The Pliocene history of C_4 grasslands on the Texas panhandle: temporal and spatial variability

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Abstract:

This study examines paleosol carbonates from two Pliocene sites in the panhandle of Texas to trace the development of C_4 biomass on the Great Plains. Isotopic data from these sites are compared to each other and to other data from the Neogene of the central and southern Great Plains. This study also analyzes outcrop-level and subsample variability. As hypothesized, the Pliocene level of C_4 biomass in the region lies between lower levels in the Miocene and higher levels in the Pleistocene.

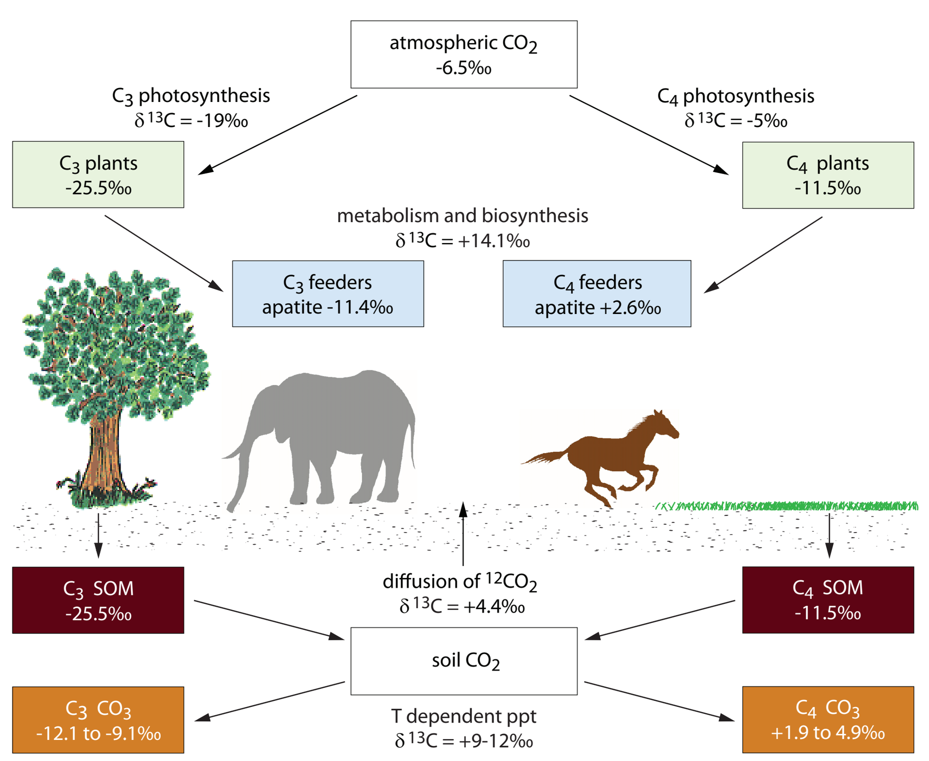


Figure 1: Sources of carbon isotope fractionation[1]

Introduction to stable isotopes:

Stable isotopes in paleosols, or fossil soils, provide evidence of past vegetational and climatic patterns. The ratio of ^{13}C to ^{12}C in paleosol carbonate nodules serves as a proxy for the relative abundance of plants using the C_3 and C_4 photosynthetic pathways. The ratio of ^{18}O to ^{16}O in these nodules reflects both soil temperature and the isotopic composition of local meteoric water at the time of carbonate precipitation. Denoted by the variable R_{sam}, the ratio of rare to common isotope in the sample is compared to a standard ratio, R_{std}, to calculate a δ value in parts per thousand ($^0/_{00}$). For example, to find the δ value of ^{13}C data:

$$\delta^{13}C = ((^{13}C_{sam}/^{12}C_{sam})/(^{13}C_{std}/^{12}C_{std}) - 1) * 1000$$
$$= ((R_{sam}/R_{std}) - 1) * 1000.$$

Carbon isotopic data are reported relative to the Vienna Pee Dee Belemnite (VPDB) standard and oxygen isotopic data are reported relative to the Vienna Standard Mean Ocean Water (VSMOW) standard.

