evidence of terraces or other erosion control factors, but proper management was likely in place to preserve this soil from major erosion events.

Profile 12 has a $\delta^{13}C$ change of 3.11‰ which provides weak evidence of maize cultivation (see Figure 3). It is on a steep shoulder slope and would be susceptible to erosion. If we consider that soil forms less slowly on the shoulder and adjust the ancient rooting depth accordingly, the change in $\delta^{13}C$ is reduced to 2.55‰. This is still weak evidence for maize cultivation during the Maya occupation. Either in the Preclassic or Classic occupation there was a point in which this entire hill was likely under maize cultivation. However, there was no charcoal or other evidence to differentiate between the two periods. It may be that it was only cultivated at one of those times, or that it was cultivated in both periods. There was no evidence in the surrounding profiles of a singular massive erosion event, however the soil may have degraded due to small erosion events if this hillside was repeatedly cleared for agriculture.

Profiles Near Settlements and Other Toeslope Soils

Soil profiles in and around settlements have been analyzed for $\delta^{13}C$ in a number of studies (Johnson et al. 2007, Burnett et al. 2012a, Burnett et al. 2012b, etc.). In this study, five profiles (excluding the terrace sample, which was previously discussed) were taken in relatively close proximity to either house mounds or a site center. Profile ET1 was taken just northeast of a group of house mounds. Profiles ET4 and ET5 were taken on opposite sides of another group of house mounds in the same transect. Profiles 18 and 19 in the transect from Rio Amarillo to Piedras Negras were taken on the south and north sides respectively of the site Piedras Negras.

Profiles ET1 and ET4 showed no evidence of C_4 plant cultivation (see Figure 8) while the profiles in the wetland between them indicate strong evidence of C_4 plant cultivation (see Figure 5). However, the $\delta^{13}C$ in the upper 75 cm of ET1 and ET4 ranges from -23‰ to -17‰, which is indicative of mixed C_3 and C_4 vegetation. ET1 and ET4 have 51.4% and 39.5% C from C_4 vegetation. It is therefore difficult to conclude whether this indicates mixed native vegetation or signature from C_4 crops. Profile ET5 shows strong evidence and is located northeast of both groups of house mounds. The data from these profiles indicates that there seems to be a small buffer zone between house mounds and the agricultural fields. This supports evidence found in other studies in the Maya area (Balzotti et al, 2013; Burnett et al, 2012; Johnson et al, 2007). There are typically patios or living spaces around groups of agrarian house mounds where household activities would have taken place. These two profiles fall into that category rather than agricultural soils. These soils are both classified as Aquic Ustorthents (Table 3).

Profiles RA18 and RA19 show varying results, however they are not equidistant from the center of Piedras Negras. RA18 was taken south of the site. RA19 was taken north east of the site and on the toe slope of a hill. Profile 19 shows strong evidence of C4 plant cultivation. RA19 also shows higher levels of phosphorus which is an essential plant nutrient. While data is lacking to completely understand what, if anything the ancient Maya were doing at all of these points, it seems that was typically space around homes and activity areas where crops would not have been grown for a number of possible reasons. Presence or absence of C_4 plant signature is not solely dependent on the soils ability to support crop growth, but is also dependent on the choice of the inhabitants to grow crops there.

Other profiles in the valley bottoms had varied results. Profile RA1 displays no evidence of forest clearing for C_4 crops, and RA2 shows strong evidence (see figure 6). RA1 is located near the bank of the Rio Amarillo, so that land may have been used for ancient agriculture if the $\delta^{13}C$ signature is masked by carbon deposited from alluvial sediments. This pedon has a significantly higher pH than most pedons in this study. The average pH for RA1 is 6.16 while the other 25 profiles have an average pH of 4.75 (Tables 1, 2, and 3). There is likely limestone upstream in the Rio Amarillo watershed causing these alluvial deposits to be less acidic than the surrounding soils.

RA3 and RA6 displayed no characteristic shift of a change to C_4 vegetation, however, the current vegetation in this area is mixed C_3 and C_4 vegetation, and therefore the signature may be masked. It is difficult to conclude whether the $\delta^{13}C$ values throughout the upper 45 cm are from only from native vegetation, or if C_4 plants were also cultivated here. RA7, RA9, and RA13 displayed weak evidence of C_4 vegetation (see Figure 7). These profiles also have a high surface $\delta^{13}C$ value at -23.95‰, -23.19‰, and -19.08‰ respectively. The signature here may partially be masked by native vegetation as well. RA8 and RA10 show strong evidence of a shift to C_4 vegetation (see Table 3).

DISCUSSION

In this study, we were able to confirm the importance of the agricultural resources near Rio Amarillo and Piedras Negras in support of populations in the Copan Valley. Much of the available land in this valley was used for C_4 agriculture. We also found soil horizon development including deep A horizons and intact B horizons in footslope and summit soils that would indicate that these soils have been intact since some time before the Classic Period collapse. While the soils show some signs of degradation, the deterioration is not extreme enough to explain the total collapse of the local city-states as proposed in other studies (Abrams et al. 1996; Abrams and Rue 1988; Diamond 2005; Rue 1986, 1987; Webster 2002; Webster et al. 2000). RA12 and RA19 have lower clay content and higher sand content than the surrounding soils (Table 1). RA12 is also a thin pedon with only 70 cm of depth while all other pedons extended over 100cm. While these are signs of erosion, they characteristic of natural hillslope erosion and do not provide evidence of a mass erosion event. The data collected in this study supports the notion that a variety of factors led to the overall collapse of the Classic Maya in this area (McNeil 2006, 2009; McNeil et al. 2010).

Footslope and Summit Soils

Footslope and summit soils are key indicators to understanding the role of soil erosion and environmental degradation in the demise of the Classic Maya in the study area. These are the most erodible soils and soil losses may have buried or damaged crops down the slope. The footslope soils all show strong isotopic evidence of maize cultivation while the summit profile shows weak evidence. The summit profile's signature may have been partially eroded with the soil if it was used anciently for agriculture.

The summit soil profile (RA12) shows only weak signature of C_4 agriculture and while this may be due to erosion, several factors indicate that it is unlikely that the signature eroded. These factors include the $\delta^{13}C$ values, the soil depth, soil formation rates, and texture analysis of surrounding soils. The $\delta^{13}C$ for shows a slight increase with increasing depth which is natural from microbial discrimination. Diagenesis would not be visible in a recently formed soil. This profile is also fairly deep for a summit soil at 75cm. With a soil formation rate of approximately 0.08 to 0.1mm yr^{-1} or 8 to 10cm yr^{-1} (Fernandez, 2005, Beach, 1998a; Ford and Williams, 1989; Jennings, 1985) and considering a summit undergoes constant erosion with no deposition, this soil would have had to be at least 65cm deep after the erosion event. This is unlikely for a summit soil that would likely have experienced severe erosion in the Middle and Late Preclassic (McNeil, 2011). In the surrounding toeslope soils, there is evidence of erosion in Profile 14. There is a 5% increase in sand and 7% increase in silt that would likely have come from this hill, however, it is at a depth (75-90cm) that would indicate an earlier erosion event such as in the Preclassic period. The $\delta^{13}C$ value also decreases at that point in RA14 and is similar to current topsoil which indicates that maize isotopic signature did not erode in that event (see Tables 1 and 2).

While the footslope soils were used for agriculture, this does not imply excessive soil erosion or degradation. Sustainable practices may have, and likely were used. The Maya typically use swidden agriculture and plant by opening small holes in the soil and placing a few seeds in each hole. This minimizes soil disturbance and protects the surface from erosion until there is sufficient cover. The footslope soils are of a depth greater than 2m, and show horizon development that would indicate a long formation period with relatively little horizon disturbance. All of the footslope soils are in the taxonomic class of Inceptisols and have a Bt horizon (See Table 1). While there is inevitably some erosion from sloped soils, there is no evidence of a Classic Period mass erosion event, which will be further discussed later. RA12 is only 70 cm in depth and is only an A horizon over a C horizon and has significantly less clay and silt than the surrounding soils. In the top 60 cm, RA12 has an average 39% clay and 21% silt while Profile 13 has 60% clay and 36% silt. This indicates that there has been some erosion of the finer soil particles; however, this seems to be natural erosion from topography. The summit soil still has a well-developed A horizon and there was no depositional layer of high sand and gravel content found in surrounding soils to indicate a mass erosion event.

While some of the organic matter may have eroded, the more likely cause for such a weak signature is that the summit soil was likely used less. The Classic Maya seem to have understood that these soils were not ideal for agriculture and used them minimally. Unfortunately, there was no visible evidence of any erosion control practices, but the ancient Maya in this area seem to have used some technique to keep these sloped soils intact while farming them.

Wetland Soils

Wetland soils provide additional land that could be used for agriculture, particularly during the dry season. Seven of the profiles collected in this study were from soils that have standing water during at least part of the rainy season. All of these profiles show strong evidence of maize agriculture. While it is still not known exactly how the Maya used wetland or *bajo* soils, several studies have shown evidence of wetland cultivation (Beach et al. 2011; Fernandez et al. 2005; Lane et al. 2004; Parker, 2015). These soils greatly expand the cultivable land area in the Rio Amarillo East Pocket and may have been vital in sustaining the population of the local city-states. Multiple cropping seasons with the use of wetland soils may have helped support the large population centers, particularly in years where upland yields were low.

