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Non-linear connections between dune activity and climate in the High Plains, Kansas and Oklahoma, USA

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ABSTRACT

Discrete dune fields are found throughout much of the Great Plains of North America, and the timing of past dune activity is often used as a proxy for paleoclimate because of the intuitive link between dune activity and a more arid climate. This research suggests that feedbacks in the soil-geomorphic system create a relationship between dune activity and climate that varies both spatially and temporally. Older eolian landforms are more resistant to activation because of the long-term accumulation of finer soil particles in a Bt horizon which retain moisture and anchor the deposit even during more arid times. Conversely, younger deposits lack these fines and are more easily reactivated. This spatially variable relationship is supported by soil stratigraphy, particle size analysis, and optical age control. Additionally, the water retention of the Bt horizons is quantifiably greater than that of the soils found in the younger dunes of the area. This complication in the relationship between eolian activity and climate is important because it suggests that caution is needed when using past dune activity as the lone proxy for paleoclimate.

Introduction

Considerable effort has been spent investigating the dune stratigraphy of the Great Plains and its relation to paleoclimate (Holliday, 1990; Madole, 1995; e.g. Arbogast, 1998; Arbogast and Muhs, 2000; Forman et al., 2001; Muhs and Zarate, 2001; Sridhar et al., 2006; Miao et al., 2007). This effort is important for at least three reasons. First, precipitation within this semiarid region is highly variable, and mesic periods are often followed by severe drought. In addition to the Dust Bowl droughts of the 1930s and 1950s, tree-ring records and historical accounts suggest that severe droughts also occurred in the Great Plains during the 1800s, 1860s, 1890s, and 1910s (Meko, 1995; Muhs and Holliday, 1995; Woodhouse and Overpeck, 1998). Understanding the range of past climatic variability and associated dune responses may provide insight into what to expect in the future. Second, sand dunes are common features within the Great Plains (Thorp and Smith, 1952). While these dunes generally have been vegetated and stable since European settlement of the region, many were active during the last 1000 yr or so (Forman et al., 2001, Fig. 13). If dune activity is related to extreme drought, then dune stratigraphy should provide a useful proxy for paleoclimate, with periods of dune activity reflecting arid times and periods of soil development reflecting mesic times. Dune stratigraphy is a particularly useful paleoclimatic proxy because of the scarcity of other proxies in the region. For example, tree-ring records are found primarily only on the periphery of the Great Plains, and pollen records mainly where lakes are present on the glaciated northern Plains (e.g. Meko, 1995; Laird et al., 1996, 1998). Third, modeling studies indicate that the Plains region could experience higher temperatures and lower summer precipitation as a consequence of increased carbon dioxide in the atmosphere (Christensen et al., 2007), potentially pushing the dunes into an active state (Muhs and Maat, 1993; Wolfe, 1997). Understanding how this sensitive landscape responded to past climate change can therefore provide insight into how it will respond to future climate change.

In spite of the potential for dune stratigraphy to shed light on past and future climate change, some problems exist. For example, until recently age control generally has been limited to radiocarbon dating of organic carbon from buried soil A horizons, which only provides minimum/maximum-limiting ages. The growing use of optical dating provides numerical ages for the actual time of eolian sand deposition, thus providing much better age control for regional dune activity (e.g. Stokes and Swinehart, 1997; Forman et al., 2004; Mason et al., 2004; Lepper and Scott, 2005; Miao et al., 2007; Forman et al., 2008). Another problem with paleoclimatic interpretation of the eolian record is that while the timing of dune activity in the region exhibits some synchroneity, important differences still exist. For example, Arbogast (1996) found evidence of several periods of activity within the past 700 yr in the Great Bend Sand Prairie of central Kansas, while Madole (1995) indicates that dune fields in northeastern Colorado

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appear to have been mostly stable during that period of time. Arbogast (1996) attributes this pattern to the more humid conditions in the eastern part of the region, which aid in preserving evidence of past dune activity, but Cordova et al. (2005) suggest that dunes in more mesic areas should have been stable for a much longer period of time than those in the more arid areas. Finally, there are locations where younger dunes (as suggested by soil development) are found contiguous to older dunes or sand sheets (e.g. Smith, 1940; Madole, 1995; Muhs et al., 1996). This juxtaposition should not occur if there is a unique climatic threshold that separates stable from partially to fully active dunes, and if all the dunes respond to shifts across this threshold with a similar, short lag (Hugenholtz and Wolfe, 2005).

Periods of dune activity as reflected in the stratigraphic record in the Great Plains generally have been attributed to increased aridity (e.g. Muhs and Maat, 1993; Stokes and Swinehart, 1997; Wolfe, 1997; Forman et al., 2001; Muhs and Holliday, 2001; Muhs and Zarate, 2001). For example, Forman et al. (2008) conclude that dune activity along the Arkansas River was likely related to regional aridity during the early- to mid-Holocene. Arbogast and Johnson (1998) reached a similar conclusion in the Great Bend Sand Prairie, while Muhs and Holliday (1995) determined that prolonged drought was the most probable cause of more recent periods of dune activity in the region.

Lancaster (1988) formulated a model to express this relationship between dune mobility and climate. In his model, the Mobility Index (M) is proportional to wind speed (W), but inversely proportional to the ratio of precipitation (P) to potential evapotranspiration (PE):

$$M = W/(P/PE)$$

Lancaster chose the P/PE ratio because it quantifies the response of vegetation to moisture availability. Using this approach, Lancaster classified values of "M" into four categories of dune activity: (1) dunes fully active ($M > 200$), (2) interdunes vegetated ($100 \leq M < 200$), (3) only dune crests active ($50 \leq M < 100$), and (4) dunes stable ($M < 50$). This classification system shows that the transition of an entire dune field from active to stable and back is gradual and not represented by a single threshold. It also implies that all dunes within a given area should go through this transition at about the same time.

Although Lancaster's M was derived based on dunes in the southwestern Kalahari, it has been widely applied to other settings (Muhs and Holliday, 1995; Wolfe, 1997; Lancaster and Helm, 2000; Muhs et al., 2003) including locations with dunes as well as sand sheets (e.g. Muhs and Maat, 1993; Muhs and Holliday, 2001). In spite of its widespread use, the mobility index does not accurately predict the level of dune activity in all locations. For example, the Lancaster model indicates that the Parker dunes of Arizona should be more active than they are (Muhs et al., 2003) and that dunes in the Canadian High Plains should be less active than they are (Wolfe, 1997). Hugenholtz and Wolfe (2005) suggested that these discrepancies with the Lancaster model could, in part, reflect the time required for dune field vegetation to respond to climatic change. They proposed a biogeomorphic model incorporating lagged response time. Muhs and Holliday (1995) proposed a model that ignores wind speed altogether, using only the ratio of precipitation (P) to potential evapotranspiration (PE). This model seems to accurately separate dunes that are active from those that are stable in the Great Plains as well as the Chihuahuan and Colorado deserts (Muhs and Holliday, 1995).

Although most work in Great Plains eolian stratigraphy has focused on precipitation and/or potential evapotranspiration as the climatic drivers of dune activity, it is possible that the inverse texture effect applies to portions of the Great Plains (Sala et al., 1988). The inverse texture effect suggests that in arid climates the most significant loss of soil moisture is from evaporation from the upper soil horizons, and that sandy soil readily allows infiltration of water deep into the soil profile, where it will not be quickly lost to the atmosphere (Noy-Meir, 1973). This creates localized areas where sand dunes will support denser vegetative cover than areas with finer soils, which lose more water from evaporation. Thus precipitation may not be the critical factor in determining whether or not a dune is mobile. Tsoar (2005) and Yizhaq et al. (2007) suggest that in some locations the inverse texture effect is so significant that precipitation can be ignored altogether in modeling dune activity because wind speed is a much more significant climatic variable. In such cases, if mobilization occurs where vegetation is damaged or destroyed by disturbance in an area with high winds, the resultant saltating sand can prevent subsequent colonization by new vegetation. Thus, two different dunes, one devegetated and mobile and the other vegetated and stationary, can both be in stable states under the same climate regime. This bistability or hysteresis behavior occurs because high wind speeds, and not precipitation, maintain the devegetated surface (Tsoar, 2005; Yizhaq et al., 2007).

An additional complication in the dune–climate relationship is suggested by the soils and geomorphology of southwest Kansas and the Oklahoma Panhandle. The High Plains surface in this area is generally mantled by loess and/or sand, and the sand is typically found either in sand sheets or small (<10 m high) dunes. An examination of the surface morphology here shows that the dunes are frequently associated with depressions within the larger sand sheets. These depressions are interpreted as deflation hollows, and the soils on the associated dunes are generally less developed and sandier throughout the sola than those of the sand sheets (Table 1). For example, in Stevens County, Kansas, the sand sheet is generally classified as Dalhart fine sandy loam or Eva loamy fine sand, both of which are Alfisols with Bt horizons in their typical profiles (Soil Survey Staff, 2005b pp. 30, 35). By contrast, the dunes within the deflation hollows include significant areas of Optima loamy find sand,

Table 1
Official soil series descriptions (http://soils.usda.gov/technical/classification/osd/, retrieved 3/25/10).

