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New correlation of stable carbon isotopes with changing late-Holocene fluvial environments in the Trinity River basin of Texas, USA

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Abstract

A late-Holocene alluvial sequence in north-central Texas has a 1 m thick buried cumulic soil with an A-C profile called the West Fork paleosol. It formed 2300 to 1000 yr BP and is a local equivalent of the Copan paleosol that is present throughout the southern US Great Plains. Stable carbon isotopes indicate that the paleosol and underlying gray clay formed under vegetation dominated by C_4 species (mean $\delta^{13}C$: −18.3 ± 0.3‰). Diverse paleoenvironmental studies indicate that the period of paleosol formation was cool and wet and that alluvial water-tables were high, resulting in broad wet meadows across alluvial valleys, characterized by communities of grasses. Present-day wet meadows and bottomlands with Mollisols with A-C profiles along streams in the Great Plains are dominated by C_4 tallgrass species and may serve as analogues to wet-meadow environments during the late Holocene. A shift in climate to warm-dry conditions about 1000 yr BP was accompanied by deep channel cutting, low alluvial water-tables, and colonization of abandoned floodplains by trees and other C_3 species, as indicated by a change in carbon isotopes to lower values (mean $\delta^{13}C$: −20.8 ± 0.5‰) and correlating with the 'Medieval Warm Period'. Other stable carbon isotope studies from late-Holocene alluvium in Texas have been mistakenly interpreted as evidence for paleoenvironmental conditions opposite to those presented in this investigation. We conclude that interpretations of stable carbon isotopes from alluvium based on broad patterns of upland C_4 grasses and climate can be in error, especially in cases where wet-meadow deposits and soils are present.

Keywords

alluvium, Copan paleosol, late Holocene, 'Medieval Warm Period', stable carbon isotopes, US Great Plains, wet meadows

Introduction

In the southern US Great Plains, Holocene alluvial deposits are thick and contain a variety of buried soils. A well-developed, 1 m thick, cumulic Mollisol with an A-C profile commonly occurs near the top of many late-Holocene alluvial sequences. Its significance was first recognized and documented by Hall (1977, 1978, 1979, 1982, 1988; Hall and Lintz, 1984) and named Copan paleosol for the community of Copan along the Little Caney River, northeastern Oklahoma (Hall, 1977). Subsequently, equivalent paleosols have been reported from Texas where they are called the Navarro paleosol (Bruseth et al., 1987), Asa soil (Waters and Nordt, 1995), Leon Creek paleosol (Nordt et al., 2002), and the West Fork paleosol (Ferring, 1986). The Copan paleosol and its geomorphology, geochronology, and paleoecology, as well as its nomenclatural equivalents, were reviewed by Hall (1990). Numerous radiocarbon ages on charcoal available at that time indicate the Copan paleosol formed *c*. 2000 to 1000 ^{14}C yr BP.

Several studies in Texas have included stable-carbon isotope analysis of alluvium and buried soils (Humphrey and Ferring, 1994; Nordt et al., 1994, 2002). In these investigations, the late-Holocene Copan paleosol was found to be characterized by high $\delta^{13}C$ values, indicating the dominance of C_4 grasses and presumed correlation with a warm-dry climate. The interpretation of a warm-dry climate follows the discovery by Teeri and Stowe (1976) that the abundance of C_4 grasses in North America is directly related to normal July minimum temperature. Extending that relationship, high (less negative) values of $\delta^{13}C$ have been correlated with greater abundance of C_4 grasses which in turn corresponds with high temperatures. However, we have observed that these interpretations of a warm-dry climate based on stable-carbon isotope data contradict the regional late-Holocene paleoecology of the southern Plains where many lines of evidence show that the climate during the formation of the Copan paleosol was, instead, cool and wet.

The geomorphic investigation of a buried archaeological site presented an opportunity to evaluate the stable carbon isotope record of a new late-Holocene alluvial sequence. The buried site (41TR170) occurs in the West Fork paleosol on the abandoned floodplain of the Clear Fork of the Trinity River in the city of Fort Worth, Tarrant County, Texas (Lintz et al., 2008). An artificial

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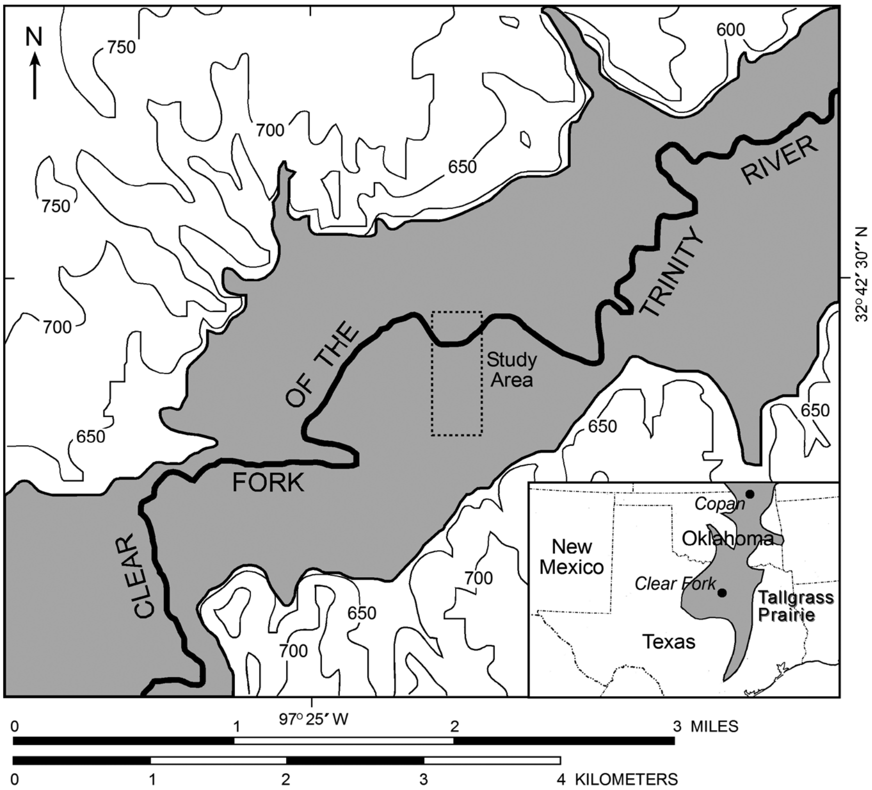