Folan and Gallegos (1992) have noted that in the area near Calakmul, in years when upland yield is insufficient, farmers will plant a "tornamil" or second planting in the bajos during the dry season. This allows them to harvest a second time during the year, and from soil that hadn't been used yet. Farmers will raise areas of soil in the wetland and plant the maize in the raised soil which helps prevent flooding. If water levels are low, they will also plant in the depressions. This agricultural technique may have been used in the wetlands near Rio Amarillo and Piedras Negras.

It is unlikely that the carbon isotope signatures for maize cultivation in these soils resulted from erosion of the upland soils. There are no characteristic changes in gravel content, courser soil textures, or any other measurable signs of soil erosion or deposition within the 23 soil profiles and pedons. Pedogenesis within the soil horizons is suggestive that the carbon isotopic signatures were developed where the soil now rests. Critics may also argue that the wetland vegetation naturally shows higher $\delta^{13}C$ values and that may contribute to the shift. However, in these soils, the surface horizon $\delta^{13}C$ values were at or below the average for the area. The shifts in carbon istotope ratios are also sufficiently large (in the range of 4.48‰ to 7.85‰) that microbial diagenesis or other factors were insignificant and only changes in vegetative histories were responsible. While high clay content and periodical saturation make the soil difficult to work with it seems that these large areas were indeed used for maize cultivation.

Profiles Near Settlements and Other Toeslope Soils

The toeslope soils provide interesting insight to agriculture in the area. Only 8 of the 15 profiles collected showed evidence of maize agriculture which is quite surprised based on the high percentage of footslope soils used for agriculture. The location of the toeslope samples provides further insight to why maize signature was not found in 7 of the profiles.

Two of the profiles were collected near rivers and it is quite likely that deposition of alluvial materials during flooding masked the maize signature. An alternative hypothesis is that the ancient Maya did not farm that close to the rivers; however, with the high fertility of these soils, the former is more likely.

The terrace sample at Rio Amarillo (RA0) showed no signature of C_4 vegetation. This terrace would not have been able to produce a large amount of maize, but we hypothesized that it may have been used to produce high value crops for rituals such as cacao. As no signature was found, the more likely alternative is that it would have been used for specialty crops or a botanical garden.

There are also three samples that were taken in close proximity to settlements. RA18 was taken from a field near Piedras Negras and ET1 and ET4 were taken near groups of house mounds. RA18 was taken approximately 200 meters from the Piedras Negras site center and this area may have been used for other purposes than agriculture. Profiles 1 and 4 from the East transect were taken within 15 meters of house mounds. Just as modern farmers have patios and living space between their homes and their fields, so did the ancient Maya farmers. This aligns with data from studies at other Maya sites (Burnett et al, 2012; Johnson et al, 2007).

Profile RA5 showed abnormal results. From the surface to 15-30cm the $\delta^{13}C$ values shift from mixed to C_3 signature. The increased $\delta^{13}C$ in the surface sample is likely due to modern contamination, so the sample from 15-30cm will be used as the base for calculating a shift in $\delta^{13}C$. From this reference point to the 45-60cm sample, there is a shift of 6.78‰ towards C_4 vegetation. The sample at 60-75cm gave a $\delta^{13}C$ value far below the range of C_3 and C_4 vegetation. It appears an errant result and will not be used in this study.

The remaining toeslope profile that does not display evidence of ancient C_4 vegetation is RA6. The $\delta^{13}C$ is high (-22.5‰) in the surface sample and remains high (above -23.0‰) through 120cm (Table 3). This indicates a mix of C_3 and C_4 vegetation over many centuries. If maize was grown here, the signature would likely be masked, therefore it is difficult to conclude if this pedon was used for ancient maize production.

CONCLUSIONS

Previous studies of the Copan, Honduras archaeological sites have used this area as a model for environmental degradation as the cause for societal collapse. These studies claimed that this degradation led to crop failure, famine, unrest, and the eventual abandonment of the area (Abrams et al. 1996; Abrams and Rue 1988; Diamond 2005; Rue 1986, 1987; Webster 2002; Webster et al. 2000). After analysis of the soil resources of Rio Amarillo and Piedras Negras, two auxiliary sites to Copan, it appears that there would have been better agricultural resources available during the Classic Period collapse than previously thought.

This study has shown that additional soil types in the area, including wetland soil, were used for agricultural production, which would have increased the total crop production. The hillslope profiles retained isotopic signature, and there was no evidence of depositional layers high in sand and gravel in the surrounding foot and toeslopes. Together, these factors refute the mass erosion event theory for the Classic Period demise because in other sites where these erosion events have occurred, the signature was removed from the hillslopes. Instead, we propose that the Maya in the area used sustainable agricultural practices. Other factors such as warfare and political unrest are becoming the leading theories for the demise based on recent evidence (McNeil, personal correspondence, 2015).

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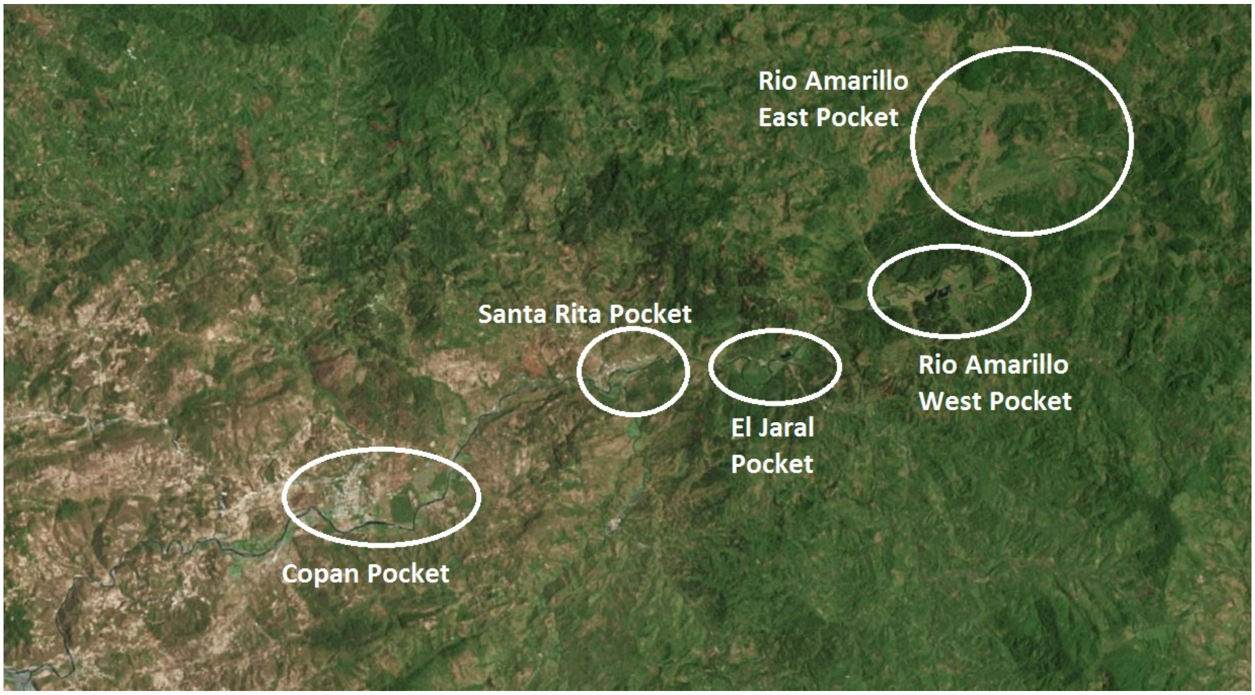

Figure 1. The five agricultural pockets in the Copan area are displayed. The study area was in the Rio Amarillo East Pocket.

