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ScienceDirect
Palaeogeography, Palaeoclimatology, Palaeoecology 245 (2007) 368–381
PALAEO
www.elsevier.com/locate/palaeo

High-resolution proxy record of Holocene climate from a loess section in Southwestern Nebraska, USA

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Received 16 April 2006; received in revised form 31 August 2006; accepted 5 September 2006

Abstract

Multi-proxy analysis was used to produce a high-resolution paleoclimatic record from an exceptionally thick section of the Holocene Bignell Loess near Wauneta, Southwestern Nebraska, in the central Great Plains. The Wauneta section has excellent age control, based on optically stimulated luminescence (OSL) and radiocarbon dating, and records multiple episodes of rapid loess deposition alternating with slower deposition and soil formation. The lowermost and uppermost OSL ages obtained from the Bignell Loess are 10,250±610 years (5.9 m depth) and 100±10 years (0.1 m depth), respectively. As a result, the Holocene has been temporally confined. Stratigraphically, the Bignell Loess overlies the Late Pleistocene Peoria Loess (deposited ~21–14 ka), and the two units are separated by the Brady Soil which is distinguished by its color and other pedogenic features.

*L*a*b** color parameters and organic carbon content of Bignell Loess are sensitive proxies to differentiate drought-induced aeolian sediment layers from the intercalated soil horizons. Soil organic carbon-derived $\delta^{13}C$ data suggest that the C_3-dominated floral environment during Peoria Loess deposition shifted dramatically to a C_4-dominated environment during Brady Soil formation in response to a warming trend. Even greater C_4 abundance characterized the late Holocene. High-resolution $\delta^{13}C$ data support the contention that C_3 vs. C_4 vegetation change in the Holocene reflects ecosystem response to frequent vegetation disturbance under arid conditions. Time series analysis reveals that $\delta^{13}C$ and color parameters display high frequency variation with periodicities of 103–118 years and 103 years, respectively. Similar periodicities were also reported in studies of North Dakota lakes, though the physical mechanism responsible is uncertain. Comparison of Bignell Loess color and tropical Pacific sea surface temperatures (SSTs) allows evaluation of a proposed teleconnection between drought in the Great Plains and La Niña-like conditions in the tropical Pacific. The loess color index and eastern tropical Pacific SST display broad similarities through the late Pleistocene and Holocene that are consistent with this teleconnection. On the other hand, drought centered at 3800 years ago is not consistent with the teleconnection, and the end of early Holocene aridity at the Wauneta section, around 6500 years ago, is much earlier than the corresponding rise in SST and increase in El Niño frequency in the eastern tropical Pacific.

Keywords: Holocene; Paleoclimate; Drought; Bignell Loess; Great Plains

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doi:10.1016/j.palaeo.2006.09.004

1. Introduction

The central Great Plains of North America is a semiarid to subhumid region, and episodes of drier-than-present climate have caused widespread aeolian activity during the Holocene (Ahlbrandt et al., 1983; Arbogast, 1996; Stokes and Swinehart, 1997; Forman et al., 2001; Mason et al., 2003a; Goble et al., 2004; Miao et al., 2005). Dune fields and loess deposits provide stratigraphic records of past aeolian activity. Because dune fields commonly contain unconformities and often lack early to middle Holocene sediments (Arbogast, 1996; Stokes and Swinehart, 1997; Holliday, 2001; Muhs and Zárate, 2001), dune field sections may not provide a complete record of aeolian activity. Where present, however, thick deposits of the Holocene Bignell Loess offer a much more continuous record of aeolian activity and inferred climate change in the central Great Plains (Mason et al., 2003a).

The widespread but patchy Bignell Loess (Schultz and Stout, 1945), is identified in the field by the well-expressed subjacent Brady Soil which developed during the Pleistocene to Holocene transition (Johnson and Willey, 2000). An increasing number of luminescence dates, crosschecked by independent radiocarbon dating, demonstrate that Bignell Loess accumulation spans the entire Holocene (Pye et al., 1995; Mason and Kuzila, 2000; Mason et al., 2003a; Miao et al., 2005, 2007).

Previous work indicated that the floodplain is the major source of the Bignell Loess, which is consistent with the traditional glaciogenic model of loess sedimentation (e.g., Pye et al., 1995; Johnson and Willey, 2000; Mason and Kuzila, 2000). More recent research, however, has revealed that the upwind aeolian sand dunes and sand sheets were probably the immediate sources of most loess in the western Nebraska, although at least some of the loess may ultimately have been derived from more distant sources (Mason, 2001; Mason et al., 2003a). Recent data on the geographic distribution of Bignell Loess shows that it is thickest proximal to the edges of the dune fields (Mason et al., 2003a) (Fig. 1). Further, optically stimulated luminescence (OSL) chronology of the Bignell Loess and the timing of dune activation provide evidence of source-sink relationships between the sand dunes and the loess deposits (Miao et al., 2007). Clusters of OSL ages from within the Bignell Loess helped identify episodes of extensive aeolian activity triggered by severe drought, centered at 700, 2490, and 3800 years ago, and