Figure 1. Topographic map of Clear Fork of the Trinity River and study area with archaeological site 41TR170; specific location of study trenches and related information can be found in Lintz et al. (2008); the early 20th century channel is shown in black and flows from left to right in this view; the floodplain is shown in gray; 50-foot contour intervals; from Benbrook 7.5-minute quadrangle, 1995; the distribution of the tallgrass prairie in the inset map is from Risser et al. (1981)

channel of the Clear Fork was cut down more than 4 m into Cretaceous limestone during the 1960s, leaving the natural channel and its floodplain about 8 m above the new-cut artificial channel. The old channel is shown on a local topographic map, and the archaeological site occurs along a south-turning bend of the old channel in the middle of the broad alluvial valley (Figure 1). Our investigation of the late-Holocene alluvial stratigraphy and associated stable carbon isotopes suggests that the paleosol represents a wet meadow environment, similar to present-day wet meadows, bottomlands, and floodplains with Mollisols with A-C profiles in the central Plains. A discussion of our findings and their significance to late-Holocene paleoecology is presented below.

Methods

Sediments from the Clear Fork alluvium, including the West Fork paleosol, were analyzed for texture and chemistry by the Milwaukee Soil Laboratory, Milwaukee, Wisconsin (Table 1). Sediment and soil properties are described according to Folk (1968) and Birkeland (1999). Conventional and AMS radiocarbon ages on bulk sediment and charcoal were provided by Beta Analytic, Inc., Miami, Florida (Table 2). Stable carbon isotopes were analyzed in the Department of Ecosystem Science and Management, Texas A & M University, College Station, Texas (Table 1). The laboratory procedure of determining carbon isotopes is described in Midwood and Boutton (1998). Although the end $\delta^{13}C$ values for C_4 and C_3 plant communities are dependent upon many factors and are discussed elsewhere (Nordt et al., 2008), we are using −19.0‰ as the transition value between 50% C_4 and 50% C_3 contributions of carbon to soil organic matter (Nordt et al., 2008).

Late-Holocene stratigraphy

Floodplain deposits were studied in a series of 28 trenches on both the north and south side of the now-abandoned natural channel of the Clear Fork of the Trinity River (Figure 1). The overall stratigraphy shown in the trenches is consistent from exposure to exposure and reflects the uniform late-Holocene floodplain environment of the Clear Fork at this locality. The dominant stratigraphic feature of the floodplain is the West Fork paleosol, a cumulic soil that serves as a marker for correlation within the floodplain deposits in the broad drainage basin.

Pre-paleosol alluvium

Two pre-paleosol units are present, based on information from sediments observed in trenches: cemented gravel (middle Holocene) and yellow clay (late Holocene). The alluvium overlies limestone of the Kiamichi Formation (Lower Cretaceous). Other Lower Cretaceous formations which outcrop in the Clear Fork drainage basin include limestone, shale, marl, and sandstone lithology.

Cemented gravel. Carbonate-cemented rounded limestone gravel occurs at the base of some trenches. The gravel has a yellow clay matrix and exhibits a moderate degree of sorting. Collectively, gravel texture is 80% granules and 20% pebbles; cobbles are rare, based on a count of 1191. All clasts are limestone; chert or quartzose lithology is not present. The individual limestone clasts are white with a weak yellowish weathering rind about 2 mm thick. Carbonate coats on the gravels are thin, less than 0.5 mm in thickness. Carbonate cementation of the gravels occurs in subrounded

Table 1. Carbon isotope and sediment data from Clear Fork of the Trinity River floodplain, Tarrant County, Texas