Soil order	Taxonomy	A-horizon thickness (cm)	Texture of A horizon	Solum thickness (cm)	Dominant texture of B horizons	AWC[a]
Sand sheet soils						
Dalhart	Haplustalf	23	Fine sandy loam	203	Sandy clay loam	0.13
Eva	Haplustalf	13	Loamy fine sand	122	Fine sandy loam	0.11
Manter	Argiustoll	33	Fine sandy loam	152	Fine sandy loam	0.17
Amarillo[b]	Paleustalf	28	Fine sandy loam	251	Sandy clay loam	0.13
Dune soils						
Vona	Haplustalf	20	Loamy fine sand	152	Sandy loam	0.08
Optima	Ustipsamments	43	Fine sand	43	–	0.08
Valent	Torripsamments	10	Sand	10	–	0.07
Tivoli[b]	Ustipsamments	18	Fine sand	18	–	0.09

[a] Available water capacity as reported in Soil Survey Staff (2009a,b,c, 2010).

[b] Amarillo and Tivoli series are regional soils included for comparison (see Taylor, 1960).

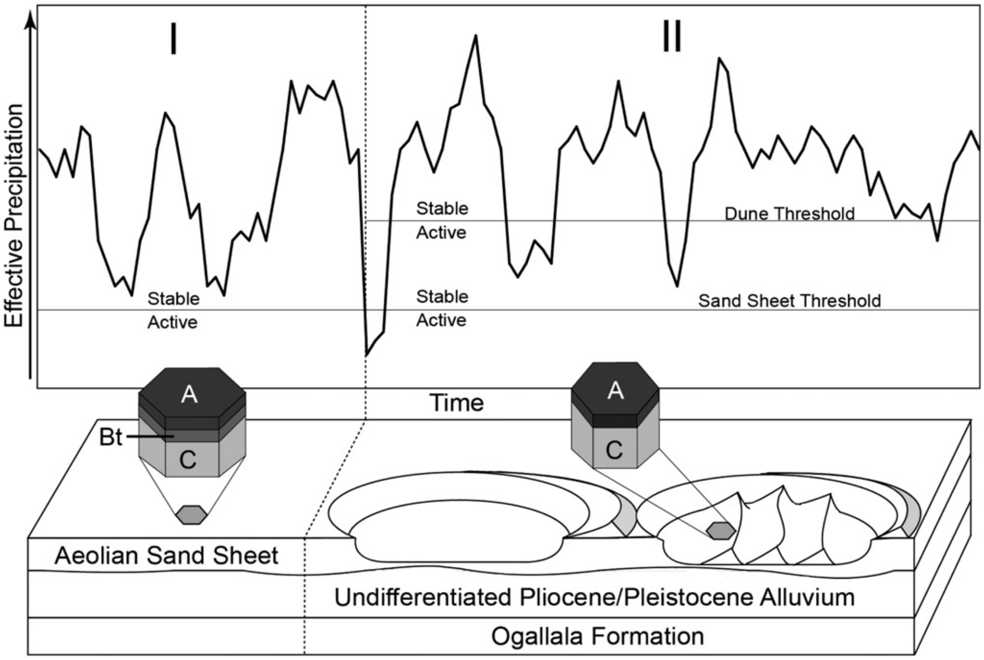

Figure 1. Schematic illustration of the hypothesized non-linear relationship between dune activity and climate. (I) Initially the sand sheet remains stable even when effective precipitation is low because of the presence of soil structure and finer textures (found in an argillic or Bt horizon). After some initial effective precipitation threshold is crossed, deflation hollows are created, soil structure is destroyed, and silt and clay are winnowed from the resultant deposits. (II) Therefore, subsequent dune activity can occur within the deflation hollows at a higher effective precipitation threshold than in the surrounding sand sheet.

a Torripsamment with little, if any, B-horizon development (Soil Survey Staff, 2005b, 35).

To explain these soil-geomorphic patterns, we hypothesize that a localized period of dune activity (i.e. the creation of a deflation hollow) will occur when the effective precipitation (P/PE) crosses below some critical threshold. Within the Great Plains, the threshold between largely active and largely inactive dunes corresponds to a P/PE ratio of roughly 0.35 (Muhs and Holliday, 1995 Fig. 4). When the deflation hollow is created, silt and clay are winnowed from the saltating sand. This loss of fines thus decreases the newly formed dunes' available water capacity (Schaetzl and Anderson, 2005) and should make the dune sand more prone to subsequent entrainment than the surrounding sand sheet. In other words, the P/PE threshold below which the deflation hollow dunes become active will subsequently be higher than for the surrounding sand sheet. This change in the threshold for dune activity occurs for two reasons. First, the loss of silts and clays will reduce the intergranular cohesion when moist (Namikas and Sherman, 1995), directly decreasing the tractive force required for entrainment. Second, the field capacity of the resulting dunes should be closer to the permanent wilting point than that of the surrounding sand sheet. If the inverse texture effect does not apply, then this would mean that the dune would experience vegetation loss due to moisture stress before the adjacent sand sheet. This loss of vegetation would subsequently allow for greater wind speed near the dune surface, increasing the likelihood of entrainment. The result of this non-linear relationship between effective precipitation and dune activity is that any P/PE threshold below which dunes become active can vary in both space and time. Figure 1 presents this conceptual model in its simplest form, but it can also be modified to accommodate the concept of significant reaction and relaxation times following a shift in climate, along the lines proposed by Hugenholtz and Wolfe (2005).

Study area

This research took place in the High Plains of southwest Kansas and the Oklahoma Panhandle between the Cimarron and Beaver (or North Canadian) Rivers (Fig. 2). The climate of the region is semiarid, with increasing precipitation from west to east. The mean annual precipitation is 480 mm at Elkhart, Kansas and 501 mm 80 km to the east at Liberal, Kansas (National Climatic Data Center, 2002a,b). Most precipitation occurs during the summer growing season, and annual rainfall varies considerably.

The High Plains surface of the study area slopes gently from west to east at a gradient of approximately 2 m km^{-1}. The general flatness of the landscape is broken by the Cimarron and Beaver rivers, which are incised as much as 100 m (Smith, 1940), and by sand dunes, which can reach heights of 10 to 15 m. The Holocene surfaces overlie undifferentiated Pliocene and Pleistocene sands and gravels, which in turn overlie the Miocene Ogallala formation (Byrne and Mclaughlin, 1948; Irwin and Morton, 1969).

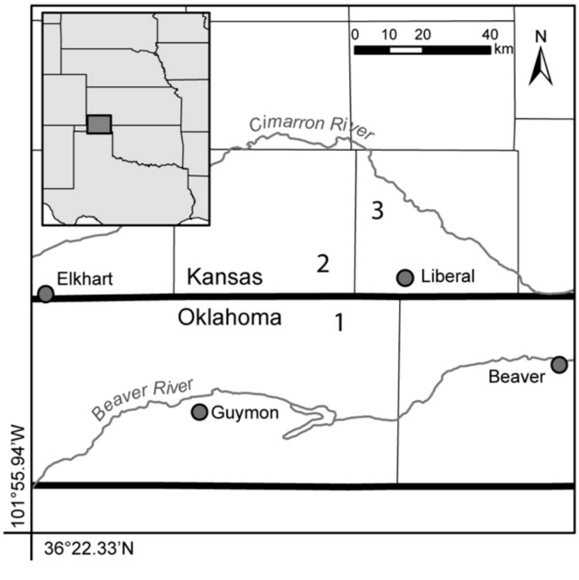

Figure 2. The Cimarron Bend study area: 1 — Albright site, 2 — Banner site, 3 — Hitch site.

Within the study area, dunes are found on two surfaces: (1) the floodplains and terraces associated with the Cimarron and Beaver Rivers, and (2) sand sheets described by Porter (1997) as eolian-modified Pleistocene alluvial-plain surfaces. Within the sand sheets, dunes are often found within depressions, which we interpret as deflation hollows. Many of these hollows are elliptical in shape, with a long axis that is roughly twice as long as the short axis, and which trends NNE–SSW. They range in area from 2 to 25 km^2, with the largest appearing to be compound features wherein two or more depressions have coalesced. The overall relief of the deflation hollows can be as much as 16 m. The mean slope steepness of the High Plains surface between the Cimarron and Beaver Rivers is only 2.5%, whereas within the three deflation hollows studied here, the mean slope is over 6.5% (Gesch et al., 2002; Gesch, 2007). These features are also visible among the Arkansas River dunes, approximately 70 km northeast of the current study sites, and may be the same "ellipse-shaped areas of active sand" described by Muhs and Holliday (1995, 205). Smith (1940, 159) described these features as "aerial blowouts," distinguishing them from the smaller blowouts he observed during his investigation.

The soils of the sand sheets are predominantly Alfisols, suggesting long-term stability and soil development, while the soils of the dunes within the sand sheet are predominantly weakly developed Entisols, suggesting a relatively short period of time for soil formation after the last period of dune activity (Table 1).