Stable isotopes in soil carbonates:

The C_3 and C_4 photosynthetic pathways discriminate against heavier molecules of CO_2 to different degrees. Plants using C_4 photosynthesis have lower isotopic selectivity than C_3 plants due to the more efficient concentration of CO_2 at the carbon fixation enzyme RuBisCO. In other words, C_3 photosynthesis depletes ^{13}C relative to ^{12}C more than than C_4 photosynthesis. $\delta^{13}C$ values of C_3 and C_4 plant tissue range from -22$^0/_{00}$ to -30$^0/_{00}$ and -10$^0/_{00}$ to -14$^0/_{00}$, respectively (Fig. 1).[2]

Decomposition of plant tissue in the soil creates a primary subsurface source of CO_2 for calcite precipitation. In soil greater than about 25 cm in depth, atmospheric CO_2 is a negligible component of the total CO_2 content.[3] The carbonate-bicarbonate equilibrium mainly controls calcite precipitation:

$$CaCO_3 + H_2O + CO_2 \leftrightarrow Ca^{2+} + 2HCO_3^-.$$

Ca^{2+} concentration and pH seem to primarily drive calcite precipitation from soil water.[3] The diffusion of soil CO_2 to the atmosphere enriches the ^{13}C content of the remaining CO_2, and the temperature-dependent precipitation of calcite results in further ^{13}C enrichment. In a soil containing only C_3 plants, isotopic fractionations during the process of calcite precipitation at depth should create carbonates with a $\delta^{13}C$ value between -12.1$^0/_{00}$ and -9.1$^0/_{00}$. Likewise, carbonates formed in soils containing only C_4 plants should have a $\delta^{13}C$ value between +1.9$^0/_{00}$ and +4.9$^0/_{00}$. On the Great Plains of the Neogene, a time when a significant proportion of C_4 plants has been present in that region, one expects that paleosol carbonates should have $\delta^{13}C$ values between the C_3 and C_4 endmember values.