Sample (cm depth)	Sand (mm)					Recalculated				$CaCO_3$	$\delta^{13}C$ (‰)	Dry color
	V. coarse	Coarse	Medium	Fine	V. fine	Sand	Silt	Clay	OC %			
TRENCH 14												
Post-paleosol alluvium												
18–23	2.0	7.9	31.1	36.3	22.7	46	35	19	0.87	42.7	−21.63	10YR 5/2
26–31	3.8	10.1	31.1	33.6	21.4	46	35	19	0.70	43.4	−20.74	10YR 5/2
West Fork paleosol												
52–57	0.2	2.1	14.8	38.4	44.5	31	44	25	1.07	35.1	−18.50	10YR 3/2
70–75	0.2	2.0	11.8	36.1	49.9	27	45	28	1.10	36.0	−18.10	10YR 3/2
82–87	0.5	3.5	14.7	38.0	43.3	31	42	27	0.95	38.3	−18.18	10YR 3/2
102–107	0.7	5.3	20.6	39.2	34.2	36	37	27	0.79	41.4	−18.40	10YR 3/2
Gray clay												
133–138	0.4	3.3	18.8	41.4	36.4	36	38	26	0.70	41.4	−18.30	10YR 4/2
148–153	0.2	1.6	12.1	41.9	44.2	33	40	27	0.77	39.0	−18.60	10YR 4/2
160–165	0.1	1.1	11.4	43.9	43.5	32	40	28	0.73	39.7	−18.90	10YR 4/2
190–195	0.1	0.7	7.2	43.0	49.0	26	43	31	0.78	38.1	−18.35	10YR 4/2
TRENCH 6												
Post-paleosol alluvium												
20–25	0.7	1.2	4.8	24.6	68.7	15	59	28	1.53	33.1	−21.75	10YR 5/2
40–45	0.6	1.2	4.7	24.4	69.1	13	59	28	1.43	34.6	−20.99	10YR 5/2
55–60	0.3	0.5	3.4	24.8	71.0	17	55	28	1.03	33.0	−19.07	10YR 5/2
West Fork paleosol												
75–80	0.1	0.6	6.6	31.3	61.4	30	45	25	1.03	31.8	−17.77	10YR 3/2
95–100	0.3	1.0	10.4	37.0	51.3	30	44	26	1.08	34.1	−18.62	10YR 3/2
115–120	0.4	1.5	12.0	36.0	50.1	27	45	28	0.79	35.8	−18.54	10YR 3/2
135–140	0.3	1.7	13.1	38.6	46.3	28	44	28	0.84	36.8	−18.16	10YR 3/2
Gray clay												
170–175	0.1	0.3	5.4	33.3	60.9	21	79	30	0.82	36.1	−18.36	10YR 4/2
185–190	0.1	0.4	4.8	27.2	67.5	15	55	30	0.85	37.3	−17.74	10YR 4/2
200–205	0.2	0.7	6.5	27.0	65.6	15	54	31	0.88	38.5	−18.61	10YR 4/3

Note: numbers are percentages, Wentworth scale; dry colors from Munsell Soil-Color Chart; OC %, organic carbon determined by Walkley-Black; carbonate % determined by chittick method; samples are in centimeters depth; analyses by Milwaukee Soil Laboratory, Milwaukee, Wisconsin; $\delta^{13}C$ analyses by Department of Ecosystem Science and Management, Texas A & M University, College Station, Texas.

Table 2. Radiocarbon ages from floodplain alluvium, Clear Fork of the Trinity River, Tarrant County, Texas

Trench cm depth	Lab no.	Material dated	Measured radiocarbon age (yr BP)	$^{13}C/^{12}C$ ratio(‰)	Corrected radiocarbon age (yr BP)	Calibrated age (2-sigma)[a]
Post-paleosol alluvium						
6: 35–42	Beta-204912	Charcoal[b]	160 ± 40	−25.6	150 ± 40	AD 1666–1784, AD 1795–1892, AD 1908–1953
West Fork paleosol						
14: 48–53	Beta-205060	Sediment	740 ± 70	−17.5	860 ± 70	AD 1033–1269
1: 66–72	Beta-205063	Sediment	1100 ± 40	−16.2	1240 ± 40	AD 680–882
14: 99–105	Beta-205059	Sediment	1410 ± 70	−17.8	1530 ± 70	AD 400–649
23: 165–175	Beta-205062	Sediment	2170 ± 50	−16.9	2300 ± 50	506–459 BC, 453–439 BC, 419–336 BC, 331–203 BC
Gray clay						
14: 205–215	Beta-204911	Charcoal[b]	1650 ± 40	−26.0	1630 ± 40	AD 268–271, AD 335–540
6: 200–205	Beta-204913	Charcoal[b]	N/A	—	2360 ± 40	730–692 BC, 659–652 BC, 543–373 BC,
Yellow clay						
18: 186–198	Beta-205061	Sediment	2860 ± 60	−22.3	2910 ± 60	BC 1293–968, BC 964–929

Data from Beta Analytic, Inc., Miami, Florida.
[a] IntCal09 calibration data base, Stuiver and Reimer (1993) and Reimer et al. (2009).
[b] AMS ages; all dated charcoal fragments exhibit wood structure and luster; bulk sediment samples were pretreated to remove carbonate and analyzed by conventional method.

lenses or masses; some gravel clasts are not cemented together. The gravel is not directly dated although the overlying yellow clay is *c*. 3000 ^{14}C yr BP; the gravel is probably middle Holocene.

Yellow clay. The yellow clay (yellowish brown, 10YR 5/6) is about 1 m thick and rests directly on the cemented gravel with which it has a sharp boundary. It is silty and sandy, massive with no bedding, calcareous with faint carbonate filaments in the lower 30 cm, and contains occasional small isolated rounded limestone pebbles. Bulk sediment from the lower 12 cm of the yellow clay has a conventional radiocarbon age of 2910 ± 60 ^{14}C yr BP, the earliest age in the geomorphic study (Table 2). The yellow clay may have been more extensive in the local late-Holocene valley fill but is now eroded.

