

Late Quaternary Vegetation and Climate Changes in Central Texas Based on the Isotopic Composition of Organic Carbon

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Stable carbon isotope analysis of organic carbon in alluvial deposits and soils of three streams in central Texas reveals significant shifts in the ratio of C_3 to C_4 plant biomass production during the past 15,000 yr. These temporal changes in vegetation appear to be in response to changes in climate. During the late Pleistocene, C_4 plants comprised only about 45 to 50% of the vegetative biomass in this area, suggesting that conditions were cooler and wetter than at any time during the past 15,000 yr. The time between 11,000 and 8000 yr B.P. is interpreted as transitional between late Pleistocene conditions and warmer and drier Holocene conditions based on a slight increase in the abundance of C_4 plant biomass. During the middle Holocene, between approximately 6000 and 5000 yr B.P., mixed C_3/C_4 plant communities were replaced almost completely by C_4 -dominated communities, indicating prairie expansion and warmer and drier climatic conditions. By 4000 yr B.P., the abundance of C_4 plant biomass decreased to levels similar to the early Holocene transitional period, suggesting a return to cooler and wetter climatic conditions. No significant shift in the ratio of C_3 to C_4 productivity has occurred during the last 4000 yr, except for a slight increase in the abundance of C_4 plant biomass around 2000 yr B.P. The results of this investigation correlate well with other regional late Quaternary climatic interpretations for central and north Texas, the Southern Plains region, and with other portions of the Great Plains. ©1994

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INTRODUCTION

Many investigators have successfully measured stable carbon isotope ratios from the organic carbon of surface and buried soils and reconstructed changes in vegetation and climate during the late Quaternary (Krishnamurthy *et al.*, 1982; Schwartz *et al.*, 1986; Schwartz, 1988; Guillet *et al.*, 1988; Ambrose and Sikes, 1991). Stable carbon

isotope analyses were performed on organic carbon from the late Quaternary alluvial deposits and soils along three streams within the Fort Hood Military Reservation of central Texas (Fig. 1). This paper presents the results of this investigation and proposes a late Quaternary vegetation and climate history for central Texas. These reconstructions are then compared with other paleoclimatic records from central and north Texas and the Great Plains.

Stable Carbon Isotope Theory and the Ecology of C_3 and C_4 Plants

The natural difference in the stable carbon isotopic composition of C_3 and C_4 plant species provides an opportunity to assess the long-term stability of plant communities and climate of a given region (Troughton *et al.*, 1974; Stout *et al.*, 1975). The basis of this approach is that during photosynthesis, C_4 plants discriminate less against $^{13}\text{CO}_2$ than C_3 plants (Vogel, 1980; O'Leary, 1981). This difference in carbon isotope fractionation during photosynthesis results in a characteristic carbon isotope ratio in plant tissue that serves as a diagnostic indicator for the occurrence of C_3 and C_4 photosynthesis. The $\delta^{13}\text{C}$ values of C_3 plant species range from approximately -32 to -20‰ , with a mean of -27‰ . In contrast, $\delta^{13}\text{C}$ values of C_4 species range from -17 to -9‰ , with a mean of -13‰ . Thus, C_3 and C_4 plant species have distinct, nonoverlapping $\delta^{13}\text{C}$ values and differ from each other by approximately 14‰ (Boutton, 1991a).

The majority of all plant species possess the C_3 photosynthetic pathway. Because nearly all trees, shrubs, forbs, and cool season temperate grasses are C_3 species, all forest communities and most other temperate zone

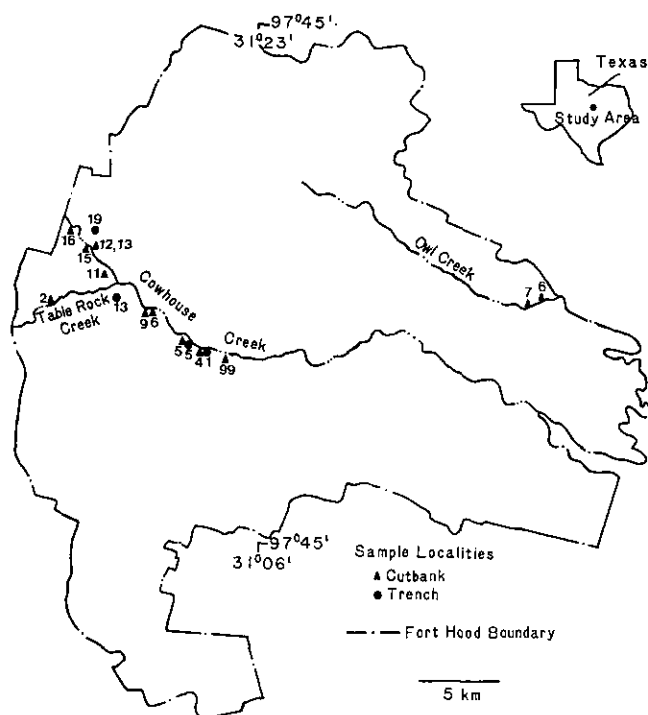


FIG. 1. Map of the Fort Hood Military Reservation showing the streams and trench and cutbank sample localities.

plant communities are dominated by C_3 species. Plants with the C_4 photosynthetic pathway are most abundant in warm, semiarid environments with high light intensity, such as grasslands, savannas, deserts, and salt marshes. Warm season grasses of tropical or subtropical origin account for more than 40% of all known C_4 species (Smith *et al.*, 1979). Tropical and subtropical grasslands consist almost exclusively of C_4 species.

In the North American Great Plains, the proportion of C_4 grass species increases from approximately 30% in North Dakota to approximately 70% in Texas (Teeri and Stowe, 1976). It has also been shown that both the proportion of C_4 species (Teeri and Stowe, 1976) and the proportion of C_4 biomass in a given community (Tieszen *et al.*, 1979; Boutton *et al.*, 1980) are highly correlated with environmental temperature. In North America, Teeri and Stowe (1976) found that the proportion of C_4 species in the grass flora was correlated strongly ($r = 0.97$) with normal July daily minimum temperature and with many other indices of temperature. In addition, the relative proportion of C_3/C_4 biomass in grassland communities has been shown to be correlated with temperature. For example, relative C_3/C_4 biomass in seven grassland communities in the western Great Plains was highly correlated ($r = 0.92$) with mean annual temperature (Boutton *et al.*, 1980). Thus, the proportion of C_4 species present in a given region, as well as the performance (biomass production) of those species, are both highly related to environmental temperature. These relationships are therefore extraordinarily useful in paleoecolog-

ical studies when the relative proportions of C_3 versus C_4 species can be reconstructed.