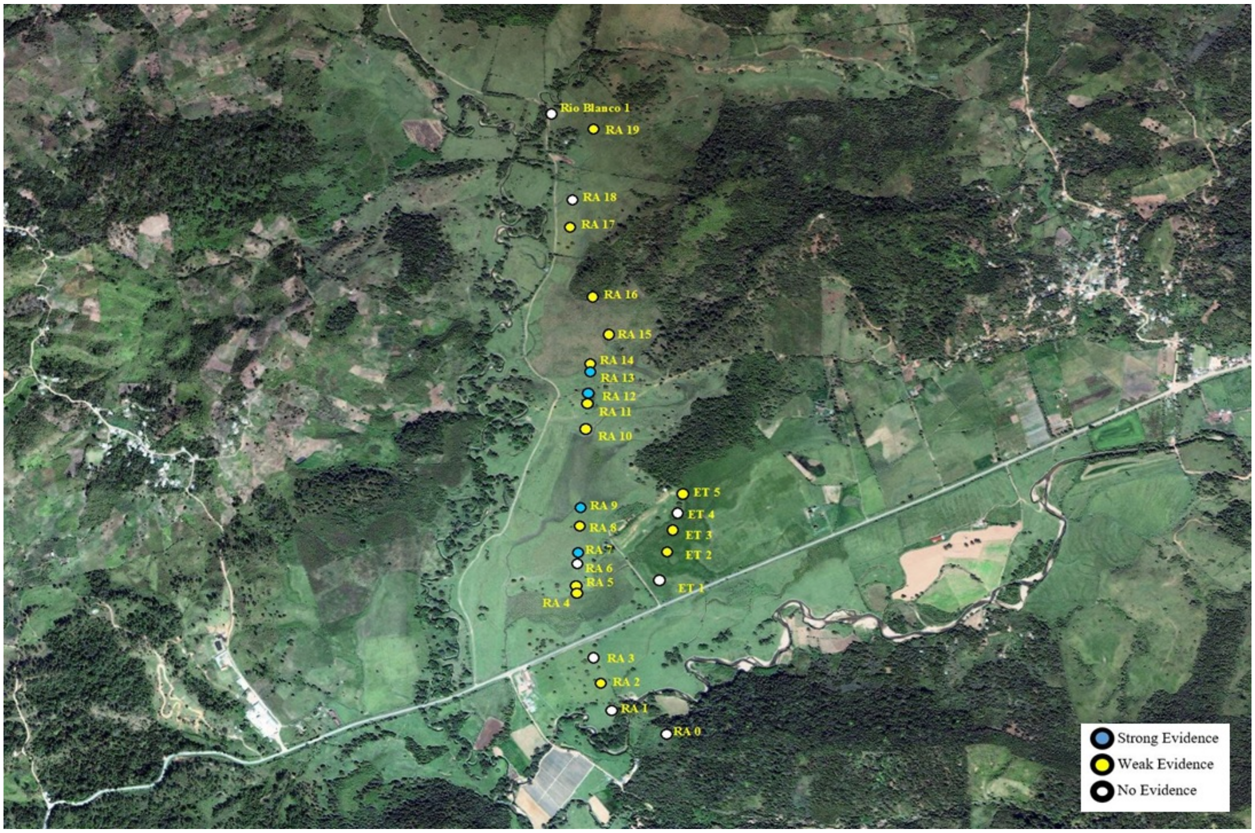

Figure 2. The locations of the soil profiles in the Rio Amarillo West Pocket. RA designates the transect from Rio Amarillo to Piedras Negras. ET designates the profiles taken in the shorter transect to the east.

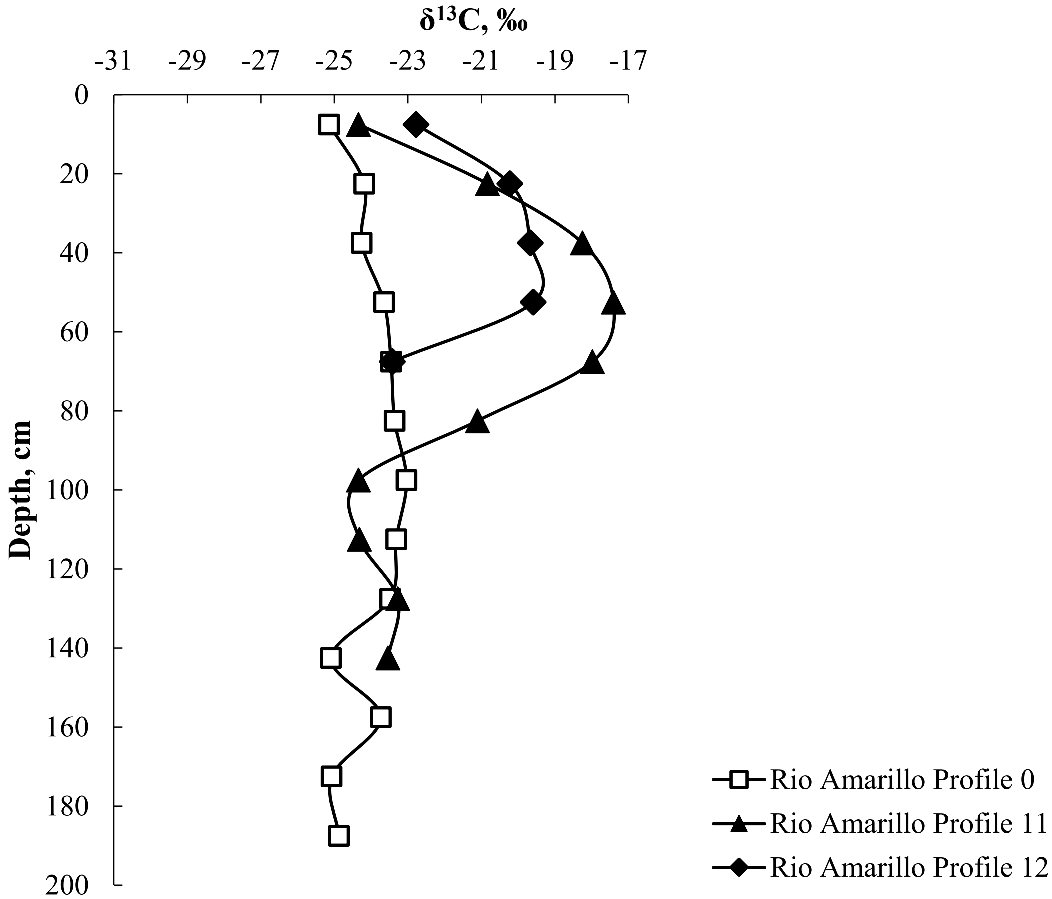

Figure 3. The changes in $\delta^{13}C$ vs Soil Depth for the summit, backslope, and footslope soils. RA11 displayed strong evidence of C_4 vegetation, while RA12 showed weak evidence and RA0 did not display evidence of C_4 vegetation.

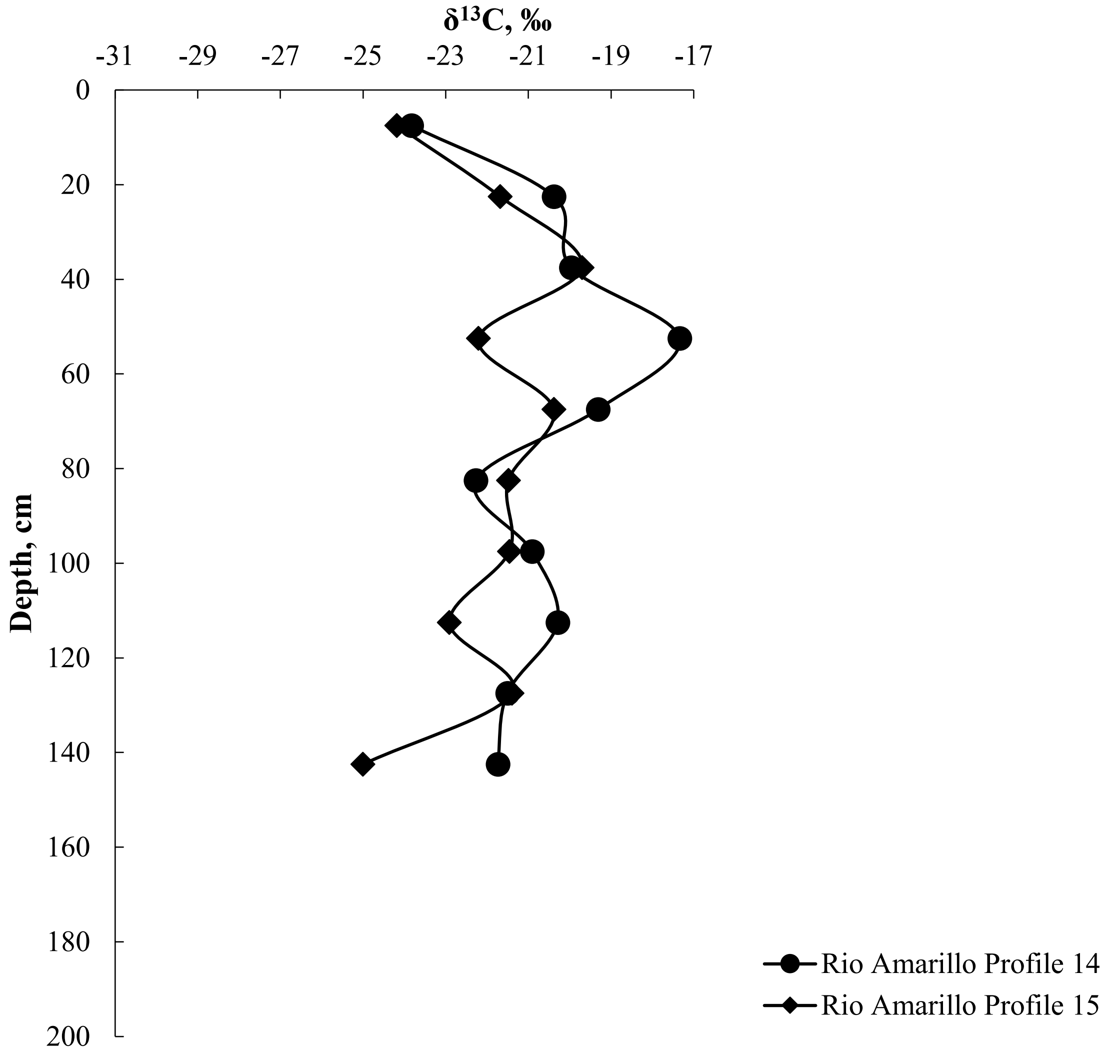

Figure 4. The changes in $\delta^{13}C$ vs Soil Depth for select wetland soils. All of the wetland profiles show strong evidence of ancient C_4 vegetation.

