Precise timing and rate of massive late Quaternary soil denudation

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ABSTRACT

Strontium isotopes are a unique tool to study soil-erosion dynamics. Changes in Sr isotope ratios ($^{87}Sr/^{86}Sr$) provide a record of late Quaternary landscape denudation of the Edwards Plateau of central Texas, United States. The use of Sr isotopes as a tracer for soil erosion is based on the observation that, in central Texas, the $^{87}Sr/^{86}Sr$ ratio of soil correlates with soil thickness. Plants and animals express the $^{87}Sr/^{86}Sr$ ratio of exchangeable Sr in the soil. Therefore, we use changes in Sr isotope ratios through a well-dated stratigraphic sequence of fossil plants and animals in Hall's Cave, Kerr County, Texas, as a proxy for temporal changes in soil thickness. By using this record we are able to characterize late Quaternary climate-driven soil-erosion dynamics on the Edwards Plateau. We find that continuous erosion removed at least 180 cm of soil at a constant minimum rate of 11 cm/k.y.; this continuous phase of erosion ended ca. 5 ka. The Sr isotope record of soil erosion is consistent with late Quaternary environmental change in central Texas that has been independently modeled by using local and regional climate records. However, the rate of this climate-driven soil-erosion event was an order of magnitude slower than recent soil erosion caused by human land use. These results link erosion to century- to millennial-scale climate change and are cautionary evidence that even greater landscape degradation may result from coincident climatic variability and anthropogenic influences.

Keywords: soil erosion, strontium, isotopes, Edwards Plateau, Quaternary.

INTRODUCTION

We employ Sr isotopes to document temporal changes in soil thickness and characterize the timing and rate of a massive, ancient soil-erosion event that had regional environmental consequences. Unlike recent anthropogenic soil erosion, global climate change facilitated sustained periods of soil erosion during Pliocene (Peizhen et al., 2001) and Quaternary (Hay, 1994) time. Future increases in precipitation intensity associated with global warming are expected to increase soil erosion in the twenty-first century (McCarthy et al., 2001). Predicting how changes in both climate and land use will affect soil erosion requires an understanding of soil-erosion rates and mechanisms at a variety of spatial and temporal scales. Here we present an isotopic record of millennial-scale, regional soil erosion that provides a geological and historical basis for the assessment of future risks to soil resources.

Increased aridity, likely accompanied by increased seasonality and intensity of precipitation, is proposed to have driven massive late Quaternary denudation of the Edwards Plateau of central Texas, United States (Toomey, 1993; Toomey et al., 1993). The plateau is a 9.7×10^{10} m^2 Cretaceous limestone platform characterized today by exposed bedrock with a thin, discontinuous soil veneer (Fig. 1). The primary study areas—Hall's Cave and the Kerr Wildlife Management Area in Kerr County, Texas—contain evidence for a thicker, more mature soil mantle on the late Pleistocene landscape. This evidence includes (1) relict thick, red, clay-rich soils preserved on broad uplands, (2) cave sediments containing fossils of burrowing mammals whose modern habitats include soils much thicker than are present on the Edwards Plateau today, and (3) Pleistocene red clay sediments found in Hall's Cave and several other central Texas cave deposits (Toomey, 1993). The red cave sediments are interpreted as having been derived from the ancient, thick, upland soil mantles based on the similar color and texture of the cave sediments and relict soils.

The proposed erosion of Edwards Plateau soils resulted in the local extinction of burrowing mammals (Toomey et al., 1993), and contributed to the increased frequency and magnitude of late Holocene flood events (Blum et al., 1994). Although the environmental impact of this denudation was severe, the timing, magnitude, and rate of erosion have been poorly constrained. Our study uses Sr isotopes as an independent test of the hypothesized erosion event on the Edwards Plateau, and as a means to precisely constrain the timing and rate of this event.