Because there is little change in the carbon isotopic composition of plant litter as it decomposes and is incorporated into the soil organic matter pool (Nadelhoffer and Fry, 1988; Melillo *et al.*, 1989), the isotopic composition of soil organic matter reflects the photosynthetic pathway type of the dominant species in the plant community that contributed the organic carbon (Stout and Rafter, 1978; Dzurec *et al.*, 1985; Nadelhoffer and Fry, 1988). Consequently, the stable carbon isotopic composition of soil organic matter has been utilized to infer vegetation change in both modern soils (Dzurec *et al.*, 1985) and paleosols (Hendy *et al.*, 1972; Krishnamurthy *et al.*, 1982). Because the percentage of C_3 and C_4 plants is controlled by climate, it is possible to reconstruct climatic conditions from changes in stable carbon isotopic values.

While -13 and -27‰ are good estimates of mean $\delta^{13}\text{C}$ values for modern C_4 and C_3 plants, respectively, one cannot be certain that these averages are representative of the last 15,000 yr. One major source of uncertainty is the $\delta^{13}\text{C}$ value of atmospheric CO_2 over the time period investigated and its effect on plant $\delta^{13}\text{C}$ values. For example, $\delta^{13}\text{C}$ of atmospheric CO_2 was estimated to be -7.1 to -6.8‰ approximately 20,000 yr B.P., -6.9 to -6.7‰ during the early Holocene, and -6.5 to -6.4‰ for the remainder of the Holocene (Leuenberger *et al.*, 1992; Marino *et al.*, 1992). At present, the $\delta^{13}\text{C}$ value of atmospheric CO_2 is approximately -7.8‰ (Levin *et al.*, 1987). Because the $\delta^{13}\text{C}$ value of atmospheric CO_2 strongly influences the $\delta^{13}\text{C}$ value of plant tissue (Farquhar *et al.*, 1989), it is reasonable to assume that plant $\delta^{13}\text{C}$ values may have changed slightly in the past 15,000 yr. In fact, mean $\delta^{13}\text{C}$ values of cellulose nitrate isolated from *Atriplex confertifolia* (a C_4 shrub) leaves recovered from packrat middens were -11.5‰ at 15,000 yr B.P., -10.9‰ during the Holocene, -10.7‰ at 200 yr B.P., and -12.3‰ in 1988 (Marino *et al.*, 1992). Similarly, mean $\delta^{13}\text{C}$ values of 12 C_3 species (trees, shrubs, and forbs) changed from -25.8‰ in A.D. 1750 to -26.4‰ at present (Penuelas and Azcon-Bieto, 1992). While these temporal changes in plant $\delta^{13}\text{C}$ values are not large enough to mask major shifts in C_3/C_4 productivity in soil organic matter, they do suggest that estimation of the relative proportions of C_3 and C_4 carbon in the soil is inexact. If C_3 and C_4 plants had more negative $\delta^{13}\text{C}$ values during the Holocene, as the above data indicate, then our mass balance equation (see below) will slightly overestimate the importance of C_4 -derived carbon and underestimate C_3 -derived carbon.

STUDY AREA

Stable carbon isotope samples were collected from alluvium of Cowhouse, Table Rock, and Owl creeks within the boundaries of the Fort Hood Military Reservation in

central Texas (Fig. 1). These streams drain approximately 1600, 175, and 70 km², respectively. The Fort Hood area is underlain by lower Cretaceous limestones and shales on the eastern margin of the Edwards Plateau, the southernmost extension of the Great Plains. Modern climate in the area is classified as subtropical subhumid to subtropical humid (Larkin and Bomar, 1983). Annual precipitation is approximately 800 mm, with mean annual low and high temperatures of 11.5°C and 25.5°C, respectively. Most precipitation events are produced by convective storms that develop between moist tropical air from the Gulf of Mexico and the southerly flow of dry continental air. Most rainfall occurs in the fall and spring when frontal activity is greatest.

The eastern margin of the Edwards Plateau under natural conditions supports a mixed tall- and mid-grass prairie with scattered oaks (*Quercus virginiana*) (U.S. Department of Agriculture, 1981). Juniper (*Juniperus ashei*) often thrives along escarpments. The natural vegetation on floodplains and low terraces consists principally of tall and mid grasses with scattered deciduous hardwood trees (*Quercus macrocarpa*, *Ulmus crassifolia*, and *Carya illinoensis*). The percentage of woody plants and forbs has increased during Historic time because of overgrazing and reduction of fire frequency (Smeins, 1982). Before the area was established as a military reservation in 1942, the broad uplands, low terraces, and floodplains were periodically cultivated. The two most commonly grown crops were cotton (C₃ plant) and corn (C₄ plant) (Jack Jackson, personal communication, 1993). Since 1942, only light cattle grazing has occurred.

Alluvial Stratigraphy

Five major alluvial stratigraphic units were identified in Cowhouse, Table Rock, and Owl creeks (Nordt, 1992). These units were labeled the Jackson, Georgetown, Fort Hood, West Range, and Ford alluvium, from oldest to youngest. Based on 41 radiocarbon analysis (26 on charcoal and 15 on bulk sediment humates), numerical ages were assigned to the alluvial units. In the following discussion, these units are described only as they occur along Cowhouse Creek because most of the $\delta^{13}\text{C}$ samples were obtained from this drainage basin. Furthermore, the five stratigraphic units are correlative among all three basins. Details of the alluvial stratigraphy and soils are given by Nordt (1992) and Nordt and Hallmark (1990).

The oldest and highest terrace along Cowhouse Creek is named T2 (terrace 2) (Fig. 2). This terrace marks the surface boundary of the Jackson alluvium about 15 m above the modern channel thalweg. The Jackson alluvium is approximately 15,000 yr old and consists of 3 to 4 m of gravelly and loamy deposits resting on a bedrock strath. The Georgetown alluvium is the oldest unit within the deeply entrenched Holocene valley and is always buried by younger deposits. Deposition of this unit began no earlier than 11,000 yr B.P. and terminated by 8000 yr B.P. The fill is 4 to 6 m thick and consists of gravelly and loamy deposits. The Royalty paleosol, formed in the top of the Georgetown alluvium, typically consists of a truncated Bk horizon containing secondary precipitates of calcium carbonate. The Fort Hood alluvium is the major Holocene unit by volume along Cowhouse Creek. It con-