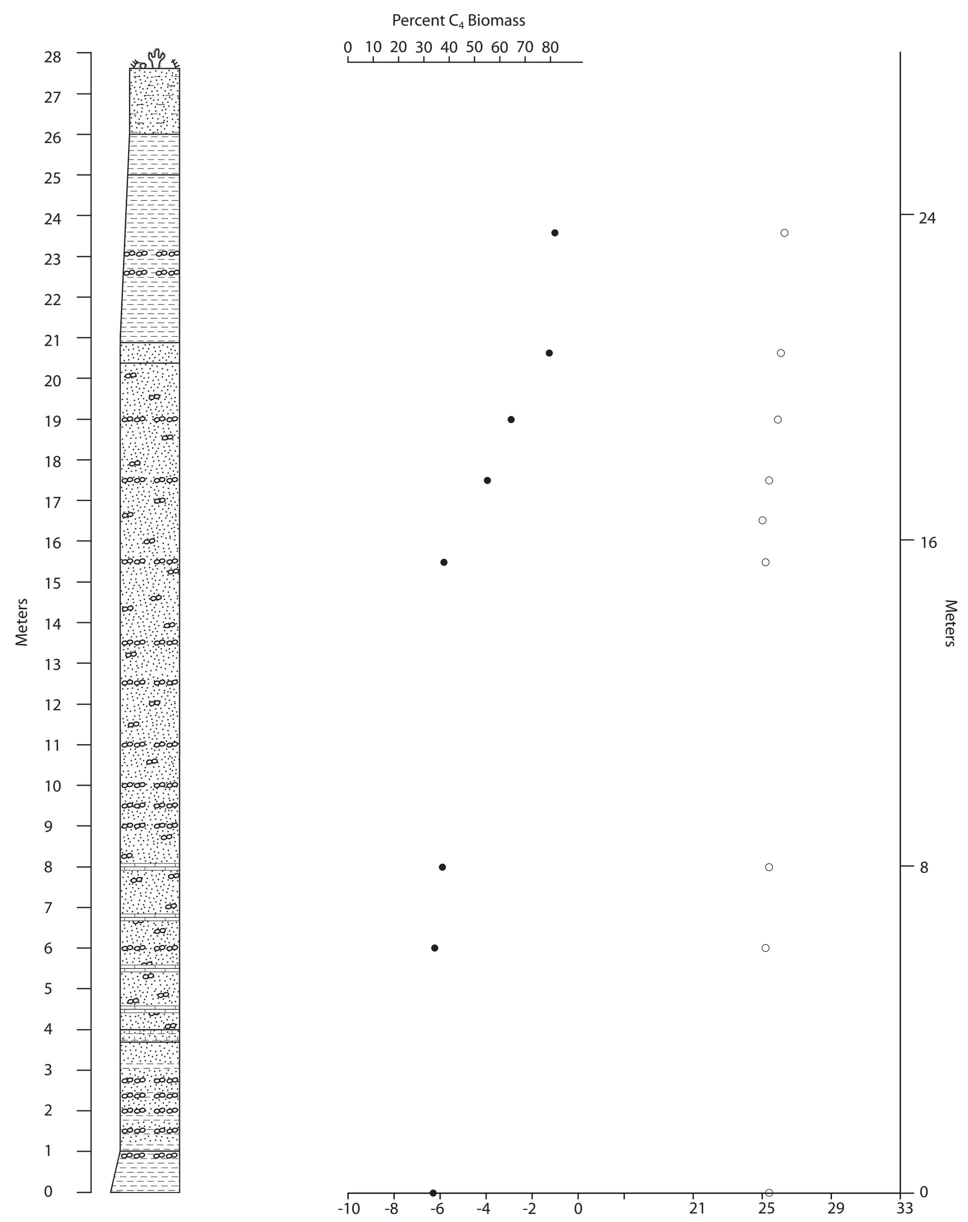


Figure 4: Christian Ranch Section 3 $\delta^{13}C$ (closed circle) and $\delta^{18}O$ (open circle) values

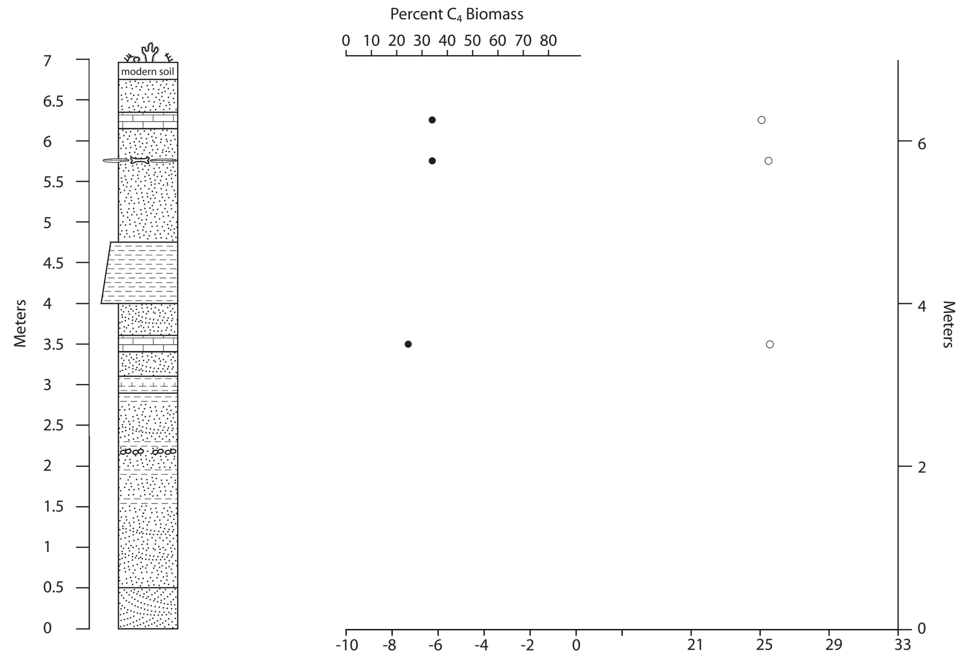


Figure 3: Christian Ranch Section 2 $\delta^{13}C$ (closed circle) and $\delta^{18}O$ (open circle) values