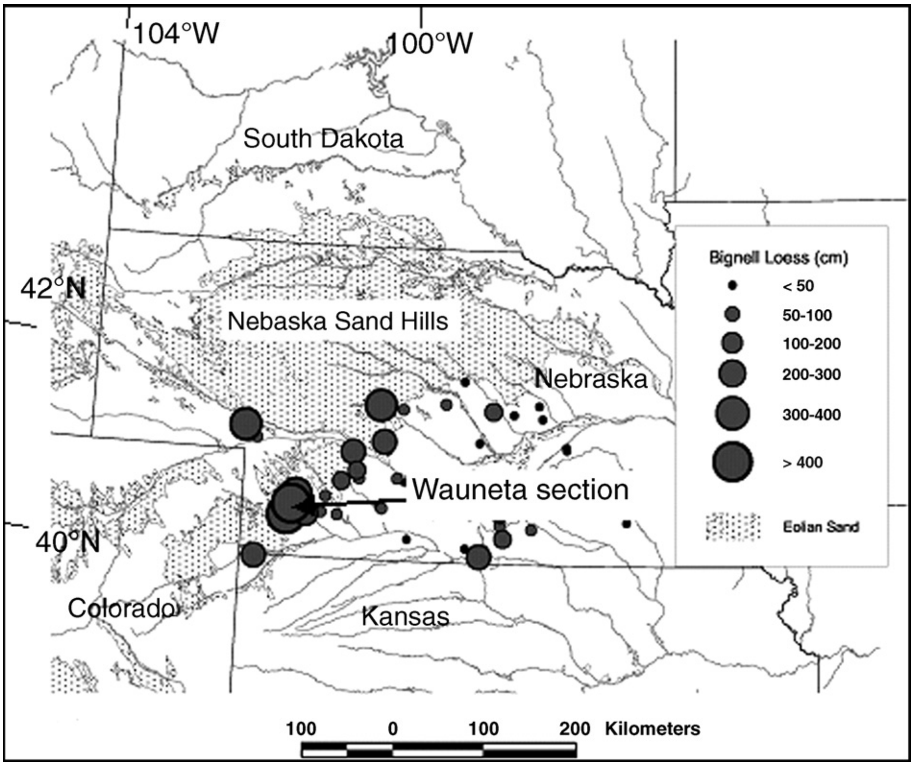

Fig. 1. Location of the Wauneta site in the central Great Plains. Stippled areas represent sand dune fields, and filled circles indicate Bignell loess thickness (adapted from Mason et al., 2003a).

sustained from 9390 to 6560 years ago; these episodes coincide with clusters of OSL ages from dune sands that represent periods of widespread dune activity (Miao et al., 2007). It appears that rapid loess accumulation resulted mainly from high dust influx when dune fields immediately upwind were active. Thus, the rate of loess accumulation is closely related to the extent of dune field activity, and periods of especially rapid loess accumulation resulted from intense and prolonged drought in the central Great Plains.

Previously studies have typically included only field stratigraphic observations and optical or radiocarbon dating. Despite the major advances in our understanding of timing of aeolian sediments and their paleoclimatic significance, there is clearly a need to move beyond this approach and produce detailed stratigraphic documentation. To extract high-resolution reconstructions of Holocene climate from the Bignell Loess, it is necessary to identify quantitative proxy data related to the rates of loess sedimentation and soil development, which can be measured at closely spaced intervals in relatively thick loess sections.

To obtain high-resolution proxy data, samples were taken at 2-cm intervals from a 7-m thick Bignell Loess sequence for analysis of $L^*a^*b^*$ color variation (explained below), grain size distribution, and magnetic susceptibility. Organic carbon content and stable carbon isotope ratios were measured at 4-cm interval in the Holocene Bignell Loess and 2-cm interval in the Brady Soil. Goals of these analyses were (1) to examine the sensitivity of each proxy to climate; (2) to better understand the significance of climate events interpreted from the most climate-sensitive proxies; and (3) to use this proxy data to further examine hypothesized linkage between tropical SSTs (sea surface temperatures) and Holocene drought in central North America (Palmer and Brankovic, 1989; Trenberth and Guillemot, 1996; Cook et al., 2004). Recent research used OSL and ^{14}C dating of episodes of rapid loess deposition and dune activity to test this proposed teleconnection (Miao et al., 2007), but the higher resolution provided by proxy data may give new insight on its validity.

2. Methods

2.1. Study site

Our study locale is north of Wauneta, Nebraska (Fig. 1). The annual mean precipitation and temperature in the Wauneta area is about 495 mm and 9.7 °C, and precipitation falls mainly from April to September during the growing season. The present vegetation at the study site is mixed C_3 and C_4 grassland, currently used as cattle pasture, and apparently never cultivated.

Two roadcuts ("Old" and "New") and numerous small gullies and bare soil slopes expose thick Bignell Loess at the Wauneta site. The Old Wauneta Roadcut exposes 6 m of thick Bignell Loess and has been intensively dated using the OSL and radiocarbon dating techniques (Fig. 2). The section is topographically high, thereby ruling out depositional processes other than airborne dustfall. Because the surface above the Old Wauneta Roadcut section was not accessible for core sampling, a continuous 7-m core was extracted, using a Giddings hydraulic soil probe, on a topographically-similar high point along the edge of the loess tableland about 1 km to the east; only one radiocarbon age was obtained from the core and other ages were all from roadcut. Because the Wauneta sections display loess-soil stratigraphy that is very similar to other thick Bignell Loess sections across the region (Mason et al., 2003a; Jacobs and Mason, 2004; Miao et al., 2005), they likely record regional climate change rather than local depositional patterns and disturbance such as grazing and burning of the vegetation. Previously, Feggestad et al. (2004) conducted low-resolution stable carbon isotope analysis on samples collected at the Old Wauneta Roadcut, and intensive OSL dating of the section has been reported by Mason et al. (2003a,b), Miao et al. (2005), and Miao et al. (2007).