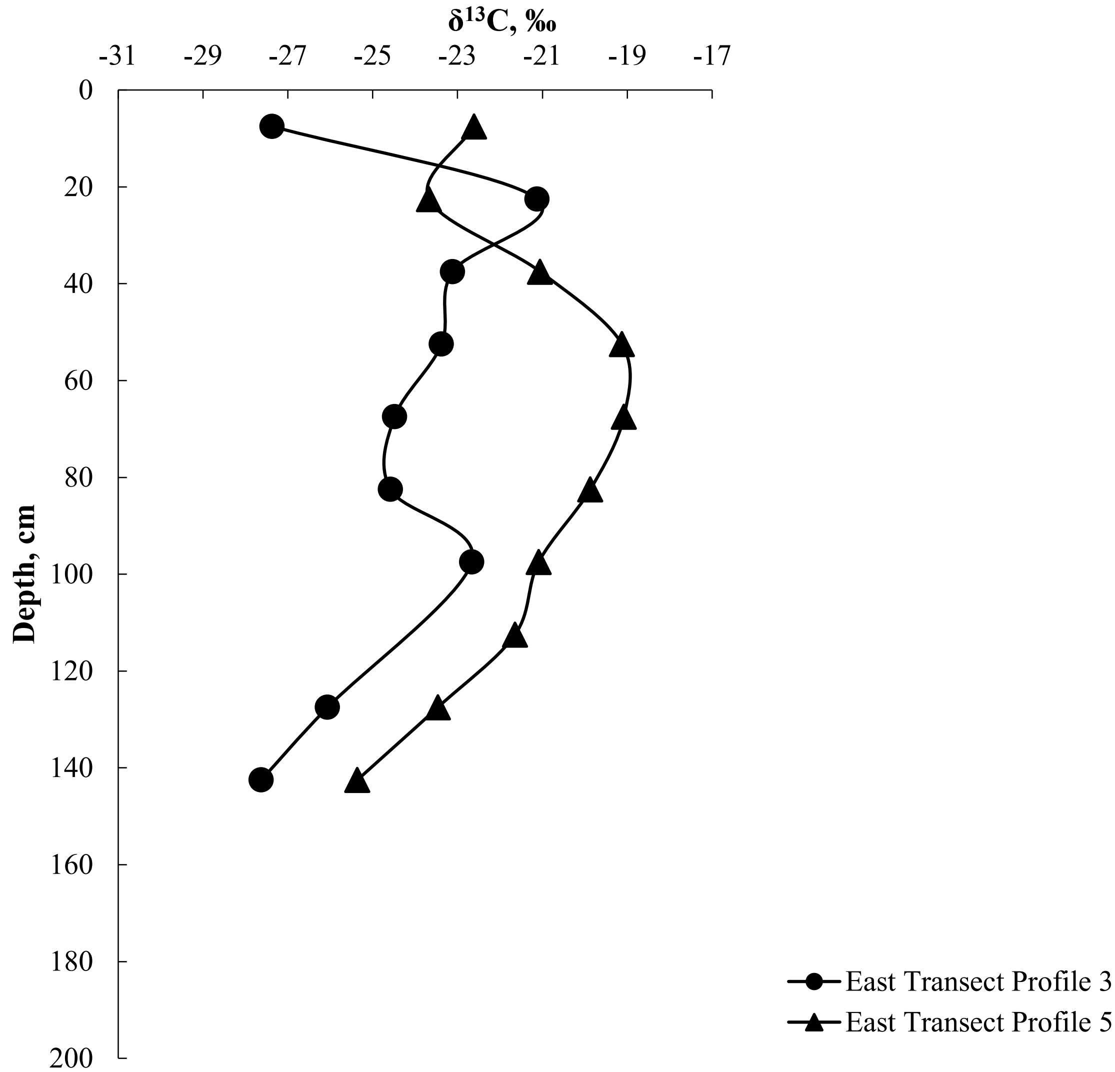

Figure 5. The changes in $\delta^{13}C$ vs Soil Depth for select wetland soils from the East Transect. All of these profiles show strong evidence of ancient C_4 vegetation.

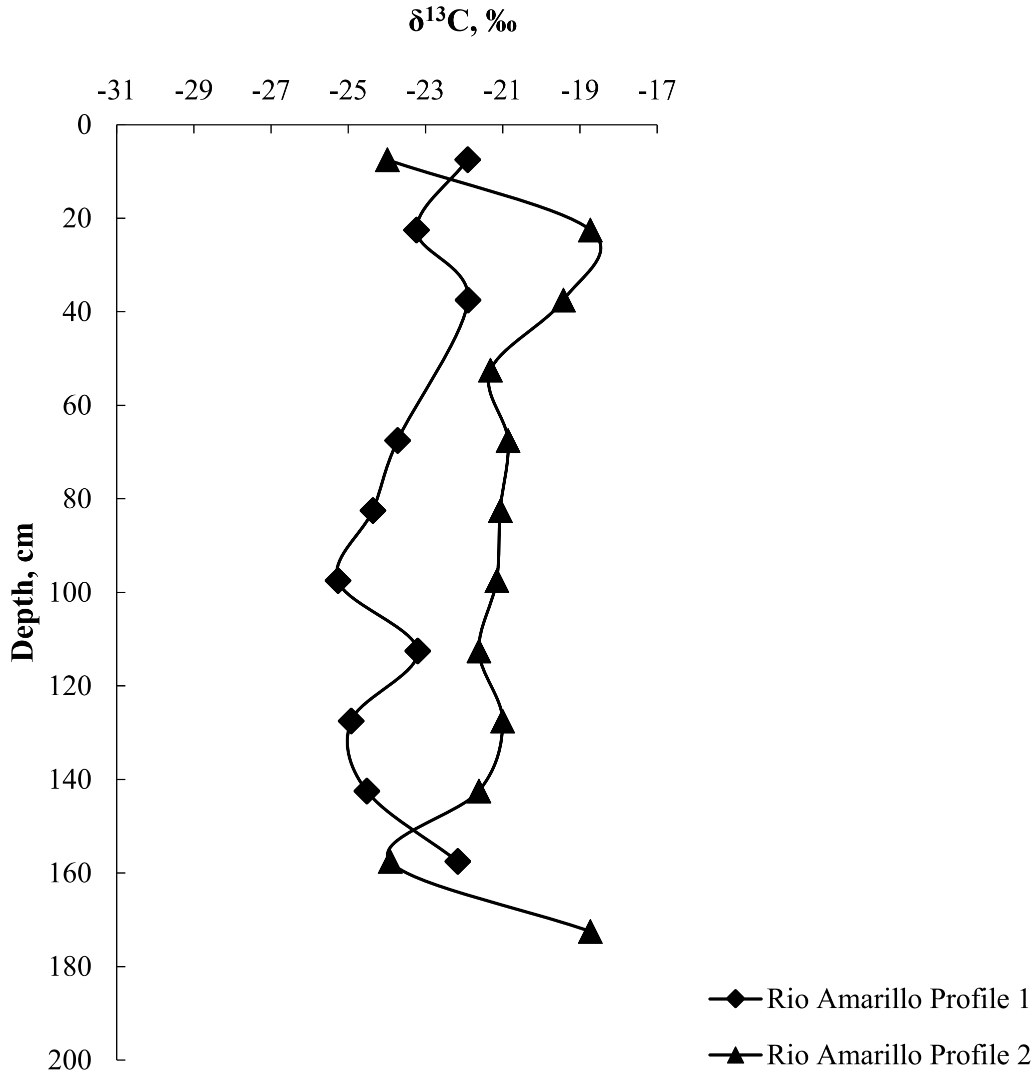

Figure 6. The changes in $\delta^{13}C$ vs Soil Depth for select toeslope soils. Profile RA1 displays no evidence of forest clearing for C_4 crops, and Profile 2 shows strong evidence. Profile 1 is located near the bank of the Rio Amarillo, so that land may have been used for ancient agriculture if the $\delta^{13}C$ signature is masked by carbon deposited from alluvial sediments.