NEW APPROACH TO ANCIENT SOIL EROSION

Understanding the dynamics such as the timing, magnitude, and rate of soil erosion is important to determining the climatic and anthropogenic causes of soil erosion, quantifying sediment and carbon fluxes, modeling soil-erosion processes, and predicting soil-erosion consequences. Advances in the high-precision quantification of basin-scale, time- and spatially-averaged erosion rates have come from studies of cosmogenic nuclide concentrations (e.g., ^{10}Be and ^{26}Al) in detrital sediments (Bierman and Steig, 1996; Granger et al., 1996; Schaller et al., 2002). Our under-

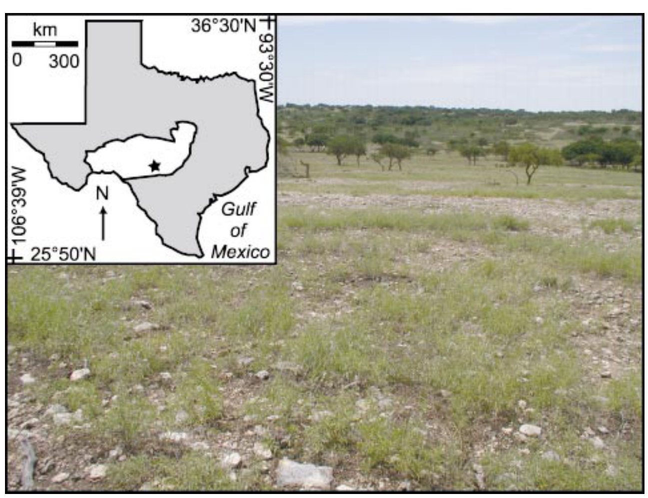

Figure 1. Edwards Plateau landscape near Hall's Cave, Kerr County, Texas. Note thin, discontinuous soil cover and exposed limestone bedrock. Inset shows study location. White area delineates Edwards Plateau physiographic province of central Texas. Star denotes location of Kerr County primary study sites: Hall's Cave (30°8′10″N; 99°32′6″W) and Kerr Wildlife Management Area (30°5′33–41″N, 99°30′47–55″W, ~5 km southeast of Hall's Cave).

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standing of soil-erosion dynamics is limited by these techniques' assumption of constant denudation. In contrast, the Sr isotope methodology presented here provides a soil-erosion history with unprecedented temporal resolution and permits the detection of changes in soil-erosion rates.

The isotopic contrast between soil and limestone bedrock in the same terrane (Banner et al., 1996) has led us to propose the use of Sr as a tracer for soil-erosion processes in such terranes. The use of Sr isotopes (in the form of the $^{87}Sr/^{86}Sr$ ratio) to determine the timing and rate of ancient soil erosion requires that two isotopically distinct sources contribute Sr to soil in proportion to soil thickness. In the study area, marine limestone bedrock of the Segovia Member of the Edwards Limestone contributes carbonate-derived Sr with a relatively low $^{87}Sr/^{86}Sr$ ratio of 0.7075–0.7079, reflecting the Sr isotope composition of Cretaceous seawater. In contrast, soil silicate minerals from insoluble limestone residues and/or dusts (Rabenhorst and Wilding, 1986) are most likely derived from weathering of old continental crust and contribute Sr with high $^{87}Sr/^{86}Sr$ ratios. One possible source for silicates in central Texas soils is Saharan dust with an average $^{87}Sr/^{86}Sr$ ratio of 0.7157 (summarized in Borg and Banner, 1996). Regardless of the source, most silicates will contribute Sr with a high $^{87}Sr/^{86}Sr$ ratio.

The $^{87}Sr/^{86}Sr$ ratio of exchangeable Sr in soil [exchangeable Sr is defined here as the Sr available in the soil for plant uptake and is denoted as $(^{87}Sr/^{86}Sr)_{exch}$] depends on the proportion of carbonate bedrock–derived Sr to silicate-derived Sr in the soil. We propose that the $(^{87}Sr/^{86}Sr)_{exch}$ ratio in soils developed on limestone varies with soil thickness because thin soils will have more carbonate bedrock–derived Sr (with a low $^{87}Sr/^{86}Sr$ ratio) compared to thick soils. This ratio may be further modified as a function of depth within the soil profile, soil age, and precipitation amount (Miller et al., 1993; Borg and Banner, 1996; Kennedy et al., 1998; Stewart et al., 2001).

Consistent with this model, the $(^{87}Sr/^{86}Sr)_{exch}$ ratios in modern central Texas soils correlate with soil thickness. Exchangeable Sr was isolated from central Texas soil samples by ammonium acetate ion-exchange treatments. The dominant, thin soils have $(^{87}Sr/^{86}Sr)_{exch}$ ratios that are similar to those of calcite in the limestone bedrock, whereas the $(^{87}Sr/^{86}Sr)_{exch}$ ratios from thick upland soils are much higher (Fig. 2 and Appendix[1]). Vegetation expresses the $(^{87}Sr/^{86}Sr)_{exch}$ in the soil (Miller et al., 1993; Kennedy et al., 1998), as seen in modern Edwards Plateau trees and grasses (Fig. 2A), and this signature is transferred to higher trophic levels (Sealy et al., 1991). Thus, late Quaternary soil denudation on the Edwards Plateau should have resulted in a decreasing $(^{87}Sr/^{86}Sr)_{exch}$ ratio in the soil with time and should have been recorded by fossil plants and animals.