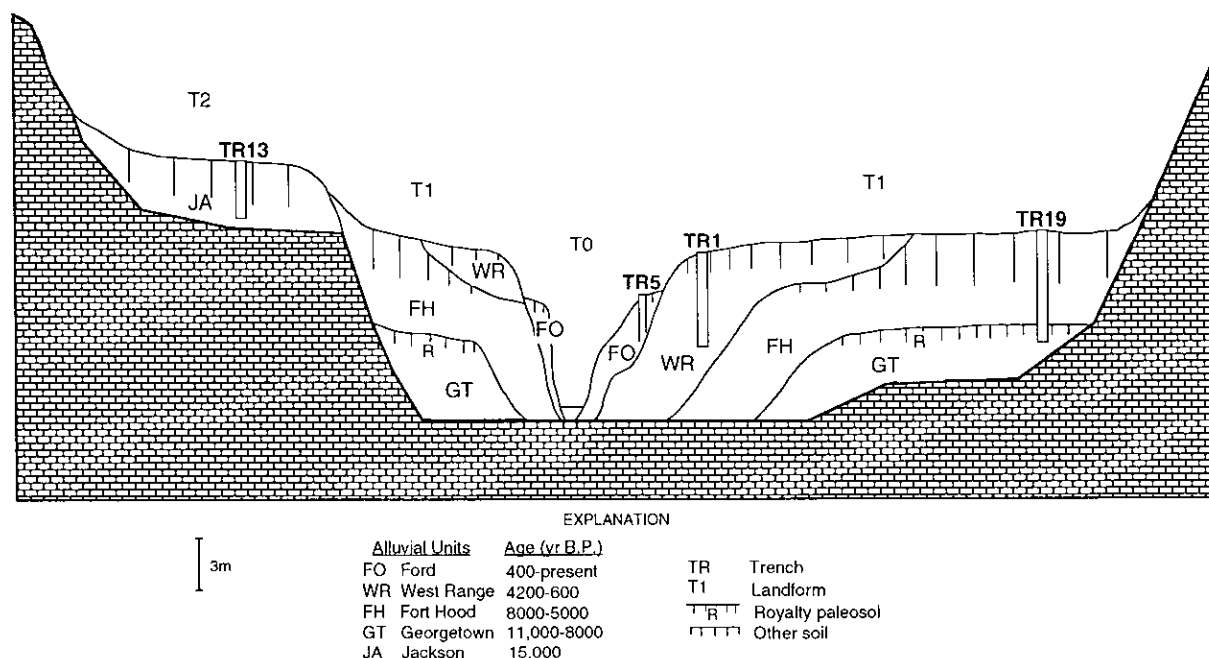


FIG. 2. Generalized composite geologic cross section of Cowhouse Creek showing the major stratigraphic units and trench localities (modified from Nordt, 1992) (not to scale).

sists of about 9 to 10 m of gravelly and loamy deposits that date to between about 8000 and 4800 yr B.P. The West Range alluvium was being deposited by 4200 yr B.P. and had ceased to accumulate by about 800 to 600 yr B.P. This unit is typically 9 m thick and in some areas partially truncates and buries the Fort Hood alluvium. Both the West Range and the Fort Hood alluvium lie beneath T1. Deposition of the Ford alluvium and construction of the modern floodplain, T0, began 400 to 600 yr ago and is continuing at present. Lithologically, the West Range and Ford alluvium are similar to the Jackson, Georgetown, and West Range alluvium.

METHODOLOGY

Field Methodology

Forty-six stable carbon isotope samples were taken from four trenches (TR1, 5, 13, 19) that exposed the five major alluvial units along Cowhouse Creek (Figs. 1 and 2; Table 1). All pedogenic horizons and the underlying parent material were sampled in each trench. An additional 14 samples were collected from cutbanks along Cowhouse, Table Rock, and Owl creeks to obtain $\delta^{13}\text{C}$ signatures dating to time intervals not represented in the four trenches (Fig. 1). Although no ^{14}C ages were obtained directly from the four trenches, their chronologies can be firmly established by placing them within the larger stratigraphic framework. Cutbank samples (CB) were taken only from horizons that had been ^{14}C dated.

The 15,000-yr-old Jackson alluvium and soil were exposed in TR13 of Cowhouse Creek (Figs. 1 and 2). Twelve $\delta^{13}\text{C}$ samples were collected from the soil profile. The soil is a Vertisol (weakly developed) with organic carbon content decreasing with depth from 2.2 to 1.0% in the upper 60 cm to less than 0.1% below 213 cm. Within a 500-m radius of the soil trench, the plant community consists primarily of a mixed grass prairie (almost all C_4 plants) that has been grazed moderately. About 10% of the plant cover consists of mesquite (*Prosopis glandulosa*), a C_3 tree, while another 10 to 15% of the cover consists of C_3 forbs. Aerial photography shows that this area was cultivated up until 1938. Two additional $\delta^{13}\text{C}$ samples of the Jackson alluvium were taken from B horizons at CB11 and CB99.

One $\delta^{13}\text{C}$ sample of the deeply buried Georgetown alluvium and associated Royalty paleosol were taken from a core adjacent to TR19 on Cowhouse Creek (Figs. 1 and 2). In addition, a sample was taken from the Royalty paleosol at CB6 on Owl Creek (Fig. 1).

The Fort Hood alluvium and soil were exposed in TR19 (Figs. 1 and 2). At this location, the sediments accumulated over a 2000- to 3000-year interval. Twelve $\delta^{13}\text{C}$ samples were collected from the associated Fort Hood soil in TR19. The soil is a Mollisol with organic carbon content decreasing with depth from 1.9 to 1.0% in the upper 60

cm to a low of 0.2% at 250 cm. Current vegetative cover consists of about 50% native grasses (mostly C_4) and 50% mesquite (*P. glandulosa*, C_3) and forbs (C_3). Aerial photographs show that this area was also cultivated until 1938 and has since been grazed moderately. Two additional samples were taken from B horizons at CB12 and CB15, and one from a buried point bar at CB6.

Trench 1 was excavated in the West Range alluvium and associated soil (Figs. 1 and 2). The West Range alluvium in this area was deposited fairly rapidly between 2400 and 2000 yr B.P. The West Range soil is a Mollisol with organic carbon content ranging with depth from 1.2 to 1.0% above 80 cm to 0.5 to 0.2% in the lower profile. Ten $\delta^{13}\text{C}$ samples were collected from this profile. The modern plant community is a savanna, with native C_4 grasses and woody species consisting mainly of oak (*Q. macrocarpa*) and elm (*U. crassifolia*). Because of recent nearby road disturbance, a small amount of bermuda grass (*Cynodon dactylon*, C_4) grows near the trench. Because of the entrenched condition of the modern channel and subsequent low water table, the woody vegetation bordering the channel near TR1 is not riparian. Aerial photographs indicate that this area has never been cropped. Seven additional $\delta^{13}\text{C}$ samples of West Range alluvium were taken from cutbanks of Cowhouse (CB13, CB5, CB16, CB9), Table Rock (CB2), and Owl (CB7) creeks.

Trench 5 exposed modern sediments deposited between 400 yr B.P. and the present (Figs. 1 and 2). As a result of variable flood magnitudes, organic carbon contents vary irregularly with depth between 1.0 and 0.2%. There is no water table or riparian vegetation related to the overbank deposits of this unit. This soil is a weakly developed Entisol. Eleven $\delta^{13}\text{C}$ samples were collected from the soil in TR5. The local vegetation consists mainly of scattered pecan (*C. illinoensis*), oak (*Q. macrocarpa*), and mesquite (*P. glandulosa*). Understory grass species are similar to those around TR13 and TR19. This area has not been cultivated and a small amount of bermuda grass grows near the trench because of nearby road disturbance. An additional $\delta^{13}\text{C}$ sample was taken from CB5.