2.2. Pedostratigraphy and geochronology at the Wauneta site

The Brady Soil, formed from about 13, 500 to 9, 000 cal. years ago according to radiocarbon dating (Johnson and Willey, 2000), separates the Late Pleistocene Peoria Loess from the Holocene Bignell Loess and is clearly recognizable by color and other pedogenic features in both the roadcuts and cores. In addition, six other buried soils, three prominent and three incipient ones, are evident in the lower and upper portions of the Bignell Loess at the Wauneta roadcut section (Fig. 2). The three prominent soils are also identifiable in the core, especially using color measurements, which permits good correlation with the roadcut.

Age control for the Old Wauneta Roadcut has been described elsewhere (Mason et al., 2003a,b; Miao et al., 2005, 2007), and full details on methods and supporting data are provided in those publications. Thirteen OSL ages have been obtained at the Old Wauneta Roadcut exposure, providing an age-depth model based on linear interpolation between two adjacent OSL ages and depths (Fig. 2). Because the stratigraphy in the core used for proxy data samples is so similar to that of the Old

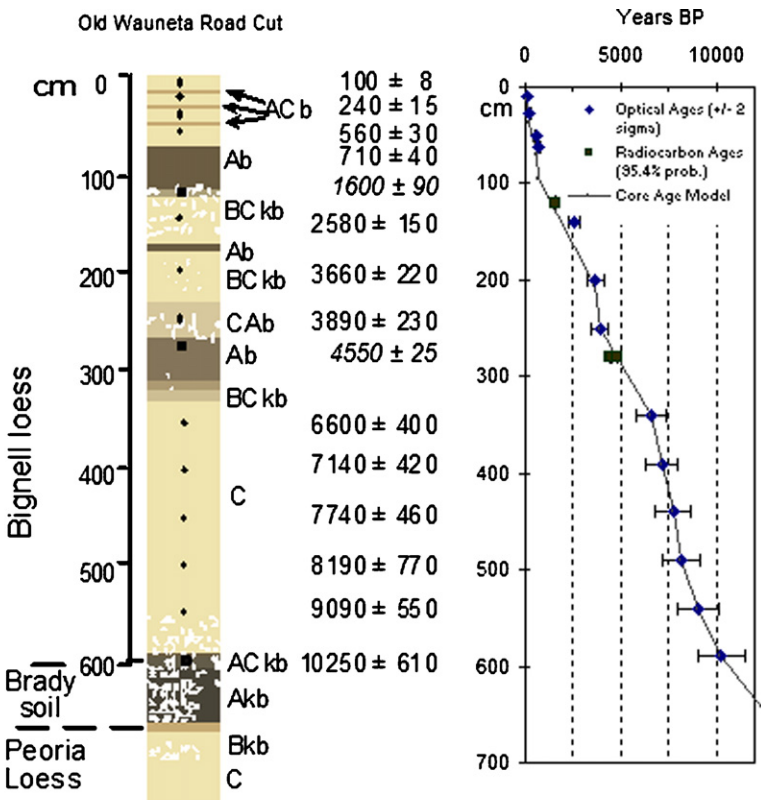

Fig. 2. Pedostratigraphy and geochronology of the Wauneta section, with the age-depth plot at the right. Ages, from Roadcut, are OSL except for with two calibrated radiocarbon ages (italicized); the upper radiocarbon age was on charcoal from the core, while the lower one was from humic acid from Roadcut. The darkest color indicates soil (A horizon); intermediately dark color indicates incipient soil development; lightest color indicates loess (C horizon); irregular white patches signify carbonate accumulations. Depth in the age model of the core is adjusted to that of the Old Wauneta Roadcut.

Roadcut, the age model is applied to the core as well. OSL ages of the Bignell Loess in the Old Roadcut ranged from 10,250±610 to 100±10 years ago (mean±one sigma), suggesting preservation of complete Holocene sediment. Two radiocarbon ages, 1, 600±90 (from charcoal in the core) and 4550±25 cal years BP (from soil organic matter in the roadcut section), were concordant with the OSL ages and provided independent evidence for the geochronology (Fig. 2).

Several OSL ages obtained from the nearby New Wauneta Roadcut (Mason et al., 2003a; Miao et al., 2005) agree very closely with those from the Old Roadcut when the two sections are correlated on the basis of pedostratigraphy. Sedimentation rates have been calculated for both roadcut sections, for intervals between pairs of OSL ages.

2.3. Soil organic carbon content

Measurement of soil organic carbon (SOC) content gives an estimate of the amount of soil organic matter (SOM) in soils as a percentage by weight. In general, the percentage of the SOM in a soil is about 1.7 times the percentage of SOC (Birkeland, 1999). The level of SOC in a soil on a stable land surface is controlled by the balance between ecosystem productivity and microbial decomposition, both strongly influenced by climate (Parton et al., 1987). Where dust deposition causes aggradation of the land surface, SOC content is also influenced by the rate of aggradation. Accumulation of SOC cannot keep up with rapid dust sedimentation, resulting in low SOC content, whereas significant SOC can be present in soil horizons affected by low rates of dust deposition (Jacobs and Mason, 2004).