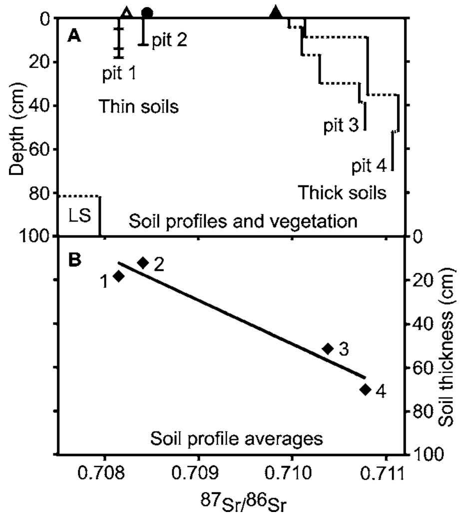

Figure 2. $^{87}Sr/^{86}Sr$ ratios of Edwards Plateau soil leachates, vegetation, and bedrock. Values are in Table DR3 (see footnote 1 in text). A: Variation in soil leachate $^{87}Sr/^{86}Sr$ ratios with depth for four soil profiles. LS field denotes $^{87}Sr/^{86}Sr$ range of local limestone bedrock; dotted line at top of this field indicates that bedrock surface varies in depth. Soil sample depth interval is solid line. Profiles of thin soils are near entrance to Hall's Cave, and thick soils are from uplands in Kerr Wildlife Management Area. Thin soil profiles (pits 1 and 2) have lower $(^{87}Sr/^{86}Sr)_{exch}$ ratios compared to ratios from thick soil profiles (pits 3 and 4). Modern grasses from pit 1 (open triangle) and pit 3 (closed triangle) and hackberry aragonite from pit 2 (closed circle) have $^{87}Sr/^{86}Sr$ ratios similar to $(^{87}Sr/^{86}Sr)_{exch}$ of local soil. B: Average $^{87}Sr/^{86}Sr$ ratios of soil leachates from Kerr County soil profiles, numbered as in A. Line in B indicates $\Delta_{S.I.R.}/\Delta_h$ of 5 × 10^{-5}/cm (±6 × 10^{-6} cm^{-1}), where $\Delta_{S.I.R.}$ is average soil pit $^{87}Sr/^{86}Sr$ ratio and Δ_h is soil pit thickness.

METHODS

To test the applicability of Sr isotopes for recording the massive soil erosion that is proposed for central Texas during the late Pleistocene to early Holocene, we measured $^{87}Sr/^{86}Sr$ ratios in fossil seeds and mammal teeth contained in a well-dated, stratified, cave-fill deposit in Hall's Cave, Kerr County, Texas. The ~3-m-thick cave sediments contain an abundance of vertebrate fossils and are composed of eroded upland soils and bedrock as well as bat guano deposited during the past 21 k.y. The stratigraphy of the cave sediments is as follows: red clay on bedrock overlain by red-brown silty clay, dark brown clayey silt, and black clayey silt. The organic and limestone-fragment contents of the sediments increase upward through the deposit (Toomey et al., 1993).

The Hall's Cave deposit is an optimal site to employ the Sr isotope methodology because (1) the cave sediments and fossil fauna provide independent evidence for soil erosion (Toomey, 1993; Toomey et al., 1993) and (2) the sedimentary sequence is well dated by accelerator mass spectrometry ^{14}C techniques (see footnote 1). This detailed radiocarbon chronology permits absolute dating of variations in $^{87}Sr/^{86}Sr$ ratios in the Hall's Cave sequence with a temporal resolution of ~±300 yr.