Laboratory Methods

Coarse roots were removed prior to sample preparation for $\delta^{13}\text{C}$ analysis. Samples were subsequently dried and ground with a mortar and pestle and passed through a 2.0-mm sieve. Carbonate carbon was removed from the samples by soaking in 1 N HCl until visible reaction ceased and pH stabilized. Soils were then washed with distilled water, dried, pulverized, and homogenized. This acid pretreatment has been shown to have no effect on the $\delta^{13}\text{C}$ value of the soil organic matter (T. W. Boutton, unpublished data). Soil organic matter was converted to

TABLE 1
 $\delta^{13}\text{C}$ Values and Radiocarbon Ages of Alluvial Deposits and Soils of Cowhouse, Owl, and Table Rock Creeks

Creek	Alluvial unit	Site ^a	¹⁴ C Age (yr B.P.) ^b	Laboratory number	Depth (cm)	Soil horizon ^c	$\delta^{13}\text{C}$ ^d
Cowhouse	Ford	TR5			0–25	A	–19.1
					25–57	2Bk1	–20.7
					57–75	2Bk2	–18.0
					75–100	3C	–19.3
					100–114	4Akb1	–19.7
					114–122	5Bwb1	–19.5
					122–143	6Akb2	–18.7
					143–171	7C1b2	–19.1
					171–220	8C2b2	–19.3
					220–237	9C3b2	–18.4
					237–266	10C4b2	–18.4
		CB5	370 ± 180	TX-6699	195	C	–19.0
		CB13	600 ± 140	TX-6700	47	Bw	–20.3
		CB4	650 ± 160	TX-6701	383	Ab	–18.4
		CB16	1690 ± 90	Beta-37450	275	BC	–19.2
		TR1			0–15	A1	–19.0
	West Range				15–34	A2	–21.4
					34–85	Bk1–Bk2	–16.7
					85–118	Bk3	–17.2
					118–166	Bk4–Bk5	–16.9
					166–215	Bk6–Bk7	–16.8
					215–267	Bk8	–17.5
					267–347	Bk9	–17.7
					347–380	Bck	–17.9
					380–520	C	–18.5
		CB13	3950 ± 290	TX-6704	725	C	–18.5
		CB9	4170 ± 100	TX-6705	600	C	–18.2
	Fort Hood	CB12	5210 ± 230	Beta-37452	165	BC	–16.5
		CB15	5740 ± 300	GX-15892	379	Bck	–16.3
		CB6	6850 ± 90	Beta-37618	625	C	–19.3
		TR19			0–16	A1	–18.2
		TR19-core			16–32	A2	–16.7
					32–59	AB	–14.6
					59–94	Bw	–14.5
					94–122	Bk1	–14.0
					122–153	Bk2	–15.4
					153–189	Bk3	–15.6
					189–252	Bk4	–16.7
					252–320	Bk5	–18.3
					320–370	Bk6	–18.6
					370–400	Bck	–18.5
Owl	Jackson	TR13			400–425	2Bkb	–20.8
					425–500	2BCb	–19.9
					0–8	A1	–19.0
					8–14	A2	–18.4
					14–38	BAk	–14.7
					38–66	Bkss1	–14.1
					66–98	Bkss2	–13.4
			3870 ± 70 (bulk humate)	Beta-62669	98–120	Bk1	–13.6
					120–150	Bk2	–14.4
					150–190	Bk3	–19.4
					190–213	Bk4	–19.8
					213–250	Bk5	–19.9
					250–270	BC	–20.3
					295–350	CB	–21.1
	West Range	CB11	890 ± 50	GX-15763	250	Bk	–20.1
		CB99			250	CaCO ₃	–5.8
		CB7			157	Bkb	–18.4
Table Rock	Georgetown	CB6	1250 ± 110	TX-6698	270	Bkb	–18.5
	West Range	CB2			300	Bw	–19.1

^a See Fig. 1; CB, cutbank; TR, trench.

^b TX, University of Texas Radiocarbon Laboratory; Beta, Beta Analytic, Inc.; GX, Geochron Laboratory Division; all ¹⁴C ages are from charcoal, except Beta 62669.

^c Detailed descriptions are given in Nordt (1992) and Nordt and Hallmark (1990).

^d All reported in units of ‰ relative to standard PDB.

CO₂ for mass spectrometric analysis by dry combustion with CuO in evacuated, sealed quartz tubes at 850°C (Boutton, 1991b). The CO₂ was purified and isolated by cryogenic distillation, and its isotopic composition determined on a VG-903 (VG Isogas, Middlewich, UK) dual inlet, triple collector isotope ratio mass spectrometer. Results are expressed as $\delta^{13}\text{C}$ values by

$$\delta^{13}\text{C}(\text{‰}) = \left[\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right] \times 10^3, \quad (1)$$

where $\delta^{13}\text{C}$ has units of parts per thousand, or per mil (‰), and R is the mass 45/mass 44 of sample or standard CO₂ (Craig, 1957). All results are reported relative to the international PDB standard. Overall precision (machine error plus sample preparation error) was 0.2‰ or better.

The proportion of organic carbon derived from C₄ sources was estimated by the mass balance equation

$$\delta^{13}\text{C}_{\text{soil}} = (\delta^{13}\text{C}_{\text{C}_4})(x) + (\delta^{13}\text{C}_{\text{C}_3})(1 - x), \quad (2)$$

where $\delta^{13}\text{C}_{\text{soil}}$ is the $\delta^{13}\text{C}$ value of organic matter in surface soils, buried soils, or alluvium; $\delta^{13}\text{C}_{\text{C}_4}$ is the average $\delta^{13}\text{C}$ value of C₄ plants (−13‰); x is the proportion of carbon from C₄ plant sources; $\delta^{13}\text{C}_{\text{C}_3}$ is the average $\delta^{13}\text{C}$ value of C₃ plants (−27‰), and $1 - x$ is the proportion of carbon derived from C₃ sources. Assumptions and limitations associated with use of this equation were discussed above.

Interpreting Stable Carbon Isotope Ratios of Organic Matter in Alluvium

Organic carbon in the late Quaternary alluvial deposits and soils of Cowhouse, Owl, and Table Rock creeks is derived primarily from two inherited sources and one pedogenic source.

The first inherited source is from the erosion and redeposition of organic-rich upland topsoil containing carbon complexed with clays. Because the drainage basins under investigation are small and encompass areas that are climatically, vegetatively, and geologically uniform, organic carbon from upland topsoil sources will reflect one set of paleoenvironmental conditions and not an average of more than one climatic or vegetational zone often associated with large drainage basins. This inherited organic source is therefore desirable for interpreting past vegetation and climate shifts.

The second inherited source of organic carbon in late Quaternary alluvial units is derived from Cretaceous rocks and older alluvium. This source is obviously undesirable, but it should not significantly bias $\delta^{13}\text{C}$ interpretations toward previous paleoecological conditions because organic carbon contents of Cretaceous rocks and older alluvium are low. Furthermore, the Cretaceous

rocks are resistant to erosion and do not contribute large amounts of sediment to Quaternary alluvium.