The vegetation of the sand sheets is dominated by mixed-grass prairie, with little blue stem (*Schizachyrium scoparium*), sideoats grama (*Bouteloua curtipendula*), and blue grama (*Bouteloua gracilis*) being representative species (Porter, 1997; Olson and Porter, 2002). The dunes tend to have more sand sage (*Artemisia filifolia*) and small soapweed (*Yucca glauca*). While grasses and shrubs dominate the uplands, the river valleys include riparian woodlands (Mclaughlin, 1947; Schumm and Lichty, 1963; Porter, 1997; Vanlooy and Martin, 2005).

For this study, three deflation hollows were examined to determine the timing of deposition within as compared to outside of each. The Albright site in Beaver County, Oklahoma, has very distinctive deflation hollow boundaries. The dunes within that depression have well-defined morphologies with slip faces on their southeast slopes. The deflation hollow at the Banner site in Stevens County, Kansas has less distinct boundaries than the Albright site, and the dunes do not have the well-defined morphology found at the Albright site. The Hitch site, in Seward County, Kansas, is the longest of these deflation hollows and has the least distinctive morphology.

Methods

Field work

A total of 22 auger holes and soil cores were sampled for this study. Auger samples were collected for subsequent laboratory analysis when hand texturing suggested a change in particle size. Particle-size distribution (PSD) was measured by laser diffraction for all auger samples and at depth intervals of 10 cm for cores.

Samples were collected for optical dating using two methods. For samples taken from auger holes, the auger head was replaced by a split-spoon sampler lined with two 15-cm-long steel pipes. Material in the lower pipe was protected from light exposure and used for dating. Additional material was collected from the upper pipe for dose rate determination. For samples collected using the soil probe, a 15-cm-long steel pipe was inserted into the end of the core barrel excluding the outermost sediment, which was separately collected for dose-rate determination. One sample (UNL-1374) was collected from within a backhoe trench by hammering a sampling tube into a cleaned trench wall and using the matrix surrounding the sample for dose-rate determination.

Laboratory work

Several tests were employed to investigate the assumptions underlying the hypothesized feedback in which loss of fine material affects the subsequent threshold for dune activity. These tests included particle size analysis, measurement of water retention near field capacity, and a procedure described here as air elutriation, which was intended to simulate eolian winnowing.

Particle-size distributions were measured by laser diffraction using a Malvern Mastersizer 2000®. A subset was also analyzed using the pipette-sieve method (Kilmer and Alexander, 1949; Walter et al., 1978), which included pretreatment with 10% HCL to remove carbonates and with H_2O_2 to remove organic matter. The pipette-sieve results were compared to four different preparations for laser diffraction: (1) no sodium hexametaphosphate (HMP) or sonication; (2) HMP added, but no sonication; (3) HMP added with 3 min of sonication; and (4) HMP added with 6 min of sonication. The laser diffraction results from the three treatments that used HMP were strongly correlated with the sieve/pipette method for sand content, with r^2 values exceeding 0.91 ($p<0.0001$). Correlations were weaker but still significant for silt ($r^2=0.81$–0.85; $p<0.0001$) and clay ($r^2=0.58$–0.76; $p<0.0001$). Laser diffraction tended to estimate a higher sand fraction and lower clay fraction than pipette/sieve, as noted in previous studies (e.g. Beuselinck et al., 1998; Mason et al., 2003). Based on this comparison, laser diffraction after 3 min of sonication with HMP was selected as the standard method for particle size analysis in this study. This method yielded sand contents that were highly correlated with sieve data ($r^2=0.93$, $p<0.0001$), and thus achieved the main objective of testing whether dune activation led to a loss of silt and clay and a corresponding increase in sand content.

The effect of the textural difference between the sand sheet and dune sand on moisture retention was evaluated using two methods. First, empirical equations for estimating moisture retention from particle size data (Rawls et al., 1992) were applied to paired samples of surface soil B horizons in sand sheets and dunes from the three study sites. For this purpose, laser diffraction data were converted to approximately equivalent sieve or pipette values using regression equations based on the comparison between methods described above. The equations of Rawls et al. (1992) include a term for organic matter effects, which was set to zero because we lacked organic matter measurements for our samples. Typical ranges of organic matter content, reported by soil surveys (0–0.6% for most dune and sand-sheet subsoil horizons, up to 1.5% for a few sand-sheet soils (Soil Survey Staff, 2009a,b,c)) suggest this approach should have minimal effect on AWHC estimates, but may underestimate the contrast between dune and sand sheet soils in a few cases. Second, the volumetric water contents of the same samples were measured at matric potentials (ψ_m) from saturation to -15 to -20 kPa, using a Tempe cell obtained from Soilmoisture Inc. (Santa Barbara, CA) (Reginato and Van Bavel, 1962). Samples were packed in the Tempe cell and saturated with de-aired water; a negative hydraulic head was then applied (Kutilek and Nielsen, 1994). These measurements should indicate differences in field capacity water content (content after most gravitational drainage has occurred), which falls in the range of $\psi_m=-10$ to -33 kPa (Kutilek and Nielsen, 1994).

An air elutriation experiment was used to simulate the effect that eolian activity would have on the particle size distribution of sand sheet soils. This was done by placing a small amount of sediment in a 2-l graduated cylinder (similar to an apparatus used to measure eolian abrasion over much longer experiments (Bullard et al., 2007)). Compressed air was fed into the cylinder so that the sediment saltated within the lower part of the cylinder for a minimum of 1 min. An outflow tube from the top of the cylinder carried suspended dust into a water-filled flask where sediment was trapped. Particle-size analysis was carried out on the original soil sample, the trapped dust, and sand remaining in the cylinder after saltation.

Optical ages were determined at the University of Nebraska-Lincoln Luminescence Geochronology Laboratory. The samples were opened under amber light, and the sediment from the center of the pipe was sieved to separate the 90–125 μm fraction. The samples were treated with 1 N HCL to remove carbonates, and then heavy minerals were removed by flotation in a 2.7 g cm^{-3} sodium polytungstate solution. The light fraction was then treated with hydrofluoric acid to remove feldspars and to etch quartz grains and sieved again to remove grains finer than 90 μm. Finally, a monolayer of treated quartz grains was mounted on aluminum disks with silicon spray. Luminescence analyses were performed on a Risø DA-15 TL/OSL reader. The single aliquot regenerative (SAR) method developed in Murray and Roberts (1998) and refined by Murray and Wintle (2000) was used to determine the equivalent dose (D_e) on a minimum of 20 accepted aliquots. The dose rate was calculated by using the abundance of potassium (K), Thorium (Th), Rubidium (Rb) and Uranium (U), which was determined by ALS-Chemex, Inc. (Sparks, NV) using ICP-MS and ICP-AES. The cosmogenic component of the dose rate was estimated using equations from Prescott and Hutton (1994). The final optical age was computed by using the equation:

$$Age = Equivalent\ Dose / Dose\ Rate$$

Results

Deflation hollow stratigraphy

The particle size and stratigraphic data from the Albright site are shown in Figure 3. Cores G4 and G10 were drilled entirely within the sand sheet on either side of the deflation hollow. G4 was taken from within a fallow wheat field, and the sandy texture near the surface coincides with the Ap horizon in that core. An increase in silt occurs at the bottom of the plow zone, below which sandier sediment continues to a depth of ~110 cm. Below that the silt percentage increases significantly. G10 was drilled within an ungrazed short-grass prairie and has a well-developed surface soil, with solum depth reaching 189 cm below the surface. G10 has a complex pattern of textural variability with depth, but the first peak of sand comparable to that found elsewhere (i.e. more than 70% sand) does not occur until a depth of 330 cm (Fig. 3b). At both G4 and G10, the soil is mapped as Dalhart fine sandy loam, an Alfisol (Soil Survey Staff, 2009c).

The data from the dunes within the deflation hollow contrast significantly with the sand-sheet data. Loamy sand is found throughout the dune, which overlies a silty stratum that appears to be widespread in the local area. The surface soils on the dunes are weakly developed Entisols without B horizons and with an average depth of solum of 38 cm.

Seven optical ages were obtained from the Albright site (Fig. 3, Table 2), six of which show that the dunes within and along the side of the hollow were active between ca. 0.8 and 0.4 ka. The only age obtained from the sand sheet was taken from the sandier layer in G10, at 306 cm, and indicates deposition ca. 40–41 ka. This age is consistent with the degree of soil development in the sand sheet, which suggests stability for thousands of years (Gile, 1979; Birkeland, 1999).

The Banner site is stratigraphically more complex than the Albright site, yet also paints a picture of an older sand sheet that surrounds younger dunes (Fig. 4). The soil development of the Banner dunes is similar to that of the Albright dunes. The soils throughout this location are mapped as Eva-Optima loamy find sands, a consociation in which the Eva Alfisol covers 45% of the surface and the Optima Entisol covers 40% (Byrd, 2006). This investigation showed that the soils on the dunes in the Banner deflation hollow are the Optima Entisol. The PSD for these dunes is similar to what was found at the Albright site, with 70–75% sand in the upper 3 m of AH2 decreasing to 60–65% sand below that.