RESULTS

We measured the $^{87}Sr/^{86}Sr$ ratios in a variety of fossils from the Hall's Cave strata including fossil hackberry tree (*Celtis*) aragonite seed coatings and tooth enamel from pocket gophers (*Geomys*) and voles (*Microtus*). To minimize diagenetic effects, we selected for analysis fossil hackberry seeds that have their original aragonite mineralogy and rodent tooth enamel that was isolated from the associated dentin and bone (see footnote 1; Budd et al., 2000). The Sr isotope ratios of both fossil hackberry seed aragonite and fossil rodent tooth enamel decreased from 21 ka to the present (Fig. 3). The $^{87}Sr/^{86}Sr$ ratios of hackberry aragonite and pocket gopher enamel decreased at similar constant rates (6 × 10^{-5} $k.y.^{-1}$ and 7 × 10^{-5} $k.y.^{-1}$, respectively) from the late Pleistocene to the Holocene. Due to the limited vole data, only $^{87}Sr/^{86}Sr$ ratios from pocket gophers and hackberries were used in the regressions to determine the rate at which fossil $^{87}Sr/^{86}Sr$ ratios decreased. The $^{87}Sr/^{86}Sr$ ratios of hackberry aragonite decreased from 21 to 11 ± 1 ka, after which the ratios remained constant and equal to the $^{87}Sr/^{86}Sr$ ratio for seed aragonite (0.7085) from a modern hackberry growing at the entrance to Hall's Cave (Fig. 3). The $^{87}Sr/^{86}Sr$ ratios of pocket gopher enamel decreased until ca. 5 ka, after which the enamel ratios appear to have stabilized at a somewhat higher value (0.7086) than that for the fossil hackberries. In strata older than 11 ka, the offset in $^{87}Sr/^{86}Sr$ between contemporaneous hackberry aragonite and rodent tooth enamel was relatively constant, with rodent tooth enamel consistently higher than hackberry seed aragonite.

DISCUSSION

Temporal changes in $^{87}Sr/^{86}Sr$ ratios of hackberry seed aragonite and rodent tooth enamel reflect changes in soil thickness during the late Quaternary on the Edwards Plateau. The near-parallel, constant slopes of decreasing $^{87}Sr/^{86}Sr$ ratios over time of two different

[1]GSA Data Repository item 2003133, supplemental information on materials and methods (Appendix), radiocarbon chronology (Appendix Table DR1), and data tables (Appendix Tables DR2 and DR3), is available online at www.geosociety.org/pubs/ft2003.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

fossil types are evidence for steady, continuous soil erosion from at least 21 to 5 ka. Hackberry aragonite $^{87}Sr/^{86}Sr$ ratios after ca. 11 ka are lowest and closest to limestone bedrock values and identical to that of a modern hackberry tree rooted in limestone at the cave's entrance (Fig. 3). Thus, we infer that after ca. 11 ka, hackberries were more commonly rooted directly in bedrock, rather than soil, and were isotopically insensitive to further changes in soil thickness. Soil erosion continued after 11 ka and is recorded by the continued decrease in $^{87}Sr/^{86}Sr$ ratios of pocket gopher enamel. The pocket gopher enamel $^{87}Sr/^{86}Sr$ ratios reached that of the modern vegetation (Fig. 2A) and appear to have stabilized at 5 ka. This result suggests that the erosion event had a discrete ending. We infer from the termination in enamel isotopic variation that the Edwards Plateau has had its present condition of discontinuous, 0–30-cm-thick soil cover for the past ~5 k.y.

Temporal variations in Sr isotope ratios are consistent with Hall's Cave faunal and sedimentologic evidence for soil erosion. As supported by the inflection in hackberry $^{87}Sr/^{86}Sr$ ratios, soil erosion dramatically altered plant and animal habitats on the Edwards Plateau by the late Pleistocene to early Holocene. Fossil vertebrate evidence corroborating our Sr isotope interpretations includes the disappearance of the burrowing prairie dog, *Cynomys*, from Hall's Cave strata at 12 ka (Toomey, 1993). The Eastern mole (*Scalops aquaticus*), also dependent on thick soil habitat, is rare after 12 ka and absent after 9 ka in the Hall's Cave strata (Toomey, 1993). Sedimentological evidence that erosion was depleting the soil mantle and beginning to expose bedrock ca. 12 ka includes an increase in limestone clasts within the cave sediments; there is also a decrease in red clay at 12 ka (Toomey, 1993). These changes are consistent with the exhaustion of sediment derived from the thick, red, clay-rich soils that are now present only as isolated, relict soils on broad plateau uplands.

The soil erosion recorded in Hall's Cave was likely a regional rather than local phenomenon. Sedimentological and faunal records of soil erosion and climate change are found in several caves on the Edwards Plateau, supporting the idea of climate-driven, regional, time-progressive denudation (Toomey, 1993). Furthermore, the agreement of multiple proxies suggests that soil erosion was not a localized episode. Rodent fossils were deposited in the cave strata dominantly in owl pellets and record changes in soil thickness within the 1–20 km feeding range of owls (summarized in Toomey, 1993). In contrast, the fossil hackberries are likely derived from a nearby source, and thus reflect changes in local soil thickness.