Upon termination of floodplain deposition, organic carbon derived from pedogenic processes is superimposed on, and mixed with, the inherited organic carbon fraction. With landscape stability and the establishment of permanent vegetation, decaying organic matter will accumulate in the soil and yield $\delta^{13}\text{C}$ signatures that are in equilibrium with ambient vegetation conditions. With time, a small portion of this new organic carbon will be translocated into subsurface horizons and mixed with the inherited portion by water movement and bioturbation. This source of organic carbon accumulation is clearly desirable for making past vegetative and climatic interpretations.

Throughout most of the Holocene, the streams in Fort Hood had entrenched channels and low floodplain water tables. These factors, coupled with numerous flash-flood events, have prevented appreciable colonization of riparian plants on point bars and along the channel that may contribute spurious transported $\delta^{13}\text{C}$ signatures to the alluvial sequence.

RESULTS AND DISCUSSION

Vegetation Interpretations Based on Stable Carbon Isotopes

Ford alluvium. The 11 $\delta^{13}\text{C}$ values from the Ford alluvium in TR5 are erratic with depth, but fall between −18 and −21‰ (Fig. 3; Table 1). This erratic pattern probably reflects the variability in modern flood magnitudes. An additional sample taken from the Ford alluvium, associated with a charcoal age of 370 ± 180 , gave a $\delta^{13}\text{C}$ value of −19.0‰ (Table 1). These 12 $\delta^{13}\text{C}$ values show that during Ford deposition, and brief intermittent periods of landscape stability and pedogenesis, approximately 50 to 65% of the organic carbon in the alluvium was of C₄ origin. As a result, both the inherited and pedogenic ^{13}C signatures indicate that climatic conditions have remained unaltered during the past 400 yr.

West Range alluvium. Deposition of West Range alluvium occurred between 4200 and 600 yr B.P. In order to reconstruct the relative contribution of C₃ and C₄ plant biomass to the West Range alluvium between 2000 and 600 yr B.P. (that time not represented by TR1 and TR5), samples containing both inherited and pedogenic organic carbon were taken from localities containing ^{14}C ages dating to this time interval. Three of these samples were collected from Cowhouse Creek and have $\delta^{13}\text{C}$ values of −20.3, −18.4, and −19.2‰ that date to 600 ± 140 , 650 ± 160 , and 1690 ± 90 yr B.P., respectively (Fig. 1; Table 1). A sample from the West Range alluvium of Owl Creek dating to 890 ± 50 yr B.P. yielded a $\delta^{13}\text{C}$ value of −18.4‰ (Fig. 1; Table 1). An additional sample from Table Rock Creek dated to 1250 ± 110 yr B.P. and had a $\delta^{13}\text{C}$ value

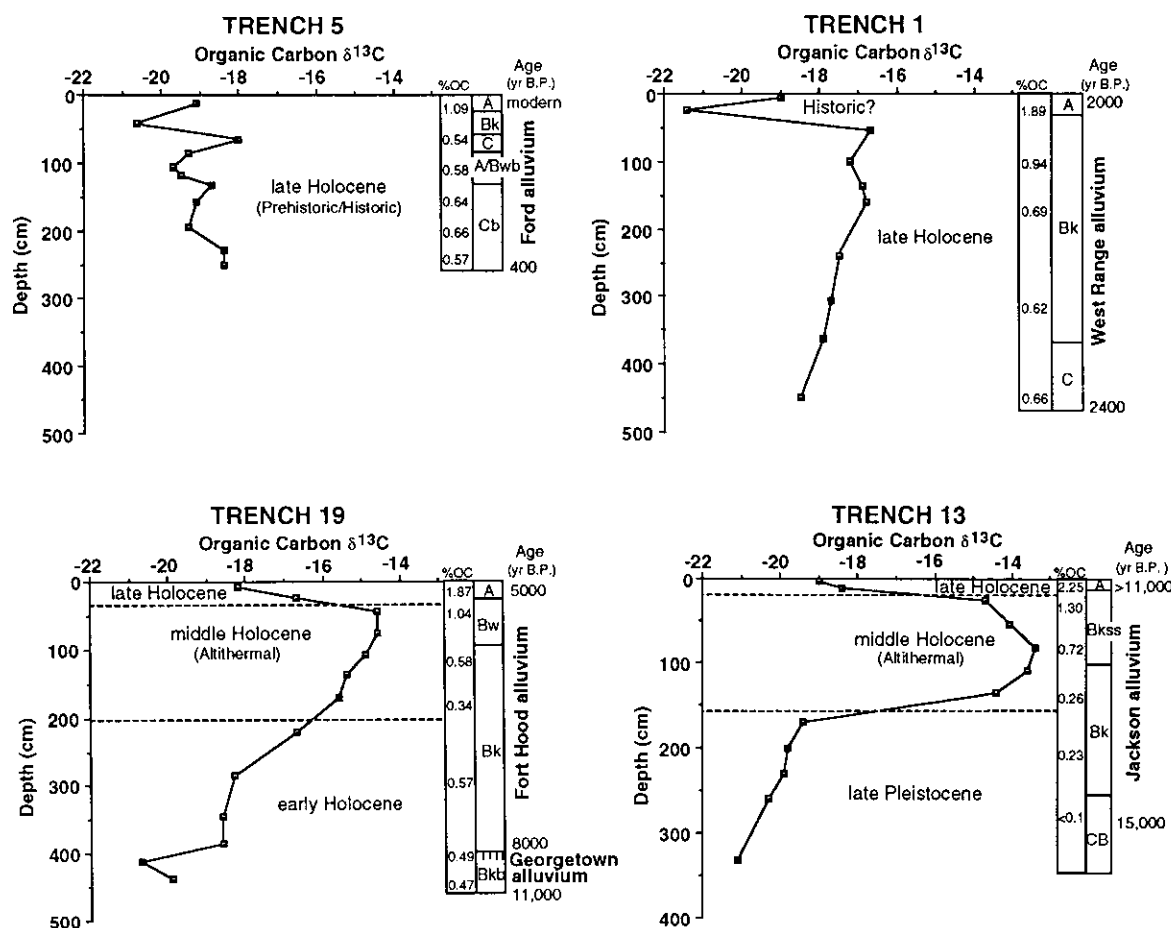


FIG. 3. Stable carbon isotope depth distributions from organic matter in the alluvial soils and deposits of Cowhouse Creek. Superimposed are the inferred time periods during which the organic matter accumulated. Soil profile horization, organic carbon (OC) contents, and stratigraphic units and their ages are shown to the right of each graph. The time periods of organic matter accumulation within the soils are indicated next to the $\delta^{13}\text{C}$ curve.

of -19.1‰ . These data reveal no discernable shift in vegetation between the deposition of the West Range alluvium between 2000 and 600 yr B.P. and the Ford alluvium during the past 400 yr.