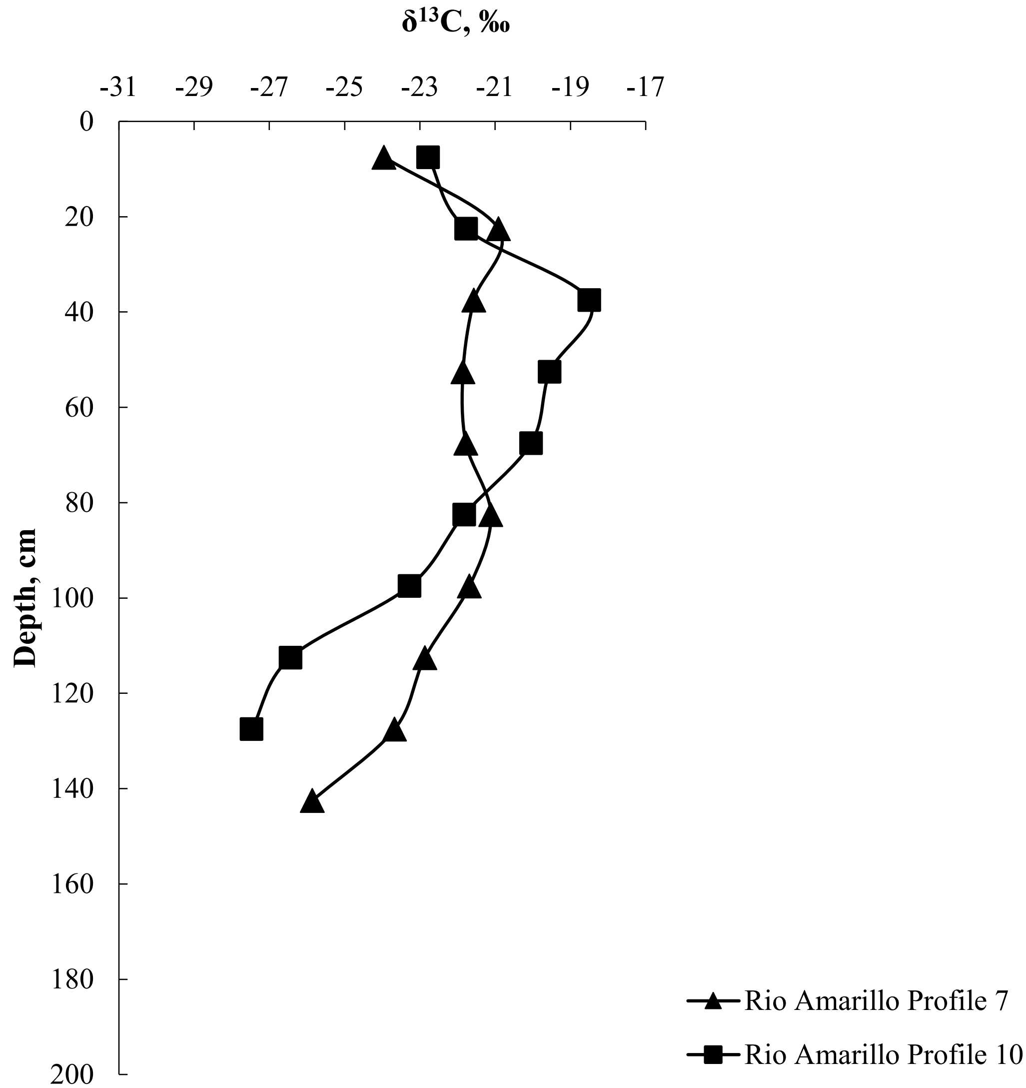

Figure 7. The changes in $\delta^{13}C$ vs Soil Depth for select toeslope soils. Profile 7 shows weak evidence of ancient C_4 agriculture. Profile 10 displays strong evidence of ancient C_4 agriculture.

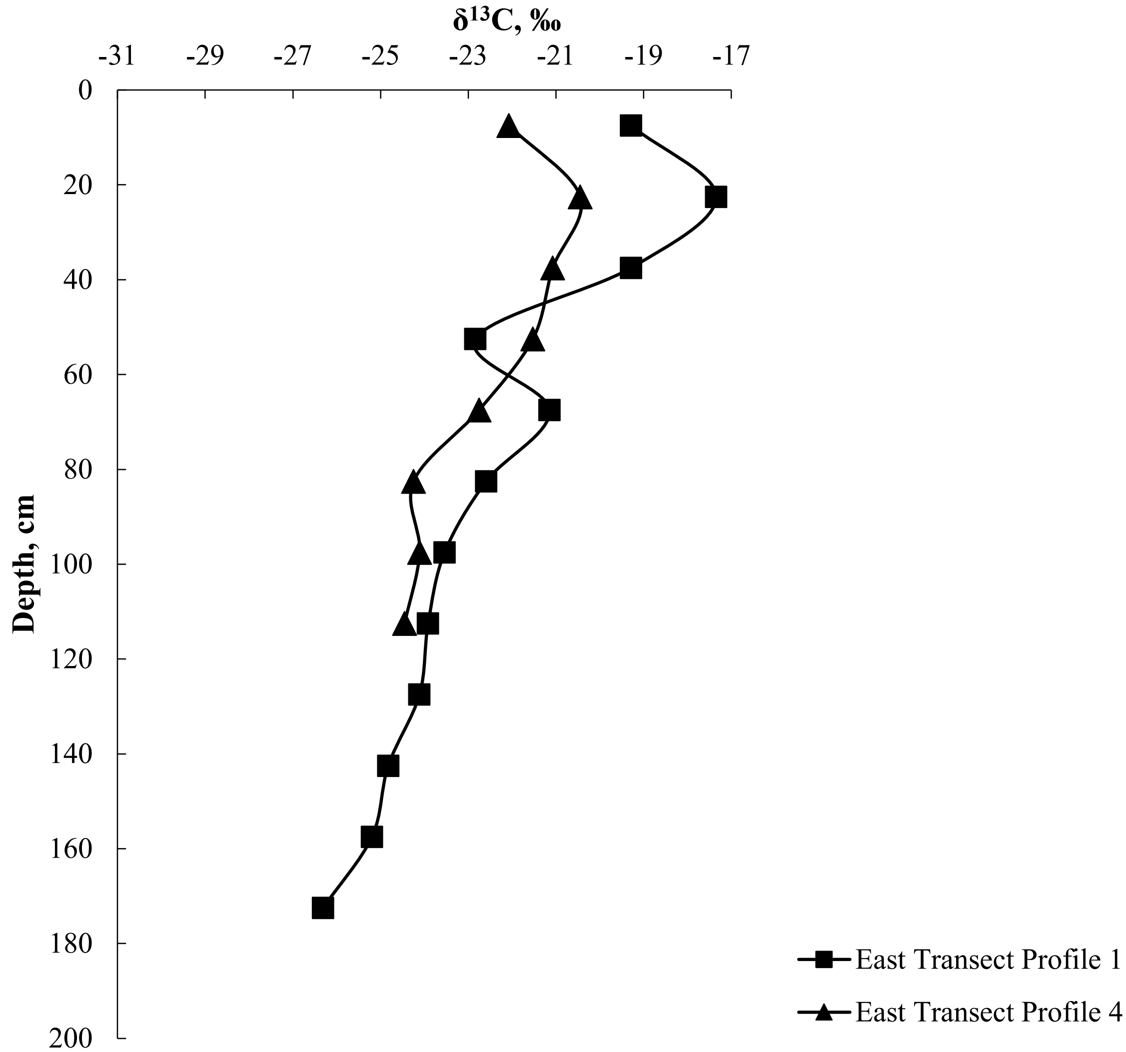

Figure 8. The changes in $\delta^{13}C$ vs Soil Depth for select toeslope soils in the East Transect (ET). Carbon isotopes in the upper 75cm of both pedons represent a mix of C_3 and C_4 vegetation over many centuries therefore it is difficult to conclude if the $\delta^{13}C$ signature ranging from -23‰ to -17‰ in the upper 75 cm is a result of mixed native vegetation or ancient agriculture.

Figure 9. Profile RA13 is a toeslope profile at the base of the large hill where RA12 was taken. RA13 is from the Aquic Dystrustepts subgroup. Mottling, a redoximorphic feature, is evident below the A horizon (at 35cm) and confirms that the soil is regularly experiences very wet conditions for an extended time (during the rainy season) and dry conditions during part of each year. If a mass erosion event had occurred, there would be a layer with increased gravel and sand content deposited in this area; however, no such layer was observed.

Figure 10. Profile RA16 is a backslope pedon that shows strong evidence of C_4 agriculture. Despite its agricultural use, the soil is still very much intact with over 2 meters of soil above bedrock and high clay content throughout the profile. RA16 is of the subgroup Typic Dystrustepts. Mottling is present below 120cm. The upper 120cm of this sloped pedon drains enough water to prevent the formation of redoximorphic features.

Figure 11. Profile RA17 is a wetland profile that shows strong evidence of ancient C_4 agriculture. The wetland soils retain high soil moisture throughout much of the dry season and may have provided an additional harvest during this time. Mottling is seen throughout the profile and indicates the presence and absence of saturated conditions at different times of the year. RA17 is of the Humic Dystrustepts taxonomic subgroup.

Table 1

Soil physical and chemical properties of profiles collected from hillslope soils near Rio Amarillo and Piedras Negras.