West Fork paleosol and gray clay

The West Fork paleosol was named from exposures along the West Fork of the Trinity River, central Tarrant Co., Texas (Ferring, 1986). Subsequent studies along the Elm Fork of the Trinity River show that the West Fork paleosol is a prominent basin-wide soil-geomorphic feature (Ferring, 1987). In our investigation along the Clear Fork of the Trinity River, the West Fork paleosol is very dark grayish brown (10YR 3/2) sandy to clayey silt (Figure 2). Its dark color distinguishes it from older and younger floodplain alluvium in the field. Its thickness ranges from 59 to 152 cm and averages about 85 cm. The paleosol has 37–45% silt and 25–28% clay (Table 1). High amounts of organic carbon are found in the paleosol, ranging from 0.79 to 1.10%, with higher percentages occurring in the upper 40 cm. The upper 40 cm is slightly darker in the field, probably related to higher organic carbon content. The paleosol is massive, lacking any evidence of primary bedding. The slow sedimentation rate, estimated about 0.80 mm/yr from its thickness and radiocarbon age, coupled with bioturbation by burrowing insects, snails, and earthworms, has resulted in the obliteration of primary microsedimentary layers; earthworm traces are especially common. The cumulic paleosol is largely devoid of pedogenic features, such as clay films and peds. The paleosol lacks a B horizon. Also, redoximorphic features, such as mottles and iron concentrations, are absent from the lower part of the paleosol and underlying gray and yellow clays. The paleosol sediments are strongly calcareous, ranging from 31 to 41%, representing carbonate particles derived from local limestone and marl bedrock in the drainage basin. A slight increase in percentages of carbonate occurs with greater depth in the paleosol, indicating an early stage prior to Bk development. However, visible secondary carbonates in the form of filaments along root traces are rare to absent and carbonate nodules are completely absent. Weak carbonate filaments can be abundant in the lower 15 cm of the paleosol and in the underlying gray alluvium.

The gray clay alluvium in which the West Fork paleosol formed is dark grayish brown (10YR 4/2) clayey to sandy silt. The alluvium is massive with no primary bedding features. It is strongly calcareous and commonly includes numerous carbonate filaments along small root traces but does not include carbonate nodules. Carbonate filaments become less abundant in the upper part of the unit where it grades into the overlying paleosol.

The gray clay and the West Fork paleosol represent a single continuously deposited body of alluvium without a discernible unconformity. The percentages of silt, clay, and carbonate are similar. The primary difference is the amount of organic carbon, the paleosol having higher percentages; the slightly darker color of the paleosol is probably a consequence of higher amounts of organic carbon and a lower sedimentation rate. Two AMS radiocarbon ages on isolated detrital charcoal from the gray clay are

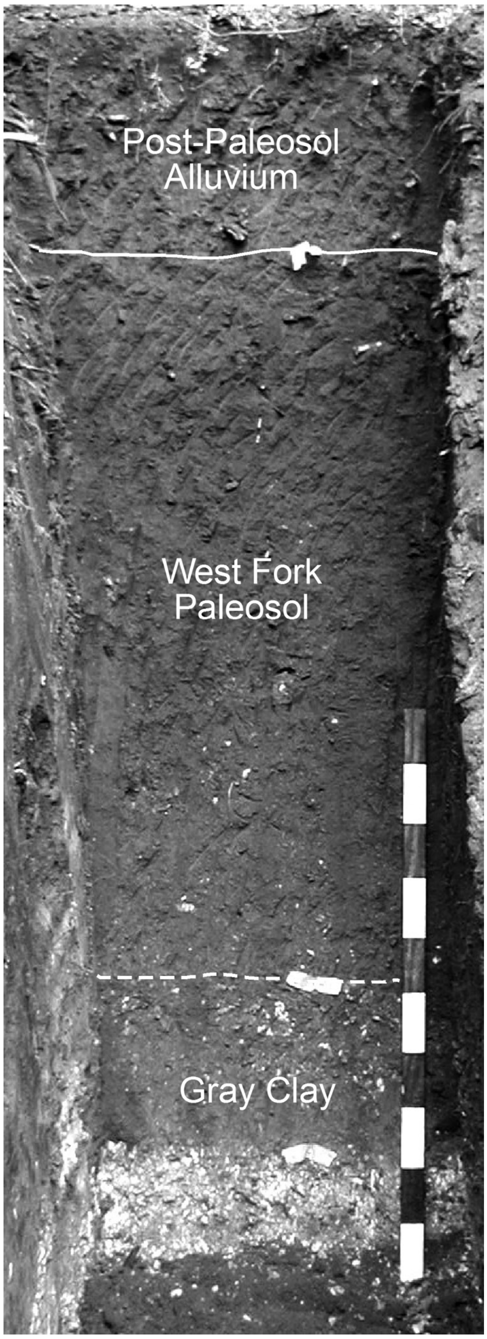

Figure 2. Buried West Fork paleosol, Clear Fork of the Trinity River floodplain, Tarrant County, Texas; white specks in paleosol are large shells of land snails; thin zone of granule-pebble gravel in the gray clay beneath the paleosol; 1 m scale

2360 ± 40 and 1630 ± 40 ^{14}C yr BP; the latter age may be a few hundred years too young for the age of the clay. Occasional thin, discontinuous beds of gravel are present in the gray clay. Clast texture is 48% granules and 52% pebbles; cobbles are rare, based on a count of 2001. All of the clasts are limestone; chert was not observed.

A few radiocarbon ages from the floodplain alluvium indicate that the paleosol began to accumulate by about 2300 ± 50 ^{14}C yr BP and that paleosol accumulation ended after 1240 ± 40 ^{14}C yr BP and perhaps continuing as late as 860 ± 70 ^{14}C yr BP. Although the radiocarbon ages from the floodplain alluvium are too few and too variable to be definitive, we conclude that the chronology of the West Fork paleosol is 2300 to 1000 ^{14}C yr BP and correlates with the regional Copan paleosol, discussed previously.