Trench 1 was excavated in a section of the West Range alluvium that was deposited between about 2400 and 2000 yr B.P. At this trench, the 10 $\delta^{13}\text{C}$ values range between -16.7 and -21.4‰ , indicating a mixed assemblage of C₃ and C₄ plant biomass present between 2400 and 2000 yr B.P. (Fig. 3; Table 1). However, there is a slight increase in C₄ biomass moving from the base of the trench dating to 2400 yr B.P. to the upper Bk horizon of the trench dating to near 2000 yr B.P. Note that because the ^{13}C values of the pedogenic (A-horizon) and inherited (C-horizon) fractions are similar, any shift in ^{13}C in the profile must represent a shift in vegetation and climate. This shift most likely represents a slight drying and warming trend. Furthermore, the return to lower $\delta^{13}\text{C}$ values in the upper 50 cm must reflect a return to increased effective moisture conditions near or shortly after 2000 yr B.P.

Two additional $\delta^{13}\text{C}$ values were obtained from deeply buried point bar sequences in the West Range alluvium.

These sediments date to 4170 ± 100 and 3950 ± 290 yr B.P. and yielded $\delta^{13}\text{C}$ values of -18.2 and -18.5‰ , respectively (Fig. 1; Table 1). These values are consistent with those in the lower profile in TR1 and indicate that the floodplains and their contributing drainage basins were characterized by a mixed C₃/C₄ plant assemblage between about 4000 and 2000 yr B.P.

In summary, the West Range alluvium and soils dating to between 4200 and 600 yr B.P. contain $\delta^{13}\text{C}$ signatures indicating the presence of a mixed assemblage of C₃ and C₄ species in the region throughout this period. This episode of vegetation stability was interrupted with a slight increase in C₄ plants about 2000 yr B.P., probably indicating a brief drying and warming episode.

Fort Hood alluvium. The Fort Hood alluvium, as exposed in TR19 of Cowhouse Creek, displays two distinctive C₃/C₄ trends with depth (Fig. 3; Table 1). The first trend occurs in the upper profile between 0 and 50 cm (Fig. 3; Table 1). Although the sediments at 50-cm depth were deposited approximately 5000 yr ago, most of the organic carbon accumulated postdepositionally by pe-

dogenesis. Accordingly, the ^{13}C values from the upper two horizons of TR19 are similar to most values recorded in the West Range and Ford alluvium and associated soils. Alternatively, the $\delta^{13}\text{C}$ values in the upper 50 cm of TR19 could be the result of cotton (C_3) cultivated before 1942; however, these same values would have already been registered as early as 4000 yr B.P. according to $\delta^{13}\text{C}$ values from the West Range alluvium at the base of TR1 and from buried point bar deposits dating to about 4000 yr B.P. This suggests that cotton may have never been grown at the site or that it was not cultivated long enough to influence the $\delta^{13}\text{C}$ values significantly.

The sediments in TR19 between a depth of 50 and 150 cm were deposited between approximately 6000 and 5000 yr B.P. This zone shows the second ^{13}C trend, where there is a significant increase in the contribution of C_4 plants. Two additional samples were taken from subsurface horizons of the Fort Hood alluvium that date to 5740 ± 300 yr B.P. and 5210 ± 230 yr B.P. and yielded $\delta^{13}\text{C}$ values of -16.3 and -16.5‰ , respectively. These samples also indicate a greater abundance of C_4 species during this time. Even though much of the organic carbon in subsurface horizons of the soils formed in the Fort Hood alluvium is inherited, some of it is most likely postdepositionally acquired. Consequently, the middle Holocene increase in C_4 grasses may have persisted as late as 4000 yr B.P. when there was a significant shift to fewer C_4 species, as recorded in the West Range alluvium. Furthermore, because some modern and possibly late Holocene C_3 plant roots have inevitably contributed organic carbon to depths of 50 to 150 cm, the enriched $\delta^{13}\text{C}$ signatures recorded in the Fort Hood soils below a depth of 50 cm may be a slight underestimation of the amount of C_4 vegetation from the middle Holocene grassland community. In any case, these data indicate relatively warm and dry climatic conditions between 6000 and 5000 yr ago.

The zone between a depth of 2.0 and 4.0 m in TR19 was deposited between about 8000 and 6000 yr ago and shows decreasing biomass production from C_4 plants (Fig. 3; Table 1). Near 8000 yr B.P. the abundance of C_4 plants was similar to the late Holocene, indicating similarities in C_3 and C_4 biomass production and climate. A sample from a buried point bar dating to 6850 ± 90 yr B.P. yielded a $\delta^{13}\text{C}$ value of -19.3‰ , validating the values at the base of TR19.

In summary, data from the Fort Hood alluvium suggest that between about 8000 and 6000 yr B.P., a mixed C_3/C_4 plant community dominated the local ecosystem. Shortly afterward, between about 6000 and 5000 yr B.P., there was a shift to a C_4 -dominated plant community that persisted no later than 4000 yr B.P. Surface horizon signatures in the Fort Hood alluvial soils were recorded during the late Holocene by pedogenic processes and compare well with values from the West Range and Ford alluvium.

This indicates that a mixed C_3/C_4 plant community, and more mesic conditions, had reemerged no later than 4000 yr B.P.

Royalty paleosol and Georgetown alluvium. The Royalty paleosol and associated early Holocene Georgetown alluvium in TR19 (core samples adjacent to the trench) has $\delta^{13}\text{C}$ values of -20.8 and -19.9‰ from the surface and subsurface horizons, respectively (Fig. 3; Table 1). This paleosol on Owl Creek (Fig. 1) yielded a $\delta^{13}\text{C}$ value of -18.5‰ (Table 1), which is similar to those from Cowhouse Creek. These values indicate the presence of a mixed C_3/C_4 plant assemblage between about 11,000 and 8000 yr B.P., but with slightly fewer C_4 plant species than during the period between 8000 and 6000 yr B.P.

Jackson alluvium. The $\delta^{13}\text{C}$ curve for the profile of the late Pleistocene Jackson alluvium exposed in TR13 is similar to that of the middle Holocene Fort Hood alluvium in TR19 (Fig. 3; Table 1). This indicates that the values in TR13 from depths of 0 to 20 cm and 20 to 155 cm are pedogenically superimposed from the late Holocene mixed C_3/C_4 and middle Holocene C_4 -dominated assemblages, respectively. Further substantiating a large pedogenic signature within the Jackson soil is the low ($<0.1\%$) organic carbon content in the parent material.

After developing our paleoclimatic model, a bulk soil humate sample was collected for ^{14}C dating from a depth of 98–120 cm in TR13. The resulting age was 3870 ± 70 yr. Although this age represents a mean residence time, the isotopic data from this trench indicates that most of the organic carbon in the subsoil accumulated near 4000 yr B.P. or possibly, because of some late Holocene root contamination, slightly earlier. This humate age is then consistent with the superimposition of a middle Holocene ^{13}C signature onto a late Pleistocene ^{13}C signature.