Pedon *Subgroup*	Slope	Depth	Horizon	Soil Color Dry	Texture Sand	Texture Clay	Texture Class	pH	Total N	Organic C*	δ ^{13}C	Change in δ 13C	UTM Zone 16 Easting	UTM Zone 16 Northing
					-----%-----				-----%-----				m	m
RA11	FS	0-15	A	5YR 5/4	13	58	Clay	4.35	0.07	3.39	-24.34	-6.94	284144	1640120
Typic Dystrustepts		15-30		5YR 6/6	0	74	Clay	4.38			-20.83			
		30-45	Bw	2.5YR 6/6	0	69	Clay	4.52			-18.25			
		45-60		2.5YR 6/6	0	73	Clay	4.46			-17.40			
		60-75		2.5YR 6/6				4.54			-17.97			
		75-90		2.5YR 5/4				4.63			-21.11			
		90-105		2.5YR 7/6				4.66			-24.34			
		105-120		2.5YR 6/4				4.56			-24.31			
		120-135	C	5YR 6/6				4.31			-23.27			
		135-150		5YR 6/4				4.37			-23.54			
RA12	SU	0-15	A	5YR 4/3	35	46	Clay	4.32	0.10	2.01	-22.78	-3.11	284147	1650161
Typic Ustorthents		15-30		5YR 5/3	44	36	Clay Loam	4.38			-20.23			
		30-45	C	5YR 5/4	38	40	Clay Loam	4.62			-19.67			
		45-60		10R 5/2	44	33	Clay Loam	4.61			-19.59			
		60-75		10R 6/2	47	31	Sandy Clay	4.59			-23.42			
RA16	BS	0-15	A	2.5YR 4/4	16	53	Clay	4.02	0.06	1.41	-27.26	-6.17	284167	1650540
Typic Dystrustepts		15-30	Bt	5YR 5/4	0	83	Clay	3.99			-24.45			
		30-45		5YR 5/4	0	78	Clay	4.15			-22.64			
		45-60		5YR 5/4	0	81	Clay	4.16			-21.09			
		60-75	C	2.5YR 5/4	10	60	Clay	4.35			-20.12			
		75-90		2.5YR 5/4	0	58	Silty Clay	4.33			-20.67			
		90-105		2.5YR 5/4	0	68	Clay	4.4			-19.72			
		105-120		2.5YR 5/4	0	60	Silty Clay	4.44			-21.22			
		120-135		2.5YR 5/4	0	63	Clay	4.51			-22.29			
		135-150		2.5YR 5/4	0	64	Clay	4.54			-22.33			
		150-165		2.5YR 5/4	3	59	Clay	4.59			-25.15			

Table 1 continued

Soil physical and chemical properties of profiles collected from hillslope soils near Rio Amarillo and Piedras Negras.

Pedon *Subgroup*	Slope	Depth	Horizon	Soil Color Dry	Texture Sand	Texture Clay	Texture Class	pH	Total N	Organic C*	δ ¹³C	Change in δ 13C	UTM Zone 16 Easting	UTM Zone 16 Northing
					-----%-----				-----%-----				m	m
RA19	FS	0-15	A1	7.5YR 3/2	28	36	Clay Loam	4.45	0.39	4.50	-25.75	-6.48	284176	1651201
Aquic Dystrustepts		15-30	A2	7.5YR 4/2	25	44	Clay	4.4			-20.57			
		30-45		7.5YR 5/2	32	43	Clay	4.28			-19.27			
		45-60		7.5YR 6/3	37	37	Clay Loam	4.06			-20.67			
		60-75		7.5YR 6/3				4.1			-20.45			
		75-90	C	10YR 7/3				4.14			-20.36			
		90-105		10YR 7/3				4.27			-20.84			
		105-120		10YR 7/3				4.25			-21.91			
		120-135		10YR 7/3				4.22			-22.23			
		135-150		10YR 7/3				4.28			-20.89			
		150-165		7.5YR 7/4				4.31			-22.43			

Table 2
Soil physical and chemical properties of profiles pedons collected from wetland soils near Rio Amarillo and Piedras Negras

Pedon				Soil Color	Texture				Total	Organic		Change	UTM Zone 16	
Subgroup	Slope	Depth	Horizon	Dry	Sand	Clay	Class	pH	N	C*	$\delta\ ^{13}C$	in δ 13C	Easting	Northing
					-----%-----				-----%-----				m	m
RA4	TS	0-15	A	2.5Y 6/2	47	31	Sandy Clay Loam	4.41	0.35	3.28	-30.85	-7.85	284099	1649373
Aeric Dystraquerts		15-30		10YR 6/3	48	33	Sandy Clay Loam	4.71			-25.05			
		30-45		10YR 5/3	48	34	Sandy Clay Loam	5.02			-23.00			
		45-60		10YR 5/3	49	37	Sandy Clay	5.21			-30.01			
		60-75	Bw1	2.5Y 7/4	49	38	Sandy Clay	5.01			-30.86			
		75-90	Bw2	10YR 7/2	49	40	Sandy Clay	4.67			-28.18			
		90-105		10YR 7/2	49	37	Sandy Clay	4.78			-25.15			
RA14	TS	0-15	A	7.5YR 5/2	26	41	Clay	4.65	0.22	3.07	-23.83	-6.49	284156	1650276
Humic Dystrustepts		15-30		7.5YR 6/2	38	36	Clay Loam	4.72			-20.38			
		30-45		7.5YR 6/2	28	39	Clay Loam	4.76			-19.96			
		45-60	Bt	7.5YR 3/1	3	65	Clay	4.88			-17.34			
		60-75	Bw	10YR 6/3	0	83	Clay	4.81			-19.32			
		75-90		10YR 6/4	5	68	Clay	4.6			-22.27			
		90-105		7.5YR 6/4	0	76	Clay	4.52			-20.91			
		105-120		10YR 7/8	0	81	Clay	4.6			-20.29			
		120-135		10YR 7/4	0	76	Clay	4.68			-21.51			
		135-150		7.5YR 7/6	0	81	Clay	4.59			-21.74			
RA 15	TS	0-15	A	5YR 5/2	0	72	Clay	4.67	0.17	1.98	-24.18	-4.48	284224	1650391
Chromic Udic Haplusterts		15-30	Bw	10YR 5/3	0	76	Clay	5.07			-21.68			
		30-45		10YR 6/4	0	71	Clay	5.2			-19.70			
		45-60		10YR 6/4	4	72	Clay	5.02			-22.21			
		60-75	C	7.5YR 6/6				5.08			-20.38			
		75-90		7.5YR 6/6				5			-21.48			
		90-105		7.5YR 6/6				4.44			-21.46			
		105-120		7.5YR 6/4				4.45			-22.91			
		120-135		7.5YR 6/4				4.55			-21.40			
		135-150		7.5YR 7/3				4.5			-25.00			

Table 2 continued

Soil physical and chemical properties of profiles pedons collected from wetland soils near Rio Amarillo and Piedras Negras

Pedon				Soil Color	Texture				Total	Organic		Change	UTM Zone 16	
Subgroup	Slope	Depth	Horizon	Dry	Sand	Clay	Class	pH	N	C*	δ ^{13}C	in δ 13C	Easting	Northing
					-----%-----				-----%-----				m	m
RA17	TS	0-15	A1	7.5YR 5/3	6	63	Clay	4.6	0.23	2.66	-24.55	-5.45	284087	1650815
Humic Dystrustepts		15-30	A2	7.5YR 6/3	1	70	Clay	4.9			-19.79			
		30-45		7.5YR 6/3	0	73	Clay	4.88			-19.57			
		45-60		7.5YR 6/4	1	81	Clay	4.6			-19.10			
		60-75	Bw	10YR 6/3				4.48			-19.46			
		75-90		10YR 6/4				5.16			-18.50			
		90-105		10YR 6/3				4.81			-20.84			
		105-120		10YR 6/3				5.09			-19.74			
		120-135		10YR 6/3				7			-19.13			
		135-150		10YR 6/3				7.75			-23.13			
		150-165		10YR 7/2				7.68						
ET2	TS	0-15	A	7.5YR 5/2	5	51	Silty Clay	4.23	0.15	2.89	-26.77	-5.73	284426	1649533
Aquic Dystraquerts		15-30		10YR 5/3	10	55	Clay	4.56			-21.54			
		30-45		10YR 5/3	12	55	Clay	4.58			-21.61			
		45-60	Bt	2.5Y 5/4	6	62	Clay	5.15			-21.04			
		60-75	Bw1	10YR 6/4				5.76			-22.56			
		75-90	Bw2	7.5YR 6/4				4.43			-23.29			
		90-105		7.5YR 6/4				4.19			-23.22			
		105-120		7.5YR 6/4				4.13			-24.34			
		120-135		7.5YR 7/3				4.03			-26.72			
		135-150		5YR 5/3				4.3			-25.35			
		150-165		7.5YR 5/2				4.51			-27.19			

Table 2 continued

Soil physical and chemical properties of profiles pedons collected from wetland soils near Rio Amarillo and Piedras Negras