Zones of elevated SOC content within the Bignell Loess should reflect more humid conditions due to both high primary productivity at the Wauneta site *and* lower rates of dust influx from upwind source areas. Conversely, low SOC levels likely indicate dry conditions with lower productivity and/or more dust influx. Although it is not possible to clearly distinguish the effects of vegetation at the study site and dust influx from upwind sources, both ultimately respond to regional climate. Consequently, variation in SOC content clearly records regional changes in effective moisture.

2.4. L*a*b* color variations

*L*a*b** color parameters are sensitive tools for distinguishing buried soils from unaltered loess or other sediments (Porter, 2000; Ji et al., 2001; Wang et al., 2003). In particular, continuous measurement of loess cores using the spectrophotometer can provide a quantitative index with which to distinguish weakly developed soils with gradational boundaries from adjacent unaltered loess units and to differentiate subtle variation in the colors of individual soils. The HunterLab MiniScan XE Plus Spectrophotometer measures visible reflectance spectra (400–700 nm wavelength, at 10 nm increments), which are converted to the *L*a*b** color indices based on human perception (CIE, 1978). The *L*a*b** color scheme consists of a luminance or lightness component (*L**; 0 for black and 100 for white) and two chromatic components (*a**, positive for red and negative for green; *b**, positive for yellow and negative for blue). Repeated measurement of *L*a*b** values for a single sample were reproducible within ±1% error after calibration with the manufacturer-recommended black and white standard tiles. In comparison to the Munsell color scheme for the soil description, the *L*a*b** color parameters can objectively and quantitatively detect subtle color variations. For example, considerable variations in the *L*a*b** parameters exist for the soil color of loess samples that are classified as 10YR 5/3 by the Munsell color chart.

2.5. Stable carbon isotope analysis

Stable carbon isotopic composition ($\delta^{13}C$) of SOC in aeolian deposits has been increasingly used to study late-Quaternary floral changes in the Great Plains (e.g., Arbogast and Johnson, 1998; Kelly et al., 1998; Johnson and Willey, 2000; Olson and Porter, 2002). Most plants (trees, shrubs, forbs and cold/shade tolerant grasses) use the C_3 photosynthetic pathway and have $\delta^{13}C$ values averaging −27‰. C_4 plants (mainly warm-season grasses) are adapted to photosynthesis under high temperature, irradiance, and moisture stress, and have $\delta^{13}C$ values averaging −13‰ (Ehleringer and Monson, 1993). The $\delta^{13}C$ values of SOM can be used to quantify the changes of C_3 and C_4 plant ratios in a non-desert environment through time (Cerling et al., 1989), because SOM accumulates from the contribution of living C_3 and C_4 biomass (Boutton, 1996).

Rootlets were removed by hand, and subsamples of about 10 g were treated with 1N HCl for 16 h at room temperature to remove carbonate. The subsamples were then dried, pulverized, and analyzed with a CE elemental analyzer and ThermoFinnigan Delta Plus mass spectrometer at the University of Kansas.

2.6. Grain size distribution

Grain size analysis of loess deposits provides information on sediment source, wind intensity, wind direction, and distance from a source area (e.g., Lu et al., 1999; Muhs and Bettis, 2000; Mason et al., 2003b; Miao et al., 2004). Miao et al. (2005) summarized grain size data obtained from the Wauneta locality using a Coulter LS100Q laser diffraction particle size analyzer and full chemical pretreatment (10% HCl, 10% H_2O_2, and 50 g L^{-1} Na-metaphosphate). These data were not from the same core as other proxy data; in addition, subsequent experiments (Mason et al., 2003b) showed that treatment of western Nebraska loess samples with ultrasound for three minutes yielded more silt and clay, indicating more effective dispersion, than was obtained with full chemical pretreatment. In this paper, we report new grain size measurements made on samples from the same core that supplied other proxy data, using a Malvern Mastersizer 2000 laser diffraction instrument after 3-min sonication in deionized water.

2.7. Magnetic susceptibility and frequency dependence of susceptibility

Magnetic susceptibility has been successfully applied to Chinese loess sequences to differentiate weakly altered loess increments from prominent soil horizons, to correlate regional loess units, and to decipher relationships between the loess stratigraphy and deep-sea isotope stages (e.g., Heller and Liu, 1986; Kukla et al., 1988). Susceptibility (χ) and other magnetic parameters have also been used to detect soil development recorded within the loess sequences in the mid-continent of North America (e.g., Feng and Johnson, 1995; Grimley et al., 1998; Johnson and Willey, 2000; Geiss et al., 2004). Frequency dependence of susceptibility (χ_{fd}), expressed as a percentage (difference between magnetic susceptibility measured at low- and high frequency of the inductive magnetic field), increases with the concentration of ultrafine magnetic materials and is believed to be a direct indicator of the degree of pedogenesis (Dearing et al., 1996).

In general, magnetic susceptibility signals in loess consist of three components: 1) the depositional (lithogenic or sedimentary) component, dependent on the properties of the dust source material; 2) syndepositional pedogenic enhancement; and 3) post-depositional enhancement acquired while an increment of loess remains shallow enough to the surface to be affected by pedogenesis (Miao et al., 2006). Magnetic enhancement in some soils may result from fires on the soil surface (Ketterings et al., 2000). In this study, samples were measured with a Bartington magnetic susceptibility meter and dual-frequency sensor. Susceptibility is normalized by mass, and frequency dependence is computed from percentage difference of magnetic susceptibility at 0.465 and 4.65 kHz.