The five $\delta^{13}\text{C}$ values below a depth of about 160 cm in TR13 reach a low of about -21‰ (Fig. 3; Table 1). These are the lowest $\delta^{13}\text{C}$ values recorded for the entire late Quaternary stable carbon isotope sequence, indicating that approximately 15,000 yr B.P., C_4 plants composed only about 45 to 50% of the vegetation in the surrounding uplands, the Jackson alluvial floodplain, or both. An additional sample from the lower soil profile of the Jackson alluvium at CB11, yielded a $\delta^{13}\text{C}$ value of -20.1‰ , which is consistent with findings in the late Pleistocene portion of TR13 (Table 1). Furthermore, a pedogenic carbonate nodule from the Jackson soil at CB99 (Fig. 1) yielded a $\delta^{13}\text{C}$ value of -5.8‰ . Cerling *et al.* (1989) show that carbon from pedogenic carbonates has $\delta^{13}\text{C}$ values 14 to 16‰ heavier (more ^{13}C -enriched) than the associated organic matter. Thus, a value of -5.8‰ for this carbonate nodule suggests that it was formed from CO_2 derived from organic matter with a $\delta^{13}\text{C}$ value of approximately -21‰ . This indicates secondary carbonate precipitation in equilibrium with soil CO_2 produced by a

plant community containing 40 to 50% C₄ plant biomass, much like what is present in the lower profile of TR13.

The $\delta^{13}\text{C}$ values from the early Holocene Royalty paleosol of Cowhouse and Owl Creek show similarities to the late Pleistocene Jackson alluvium (Fig. 3; Table 1). This similarity can be explained by one or more of the following possibilities: (1) climatic conditions of the late Pleistocene continued into the early Holocene and did not change much until after 8000 yr B.P.; (2) floodplains were favorable for C₃ biomass production, while at the same time C₄ plant communities were replacing C₃ plants in the surrounding uplands where moisture conditions were more xeric; or (3) a significant proportion of the organic carbon in the Royalty paleosol and Georgetown alluvium was eroded and redeposited from the Jackson alluvium. Although all of these conditions may have been working to some degree simultaneously, it is clear that a basin-wide shift to a mixed C₃/C₄ plant community was underway by 8000 yr B.P. Because the Georgetown alluvium and Royalty paleosol $\delta^{13}\text{C}$ values are intermediate between those of the late Pleistocene (15,000 yr B.P.) and early Holocene (8000 to 7000 yr B.P.), it seems probable that a transitional climate characterized the early Holocene.

Summary of Late Quaternary Vegetation and Climate of Central Texas

During deposition of the Jackson alluvium 15,000 yr B.P., the vegetation community in central Texas consisted of 50 to 60% trees and C₃ grasses and 40 to 50% C₄ grasses. This late Pleistocene plant community probably reflected climatic conditions that were cooler, wetter, or both, relative to any subsequent period during the Holocene.

During deposition of the Georgetown alluvium between 11,000 and 8000 yr B.P., the vegetation and climate were transitional between cooler/wetter late Pleistocene and warmer/drier Holocene climates. This shift was relatively slow, taking as much as 5000 yr before transforming to middle Holocene grassland conditions about 6000 yr B.P.

The maximum abundance of C₄ grasses occurred during deposition of the Fort Hood alluvium between about 6000 and 5000 yr B.P. (Fig. 3). This is interpreted as a time of maximum drying and warming that led to expansion of open grassland where C₄ species constituted as much as 95% of the biomass production in the local uplands and floodplains.

By 4000 yr B.P., the abundance of C₄ grasses had decreased to levels similar to those of the transitional early Holocene that existed around 8000 yr B.P. Thus, more mesic climatic conditions had emerged by 4000 yr B.P. and continued into modern times, except for a possible brief shift to more C₄ plants during a drying and warming episode around 2000 yr B.P.

Regional Correlation of Late Quaternary Climates

A summary of previous late Quaternary climatic interpretations for central and north Texas, and their relation to the results of this study are shown in Fig. 4. There is strong agreement among these studies regarding environmental conditions prior to ca. 12,000 yr B.P. Based on fossil pollen data from Boriack bog in central Texas, Bryant and Holloway (1985) demonstrate that climatic conditions during full-glacial time (22,500–14,000 yr B.P.) were cooler and wetter than today. More specifically, they conclude that July temperatures were as much as 5.5°C cooler than those at present based mainly on scattered spruce pollen. Stute *et al.* (1992) concur with this interpretation based on noble gas concentrations dissolved in groundwater of different ages spanning the last 40,000 yr in south Texas. Paleoenvironmental data from northwest Texas (Holliday *et al.*, 1983; Holliday, 1985; Pierce, 1987; Johnson, 1987) indicate that a parkland ecosystem existed there during the late Pleistocene, with less seasonal fluctuation in temperature and precipitation. The abundance of C₃ vegetation and inferred cooler and wetter conditions during the late Pleistocene at Fort Hood is consistent with climatic conditions interpreted for the late Pleistocene elsewhere in Texas.

A gradual shift to drier and warmer conditions occurred during the late Pleistocene (Fig. 4). Bryant and Holloway (1985) inferred a transition between 14,000 and 11,000 yr B.P., based on a pollen shift from deciduous woodlands to oak savannas and grasslands, but showed no further changes during the Holocene. Other investigators report a lengthy early Holocene climatic transition between cooler and wetter late Pleistocene conditions

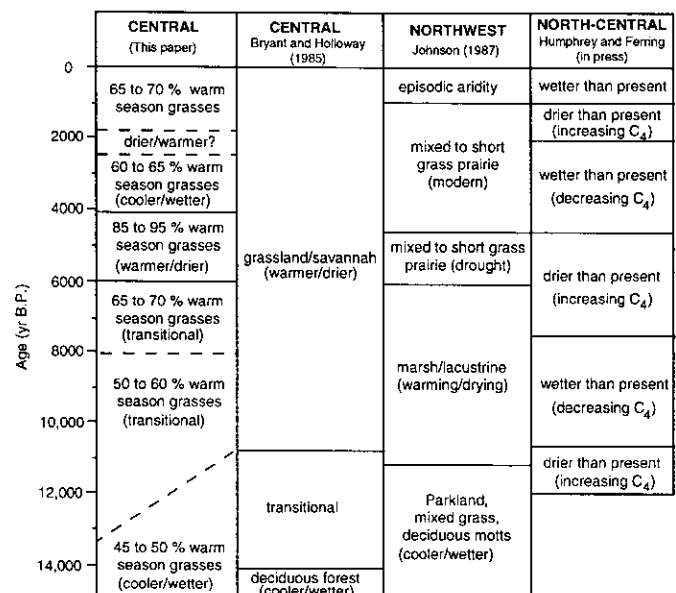


FIG. 4. Summary diagram comparing interpretations of late Quaternary paleoenvironments of central and north Texas.

and drier and warmer Holocene conditions. During this time, streams of northwest Texas were shifting from perennial flow to isolated lacustrine ponds and intermittent flow that was accompanied by increasing mean annual temperatures (Holliday *et al.*, 1983; Holliday, 1985; Johnson, 1987; Pierce, 1987). Using stable oxygen and carbon isotopes from lacustrine and soil carbonates in north-central Texas, Humphrey and Ferring (1994) showed that mesic conditions continued until 7500 yr B.P., except for a brief drying period between about 12,000 and 11,000 yr B.P. The slow replacement of C_3 by C_4 plants at Fort Hood agrees with an extended warming and drying climatic transition during the early Holocene.