Pedon *Subgroup*	Slope	Depth	Horizon	Soil Color Dry	Texture Sand	Texture Clay	Texture Class	pH	Total N	Organic C*	$\delta^{13}C$	Change in δ 13C	UTM Zone 16 Easting	UTM Zone 16 Northing
					-----%-----				-----%-----				m	m
ET3	TS	0-15	A	10YR 4/2	9	50	Silty Clay	4.03	0.29	4.40	-27.37	-6.25	284449	1649618
Aquic Dystraquerts		15-30		10YR 5/4	4	65	Clay	4.43			-21.13			
		30-45		10YR 6/6	0	73	Clay	4.53			-23.12			
		45-60	Bw1	7.5YR 6/4	1	65	Clay	5.79			-23.38			
		60-75		7.5YR 6/4	6	63	Clay	4.71			-24.48			
		75-90		7.5YR 6/4	9	58	Clay	4.96			-24.58			
		90-105		7.5YR 6/6	1	63	Clay	5.01			-22.67			
		105-120	Bw2	5YR 6/4	0	63	Clay	4.89						
		120-135	Bw1'	7.5YR 6/4	0	60	Silty Clay	4.92			-26.06			
		135-150		7.5YR 6/4	0	63	Silty Clay	4.96			-27.63			
ET5	TS	0-15	A	7.5YR 6/4	0	56	Silty Clay	4.32	0.03	1.33	-22.61	-3.49	284486	1649761
Aquic Dystraquerts		15-30	Bw	7.5YR 6/3	0	63	Clay	4.55			-23.67			
		30-45		7.5YR 6/4	1	68	Clay	4.58			-21.05			
		45-60		7.5YR 6/4	0	66	Clay	4.68			-19.12			
		60-75	C	7.5YR 6/4	8	61	Clay	4.89			-19.08			
		75-90		7.5YR 6/4	11	58	Clay	4.82			-19.87			
		90-105		5YR 6/4	13	52	Clay	4.91			-21.09			
		105-120		5YR 6/4	16	51	Clay	4.95			-21.65			
		120-135		5YR 6/4	11	56	Clay	4.87			-23.47			
		135-150		5YR 6/4	16	51	Clay	4.85			-25.36			

Table 3

Soil physical and chemical properties of profiles pedons collected from toeslopes and near settlements.

Pedon *Subgroup*	Slope	Depth	Horizon	Soil Color Dry	Texture Sand	Clay	Class	pH	Total N	Organic C*	δ 13C	Change in δ 13C	UTM Zone 16 Easting	Northing
					-----%-----				-----%-----				m	m
RA-PN Profile 0	TS	0-15	A	5YR 5/3	36	36	Clay Loam	4.45	0.20	2.33	-25.14	-0.89	284419	1648813
Typic Kandiudults		15-30	Abw	5YR 5/4	33	44	Clay	4.34			-24.19			
		30-45		5YR 5/4	36	41	Clay	4.56			-24.25			
		45-60		5YR 5/4	34	43	Clay	4.29			-23.65			
		60-75		5YR 5/4	34	44	Clay	4.33			-23.46			
		75-90	Bt	5YR 5/4	29	54	Clay	4.71			-23.36			
		90-105		5YR 5/4	26	52	Clay	4.31			-23.04			
		105-120		5YR 5/4	26	51	Clay	4.44			-23.32			
		120-135		5YR 5/4	31	55	Clay	4.33			-23.48			
		135-150		5YR 5/4	24	56	Clay	4.32			-25.09			
		150-165		5YR 5/4	20	59	Clay	4.32			-23.74			
		165-180		5YR 5/4	22	60	Clay	4.46			-25.07			
		180-195		5YR 5/4	22	57	Clay	4.64			-24.87			
RA-PN Profile 1	TS	0-15	A	2.5YR 5/2	40	27	Clay Loam	5.73	0.07	1.07	-21.91	-1.33	284220	1648910
Oxyaquic Udifluvents		15-30	C	2.5YR 5/3	39	25	Loam	5.82			-23.23			
		30-45		2.5YR 5/3	28	30	Clay Loam	5.34			-21.90			
		45-60		2.5YR 6/4	73	41	ıdy Clay Lc	5.54						
		60-75		2.5YR 5/3				6.26			-23.72			
		75-90		2.5YR 5/3				6.27			-24.37			
		90-105		2.5YR 5/3				6.50			-25.27			
		105-120		2.5YR 5/3				6.70			-23.20			
		120-135		2.5YR 5/3				6.52			-24.93			
		135-150		2.5YR 5/3				6.64			-24.52			
		150-165		2.5YR 5/3				6.44			-22.17			

Table 3 continued

Soil physical and chemical properties of profiles pedons collected from toeslopes and near settlements.

Pedon				Soil Color	Texture				Total	Organic		Change	UTM Zone 16	
Subgroup	Slope	Depth	Horizon	Dry	Sand	Clay	Class	pH	N	C*	$\delta^{13}C$	in δ 13C	Easting	Northing
					-----%-----				-----%-----				m	m
RA-PN Profile 2	TS	0-15	A	5YR 6/2	11	60	Clay	5.22	0.21	2.56	-23.99	-5.26	284181	1649017
Aquic Dystrustepts		15-30	B1t	7.5YR 6/3	0	68	Clay	4.86			-18.73			
		30-45		7.5YR 6/4	0	78	Clay	4.74			-19.43			
		45-60		7.5YR 6/4	4	80	Clay	4.78			-21.32			
		60-75		7.5YR 6/4	0	81	Clay	5.28			-20.86			
		75-90	B2w	5YR 7/4	0	79	Clay	4.66			-21.07			
		90-105		5YR 7/4	0	77	Clay	4.70			-21.16			
		105-120		5YR 6/4	0	77	Clay	5.28			-21.62			
		120-135		5YR 6/4	0	76	Clay	4.83			-21.00			
		135-150		5YR 7/4	0	74	Clay	5.05			-21.62			
		150-165		5YR 7/4	7	75	Clay	4.96			-23.92			
		165-180		5YR 7/4	0	75	Clay	5.70			-18.73			
RA-PN Profile 3	TS	0-15	A1	7.5YR 6/3	0	64	Clay	4.70	0.16	1.97	-23.25	-2.01	284157	1649118
Aquic Dystrustepts		15-30	A2	7.5YR 7/6	0	65	Clay	4.62			-21.24			
		30-45	Bw	5YR 7/4	0	71	Clay	5.14			-21.46			
		45-60		5YR 7/4	0	72	Clay	5.01			-29.66			
		60-75		5YR 7/4				5.11			-22.06			
		75-90		5YR 7/4				5.03			-21.77			
		90-105		5YR 6/4				5.12			-33.55			
		105-120		5YR 7/4				5.40			-22.27			
		120-135		5YR 7/4				5.29			-22.91			
		135-150		5YR 7/4				5.45			-22.69			
		150-165		5YR 7/4				5.27			-24.37			
		165-180		5YR 7/4				5.44			-35.54			

Table 3 continued

Soil physical and chemical properties of profiles pedons collected from toeslopes and near settlements.

Pedon				**Soil Color**	**Texture**				**Total**	**Organic**		**Change**	**UTM Zone 16**	
Subgroup	**Slope**	**Depth**	**Horizon**	**Dry**	**Sand**	**Clay**	**Class**	**pH**	**N**	**C***	**δ ^{13}C**	**in δ 13C**	**Easting**	**Northing**
					-----%-----				-----%-----				**m**	**m**
RA-PN Profile 5	TS	0-15	A	7.5YR 6/3	0	62	Clay	4.28	0.09	1.68	-22.23	-6.78	284096	164401
Aquic Dystrustepts		15-30	Bw1	5YR 7/3	0	75	Clay	4.38			-28.92			
		30-45	Bw2	2.5YR 6/4	0	69	Clay	4.44			-30.84			
		45-60		2.5YR 6/4	0	58	Silty Clay	4.94			-22.14			
		60-75		2.5YR 6/4				5.24						
		75-90		2.5YR 6/4				5.83			-22.34			
		90-105	C1	7.5YR 6/4				5.45			-24.27			
		105-120	C2	5YR 6/3				6.35			-25.05			
		120-135		5YR 5/3				7.01			-24.35			
		135-150	C1'	7.5YR 6/3				6.66			-24.24			
RA-PN Profile 6	TS	0-15	A1	5YR 5/2	21	41	Clay	5.05	0.15	1.69	-22.53	-2.24	284102	1649488
Typic Fragiaquepts		15-30	A2	7.5YR 7/2	18	39	lty Clay Loa	5.24			-20.29			
		30-45		5YR 7/2	25	39	Clay Loam	5.27			-21.31			
		45-60	Bgt	5YR 6/3	21	51	Clay	5.04			-21.96			
		60-75		5YR 6/3	27	47	Clay	5.56			-22.14			
		75-90		5YR 6/4	0	73	Clay	5.03			-21.88			
		90-105		7.5YR 6/1	0	78	Clay	5.60			-21.34			
		105-120		10YR 8/4	5	68	Clay	5.81			-23.13			
		120-135	Bw	2.5YR 6/3	12	51	Clay	5.68			-26.19			
		135-150		2.5YR 6/4	2	54	Silty Clay	5.89			-25.64			
		150-165		2.5YR 6/3	0	64	Clay	7.01			-27.22			
		165-180		2.5YR 6/3	0	67	Clay	7.20			-25.58			

Table 3 continued

Soil physical and chemical properties of profiles pedons collected from toeslopes and near settlements.