3. Results and discussion

3.1. Sedimentation rate

The depth-age model indicates high average sedimentation rates during the accumulation of light-colored loess with little pedogenic alteration and low sedimentation rates for intervals containing buried soils (Table 1; Fig. 2). This lends support to the concept that buried soils represent periods of relatively low dust influx. The overall sedimentation rate during the entire Holocene, from about 10,250 cal year to the present, is 0.58 mm/year, while the average sedimentation rate during deposition of the light-colored, early Holocene loess increment at Old Wauneta Roadcut, between 9080 years to 6600 years ago, was about 0.81 mm/year. The average sedimentation rate of the light-colored loess capping the roadcut, from about 710 years ago to the present, was approximately 0.89 mm/year. In contrast, portions of the loess column containing prominent buried Holocene soils, from the oldest to the youngest, have average sedimentation rates of 0.33, 0.56 and 0.42 mm/year. Because OSL sampling points lie within light-colored loess layers (=C horizons) above and below the buried soils (=A or B horizons), these values probably overestimate the sedimentation rate during times that buried soils were actually forming. Therefore, each calculated interval partially incorporates a period of rapid loess deposition. In general, sedimentation rates were 1.4 to 2.7 times higher during times represented by light-colored, largely unaltered loess, than during the intervals of soil formation (Table 1).

3.2. Organic carbon content and L*a*b* color variations

SOC content, high in buried soils and low in intervening loess, varies from a minimum of 0.05% to a maximum of 0.54%, except for a value of 0.7% where charcoal was found (Fig. 3). Concentrations are higher in the Brady Soil than in any of the other buried soils, which suggests greater primary productivity (and probably greater effective moisture) during Brady Soil formation than at any later time in the Holocene. A very slow rate of dust deposition during Brady Soil formation could also be a factor, however. Above the Brady Soil, SOC is lowest in the loess increment formed during the early to mid-Holocene, indicating that both rapid loess deposition and a persistent drier-than-present climate limited organic matter accumulation at that time. In loess deposited from about 6500 years ago to the present (buried soil 3 and above), SOC content is consistently higher than in the early to mid-Holocene. This suggests climatic conditions that were, on average, more humid than before 6500 year ago, but the increased variability indicates large short-term variations in effective moisture. These broad patterns of climate variation through the Holocene were also inferred from field observations of the soil stratigraphy

Table 1
Loess accumulation rates during eolian sedimentation and soil development at the two Wauneta roadcuts

Old Wauneta Roadcut	Start (cal year)	End (cal year)	Duration (cal year)	Thickness (mm)	Accumulation rate (mm/year)
Eolian sedimentation	9080	6600	2480	2000	0.81
Soil development	6600	3890	2710	900	0.33
Soil development	3660	2580	1080	600	0.56
Soil development	2580	710	1870	770	0.41
Eolian sedimentation	710	0	710	630	0.89
Overall	10,250	0	10,250	5950	0.58
New Wauneta Roadcut					
Eolian sedimentation	8990	6630	2360	1700	0.72
Soil development	6630	3720	2910	1000	0.34
Soil development	3720	2350	1370	430	0.31
Soil development	2350	0	2350	470	0.20
Overall	8990	0	8990	3600	0.40