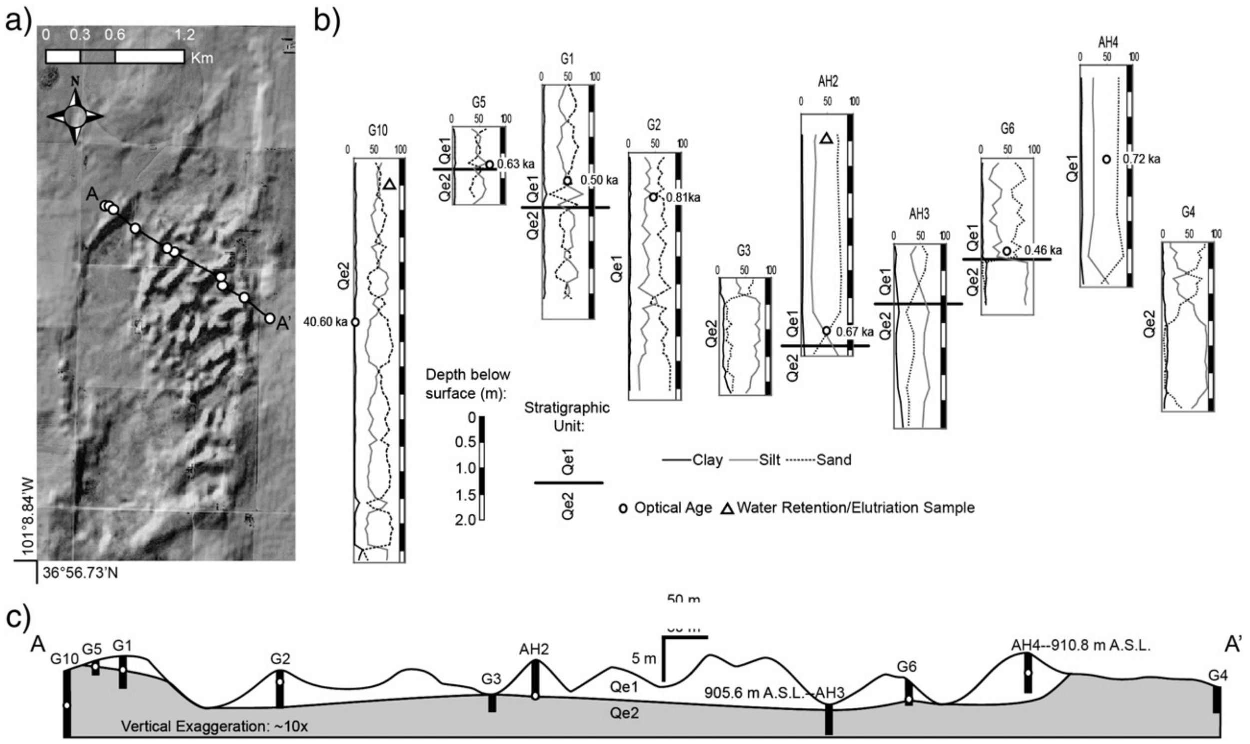

Figure 3. Albright site. (a) The deflation hollow — visible here in a shaded relief map with vertical exaggeration of ~5× derived from the National Elevation Dataset, 1/3″ (http://ned.usgs.gov/ned) — was sampled in a transect perpendicular to its long axis. (b) Particle size distribution and optical ages provide information to discern the generalized stratigraphy of the site (c). Qe2 is the sand sheet and Qe1 is the dunes. Nomenclature for units is based on field and laboratory work and not on other published work. Optical ages are reported with 1 SD error in Table 2.

Table 2
Field and laboratory data, and OSL results, arranged from youngest to oldest sample.

Site/setting		Lab no.	Depth[a] (m)	U (ppm)	Th (ppm)	K_2O (%)	H_2O (% *in situ*)	D_{cosmic}[b] (Gy ka^{-1})	D_{total}[c] (Gy $ka^{-1} \pm 1\sigma_s$)	D_e[d] (Gy $\pm 1\sigma_s$)	Age[e] (a $\pm 1\sigma$)	Aliquots (n)
Albright site												
Sample source	Soil horizon											
G6	C	UNL-1379	1.8	0.6	2.7	1.18	0.67	0.19	1.46 ± 0.05	0.67 ± 0.01	460 ± 40	23
G1	C	UNL-1381	1.8	0.9	3.9	1.52	5.1	0.19	1.79 ± 0.20	0.89 ± 0.01	500 ± 70	26
G5	C	UNL-1378	0.7	1.2	6.0	1.48	2.8	0.22	2.06 ± 0.07	1.30 ± 0.10	630 ± 70	21
AH2	C	UNL-1372	4.2	0.6	2.4	1.11	0.67	0.14	1.33 ± 0.04	0.89 ± 0.16	670 ± 130	25
AH4	C	UNL-1452	1.8	0.6	2.5	1.06	0.83	0.19	1.35 ± 0.05	0.98 ± 0.15	720 ± 120	26
G2	C	UNL-1453	0.8	0.9	4.1	1.35	1.64	0.22	1.78 ± 0.05	1.43 ± 0.08[f]	810 ± 90[f]	36
G10	2Cb2[g]	UNL-1448	3.5	0.8	3.2	1.19	5	0.13	1.42 ± 0.16	57.71 ± 2.50	40 600 ± 5620	23
Banner site												
Sample Source	Soil horizon											
AH2	C	UNL-1455	1.3	0.6	2.6	1.29	2.32	0.21	1.52 ± 0.09	0.80 ± 0.02	520 ± 50	22
AH2	C	UNL-1456	4.4	1.0	3.7	1.43	1.56	0.14	1.76 ± 0.08	1.11 ± 0.02	630 ± 50	25
G9	C	UNL-1380	0.9	0.6	2.3	1.30	0.36	0.22	1.56 ± 0.05	1.20 ± 0.07	770 ± 70	20
AH1	C	UNL-1373	1.4	1.0	4.6	1.55	4.32	0.20	1.91 ± 0.18	4.83 ± 0.07	2530 ± 300	23
BH1	C	UNL-1374	0.9	0.7	2.8	1.34	4.27	0.22	1.57 ± 0.15	10.12 ± 0.15	6440 ± 760	25
AH1	Btk2b	UNL-1457	3.7	1.0	3.7	1.43	1.56	0.15	1.77 ± 0.05	21.95 ± 0.36	12 400 ± 940	20
AH3	Bt3b	UNL-1454	3.5	0.6	1.7	1.24	0.31	0.20	1.40 ± 0.04	374.27	>266 000[h]	3
Hitch site												
Sample Source	Soil horizon											
AH1	C	UNL-1463	1.4	0.9	3.3	1.49	3.91	0.20	1.76 ± 0.16	6.29 ± 0.09	3570 ± 400	22
AH3	C	UNL-1460	1.2	0.7	3.0	1.51	3.13	0.21	1.73 ± 013	6.20 ± 0.07	3590 ± 360	22
AH3	C	UNL-1461	4.5	0.6	2.3	1.45	1.48	0.14	1.57 ± 0.07	5.67 ± 0.08	3620 ± 300	23

[a] Depth of sample below modern land surface. Samples are arranged in order of increasing age at each site.
[b] Cosmic ray dose rate. Derived from sample elevation, latitude, longitude and depth of burial (Prescott and Hutton, 1994).
[c] Total dose rate.
[d] Equivalent dose.
[e] Years before 2005 AD.
[f] Based on median D_e from aliquots due to skewed distribution. The mean $D_e = 1.93$ Gy, which yields an age of 960 ± 90.
[g] Buried soils are numbered sequentially following the last letter of the horizon following Holliday (1990).
[h] Minimum age based on extrapolation from 3 aliquots. The D_e was too high to bracket for interpolation.

The sand sheet surrounding the Banner site has more extensive soil development. Both AH1 and BH1 have well-developed B horizons associated with the surface soil and are interpreted as the Eva Alfisol. The solum thickness at AH1 is 91 cm, and at BH1 it is 78 cm. The sand sheet's PSD profile (Fig. 4b) shows that although there is as much as 60–70% sand in the sand sheet, there are some beds in which sand content drops below 50%.

The optical ages for the Banner site include more mid- to late-Holocene ages than found at the Albright site (Fig. 4, Table 2). While the Holocene chronology of the sand sheet is complex, that of the dunes is not, with all dated dune activity occurring between 0.63 and 0.52 ka. The ages from the sand sheet vary from 2.53 ka below the B horizon in AH1 to 12.4 ka 2 m below that. The Banner data show that the dunes within the hollow are late-Holocene deposits, while the surrounding sand sheet was deposited in several episodes during the mid and mid- to late-Holocene, including the period from 6 to 3 ka that was reported by Porter (1997).

The deflation hollow at the Hitch site is less distinctive than the others that were studied; a long dune-like ridge dominates the eastern margin, while the western margin is indistinct over most of its length (Fig. 5a). Accessibility problems led to sampling only the northernmost part of this hollow, where there were no internal dunes. On the western boundary of the depression, AH1 has an A/Bt1/Bt2 profile reaching a depth of 56 cm and is mapped as the Eva Alfisol (Soil Survey Staff, 2005a). The soil texture is somewhat variable, with sand content ranging from 38 to 70% (Fig. 5b). The dune ridge on the eastern side of the depression is mapped as Optima fine sand, a Torripsamment. This investigation confirmed that there is minimal soil development, with the solum reaching a depth of only 34 cm. This dune shows little textural variability with depth, and sand content averages 64% (Fig. 5b). Three optical ages were obtained from two cores at the Hitch Site, and all three are remarkably consistent, reflecting a period of dune activity ca. 3.6 ka (Fig. 5, Table 2).