By the middle Holocene, drying had reached a maximum according to most studies (Fig. 4). Northwest Texas was experiencing conditions of maximum temperatures, minimum precipitation, and eolian activity between 6000 and 4500 yr B.P. (Holliday *et al.*, 1983; Holliday, 1985, 1989; Johnson, 1987; Pierce, 1987). This episode coincides with $\delta^{13}C$ values from soil organic matter from the same area revealing a shift from -23‰ in the early Holocene to -15‰ in the middle Holocene (Haas *et al.*, 1986). These results were interpreted to represent a shift from cool-season C_3 grasses to warm-season C_4 grasses. Based on enriched $\delta^{13}C$ values in soil carbonates from northwest Texas, Humphrey and Ferring (1994) also show a middle Holocene xeric episode, although the $\delta^{18}O$ values from these same carbonates do not indicate a significant temperature change. The results from Fort Hood also provide compelling evidence for a middle Holocene drying episode (i.e., Altithermal), as interpreted from a shift in the abundance of C_4 species from slightly under 50% during the late Pleistocene to 85 to 95% in the middle Holocene.

A noticeable shift back to cooler and/or wetter conditions was detected in many areas shortly after 5000 yr B.P. (Fig. 4). Northwest Texas transformed to conditions much like the present, with brief episodes of increased aridity during the past 1000 yr (Holliday *et al.*, 1983; Holliday, 1985; Johnson, 1987; Pierce, 1987). According to Humphrey and Ferring (1994), the return to mesic conditions after 5000 yr B.P. (decreasing $\delta^{13}C$ values) was interrupted in north-central Texas by a brief warming and drying episode between 2000 and 1000 yr B.P. Based on depositional environments, they concluded that cooler and wetter conditions returned after 1000 yr B.P. Furthermore, a pollen core taken from an east-central Texas bog revealed the presence of a deciduous woodland forest and inferred mesic conditions between about 3000 and 2000 yr B.P. and more xeric conditions after 2000 yr B.P. when deciduous forests gave way to a savanna (Holloway *et al.*, 1987). In contrast to the above two investigations, Hall (1990, 1988) believes that north-central Texas was cool and wet between 2000 and 1000 yr B.P., based mainly on the development of thick cumelic soils and

high floodplain water tables. He further concludes that warm and dry conditions returned during the last 1000 yr, based largely on regional channel trenching. The Fort Hood isotopic data show a brief period of more xeric conditions around 2000 yr B.P. that approximates a similar dry period proposed by Humphrey and Ferring (1994) and Holloway *et al.* (1987). The results from Fort Hood also show a return to more mesic conditions after 2000 yr B.P., with no subsequent changes.

Our results are also in general agreement with Holocene climatic trends observed for other portions of the Great Plains. $\delta^{18}O$ analysis on uranium/thorium-dated samples of speleothem calcite from a cave in northeastern Iowa indicate a middle Holocene (5900–3700 yr B.P.) that was approximately $3^\circ C$ warmer than the preceding early Holocene (8000–5900 yr B.P.) and approximately $4^\circ C$ warmer than the late Holocene (3700–1000 yr B.P.) (Dorale *et al.*, 1992). Furthermore, this middle Holocene warm period in northeastern Iowa was accompanied by a significant increase in the proportion of C_4 -derived carbon, as evidenced by a 4‰ increase in the $\delta^{13}C$ values of these same calcites (Dorale *et al.*, 1992). Pollen and faunal analyses in northeastern South Dakota have indicated that this area was a cool, moist boreal forest prior to 10,000 yr B.P., slightly warmer and covered by deciduous forest from 10,000–8000 yr B.P., warm and dry with tall grass prairie from 8000–4000 yr B.P., and slightly more mesic from 4000 yr B.P. to the present (Watts and Bright, 1968).

It is well-known that mechanisms other than climate are capable of inducing dramatic changes in vegetation, either through their direct effects or through interaction with climate (Foster *et al.*, 1990). For example, plant communities subjected to livestock grazing in central and north-central Texas often experience an increase in C_3 grasses, forbs, and woody plants relative to comparable ungrazed communities (Dyksterhuis, 1946, 1948; Launchbaugh, 1955). Thus, grazing by bison populations documented in this region during the late Quaternary (Dillehay, 1974) may have influenced vegetation composition over the time period included in our study. Fire is a natural component of the disturbance regimen of all grasslands (Anderson, 1990) and in the North American tallgrass prairie usually favors C_4 perennial grasses and inhibits C_3 grasses and woody plants (Risser, 1990). Evidence also suggests that prehistoric humans often started grassland fires as a means of manipulating wildlife populations (Collins, 1990), thereby altering fire frequency and, potentially, vegetation composition. It is not possible to determine the relative importance of these potential agents of vegetation change in our study. However, because our work at Fort Hood correlated strongly with other climatic reconstructions and interpretations not only from this region but also from other portions of the Great Plains, we favor climate as the driving force behind the vegetation changes documented here.

CONCLUSIONS

Based on $\delta^{13}\text{C}$ values from organic matter of alluvial soils and depositional facies of three streams in the Fort Hood Military Reservation of central Texas, a late Quaternary vegetation and climatic record is proposed. Based on $\delta^{13}\text{C}$ values of -21‰ , full-glacial (15,000 yr B.P.) C₄ species constituted only about 45 to 50% of the plant community contributing organic matter to the soils. This suggests that late Pleistocene conditions were cooler and probably wetter than at any time in the Holocene. Between 11,000 and 8000 yr B.P., the abundance of C₄ species increased to about 65 to 70% of the total plant community and reached a maximum of 85 to 95% between 6000 and 5000 yr B.P. The latter interval is interpreted as a middle Holocene Altithermal when warm and dry conditions reached a maximum. By 4000 yr B.P., C₄ species decreased to 65 to 70% of the total plant community indicating a renewal of cooler and wetter conditions. This condition has persisted to the present except for a possible brief drying episode about 2000 yr B.P.

The Fort Hood late-Quaternary vegetation and climatic record correlates well with other studies in northwest and north-central Texas and in portions of the Great Plains that show relatively cool and wet late Pleistocene conditions, followed by a transition to warmer and drier conditions in the early Holocene. Most of these studies also point to a middle Holocene Altithermal interval when warming and drying reached its maximum expression. While a shift to more mesic conditions around 4000 yr B.P. is well documented, interpretations of the last 2000 yr are conflicting. Perhaps diachronous climatic events characterized the last 2000 yr producing stratigraphic records that are noncorrelative. Alternatively, differing climatic interpretations may have resulted from the use of different methodologies or from varying degrees of methodological or field resolution.

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