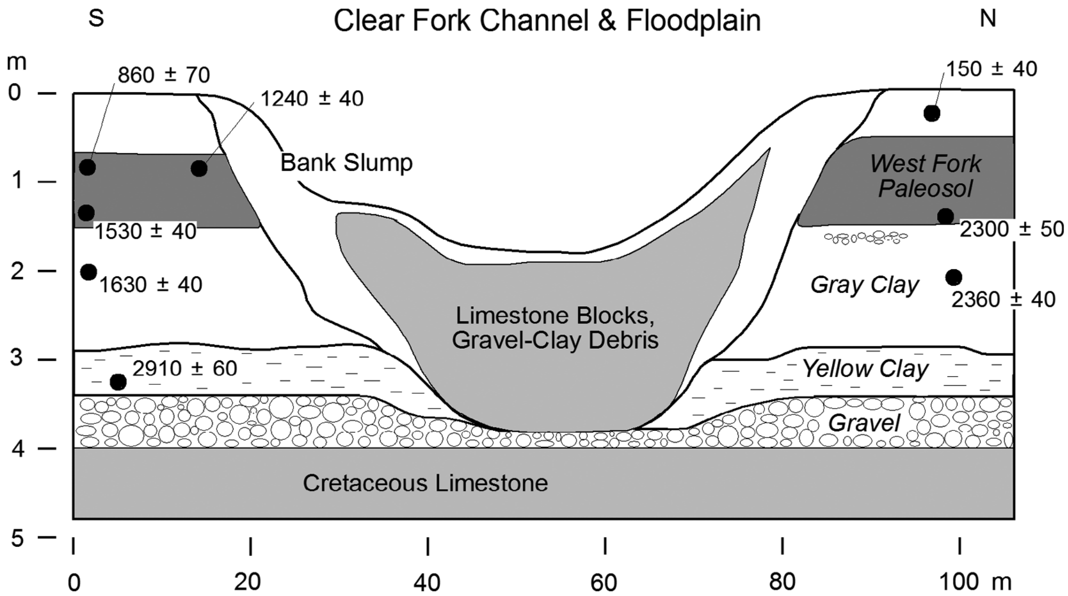

Figure 3. Cross-section of the Clear Fork channel and radiocarbon-dated floodplain stratigraphy; three radiocarbon ages shown at the left are uniformly too young for the age of the paleosol, perhaps because of the presence of a slight topographic rise at this locality and delayed sediment accumulation compared with elsewhere on the floodplain; the natural channel was abandoned and partly filled with construction debris in the 1960s when the floodplain was channeled nearby for flood control

Post-paleosol alluvium

The formation of the cumulic West Fork paleosol ended upon its burial by recent alluvium. Post-paleosol alluvium mantles the paleosol in every trench exposure. The post-paleosol alluvium is grayish brown (10YR 5/2) silty sand to clayey silt and lighter in color than the very dark grayish brown paleosol. It ranges from 34 to 68 cm and averages 48 cm in thickness. It is massive and primary bedding structures are not preserved. The sediments are calcareous but lack visible carbonates such as filaments along root traces. A single radiocarbon age of 150 ± 40 ^{14}C yr BP on charcoal from a buried burned tree was obtained from the post-paleosol alluvium. The post-paleosol alluvium, correlating with other post-paleosol alluvial units in the region, may have been deposited about 800 to 100 years ago. The end of the deposition of the post-paleosol alluvium coincides with widespread channel downcutting during the late nineteenth century.

Floodplain and channel of the Clear Fork

The Clear Fork extends about 70 km upstream from the study area with a drainage basin of about 1040 km^2 (200 square miles) that includes silver bluestem tallgrass prairie, post oak woods, and grassland mosaic vegetation types (McMahan et al., 1984). The floodplain of the Clear Fork of the Trinity River at the study area is moderately wide, 1.5 to 2.1 km (0.9 to 1.3 miles) across. The channel was 60 m wide and approximately 3 to 4 m deep prior to it being filled with construction debris (Figure 3). The 60-m wide channel is the one that was cut or expanded in the late 19th century. The 28 trenches across the study area did not encounter another channel of any size or stratigraphic position in the floodplain alluvium. We conclude that this channel may be an expanded version of the one that was cut about 1000 yr BP. Based on the apparent absence of any other channel, this channel may also occupy the position of the active channel when the gray clay and West Fork paleosol were aggrading, although at that time the channel may have been shallower.

Late-Holocene paleoecology

A modest shift in climate during the last 2300 years has resulted in dramatic changes in geomorphology, floodplain vegetation, and faunas in the southern Great Plains. The period 2300 to 1000 yr BP is characterized by conditions that were significantly cooler and moister than present. About 1000 yr BP, the regional climate changed to conditions that were warmer and drier than present. The magnitude of climate change at that time, from wetter-than-present to drier-than-present, resulted in major changes in the landscape, especially in wide river valleys. The empirical record that documents the history of climate and landscape change described above is summarized by many workers in the fields of fluvial geomorphology, eolian geomorphology, vertebrate paleontology, molluscan paleontology, and pollen analysis (Blum and Valastro, 1994; Blum et al., 1994; Daniels and Knox, 2005; Hall, 1982, 1988, 1990; Hall and Lintz, 1984; Hanson et al., 2010; Lepper and Scott, 2005; Toomey, 1993; Toomey et al., 1993).