Moisture retention

The equations of Rawls et al. (1992), based on particle-size data, predict that the available water-holding capacity of the sand sheet soils is from 1.5 to 1.8 times that of the dune soils (Table 3). The difference is largely related to greater field capacity moisture content in the sand sheet samples because of lower sand content. Measured moisture retention at ψ_m from saturation to about −20 kPa in samples from the Hitch and Banner sites confirmed that the B horizons of the sand sheet retain more moisture near field capacity than the dune soils. In fact, the measured difference of 10–15 vol.% water content is substantially greater than predicted from particle size (Fig. 6, Table 3). Measurements on samples from the third site (Albright) did not provide clear evidence of greater retention near field capacity for the sand sheet soil. Discrepancies between methods are not surprising, given the uncertainty of the particle size-based estimates and sensitivity of measured values to minor differences in packing and other factors.

Air elutriation

The elutriation data show that fine, silt-sized particles were removed from the sand sheet by the process of saltation, although the details varied among the sites (Table 4). The effect of this removal on the overall particle-size distribution was most pronounced for samples from the Banner and Hitch sites but is also evident in the Albright data.

Discussion

The data presented from the Albright and Banner sites are consistent with the proposed non-linear relationship between climate and dune activity. Optical dating and soil stratigraphy confirm that the

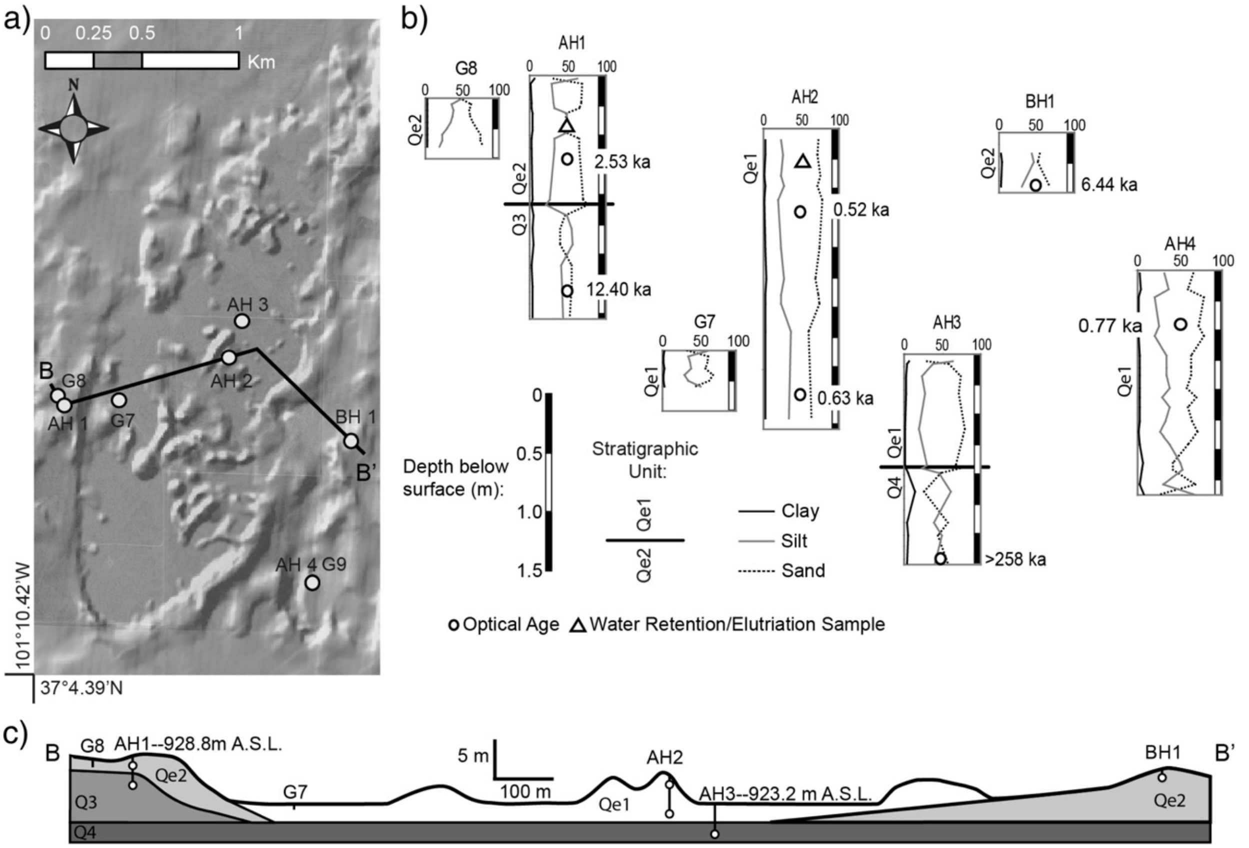

Figure 4. Banner site. (a) The deflation hollow — visible here in a shaded relief map with vertical exaggeration of ~5× derived from the National Elevation Dataset, 1/3″ (http://ned.usgs.gov/ned) — and locations of cores. (b) Particle size distribution and optical ages provide information to infer the generalized stratigraphy of the site (c). Nomenclature is based on field and laboratory work and not on previously published work. Note that Q3 and Q4 are of indeterminate origins, and that AH4 was sampled from outside the deflation hollow on a small dune ridge in the sand sheet.

sand sheet has generally been stable for longer periods of time than the dunes, although the sand-sheet deposits vary widely in age. Particle-size data, moisture-retention estimates and measurements, and lab simulation of winnowing during saltation all provide support for the proposed feedback mechanism by which the creation of a deflation hollow results in a higher effective precipitation threshold for subsequent activity (Fig. 1).

The above conclusion is only warranted if the inverse texture effect does not apply to the conditions described. Sala et al. (1988) found that within the Great Plains area, the inverse texture effect was not applicable to locations with annual precipitation greater than 370 mm. Under the current climate regime, the study area receives over 470 mm per year; however, it is plausible that during significant dry periods in the Holocene, annual precipitation may have fallen below 370 mm, potentially allowing a significant inverse texture effect.

We believe the inverse texture effect is unlikely to play a role in this specific area because the B horizons of three of the four representative sand sheet Alfisols have finer textures than the A horizons (Table 1). Taylor (1960) suggests that most water loss due to evapotranspiration in the Southern High Plains occurs within the upper 15 cm of the soil. In the case of soils that have sandy A horizons and finer B horizons, the situation "combines the best features of sandy and finer textured profiles" (Taylor, 1960, 80) because the coarser A horizon allows water to move quickly downward into the profile, where it will avoid evaporation. Once it reaches the subsoil, the water will not then be lost to downward percolation because of the finer textured soils of the B horizon. This situation was not considered in computing the 370 mm precipitation threshold because Sala et al. (1988) relied solely on the texture of the A horizon in their computations.

The moisture-retention estimates and elutriation experiments support the proposed causal mechanism for the spatially and temporally variable effective precipitation threshold for dune activity. Soils in the sand sheet retain more moisture against more negative matric potentials because of greater fine particle content. This would increase resistance to wind erosion in two ways: (1) it would directly resist entrainment by wind because the moisture and finer particles would add cohesive strength, and (2) it would indirectly resist entrainment by providing moisture for vegetation at times when the sandier soil is desiccated. The elutriation experiment clearly showed that saltation during dune building can remove finer particles from the resultant deposits. Again, this supports the causal mechanism behind the non-linear response model because, in the absence of an inverse texture effect, the loss of fines can make subsequent eolian entrainment easier within the dunes, while the accumulation of fines makes entrainment more difficult within the sand sheet.

While the stratigraphy of the Albright and Banner sites is consistent with the non-linear hypothesis, the Hitch site is more difficult to interpret (Fig. 5). The geomorphology of the Hitch site is not as clearly indicative of a deflation hollow as at the other sites, and the three auger holes were drilled within the sand sheet, the interdune, and the single dune ridge. The soil stratigraphy, particle-size analysis, moisture-retention data, and elutriation experiment are all consistent with the non-linear hypothesis; however, the optical ages from the Hitch site are remarkably consistent in showing a local period of eolian activity ca. 3.6 ka that is not reflected at the other sites. Furthermore, these ages show that both the sand sheet and the