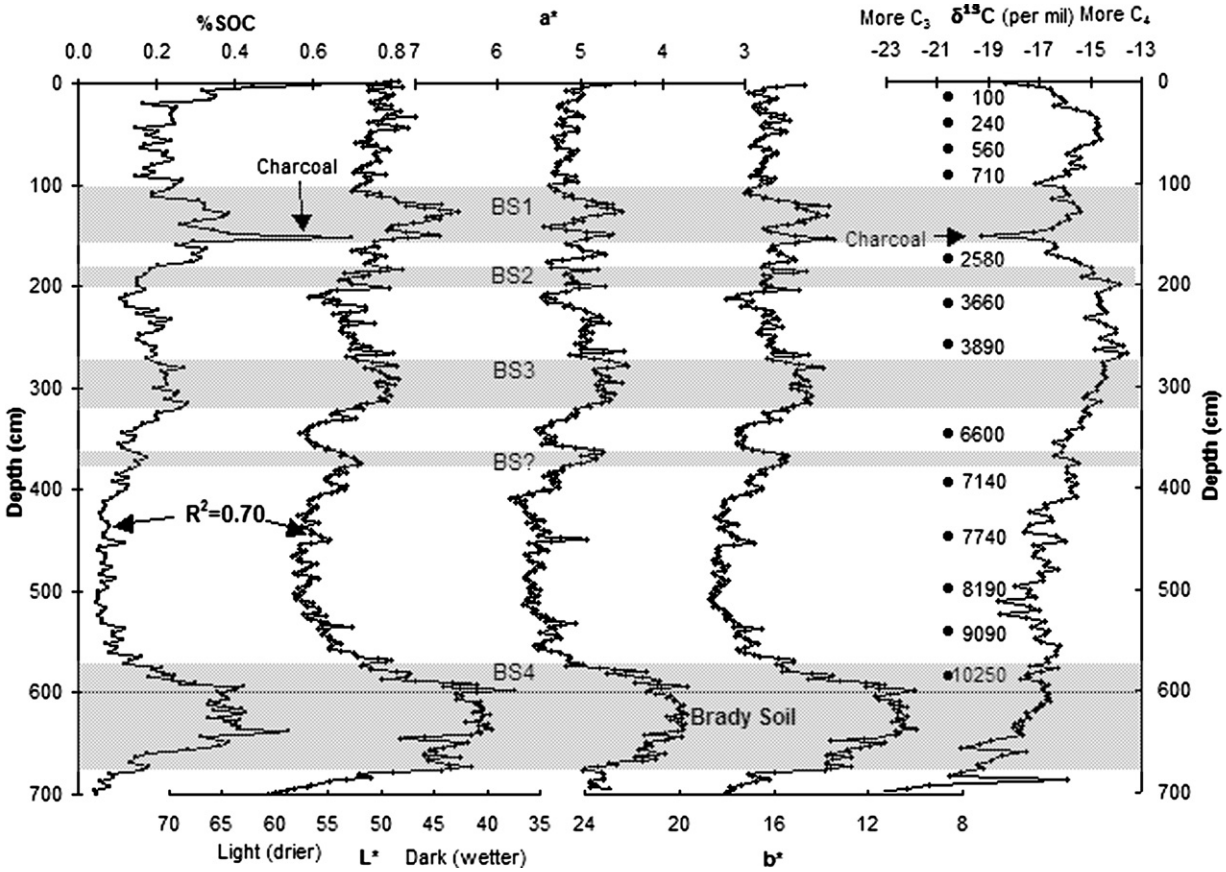

Fig. 3. Organic carbon, L^*a^*b color, and carbon isotope data of Bignell loess. Gray bands indicate positions of the buried soils (BS); numbers next to full circles are ages from Fig. 2. R^2 of 0.70 suggests good correlation between color (L) and organic carbon content.

(Mason et al., 2003a; Miao et al., 2005), but the SOC data provide quantitative support for those interpretations.

The high-resolution SOC data from the Wauneta core also bring out subtle variations in loess sedimentation and soil formation. Each of the three thickest buried soils, including the Brady Soil, displays multiple peaks of SOC content, rather than the single near-surface peak common in many modern-surface soils. These multiple peaks are difficult to explain if the soils developed strictly through "top-down" soil development during which little aeolian dust was added on the land surface. Instead, the buried soils were probably cumulative, implying that the aeolian dust influx, though reduced, was still significant even during the soil forming intervals. If so, then the multiple peaks of SOC within thick soils probably reflect short-term variation in climate and loess sedimentation during generally humid periods. Transition zones of decreasing SOC content are also evident at the top of the three thickest buried soils, suggesting that the uppermost parts of these soils formed during transitions toward a drier climate, in which dust influx was increasing and primary productivity at the site was decreasing.

SOC content negatively correlates with L^* value, $R^2=0.70$ (Fig. 3), indicating that SOC content can explain much of the variation in soil lightness. Interestingly, both SOC and color parameters display peaks at a depth of 370 cm, suggesting a possible very weakly developed buried soil in the loess core (Fig. 3), which was not clearly visible in exposures. Both SOC content and $L^*a^*b^*$ color parameters are sensitive detectors of weakly developed soils and indicate the relative degree of soil development in loess sequences. Because the color measurements are quick and non-destructive, they may be preferable to SOC measurements for obtaining high-resolution data on soil development from other thick loess sections.

Values for the two chromatic components, a^* and b^*, are all positive, which indicates that the Bignell Loess and intercalated soils display predominantly red and yellow hues as opposed to green and blue hues on the continuous color spectrum. This is in agreement with field observations using Munsell color chips. The red and the yellow colors in the buried soils could result from the existence of iron oxide minerals such as hematite and goethite, respectively (Balsam et al., 2004). Both *a** and *b** components track closely with *L**, however, and provide little additional information.

3.3. Stable carbon isotopes

SOC $\delta^{13}C$ values increase from −23.7‰ in the Peoria Loess just below the Brady Soil to −16.6‰ just above the Brady Soil in the Bignell Loess (Fig. 3). The dramatic shift of about 7‰ indicates that in the Wauneta area a C_3-dominated ecosystem during the late-Wisconsin glacial interval gave way to a C_4-dominated flora during the Holocene. The progressive elevation of $\delta^{13}C$ values throughout the Brady Soil probably represents vegetational responses to increasing temperature (Feggestad et al., 2004). This agrees with studies in the northern Great Plains that have indicated a fairly rapid transition from cooler and wetter growing seasons during the late Pleistocene (Grüger, 1973; Jacobson et al., 1987; Wang et al., 2000) to warmer conditions during the early Holocene (Grimm, 2001).