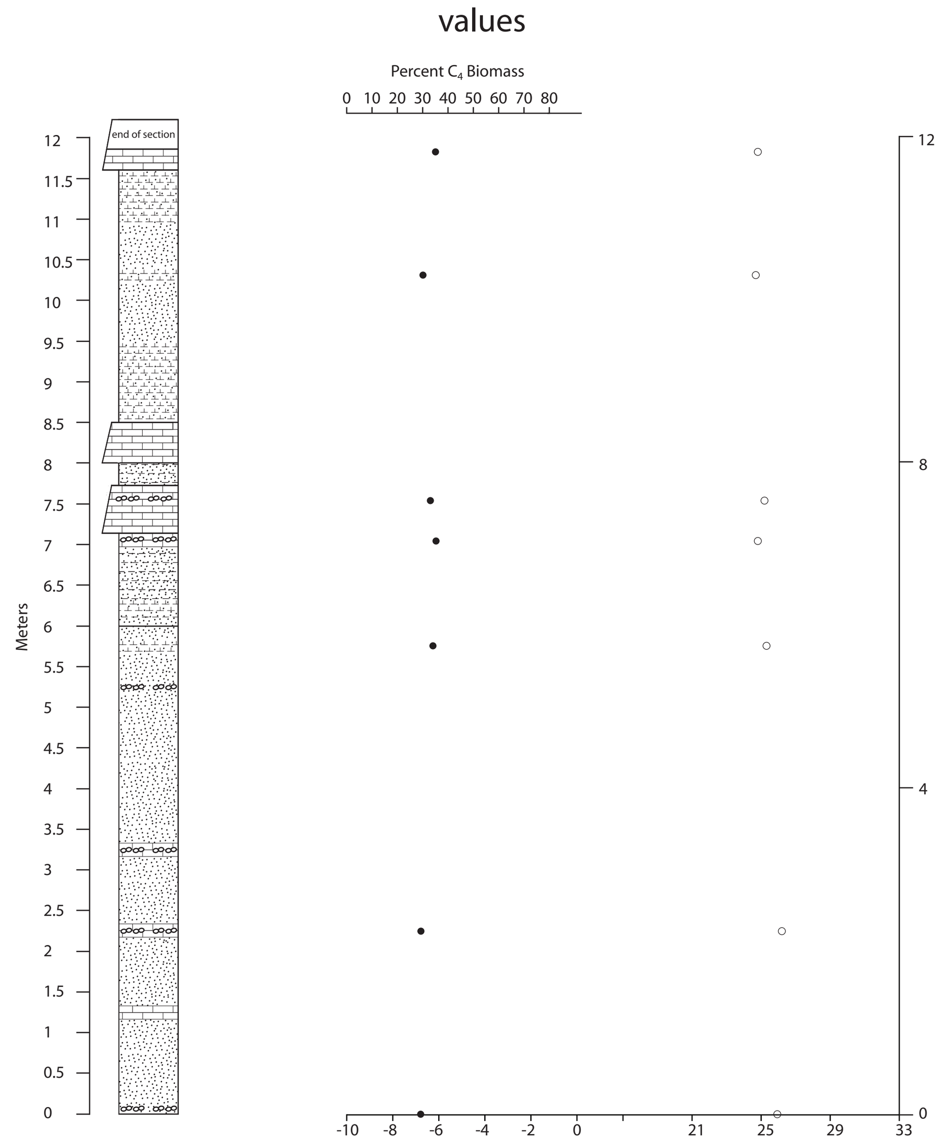


Figure 2: Christian Ranch Section 1 $\delta^{13}C$ (closed circle) and $\delta^{18}O$ (open circle) values