Mussel fauna

Ten species of mussels were recovered from the West Fork paleosol along the Clear Fork in this investigation (Lintz et al., 2008). Mussel shells are concentrated with prehistoric cultural features in the buried archaeological site 41TR170. Radiocarbon ages of charcoal from the various features range from 1570 ± 40 to 1270 ± 40 ^{14}C yr BP (Table 3). The mussels did not live on the floodplain, rather they were harvested by prehistoric inhabitants from the late-Holocene channel of the Clear Fork and brought to campsites where they were cooked, eaten, and shells discarded and later buried by continued alluvial deposition.

The presence of the mussels indicates that the Clear Fork was a permanent stream during the formation of the West Fork paleosol 2300 to 1000 yr BP, even though one species, *Amblema plicata*, can endure temporary drying (Howells et al., 1996). The shift to significantly drier climate about 1000 yr BP, the downcutting of the river valley, and the lowering of

Table 3. Unionid mussels from the West Fork paleosol associated with excavated blocks and features at buried archaeological site 41TR170, Clear Fork of the Trinity River, Tarrant County, Texas

Species	Block 1				Block 2	Block 3		
	F6	F9	F10	F13[a]	F3[b]	F15	F16[c]	F17[d]
Amblema plicata		X	X	X	X	X	X	X
Fusconaia askewi		X					X	
Lampsilis hydiana			X		X			
Lampsilis teres			X	X			X	X
Ligumia subrostrata			X					X
Plectomerus dombeyanus	X		X				X	X
Potamilus purpuratus					X			
Quadrula apiculata							X	X
Quadrula mortoni	X	X	X					
Tritogonia verrucosa			X			X	X	

Note: the F- numbers refer to cultural features in excavation blocks; see Lintz et al. (2008)
Radiocarbon ages in ^{14}C yr BP on charcoal associated with mussel shell assemblages in features at 41TR170:
[a] 1360 ± 40 (Beta-213094).
[b] Dates from adjacent Features 12, 20, and two associated ashy zones: 1270 ± 40 (Beta-213095), 1360 ± 40 (Beta-213093), 1450 ± 40 (Beta-213097), 1570 ± 40 (Beta-213096).
[c] 1450 ± 40 (Beta-213098).
[d] 1310 ± 40 (Beta-213099).

the alluvial water-table may have altered the hydrology of streams in the upper Trinity River basin from permanent to seasonal or ephemeral. This change would have had a significant impact on the local mussel fauna, perhaps leading to extirpation of species that are not adapted to extended drying (Randklev et al., 2010).

Freshwater and terrestrial mollusks

The late-Holocene gray clay and West Fork paleosol contain shells of a variety of freshwater and terrestrial snail species. Freshwater species are concentrated in thin zones in the gray clay that probably represent shallow floodplain ponds. Freshwater mollusks include the pill clams *Pisidium* sp. and *Sphaerium* sp. and the snails *Cincinnatica cincinnatiensis*, *Fossaria* sp., *Gyraulus parvus*, *Helisoma anceps*, and *Physa gyrina*. Calcified oogonia of freshwater charophytes (green algae) are also present in the gray clay and paleosol alluvium but were not identified to species. The freshwater mollusks, including the unionids discussed previously, are firm evidence of higher water tables and wetter conditions before 1000 yr BP.

Shells of land snails are generally scattered throughout the alluvium and are moderately common in the gray clay and West Fork paleosol, especially large shells of *Rabdotus dealbatus* and *Helicina orbiculata*. Other land snail species in the alluvium include *Carychium* sp., *Deroceras* sp., *Gastrocopta procera*, *G. tappaniana*, *Hawaiia minuscula*, *Glyphyalinia indentata*, and succineids (species undetermined). Also common on the present-day wooded floodplain of the Clear Fork is *Rumina decollata* (Linné), a European land snail that today in Texas is a garden pest. It is first reported in the United States from South Carolina in 1822 and later in Brownsville, Texas, in 1913 and in Dallas, Texas, in 1933 (Pilsbry 1946: 170). Although it burrows, shells of *R. decollata* were not observed in the recent alluvium overlying the West Fork paleosol, indicating that the young post-paleosol alluvium may be predominantly older than the 20th century.

Stable carbon isotopes

Two stratigraphic sections from the gray clay and West Fork paleosol were collected for stable carbon isotope analysis. The results from the two sections are identical (Figure 4). From both sections, the gray clay and West Fork paleosol have a mean $\delta^{13}C$ value of −18.3 ± 0.3‰. The post-paleosol alluvium has a mean $\delta^{13}C$ value of −20.8 ± 0.5‰ (Table 1). In concurrence, the mean $\delta^{13}C$ of the four radiocarbon ages on bulk sediment from the paleosol is −17.1 ± 0.7‰ (Table 2). The stable carbon isotope data indicate that the proportion of C_3 and C_4 plants in the vegetation was fairly constant during the period 2300 to 1000 yr BP, with C_4 plants dominating the floodplain vegetation. Subsequent to the end of the formation of the West Fork paleosol, after 1000 yr BP, the floodplain vegetation shifted to a community dominated by C_3 species. Although routine pollen analysis cannot differentiate between C_3 or C_4 vegetation, pollen studies in the Copan paleosol type area show the dominance of grasses on late-Holocene floodplains and, after 1000 yr BP, a shift to woodland floodplain vegetation (Hall, 1982). Future studies of stable carbon isotope composition of grass pollen grains could reveal more detailed information on the composition of wet meadow and floodplain grass communities (Nelson et al., 2006).