Feggestad et al. (2004) proposed that the $\delta^{13}C$ variation within the Bignell Loess in the Old Wauneta Roadcut largely reflected the response of the ecosystem to fluctuations of both precipitation and landscape stability. It was concluded that C_3 plant productivity increased under drier-than-present climates that enhanced loess deposition rates, and that C_4 productivity apparently increased relative to C_3 productivity during wetter and periods with more land surface stability. To explain this, Feggestad et al. (2004) proposed that both C_3 and C_4 grasses decline during droughts, but invasion by weeds, many of which are C_3, is common in the disturbed areas including sites affected by rapid dust deposition. For example, during the 1930s drought, burial of existing vegetation by a thin layer of dust led to death of dominant native prairie species (C_4) and promoted widespread growth of weedy annuals (Hopkins, 1951). Similarly, stable isotope variations from Kettle Lake in North Dakota revealed a slight decrease of $\delta^{13}C$ values during intense drought intervals (Clark et al., 2002). To the east, Nelson et al. (2004) found a similar pattern in two lakes in Minnesota, where increased percentages of *Ambrosia* and *Artemisia* pollen occurred during the dry middle Holocene with a concurrent decrease of the proportion of C_4 plants.

The high-resolution $\delta^{13}C$ data from the Wauneta site core support the above arguments (Fig. 3). During the Holocene, the most negative $\delta^{13}C$ value is −18.7‰ at 8600 years ago, in a period of sustained dry climate. Meanwhile, in the buried soil overlying this loess increment, $\delta^{13}C$ increases to −13.6‰ indicating an almost pure C_4 vegetation ecosystem at the Wauneta site. Overall, the range of $\delta^{13}C$ values within the Holocene is as much as 4.9‰, from the driest early Holocene to the mid-Holocene period of soil formation.

The *L***a***b** color parameters, organic carbon content, and the $\delta^{13}C$ data all show significant short-term variation in the upper part of the Bignell Loess, suggesting that the climate during the second half of the Holocene varied over both centennial and millennial timescales. Overall though, plants using the C_4 metabolism appeared to have dominated this site during much of the past 6000 years.

3.4. Grain size and magnetic susceptibility

The Bignell Loess core used for this study has a coarse grain size: sand (>63 μm) content averages 40%, with a standard deviation of ±3% (Fig. 4). The sand content is somewhat lower than the average sand content of 48% reported by Miao et al. (2005), probably because of both more effective dispersion with ultrasound and use of a different instrument. Nonetheless, the new results still indicate that much of the Bignell Loess at this locality was probably transported only a few tens of kilometers from the last point of entrainment (Pye, 1987), within the dune fields upwind of the study site. Clay (<2 μm) content measured by laser diffraction is only about 2–4% (Fig. 4), which corresponds to about 9–14% clay as measured by pipette (Mason et al., 2003b); much of this clay may have been transported in aggregates or grain coatings.

In contrast to the patterns observed in other loess sequences, buried soils in the Bignell Loess at Wauneta actually contain slightly less clay and more sand than less altered loess increments. In Chinese loess there is a positive relationship between the deposition rate and grain size that has been applied to adjust the time scale (Vandenberghe et al., 1997). However, in the Bignell Loess, the grain size distribution does not correlate with the sedimentation rate (Fig. 4; Table 1). We conclude that the grain size of Bignell Loess can provide valuable information on sedimentary processes, especially transport distance, but does not provide a proxy record that can easily be related to climate change.

As shown for grain size, the peaks and troughs in magnetic susceptibility are not indicative of paleosols and unaltered loess layers (Fig. 4), as they clearly are on the Chinese Loess Plateau. For example, the Brady Soil, the best-expressed soil at the Wauneta section, shows unexpectedly low magnetic susceptibility, although two magnetic susceptibility peaks correspond loosely to the buried soils (BS1 and BS3). Many irregular spikes inhibit the climatic interpretation of magnetic susceptibility. The peak values of magnetic susceptibility were found during one of the periods with most rapid dust deposition, from depths of 25 to 60 cm. Moreover, magnetic susceptibility fluctuates more rapidly in the upper part of the section, above a depth of 350 cm, than in the lower part of the section.

We propose that patterns of magnetic susceptibility in the Bignell Loess are not directly related to the pedogenic processes controlled by climate change, but instead may be mainly depositional in origin. That is, magnetic susceptibility signals are predominantly inherited from the dust source materials, not from the pedogenic enhancement during and/or after the dust deposition. Below the depth of 350 cm and above the Peoria Loess, low and relatively uniform susceptibility values may correspond to low susceptibility in the dust sources that were active from the last glacial maximum through the early Holocene. In contrast, somewhat enhanced susceptibility in the incoming dust due to pedogenesis in parts of the dust source area after about 6500 years ago, resulted in a wide range of inherited susceptibility values (Fig. 4).

Interpretation of a depositional origin is supported by the frequency dependence magnetic susceptibility values and coarse silt data (Fig. 4). If climatically related, pedogenic enhancement should be significant, and therefore higher frequency dependence magnetic susceptibility values would be expected in the buried soils. However, the frequency dependence values in soil horizons consistently show a lack of the high frequency dependence signals caused by strong pedogenic enhancement. Moreover, most of peaks in the coarse silt (40–63 μm%) curve correspond to troughs in susceptibility during the Holocene, and vise versa (Fig. 4). This strongly suggests depositional controls on susceptibility.

Alternatively, the highly varied magnetic susceptibility during late Holocene could be the product of wildfires, especially evidenced by the high spikes. Low variation of frequency dependence magnetic susceptibility does not favor this possibility, however, since fire-induced magnetic susceptibility enhancement would correspond to elevated frequency dependence susceptibility due to formation of ultrafine particles by fire combustion (Ketterings et al., 2000).