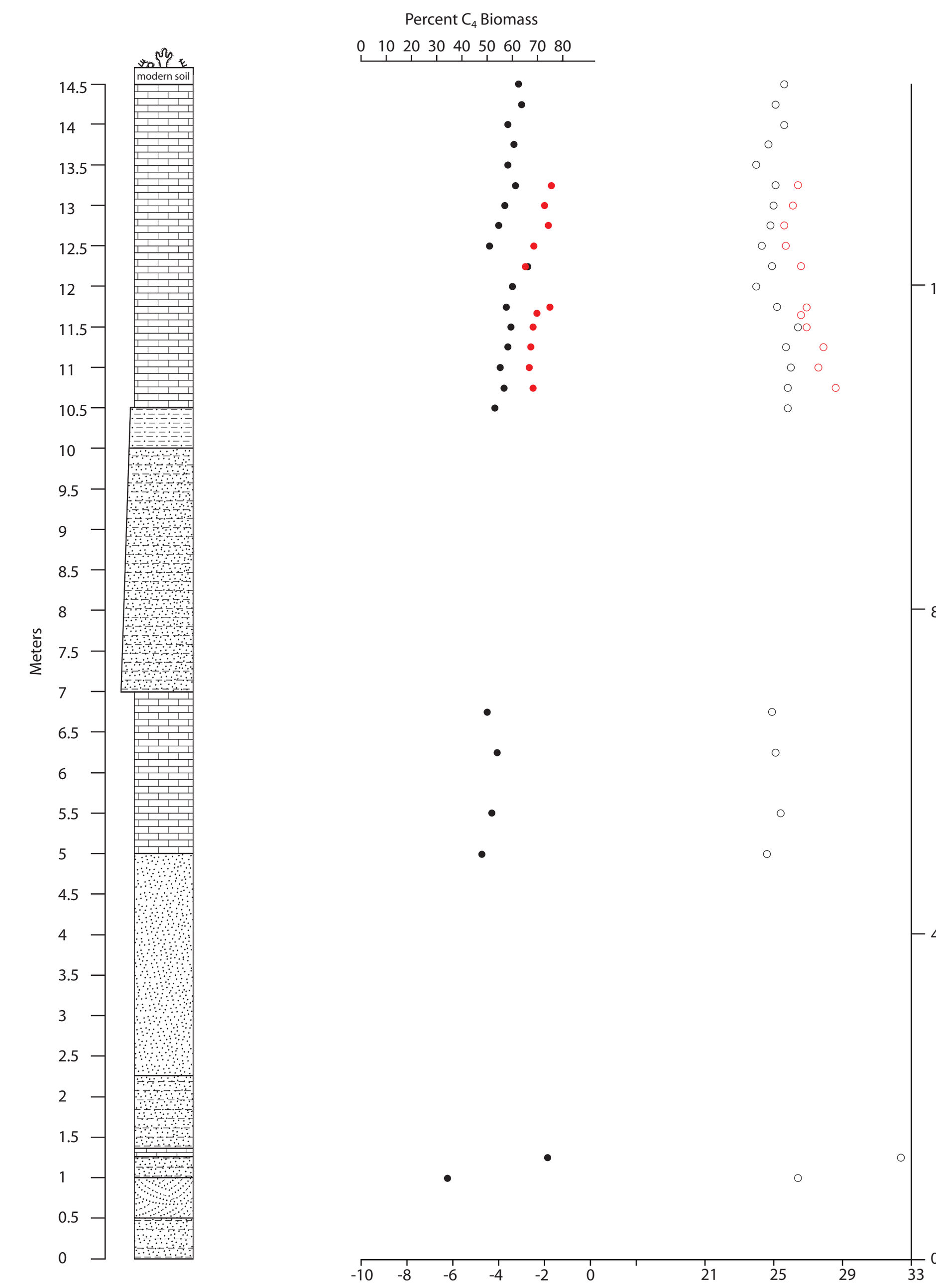


Figure 5: North Cita Canyon $\delta^{13}C$ (closed circle) and $\delta^{18}O$ (open circle) values. Data points in red were taken about 10 m away from and parallel to the black data points on the face of the outcrop. The data at 1.25 m are anomalous.