We interpret the high $\delta^{13}C$ values from the West Fork paleosol and underlying gray clay as representing tallgrass prairie vegetation on a wet meadow floodplain, similar to present-day wet meadow and bottomland vegetation and associated Mollisols with A-C profiles along streams in the central Plains, discussed below. The shift to lower $\delta^{13}C$ values after 1000 yr BP is seen as a response to the change to drier climate with lower water-tables, channel downcutting, and invasion of the dry floodplain by trees, a scenario discussed by Hall (1982, 1990). We note again that this reconstruction conflicts with previous interpretations of stable carbon isotope data (Humphrey and Ferring, 1994; Nordt et al., 1994, 2002).

Mollisols and wet meadows

Present-day floodplains of many tributary and master streams across the southern Plains are dry and wooded because of a combination of channel downcutting and lowering of alluvial water-tables in the past 100 years. Gallery forests commonly mark the paths of floodplains across the prairies. The vegetation and geomorphology of modern floodplains differ significantly from late-Holocene reconstructions. However, we propose that wet meadows and associated Mollisols with A-C profiles along streams in the central Plains represent a modern analogue for the late-Holocene West Fork paleosol.

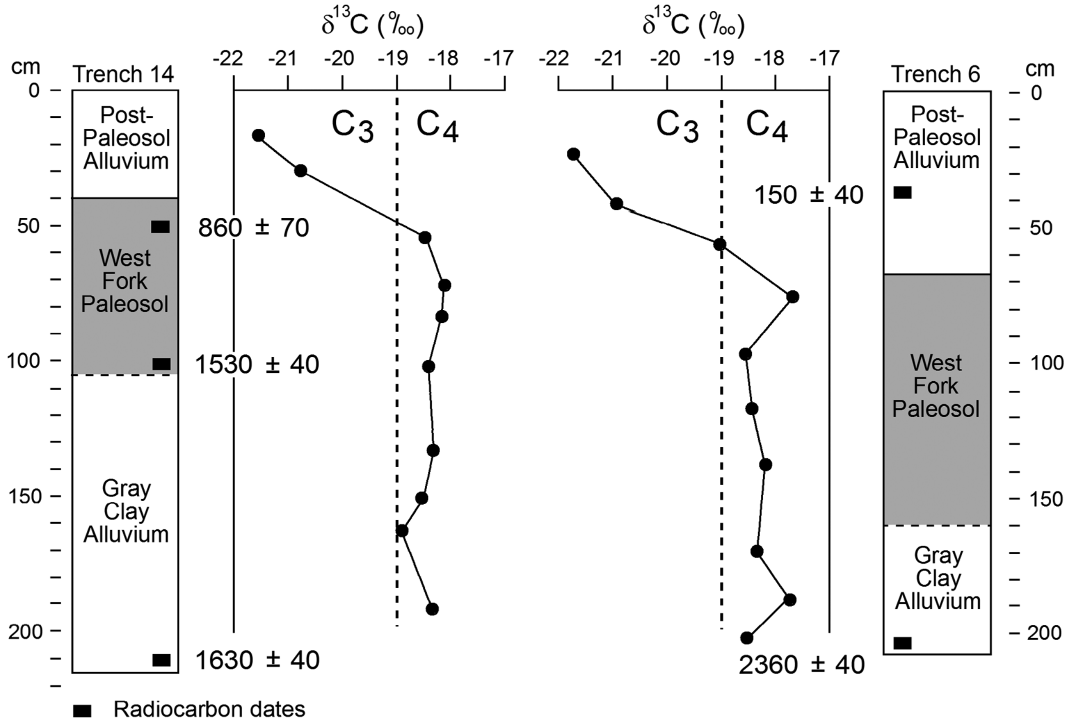

Figure 4. Stable-carbon isotope values plotted by depth, Clear Fork of the Trinity River floodplain, Tarrant County, Texas (Table 1); four additional $\delta^{13}C$ values from radiocarbon ages of bulk sediment from the West Fork paleosol range from −16.2 to −17.8‰ (Table 2)

Wet meadow soils are typically gray colored, fine-loamy Mollisols. The Lex series is representative of soils occurring on wet meadows and poorly drained bottomlands, such as along the Platte River of central Nebraska. It has a 46 cm thick gray silty loam A horizon overlying a light gray C horizon; a B horizon is absent. The alluvial water-table in areas of the Lex series is 0.3 to 2.0 m depth, generally higher in winter and early spring and lower during the summer. The high water-table commonly results in redoximorphic features such as mottles and iron concentrations in the C horizon (Buller et al., 1974). While the Lex and other bottomland soils are extensively farmed, the native grasses are C_4 tallgrass prairie species (Wahl et al., 1984).

The term ‘wet meadow’ has been used to describe lowland areas in the central Plains that have a water-table near the surface, sometimes along streams or in sand-hill country (Weaver and Albertson, 1956: 190–192). A multiyear investigation of a wet meadow remnant along the Platte River, central Nebraska, documents the dominance of *Andropogon gerardii*, *Panicum virgatum*, and *Sorghastrum nutans*, all C_4 tallgrass species (Currier, 1989). The local alluvial water-table fluctuated monthly and yearly over a maximum vertical distance of 127 cm during a period of six years. Currier (1989) found that higher water levels favored sedges, lower water levels tended to favor *A. gerardii*, and *S. virgatum* was abundant with either high or low water levels. Although seasonal and year-to-year changes in local water-table can affect species abundance, over time the wet meadow community was fairly stable.