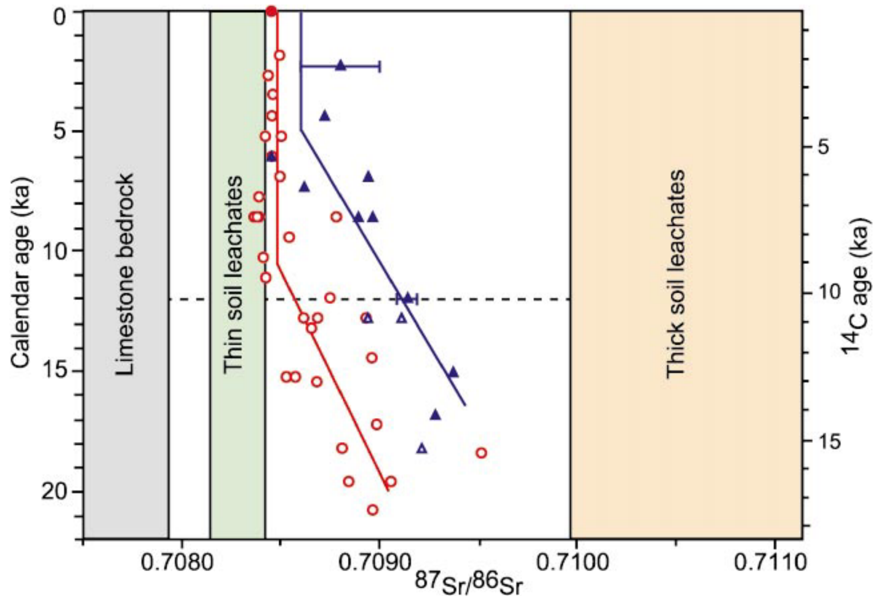

Figure 3. Temporal Sr isotope variation of Hall's Cave fossils. Fossil calendar ages (left *y* axis) and corresponding ^{14}C ages (right *y* axis) are interpolated from Hall's Cave deposit radiocarbon chronology measured by T.W. Stafford (Table DR1; see footnote 1 in text). From late Pleistocene to middle Holocene time, $^{87}Sr/^{86}Sr$ ratios of fossil hackberry aragonite (open circles) and vole (open triangle) and pocket gopher (closed triangle) tooth enamel decreased from higher $^{87}Sr/^{86}Sr$ ratios (similar to those of thick soil leachates) to lower $^{87}Sr/^{86}Sr$ ratios that resemble those of limestone bedrock, thin soil leachates, and modern hackberry aragonite (closed circle) values (Table DR2; see footnote 1 in text). Orthogonal regressions of hackberry $^{87}Sr/^{86}Sr$ ratios (excluding outlier at 18.4 ka) through 9.4 ka (red line, $r^2 = 0.5$) and pocket gopher enamel $^{87}Sr/^{86}Sr$ ratios through 4.4 ka (blue line, $r^2 = 0.8$) yield $^{87}Sr/^{86}Sr$ ratio decrease with time of 6×10^{-5} k.y.$^{-1}$ (hackberries) and 7×10^{-5} k.y.$^{-1}$ (pocket gophers) ($\pm 1 \times 10^{-5}$ k.y.$^{-1}$). Sudden change in slope in hackberry $^{87}Sr/^{86}Sr$ ratios occurs at approximately same time as reduction in red clay, increase in limestone fragments, disappearance of prairie dog fossils, and reduction of mole fossils (dashed line) (Toomey, 1993; Toomey et al., 1993). Analytical errors for $^{87}Sr/^{86}Sr$ ratios are smaller than size of symbols, except for two samples noted.

The offset between the Sr isotope ratios of contemporaneous fossil hackberry and rodent tooth enamel samples likely reflects the different soil depths from which each organism obtains nutrients, including Sr. Hackberry tree rooting depths to 6 m have been found on the Edwards Plateau (Jackson et al., 1999); therefore, hackberry seed aragonite should express lower $^{87}Sr/^{86}Sr$ ratios that are more similar to that of the limestone bedrock. In contrast, contemporaneous rodents will have tooth enamel $^{87}Sr/^{86}Sr$ ratios higher than those of hackberry seeds, because rodents may ingest radiogenic silicates while feeding in burrows and their diet typically includes vegetation rooted into the upper soil horizons. Shallowly rooted grasses and forbs take up relatively more silicate-derived Sr (with high $^{87}Sr/^{86}Sr$ ratios) compared to hackberry trees.