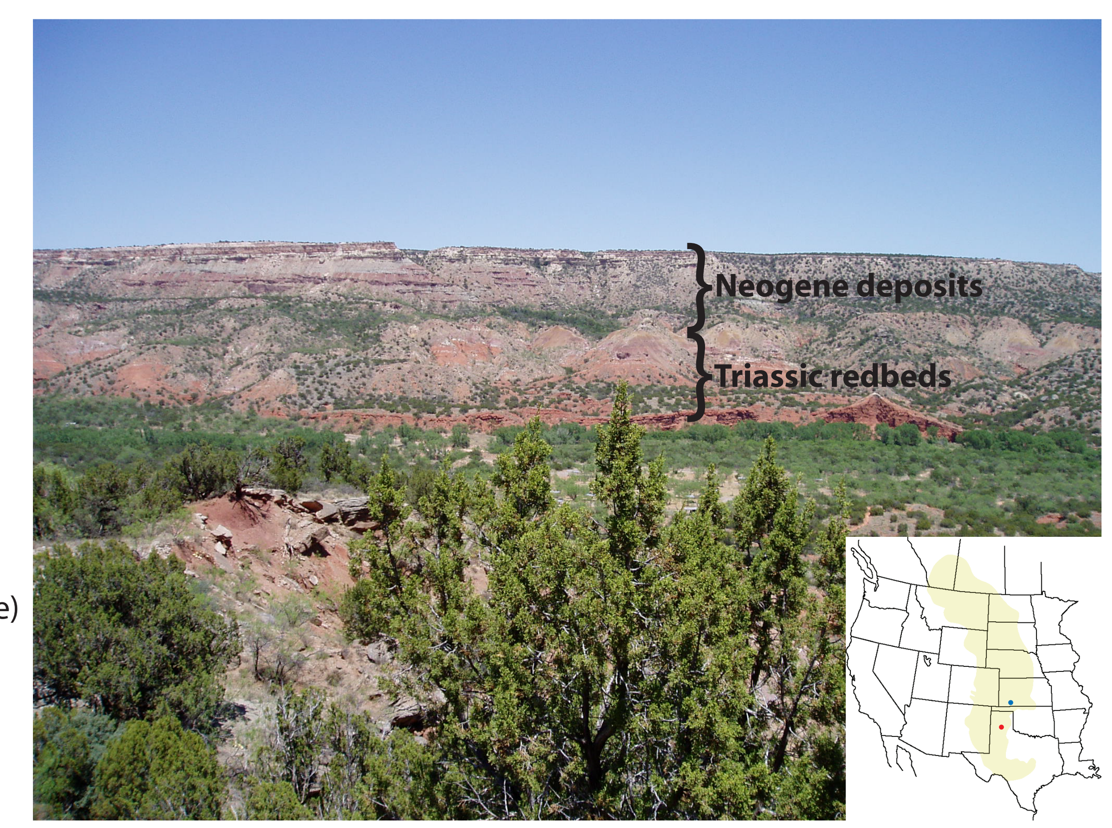
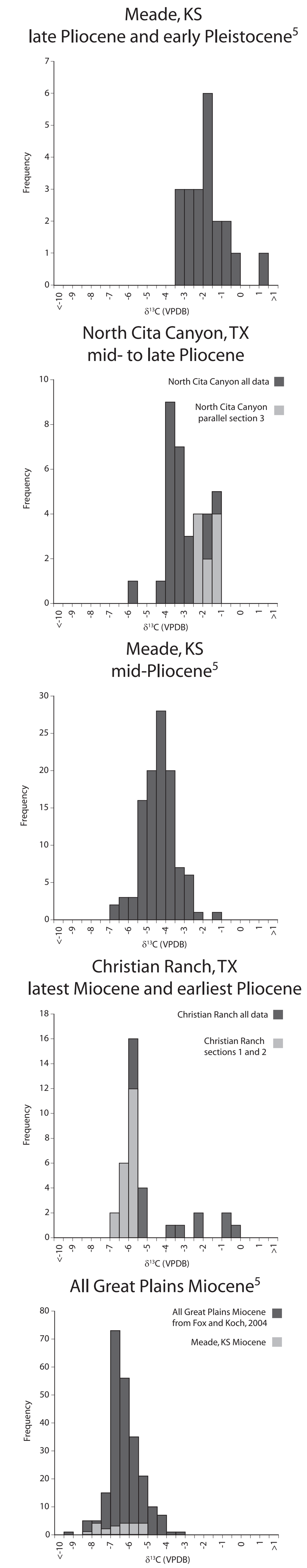


Figure 6: A view of Palo Duro Canyon. North Cita Canyon is a tributary of this system, which lies at the headwaters of the Red River. The shaded yellow region of the inset map shows the current extent of the Great Plains.[4] The red dot marks the location of Palo Duro Canyon (Christian Ranch is approximately 10 miles to the east). The blue dot marks the location of Meade, KS.