An interesting case of grassland vegetation in a wet floodplain is included in the classic study of C_4 and C_3 plant communities versus elevation in southeastern Wyoming (Boutton et al., 1980). The low elevation study site at 1405 m is on the floodplain of the Laramie River just west of Wheatland. The dominant grasses are *Sporobolus airoides*, *Spartina pectinata*, *Schizachyrium scoparium*, *P. virgatum*, *S. nutans*, and *A. gerardii*, the first two found commonly in wet habitats and the others typical of tallgrass prairie; all are C_4 species. The C_4 wet meadow-tallgrass community at the study site is surrounded by uplands with C_4 shortgrass prairie vegetation that extends for great distances in all directions. The western edge of the Sandhills prairie, with tallgrass species, and the true tallgrass prairie are located about 160 km (100 miles) and 565 km (350 miles) east of the 1405 m study site, respectively (Kaul, 1975). The study site represents a wet meadow-tallgrass community that follows bottomlands along river valleys in the Plains.

The Fort Worth Prairie is the northwestern-most of the tallgrass prairies in Texas and includes the Clear Fork watershed (Diamond and Smeins, 1985). In a survey of the upper Clear Fork, it was found that 61% of the ‘coverage × frequency’ values of species on benches and bottoms were grasses that are now known to be C_4 (Dyksterhuis, 1946). Four of the C_4 species that are more abundant on benches and bottoms, compared with hillsides and ridges, are *Sporobolus asper*, *A. gerardii*, *Buchloë dactyloides*, and *S. nutans*. Two of these, *A. gerardii* and *S. nutans*, are characteristic of tallgrass prairies, while *S. asper* and *B. dactyloides* are found more commonly in mixedgrass and shortgrass communities, respectively (Derner et al., 2006).

In summary, wet meadows and bottomlands along stream valleys in the Great Plains are characterized by Mollisols with gray, fine-textured A-C profiles and with plant communities dominated by native tallgrass prairie species. Today, big bluestem (*A. gerardii*), little bluestem (*S. scoparium*), indian grass (*S. nutans*), and switchgrass (*P. virgatum*) are the ‘big four’ in the true tallgrass prairie (Gould, 1975). All are C_4 grasses and are found in wet meadows. Their abundance results in high $\delta^{13}C$ values such as documented in the West Fork paleosol as well as other similar paleosols in the southern Plains. Stable-carbon isotope content of upland tallgrass prairie soils can range as high as −14‰ (Johnson et al., 2007).

Discussion

Our new interpretation of the stable carbon isotope record from southern Plains alluvium is consistent with the regional late-Holocene paleoecological record, cited previously. It is noteworthy that these records do not stand alone but correlate as well with emerging reconstructions of eolian activity and associated paleoenvironmental conditions in the central Plains. Studies of several sequences of eolian sand, dated by optically stimulated luminescence and radiocarbon, indicate that accumulation of dune sand occurred during the periods 4500 to 2300 yr BP and 1000 to 700 yr BP (Hanson et al., 2010; Mason et al., 2004; Miao et al., 2007). The period devoid of dune activity, 2300 to 1000 yr BP, is instead characterized by interdune wetland deposits, establishing the climate connection for late-Holocene dune activity in the central Plains: eolian sand is entrained and deposited during dry periods, and dune fields are stable during periods of wet climate (Mason et al., 2004). The alluvial and eolian sequences show a synchronous pattern of geomorphic response to late-Holocene climate change, extending through the southern and central Great Plains.

The original study by Teeri and Stowe (l976) showed that the abundance of C_4 grasses across North America correlates most strongly with normal July minimum temperature: higher temperatures correlate with higher percentages of C_4 grasses. Climate variables involving precipitation were also analyzed but did not correlate significantly with C_4 grass abundance. Nevertheless, our study along the Clear Fork establishes that wet environments may indeed be dominated by C_4 vegetation. A similar observation has been made in the central Plains by Feggestad et al. (2004) where C_4 vegetation occurs under wetter conditions, eolian landscape stability, and soil formation, while C_3 vegetation may be related to drought and possibly to disturbance with an increase in weedy species. These interpretations are contrary to the connections between modern temperature and C_4 abundance shown by Teeri and Stowe (1976). Evidently, as the sedimentary record is examined at a fine scale, complexities in the relationships between C_3 and C_4 vegetation, geomorphology, and climate are becoming more apparent.

Conclusions

We conclude from geomorphology, molluscan faunas, and stable carbon isotopes that the cumulic West Fork paleosol formed in a wet meadow environment dominated by C_4 tallgrass species. Alluvial water-tables were high, reflecting greater amounts of rainfall than today, and the Clear Fork was a permanently flowing stream. The cumulic paleosol with an A-C profile formed on the wet bottomland of the Clear Fork during the period 2300 to 1000 yr BP. Paleosol development ended by 1000 yr BP with the drying of the climate, the lowering of the alluvial water-table, and the trenching of alluvial valley floors. The episode of dry climate corresponds to the widely documented 'Medieval Warm Period' (Bradley et al., 2003; Cook et al., 2004). The wet meadow-cumulic paleosol is now buried by alluvium that was deposited 800 to 100 yr BP. Today, many stream valleys in the southern Plains are deeply incised and alluvial water-tables are low, resulting in dry wooded floodplains above the modern channels. Modern analogues of the late-Holocene alluvial record are found along the Platte River in the central Plains where wet meadows and bottomlands are characterized by high water-tables, C_4 grasses from the tallgrass prairies, and Mollisols. Finally, the results from this investigation show that paleoclimatic interpretations of $\delta^{13}C$ values, using the patterns of C_4 species abundance and climate presented by Teeri and Stowe (1976) and refined by Nordt et al. (2007), may be in error when applied to late-Quaternary wet-meadow deposits and thick paleosols with A-C profiles.

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