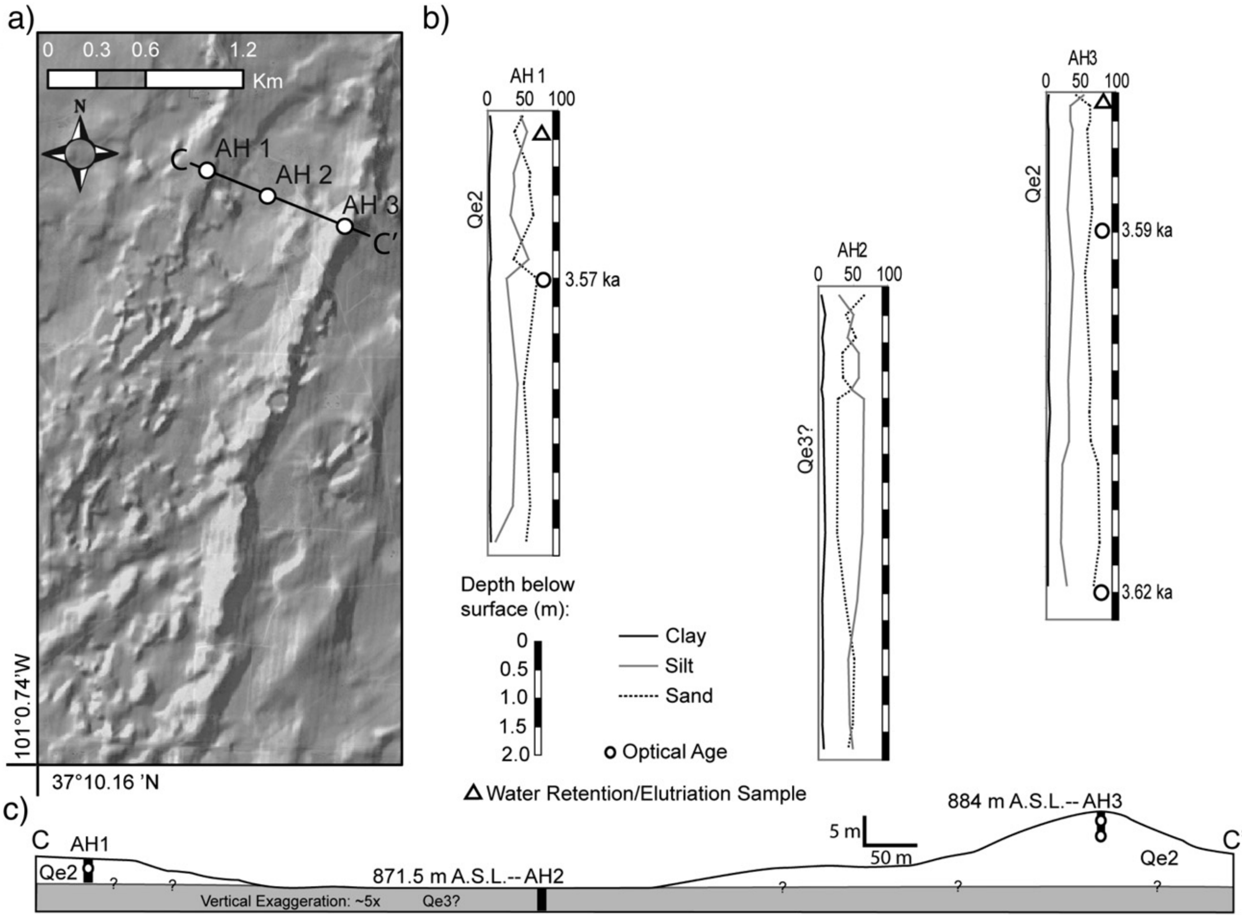

Figure 5. Hitch site. (a) The deflation hollow — visible here in a shaded relief map with vertical exaggeration of ~5× derived from the National Elevation Dataset, 1/3″ (http://ned.usgs.gov/ned) — was sampled in a transect across its northern end. (b) Textural data show significant differences between the eastern and western margins of the depression, but the optical ages are remarkably consistent. (c) The generalized stratigraphy of the Hitch deflation hollow. Marginal deposits are labeled as Qe2 based primarily on the ages and proximity to Qe2 at the Banner site (Figs. 2 and 4). Qe3 is defined based on soil development in the absence of age control. Although Qe3 is enriched in fines, it is well sorted and tentatively interpreted as eolian.

dune were active at the same time. Given the similarity of optical ages in the sand sheet and dune, it would be reasonable to expect both deposits to have a similar soil profile, but the dune is mantled by the Optima Torripsamment while the sand sheet is mantled by the Eva Haplustalf. If the non-linear climatic threshold is applicable, then these soil properties should have led to more recent deposition of the dune on the eastern ridge of the Hitch site. There are three possible interpretations of these data as they relate to the non-linear response model: (1) thresholds for dune activity are not variable in time and space, and thus the hypothesis is refuted, (2) the ridge dune at the Hitch site was active at the same time as other dunes in the area (ca. 0.5–0.6 ka), but the resulting stratigraphic unconformity is masked and no age samples were taken from above the unconformity, and (3) the Hitch locale was not dry enough for dune activity ca. 0.5–0.6 ka. Of

Table 3
Soil textures derived by laser diffraction, then converted to sieve/pipette equivalents by regression, and the water holding capacities estimated from pipette soil texture (Rawls et al., 1992).

Site	% Sand		% Silt		% Clay		−10 kPa (θ)	−33 kPa (θ)	−1500 kPa (θ)	AWHC1[a]	AWHC2[b]	AWHC factor[c]	
Setting, sample source, depth, horizon	Laser	Pip.	Laser	Pip.	Laser	Pip.						AWHC 1	AWHC 2
Albright site													
Sandsheet, G10, 50 cm, Btk	50.72	65.13	46.70	27.14	2.58	7.73	0.234	0.155	0.065	0.091	0.13	1.58	1.63
Dune, AH2, 40 cm, AC	69.50	81.96	28.25	10.72	2.24	7.32	0.183	0.120	0.063	0.057	0.08		
Banner site													
Sandsheet, AH1, 86 cm, Bt2	47.30	62.07	48.88	28.72	3.82	9.21	0.247	0.167	0.072	0.095	0.11	1.79	1.38
Dune, AH2, 44 cm, Bw	71.44	83.70	25.64	8.16	2.92	8.14	0.179	0.119	0.067	0.053	0.08[d]		
Hitch site													
Sandsheet, AH1, 19 cm, Bt1	38.56	54.24	55.82	34.40	5.61	11.36	0.275	0.190	0.083	0.107	0.11	1.55	1.38
Dune, AH3, 12 cm, Bw	62.66	75.83	34.77	16.44	2.58	7.73	0.202	0.134	.065	0.069	0.08		

[a] Average water holding capacity between −33 kPa and −1500 kPa.
[b] Average water holding Capacity based on soil series properties (Soil Survey Staff, 2009a,b,c).
[c] AWHC factor = $AWHC_{sandsheet}/AWHC_{dune.}$
[d] Based on Optima fraction of Eva-Optima loamy find sand soil consociation.

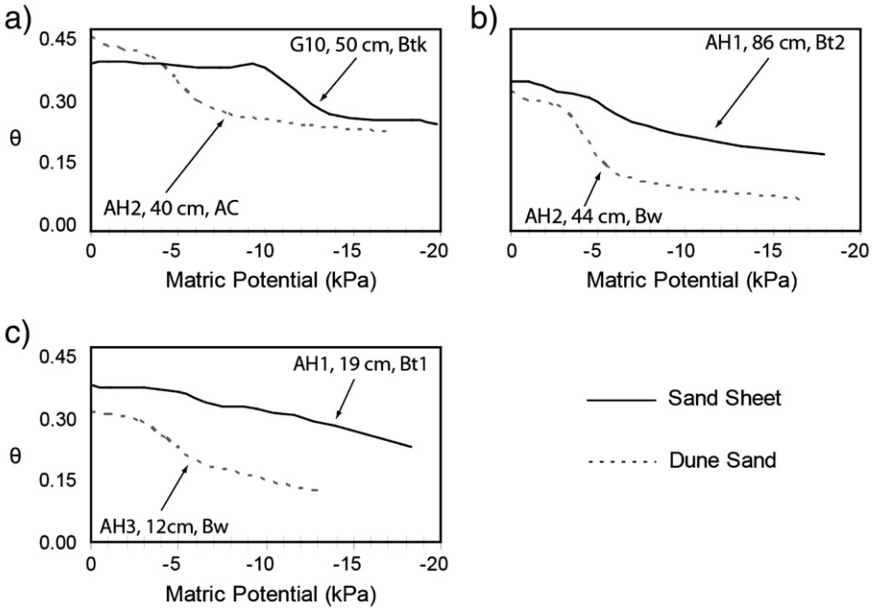

Figure 6. Soil water retention curves for B horizons of sand dunes and sand sheets for the Albright (a), Banner (b), and Hitch (c) sites. The Banner and Hitch data show that the sand sheet retains substantially more water near field capacity than the dune soils, while the Albright data do not show a clear relationship.

these interpretations, only the last seems unreasonable because the greatest distance between all sites is only 30 km; thus all sites likely have a similar climatic history. Interpretation 2 would be similar to the situation in the Cimarron River dunes 270 km southeast of this study, where a truncated dune deposit was not visible in the soil stratigraphy but was revealed by optical dates from above and below the unconformity (Lepper and Scott, 2005). In that study, the sand below the truncation was deposited ca. 3.3 ka, while the sand above was deposited ca. 0.8 ka. The most that can be said about the currently available data from the Hitch site is that they neither support nor refute the non-linear hypothesis.