Materials and methods:

This study analyzes unpublished isotopic data from paleosol carbonates of Palo Duro Canyon State Park and Christian Ranch in the panhandle of Texas. Previously published Great Plains data from the Neogene are used for comparison.[5] Most collection sites were assigned an age estimate using the extensive mammalian biostratigraphy of the Great Plains. Carbonate nodules were collected from lower boundaries of carbonate layers and at least 30 cm below the top of the uppermost stratigraphic boundary to minimize the amount of carbon in the sample derived from atmospheric CO_2. Nodules were identified as pedogenic (soil-formed) on the basis of external morphology, the presence of inclusions of overgrown clastic sediment, and the presence of nearby rhizoconcretions, or calcitic root traces. Two powder samples were drilled from different places on an unweathered surface of each nodule to estimate small-scale isotopic variability. These were roasted *in vacuo* at 400°C for at least 1 hour to remove organic matter and water. Samples were reacted with H_3PO_4 at 70°C in a Kiel automatic carbonate extraction device and the isotopic composition of the resulting CO_2 was measured using a Finnigan MAT 252 gas source isotope ratio mass spectrometer at the University of Kansas.



N = 21
Mean = -2.33
Standard deviation = 1.11

All data:
N = 34
Mean = -3.41
Standard deviation = 1.04

Section 3:
N = 11
Mean = -2.21
Standard deviation = 0.59

N = 107
Mean = -4.91
Standard deviation = 0.90

All data:
N = 35
Mean = -5.61
Standard deviation = 1.73

Sections 1 and 2:
N = 20
Mean = -6.52
Standard deviation = 0.36

All data:
N = 230
Mean = -6.75
Standard deviation = 0.83

Meade, KS Miocene:
N = 22
Mean = -7.10
Standard deviation = 0.83

Figure 6: Histograms of $\delta^{13}C$ values, with the bottom graph containing the oldest samples and the top graph containing the youngest. To the right are descriptive statistics of each histogram's data.

Correlating isotopes with biomass:

A simple linear-mixing model is used to correlate $\delta^{13}C$ with C_4 biomass:

$$\delta^{13}C = \%C_4\ biomass * \delta^{13}C_{C_4\ endmember} + (1- \%C_4\ biomass) * \delta^{13}C_{C_3\ endmember}$$

Carbonate nodules form on a scale of hundreds to thousands of years, so $\delta^{13}C$ values integrate a vegetational signal over that time.[5]

Chronology:

Stage-of-evolution biochronology dates the Christian Ranch Local Fauna of the Texas Panhandle at 5.8 to 5.1 Ma, or the latest Miocene and earliest Pliocene.[6] In conjunction with magnetostratigraphy, the same approach dates the Upper and Lower Cita Canyon faunas at 3.9 to 3.4 Ma.[7] The overlap between the geochronologically dated first and last appearances of fossils found together at the site place the Cita Canyon faunas at 3.3 Ma.[8] Both approaches yield a date in the mid- to late Pliocene.

The layers containing the two vertebrate assemblages of Upper Cita Canyon lie between 2.25 m and 7 m in the section (Fig. 5). The siltstone from 7 to 10 m outcrops at another site, Harrell Ranch, within North Cita Canyon, over which lies a Type O Pearlette Ash Bed.[9] This ash is dated at 0.60 Ma.[10] A majority of carbonate samples from Upper Cita Canyon were taken from a layer of prismatic carbonate above 10 m in the section, but are not necessarily younger than 0.60 Ma. If the ash was deposited after the carbonate, an upper age constraint of 0.60 Ma can be placed on the Upper Cita Canyon isotopic data.