If we apply the observed linear correlation of changes in the modern soil thickness with the changes in the soil $(^{87}Sr/^{86}Sr)_{exch}$ ratio (Fig. 2B) to the linear rate of decrease in Hall's Cave fossil $^{87}Sr/^{86}Sr$ ratios (Fig. 3), we can estimate a soil-erosion rate. This method yields a late Quaternary erosion rate of 1–2 cm/k.y. This range is a lower boundary owing to the likely disequilibrium between the modern soil thickness and its Sr isotope composition. Such disequilibrium is interpreted because the thick upland soils have evidence that they are truncated from a greater thickness in the past (Dittemore and Coburn, 1986). Consequently, the observed $\Delta_{S.I.R.}/\Delta_h$ (soil pit $^{87}Sr/^{86}Sr$ and soil pit thickness) (Fig. 2B) is a maximum value resulting in a minimum estimate of the soil-erosion rate.

Another approach to determining the soil-erosion rate relies on paleontological and geochemical soil-depth constraints. Modern prairie dogs, which have not been documented in Kerr County in historic time, live in colonies covering several square kilometers and excavate burrows 1–3 m deep (Sheets et al., 1971; Davis and Schmidly, 1994; Hoogland, 1996). Prairie dog fossils in Hall's Cave provide evidence that continuous soil cover at least 1 m deep existed until 12 ka, when prairie dogs became locally extinct (Toomey, 1993). The $^{87}Sr/^{86}Sr$ ratios of fossil pocket gopher enamel stabilized at values most similar to those of modern thin soils by ca. 5 ka, suggesting that the modern condition of discontinuous soils (with an average thickness of ~20 cm) was established by 5 ka. These vertebrate biological and isotopic constraints on soil depth provide a conservative estimate of 80 cm (±10 cm) of soil erosion between 12 and 5 ka (±1 k.y.) and correspond to an erosion rate of 11 cm/k.y. (+7/−3 cm/k.y.)(see footnote 1). This erosion rate is more consistent with the ~3 m of sediment deposited in the cave over the past 21 k.y. than the 1–2 cm/k.y. erosion rate determined by using the truncated relict soil $\Delta_{S.I.R.}/\Delta_h$. We interpret the linear decrease in $^{87}Sr/^{86}Sr$ ratios between 21 and 5 ka as evidence for a constant soil-erosion rate over this 16 k.y. interval. Erosion at the rate of 11 cm/k.y. would result in the gradual removal of 180 cm of soil.

IMPLICATIONS

Our study quantifies the timing, magnitude, and rate of an ancient soil-erosion event by using a new Sr isotope method that is applicable to other fossil-bearing sediment deposits in geologic settings in which the eroded soil and bedrock are isotopically distinct. This method can determine changes in soil-erosion rates through time rather than giving time-averaged erosion rates. In particular, our results show that the denudation of the Edwards Plateau occurred as a prolonged episode of gradual, but massive, soil erosion that encompassed the Pleistocene to Holocene transition. The Sr isotope record suggests that the modern soil condition was established in the middle Holocene.

Geomorphic, palynological, and paleontological records suggest that increased aridity and increased seasonality and intensity of precipitation affected central Texas environments during the late Quaternary (Toomey et al., 1993). It has been proposed that these changes facilitated massive soil erosion, hydrologic extremes, and ecologic disturbance on the Edwards Plateau (Toomey et al., 1993; Blum et al., 1994). Increased summer drying over many midlatitude regions and more intense and seasonal precipitation events are predicted to characterize the global climate of the twenty-first century (Houghton et al., 2001), producing conditions similar to the late Quaternary climate of central Texas. In contrast to the soil erosion documented in this study, land use is the dominant cause of soil erosion today. The average erosion rate for modern U.S. croplands is ~100 cm/k.y. (as summarized in Pimentel et al., 1995), an order of magnitude higher than the natural, climate-driven soil-erosion rate identified in our study for the late Pleistocene to middle Holocene of central Texas. This contrast suggests that the predicted climate changes of greater summer aridity and more frequent, intense rainfall may magnify the soil-erosion potential of future land-use change.

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