The current research provides new ages for eolian activity in southwest Kansas and the Oklahoma Panhandle. This allows us to compare the local eolian chronology to other regional chronologies (Fig. 7). The picture emerging from the increasing number of regional chronologies suggests a period of fairly widespread dune activity between 400 and 1000 yr ago (Lepper and Scott, 2005; Forman et al., 2008; Hanson et al., 2010). This period overlaps with eolian activity in the Nebraska Sand Hills and other locales in the central Great Plains (Miao et al., 2007) as well as with eolian activity in the Muleshoe dunes of the Southern High Plains (Holliday, 2001).

Table 4
Mean and median diameters of sand-sheet material from the elutriation experiment.

Site	Mean diameter (μm)	Median diameter (μm)
Albright sand sheet, G10, Btk horizon, 60 cm		
Before elutriation	141	113
After elutriation	149	126
Material carried in suspension during elutriation	55	22
Banner sand sheet, AH1, Bt1, 63 cm		
Before elutriation	148	125
After elutriation	202	196
Material carried in suspension during elutriation	24	15
Hitch sand sheet, AH1, Bt1, 19 cm		
Sand sheet B horizon before elutriation	76	43
Sand sheet B horizon after elutriation	91	64
Material carried in suspension during elutriation	29	27

Conclusions

In summary, this research shows that (1) the upland sand dunes have fewer fines and less well-developed soil profiles than the surrounding sand sheet, (2) saltation of the sand-sheet material can result in a loss of finer particles, (3) the dune sediment generally has a lower water holding capacity than the sand sheet material, and (4) the dunes in two of the three study sites are consistently younger than the surrounding sand sheet. This evidence is generally consistent with a non-linear relationship between climate and dune activity in the study area that is caused by feedback within the soil-geomorphic system. Older eolian landforms are more resistant to activation because of the presence of finer soil particles, which accumulate as the soil forms over time. These finer particles retain moisture that sustains vegetation, anchoring the deposit even during more arid times. Conversely, younger deposits lack these fine particles and are more easily reactivated.

The dune fields of the Great Plains display significant variability in dune forms, particle-size characteristics, and Holocene geomorphic history. If there is a corresponding variability in climatic thresholds for dune mobility, then this must be taken into account for accurate prediction or reconstruction of regional landscape response to climate change. In this case, an index of dune activity that is based on unique climatic thresholds may be adequate for initial, regional interpretations of dune activity (e.g. Lancaster, 1988; Muhs and Holliday, 1995), but should ultimately be replaced with more complex models incorporating multiple thresholds as well as lagged vegetation response to climate and, where applicable, the inverse texture effect. It is possible that winnowing during dune activation alters not only the climatic threshold for subsequent activation, but also reaction and relaxation times of the eolian system (Hugenholtz and Wolfe, 2005) after the threshold is crossed.

The form of non-linear response described here can be useful because, like the hysteresis model of Yizhaq et al. (2007), it provides a plausible explanation for contiguous eolian features of significantly different ages. While it is still appropriate to link past periods of dune activity to drought, complications like this should not be ignored. This model shows that the relationship between climate and dune behavior is not as straightforward as is often believed, and paleoclimatic reconstructions based primarily on the timing of past dune activity should consider this additional complexity in the traditional dune–climate conceptual framework.

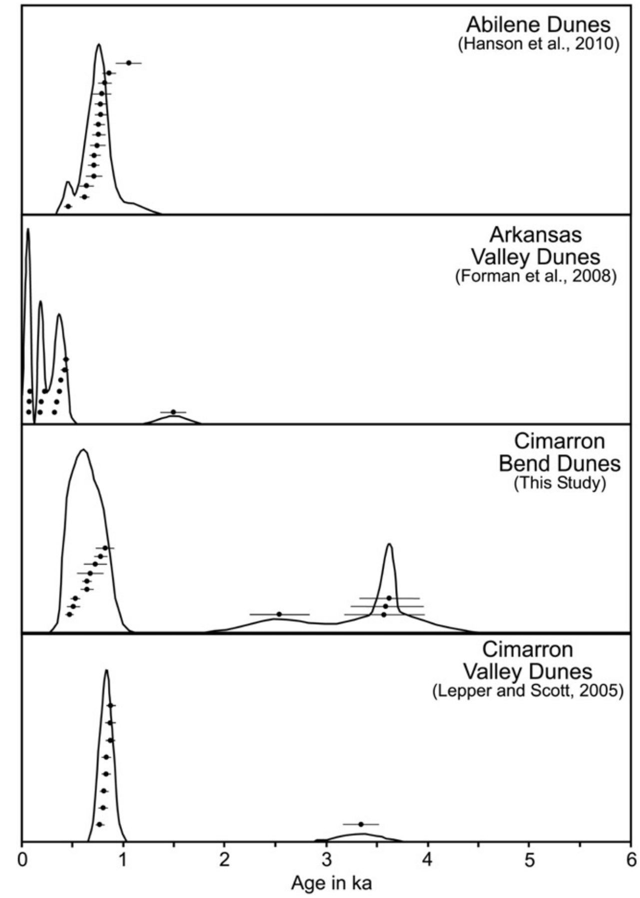

Figure 7. Cumulative frequency plots of eolian chronologies since 6 ka from recent publications near the study area (vertical scales are in arbitrary units).

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References

Arbogast, A.F., 1996. Stratigraphic evidence for late-Holocene aeolian sand mobilization and soil formation in south-central Kansas, U.S.A. Journal of Arid Environments 34, 403–414.

Arbogast, A.F., 1998. Late Quaternary paleoenvironments and landscape evolution on the Great Bend Sand Prairie. Kansas Geological Survey Bulletin 242.

Arbogast, A.F., Johnson, W.C., 1998. Late-Quaternary landscape response to environmental change in south-central Kansas. Annals of the Association of American Geographers 88 (1), 126–145.

Arbogast, A.F., Muhs, D.R., 2000. Geochemical and mineralogical evidence from eolian sediments for northwesterly mid-Holocene paleowinds, central Kansas USA. Quaternary International 67 (1), 107–118.

Beuselinck, L., Grovers, G., Poeson, J., Degraer, G., Froyen, L., 1998. Grain-size analysis by laser diffractometry: comparison with the sieve-pipette method. Catena 32, 193–208.

Birkeland, P.W., 1999. Soils and Geomorphology. Oxford University Press, New York.

Bullard, J.E., Mctainsh, G.H., Pudmenzky, C., 2007. Factors affecting the nature and rate of dust production from natural dune sands. Sedimentology 54, 169–182.

Byrd, T.C., 2006. Soil Survey for Stevens County, KS. National Resource Conservation Service.

Byrne, F.E., Mclaughlin, T.G., 1948. Geology and Groundwater Resources of Seward County, Kansas. Kansas Geological Survey Bulletin 69.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.-T., Laprise, R., Magana Rueda, V., Mearns, L., Menendez, C.G., Ralsanen, J., Rinke, A., Sarr, A., Whetton, P., 2007. Regional climate projections. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: the Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Cordova, C.E., Porter, J.C., Lepper, K., Kalchgruber, R., Scott, G.F., 2005. Preliminary assessment of sand dune stability along a bioclimatic gradient, north-central and northwestern Oklahoma. Great Plains Research 15, 227–249.

Forman, S.L., Marin, L., Gomez, J., 2004. Eolian depositional records from southwestern Kansas and southeastern Colorado, a potential landscape response to droughts in the past 10,000 years. Abstracts with Programs — Geological Society of America 36 (5), 412.

Forman, S.L., Marin, L., Gomez, J., Pierson, J., 2008. Late Quaternary eolian sand depositional record for southwestern Kansas: landscape sensitivity to droughts. Palaeogeography, Palaeoclimatology, Palaeoecology 265, 107–120.

Forman, S.L., Oglesby, R., Webb, R.S., 2001. Temporal and spatial patterns of Holocene dune activity on the Great Plains of North America: megadroughts and climate links. Global and Planetary Change 29, 1–29.

Gesch, D.B., 2007. The national elevation dataset, In: Maune, D. (Ed.), Digital Elevation Model Technologies and Applications: The DEM Users Manual, 2nd ed. American Society for Photogrammetry and Remote Sensing, Bethesda MD, pp. 99–118.

Gesch, D.B., Oimoen, M., Greenlee, S., Nelson, C., Steuck, M., Tyler, D., 2002. The national elevation dataset. Photogrammetric Engineering and Remote Sensing 68 (1), 5–11.

Gile, L.H., 1979. Holocene soils in eolian sediments of Bailey County, Texas. Soil Science Society of America Journal 43, 994–1003.

Hanson, P.R., Arbogast, A.F., Johnson, W.C., Joeckel, R.M., Young, A.R., 2010. Megadroughts and late Holocene dune activation at the eastern margin of the Great Plains, north-central Kansas, USA. Aeolian Research 1 (3–4), 101–110.

Holliday, V.T., 1990. Soils and landscape evolution of eolian plains: the southern High Plains of Texas and New Mexico. Geomorphology 3, 489–515.

Holliday, V.T., 2001. Stratigraphy and geochronology of upper Quaternary eolian sand on the southern High Plains of Texas and New Mexico, United States. GSA Bulletin 113 (1), 88–108.

Hugenholtz, C.H., Wolfe, S.A., 2005. Biogeomorphic model of dunefield activation and stabilization on the northern Great Plains. Geomorphology 70 (1–2), 53–70.