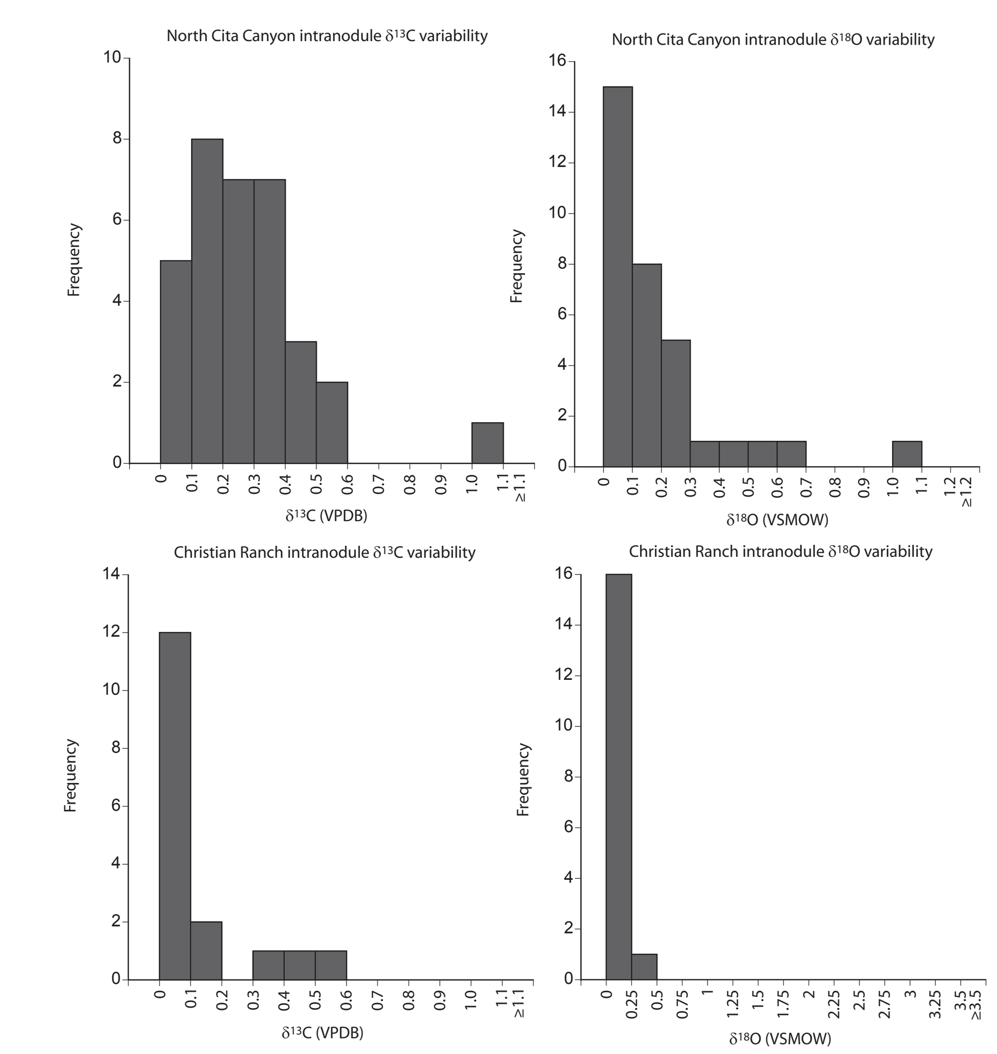


Figure 7: Histograms of intrasample $\delta^{13}C$ and $\delta^{18}O$ differences.

Statistical analysis:

Fig. 6 shows the increasing abundance of C_4 plants on the Great Plains through the Neogene. ANOVA indicates that not all the $\delta^{13}C$ means of the data sets from Fig. 6 are similar. The comparison of all pairs of means using Scheffé's Test at the significance level α of 0.05 discerns individual mean inequalities. Of note, the difference between the North Cita Canyon and early Pliocene Meade, KS means is greater than the critical difference, indicating that they are statistically dissimilar. These data could overlap temporally, suggesting that the difference in C_4 biomass might be controlled by latitudinal mean annual temperature variation, with higher C_4 biomass in warmer southern climes. This pattern controls much of the distribution of C_3 and C_4 plants on the modern Great Plains.[11]

Fig. 7 shows that the variability within carbonate nodules is small relative to the standard deviations of the isotopic data from each locality. Thus, variation within sections is not significantly influenced by intrasample variability. Isotopic values from two parallel sections in North Cita Canyon vary considerably (Fig. 5). Consistent with observations of the canyon's modern vegetational dispersion, this indicates landscape-level patchiness in C_4 dominance and fluctuations in aridity and soil water source.

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