Pedon				Soil Color	Texture				Total	Organic		Change	UTM Zone 16	
Subgroup	Slope	Depth	Horizon	Dry	Sand	Clay	Class	pH	N	C*	$\delta^{13}C$	in δ 13C	Easting	Northing
					-----%-----				-----%-----				m	m
RA-PN Profile 7	TS	0-15	A	7.5YR 6/3	3	53	Silty Clay	4.49	0.04	0.09	-23.95	-3.03	284105	1649533
Plinthitic Fragiaquults		15-30	Bgt	5YR 6/4	0	74	Clay	4.83			-20.91			
		30-45		2.5YR 6/4	0	77	Clay	4.67			-21.56			
		45-60		5YR 6/4	0	78	Clay	4.28			-21.85			
		60-75		5YR 6/4				4.53			-21.78			
		75-90		5YR 6/3				4.37			-21.11			
		90-105	Bw	5YR 7/4				4.88			-21.68			
		105-120		5YR 6/3				4.78			-22.87			
		120-135		5YR 6/3				4.84			-23.67			
		135-150		7.5YR 7/1				4.91			-25.86			
RA-PN Profile 8	TS	0-15	A	5YR 4/1	20	46	Clay	4.50	0.35	3.50	-24.22	-4.58	284112	1649637
Plinthitic Fragiaquults		15-30		5YR 4/1	17	51	Clay	4.41			-25.34			
		30-45	Bg	5YR 5/2	4	72	Clay	4.52			-19.64			
		45-60		5YR 5/2	7	71	Clay	4.63			-20.41			
		60-75		5YR 6/2	23	54	Clay	4.70			-20.87			
		75-90		5YR 6/2	17	64	Clay	4.73			-21.07			
		90-105		5YR 6/2	8	69	Clay	4.54			-21.92			
RA-PN Profile 9	TS	0-15	A	5YR 4/2	1	63	Clay	4.55	0.45	4.24	-23.19	-2.88	284116	1649710
Typic Humaquepts		15-30	Bg	5YR 5/2	0	76	Clay	4.45			-20.79			
		30-45		7.5YR 6/3	0	76	Clay	4.81			-21.45			
		45-60		7.5YR 5/1	0	80	Clay	4.52			-20.30			
		60-75		7.5YR 5/1				4.60			-20.23			

Table 3 continued

Soil physical and chemical properties of profiles pedons collected from toeslopes and near settlements.

Pedon				**Soil Color**	**Texture**				**Total**	**Organic**		**Change**	**UTM Zone 16**	
Subgroup	**Slope**	**Depth**	**Horizon**	**Dry**	**Sand**	**Clay**	**Class**	**pH**	**N**	**C***	**$\delta^{13}C$**	**in δ 13C**	**Easting**	**Northing**
					-----%-----				-----%-----				**m**	**m**
RA-PN Profile 10	TS	0-15	A	5YR 3/1	6	53	Silty Clay	4.21	0.46	5.57	-22.78	-4.28	284137	1650020
Umbric Fragiaquults		15-30		5YR 4/2	5	59	Clay	4.39			-21.77			
		30-45		5YR 5/2	0	68	Clay	4.56			-18.50			
		45-60	Bt	7.5YR 6/6	0	86	Clay	4.57			-19.55			
		60-75	Bw	5YR 7/6	0	87	Clay	4.46			-20.05			
		75-90		5YR 7/6	0	85	Clay	4.48			-21.82			
		90-105		5YR 7/6	0	79	Clay	4.24			-23.27			
		105-120	Bg	7.5YR 7/2	0	82	Clay	4.17			-26.44			
		120-135		7.5YR 8/2	0	74	Clay	4.24			-27.47			
RA-PN Profile 13	TS	0-15	A	5YR 4/2	10	54	Clay	4.62	0.24	3.43	-19.08	-1.94	284155	1650244
Aquic Dystrustepts		15-30		5YR 3/1	5	53	Silty Clay	4.71			-20.24			
		30-45	Bgt	7.5YR 5/3	2	64	Clay	4.50			-17.14			
		45-60		7.5YR 6/4	0	69	Clay	4.49			-17.41			
		60-75		5YR 6/6				4.39			-17.55			
		75-90	Bgw	2.5YR 6/4				4.30			-20.00			
		90-105		2.5YR 6/4				4.29			-21.04			
		105-120		2.5YR 7/6				3.82			-22.23			
		120-135		2.5YR 7/4				4.01			-22.64			
		135-150		2.5YR 7/4				4.07			-21.03			

Table 3 continued

Soil physical and chemical properties of profiles pedons collected from toeslopes and near settlements.

Pedon				Soil Color	Texture				Total	Organic		Change	UTM Zone 16	
Subgroup	Slope	Depth	Horizon	Dry	Sand	Clay	Class	pH	N	C*	δ ^{13}C	in δ 13C	Easting	Northing
					-----%-----				-----%-----				m	m
RA-PN Profile 18	TS	0-15	A	5YR 4/2	2	59	Clay	5.33	0.28	2.73	-19.32	-1.95	284096	1650923
Oxyaquic Ustifluvents		15-30	Bw	5YR 6/3	0	64	Clay	4.92			-19.73			
		30-45		5YR 6/3	0	66	Clay	5.04			-17.46			
		45-60	BAb	7.5YR 5/3	1	65	Clay	4.74			-17.37			
		60-75	Ab	7.5YR 5/2	0	64	Clay	4.60			-17.81			
		75-90		7.5YR 5/2	0	72	Clay	4.59			-17.41			
		90-105	Bbw	7.5YR 5/3	0	75	Clay	4.70			-18.14			
		105-120		7.5YR 5/3	0	66	Clay	4.61			-18.58			
		120-135		7.5YR 5/3	0	69	Clay	4.62			-19.83			
		135-150		7.5YR 6/3	0	78	Clay	4.70			-20.99			
Rio Blanco	TS	0-15	A	7.5YR 5/4	0	56	Clay	4.55	0.15	2.25	-17.93	3.88	284024	1651263
Typic Ustifluvents		15-30		7.5YR 5/4	0	63	Clay	4.52			-22.05			
		30-45	C	7.5YR 6/4	0	68	Clay	4.78			-21.81			
		45-60		7.5YR 6/4	0	66	Clay	4.96			-22.17			
		60-75		7.5YR 6/4	8	61	Clay	4.92			-21.84			
		75-90		7.5YR 6/4	11	58	Clay	4.82			-21.14			
		90-105	Ab	7.5YR 5/3	13	52	Clay	4.65			-18.89			
		105-120		7.5YR 5/4	16	51	Clay	4.72			-19.87			
		120-135	Cb	7.5YR 6/4	11	56	Clay	4.76			-20.35			
		135-150		7.5YR 6/4	16	51	Clay	4.82			-20.03			
		150-165		7.5YR 6/4	15	50	Clay	4.88			-20.72			
		165-180		7.5YR 6/4	15	53	Clay	4.72			-21.40			

Table 3 continued

Soil physical and chemical properties of profiles pedons collected from toeslopes and near settlements.

Pedon				Soil Color	Texture				Total	Organic		Change	UTM Zone 16	
Subgroup	Slope	Depth	Horizon	Dry	Sand	Clay	Class	pH	N	C*	δ ^{13}C	in δ 13C	Easting	Northing
					-----%-----				-----%-----				m	m
ET Profile 1	TS	0-15	A1	7.5YR 5/3	30	35	Clay Loam	4.23	0.05	1.44	-19.29	-1.94	284399	1649421
Aquic Ustorthents		15-30	A2	5YR 5/4	40	32	Clay Loam	4.14			-17.34			
		30-45		5YR 5/4	42	33	Clay Loam	4.04			-19.29			
		45-60		5YR 6/4	42	33	Clay Loam	4.14			-22.83			
		60-75	C1	5YR 5/3	63	23	ıdy Clay Lc	4.07			-21.15			
		75-90	C2	5YR 5/4	33	36	Clay Loam	4.19			-22.59			
		90-105		5YR 5/4	21	40	Clay	4.21			-23.54			
		105-120		5YR 5/4	34	33	Clay Loam	4.35			-23.92			
		120-135		7.5YR 6/4	31	41	Clay	4.38			-24.11			
		135-150		7.5YR 5/4	41	35	Clay Loam	4.55			-24.83			
		150-165		7.5YR 6/6	32	35	Clay Loam	4.72			-25.20			
		165-180	C3	7.5YR 7/4	40	30	Clay Loam	4.83			-26.31			
ET Profile 4	TS	0-15	A	7.5YR 5/3	31	43	Clay	4.22	0.10	1.84	-22.07	-1.62	284466	1649688
Aquic Ustorthents		15-30	C	7.5YR 6/6	24	53	Clay	4.35			-20.45			
		30-45		5YR 6/6	27	45	Clay	4.57			-21.07			
		45-60		7.5YR 6/4	30	45	Clay	4.62			-21.53			
		60-75		7.5YR 6/4				4.92			-22.75			
		75-90		7.5YR 6/4				5.02			-24.25			
		90-105		7.5YR 6/3				5.04			-24.11			
		105-120		7.5YR 6/4				5.12			-24.45			