Irwin, J.H., Morton, R.B., 1969. Hydrogeologic information on the Glorieta sandstone and the Ogallala formation in the Oklahoma Panhandle and adjoining areas as related to underground waste disposal. U.S. Geological Survey Circular, vol. 630. United States Geological Survey.

Kilmer, V.J., Alexander, L.T., 1949. Methods of making mechanical analyses of soils. Soil Science 68, 15–24.

Kutilek, M., Nielsen, D.R., 1994. Soil Hydrology. Catena Verlag, Cremlingen-Destedt Germany.

Laird, K.R., Fritz, S.C., Cumming, B.F., Grimm, E.C., 1998. Early-Holocene limnological and climatic variability in the northern Great Plains. The Holocene 8, 275–285.

Laird, K.R., Fritz, S.C., Maasch, K.A., Cumming, B.F., 1996. Greater drought intensity and frequency before AD 1200 in the northern Great Plains, USA. Nature 384, 552–554.

Lancaster, N., 1988. Development of linear dunes in the southwestern Kalahari, Southern Africa. Journal of Arid Environments 14, 233–244.

Lancaster, N., Helm, P., 2000. A test of a climatic index of dune mobility using measurements from the southwestern United States. Earth Surface Processes and Landforms 25, 197–207.

Lepper, K., Scott, G.F., 2005. Late Holocene aeolian activity in the Cimarron River valley of west-central Oklahoma. Geomorphology 70, 42–52.

Madole, R.F., 1995. Spatial and temporal patterns of Late Quaternary eolian deposition, Eastern Colorado, U.S.A. Quaternary Science Reviews 14, 155–177.

Mason, J.A., Jacobs, P.M., Greene, R.S.B., Nettleton, W.D., 2003. Sedimentary aggregates in the Peoria Loess of Nebraska, USA. Catena 53, 377–397.

Mason, J.A., Swinehart, J.B., Goble, R.J., Loope, D.B., 2004. Late Holocene dune activity linked to hydrological drought, Nebraska Sand Hills, USA. The Holocene 14 (2), 209–217.

Mclaughlin, T.G., 1947. Accelerated channel erosion in the Cimarron Valley in southwestern Kansas. Journal of Geology 55, 76–93.

Meko, D.M., 1995. Dendroclimatic evidence from the Great Plains of the United States. Climate since A.D. 1500. R. S. Bradley and P. D. Jones. London; New York, Routledge: 312–330.

Miao, X., Mason, J.A., Swinehart, J.B., Loope, D.B., Hanson, P.R., Goble, R.J., Liu, X., 2007. A 10,000 year record of dune activity, dust storms, and severe drought in the central Great Plains. Geology 35 (2), 119–122.

Muhs, D.R., Holliday, V.T., 1995. Evidence of active dune sand on the Great Plains in the 19th century from accounts of early explorers. Quaternary Research 43, 198–208.

Muhs, D.R., Holliday, V.T., 2001. Origin of late Quaternary dune fields on the southern High Plains of Texas and New Mexico. GSA Bulletin 113 (1), 75–87.

Muhs, D.R., Maat, P.B., 1993. The potential response of eolian sands to greenhouse warming and precipitation reduction on the Great Plains of the U.S.A. Journal of Arid Environments 25 (4), 351–361.

Muhs, D.R., Reynolds, R.L., Been, J., Skipp, G., 2003. Eolian sand transport pathways in the southwestern United States: importance of the Colorado River and local sources. Quaternary International 104, 3–18.

Muhs, D.R., Stafford, T.W., Cowherd, S.D., Mahan, S.A., Kihl, R., Maat, P.B., Bush, C.A., Nehring, J., 1996. Origin of the late Quaternary dune fields of northeastern Colorado. Geomorphology 17, 129–149.

Muhs, D.R., Zarate, M., 2001. Late Quaternary eolian records of the Americas and their paleoclimatic significance. In: Markgraf, V. (Ed.), Interhemispheric Climate Linkages. Academic Press, San Diego, pp. 183–216.

Murray, A.S., Roberts, R.G., 1998. Factors controlling the shape of the OSL decay curve in quartz. Radiation Measurements 29, 503–515.

Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32, 57–73.

Namikas, S.L., Sherman, D.J., 1995. A review of the effects of surface moisture content on aeolian sand transport. In: Tchakerian, V.P. (Ed.), Desert Aeolian Processes. Chapman and Hall, London, pp. 269–293.

National Climatic Data Center, 2002a. Monthly station normals of temperature, precipitation, and heating and cooling degree days 1971–2000: Kansas, Climatography of the United States, No. 81. National Oceanic and Atmospheric Administration.

National Climatic Data Center, 2002b. Monthly station normals of temperature, precipitation, and heating and cooling degree days 1971–2000: Oklahoma, Climatography of the United States, No. 81. National Oceanic and Atmospheric Administration.

Noy-Meir, I., 1973. Desert ecosystems: environment and producers. Annual Review of Ecology and Systematics 4, 25–51.

Olson, C.G., Porter, D.A., 2002. Isotopic and geomorphic evidence for Holocene climate, southwestern Kansas. Quaternary International 87, 29–44.

Porter, D.A., 1997. Soil genesis and landscape evolution within the Cimarron Bend area, southwest Kansas. Unpublished Ph.D. dissertation, Kansas State University.

Prescott, J.R., Hutton, J.T., 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long-time variations. Radiation Measurements 23, 497–500.

Rawls, W.J., Ahuja, L.R., Brakensiek, D.L., 1992. Estimating soil hydraulic properties from soil data. In: Van Genuchten, M.T., Leij, F. (Eds.), Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils. University of California and U.S. Salinity Lab, Riverside CA, pp. 329–340.

Reginato, R.J., Van Bavel, C.H.M., 1962. Pressure cell for soil cores. Soil Science Society of America Proceedings 26, 1–3.

Sala, O.E., Parton, W.J., Joyce, L.A., Lauenroth, W.K., 1988. Primary production of the central grassland region of the United States. Ecology 69 (1), 40–45.

Schaetzl, R.J., Anderson, S., 2005. Soils; Genesis and Geomorphology. Cambridge University Press, New York.

Schumm, S.A., Lichty, R.W., 1963. Channel widening and flood-plain construction along Cimarron River in southwestern Kansas. Geological Survey Professional Paper 352-D.

Smith, H.T.U., 1940. Geologic studies in southwestern Kansas.

Soil Survey Staff, 2005a. Spatial and tabular data of the Soil Survey for Seward County, KS. National Resource Conservation Service.

Soil Survey Staff, 2005b. Spatial and tabular data of the Soil Survey for Stevens County, KS. National Resource Conservation Service.

Soil Survey Staff, N.R.C.S, 2009a. Soil Survey Geographic (SSURGO) Database for Seward County, Ks. United States Department of Agriculture.

Soil Survey Staff, N.R.C.S, 2009b. Soil Survey Geographic (SSURGO) Database for Stevens County, Ks. United States Department of Agriculture.

Soil Survey Staff, N.R.C.S, 2009c. Soil Survey Geographic (SSURGO) Database for Texas County, OK. United States Department of Agriculture.

Soil Survey Staff, N.R.C.S, 2010. Soil Survey Geographic (SSURGO) Database for Roberts County, Tx. United States Department of Agriculture.

Sridhar, V., Loope, D.B., Swinehart, J.B., Mason, J.A., Oglesby, R.J., Rowe, C.M., 2006. Large wind shift on the Great Plains during the Medieval Warm Period. Science 313, 345–347.

Stokes, S., Swinehart, J.B., 1997. Middle- and late-Holocene dune reactiviation in the Nebraska Sand Hills, USA. Holocene 7 (3), 263–272.

Taylor, H.M., 1960. Moisture relationships of some rangeland soils of the southern Great Plains. Journal of Range Management 13, 77–80.

Thorp, J., Smith, H.T.U., 1952. Pleistocene Eolian Deposits of the United States, Alaska, and parts of Canada. National Research Council Committee for the Study of Eolian Deposits, Geological Society of America, scale 1:2,500,000.

Tsoar, H., 2005. Sand dunes mobility and stability in relation to climate. Physica A 357, 50–56.

Vanlooy, J.A., Martin, C.W., 2005. Channel and vegetation change on the Cimarron River, southwestern Kansas, 1953–2001. Annals of the Association of American Geographers 95 (4), 727–739.

Walter, N.F., Hallberg, G.R., Fenton, T.E., 1978. Particle size analysis by the Iowa State University Soil Laboratory. In: Hallberg, G.R. (Ed.), Standard Procedures for the Evaluation of Quaternary Materials in Iowa. : Technical Information Series, vol. 8. Iowa Geological Survey, pp. 61–74.

Wolfe, S.A., 1997. Impact of increased aridity on sand dune activity in the Canadian Prairies. Journal of Arid Environments 36, 421–432.

Woodhouse, C.A., Overpeck, J.T., 1998. 2000 years of drought variability in the central United States. Bulletin of the American Meteorological Association 79 (12), 2693–2714.

Yizhaq, H., Ashkenazy, Y., Tsoar, H., 2007. Why do active and stabilized dunes coexist under the same climatic conditions? Physical Review Letters 98, 188001-1–188001-4.