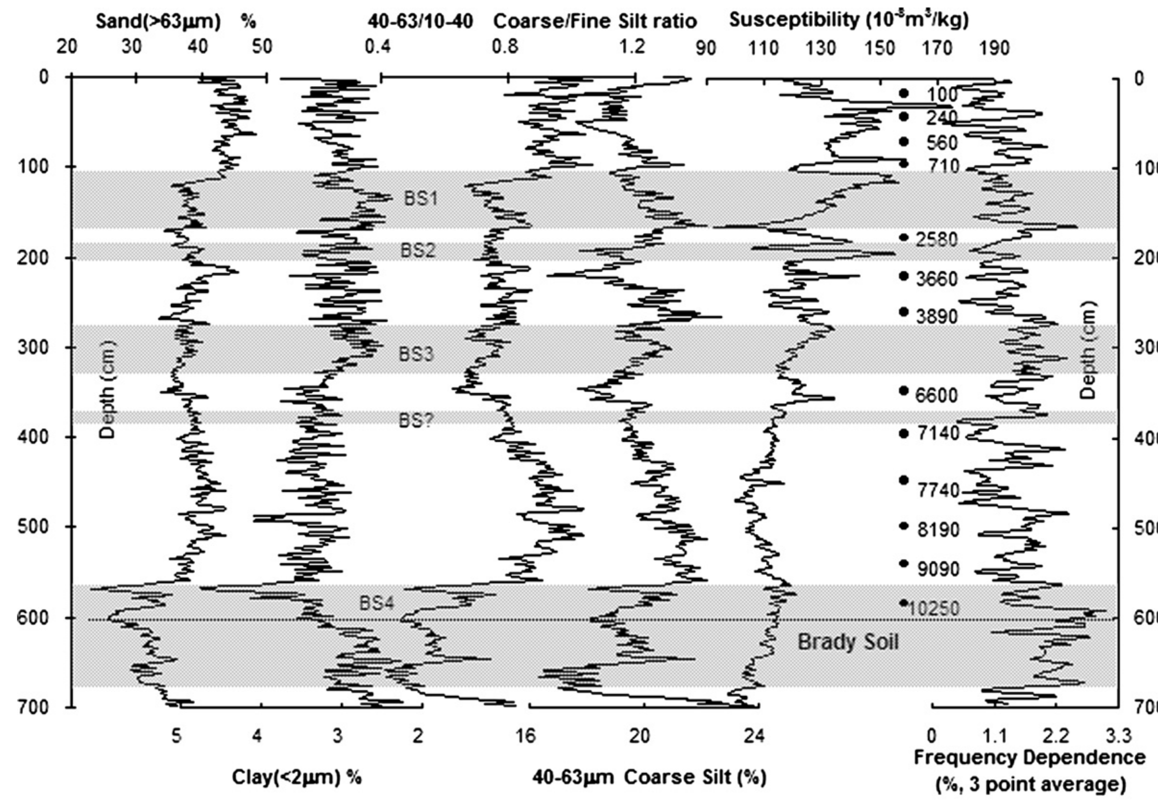

Fig. 4. Grain size, low-frequency magnetic susceptibility and frequency dependence of magnetic susceptibility against depth. Gray bands indicate positions of the buried soils (BS); numbers next to full circles are ages from Fig. 2.

3.5. Color, SST and drought

It has been proposed, based on modern observations, that Great Plains droughts occur under persistent La Niña conditions (cold phase of El Niño/Southern Oscillation, ENSO) (Trenberth and Guillemot, 1996; Cole et al., 2002). Previous studies have also linked historical Great Plains droughts to low SSTs in the eastern tropical Pacific and high SSTs in the western Pacific and/or Indian oceans (Hoerling and Kumar, 2003; Schubert et al., 2004a,b), a "La Niña-like" SST gradient. It has been suggested that similar teleconnections are at least partially responsible for prehistoric dry periods in central North America (Forman et al., 2001; Cook et al., 2004). Other mechanisms also provide plausible explanations for at least some Holocene dry episodes, however. Schubert et al. (2004a) noted that the 1930s Dust Bowl drought on the Great Plains coincided with high SST in the North Atlantic. Linkage between the Atlantic and the Great Plains may occur through changes in the position of the Bermuda High, which could in turn affect low-level moisture transport into the Plains from the Gulf of Mexico (Forman et al., 2001). Yu and Ito (1999) suggest solar forcing of high-frequency drought cycles, while sustained early to middle Holocene aridity has often been attributed to direct or indirect effects of varying summer insolation (Kutzbach, 1987; COHMAP, 1988; Harrison et al., 2003).

Stratigraphic patterns of sand-loess-soil and OSL dating reveal that major dry episodes recorded in numerous loess and dune field sections across the region are centered on 700, 2490, and 3800, with a period of sustained dry climate from 9390 to 6560 years ago (Miao et al., 2007). This provides a binary signal (wet vs. dry), with coarse temporal resolution. In this study, the hypothesized linkage between Great Plains drought and tropical Pacific SST records is examined from a different perspective, using the color index (generated from $L*a*b$ after statistical normalization) from the Wauneta core as a high-resolution, continuously varying paleoclimatic proxy (Fig. 5). Though most directly related to variations in the degree of soil development, color index is ultimately a proxy for variation in effective moisture in the Great Plain aeolian sediments, considering the broad semiarid climate of the southeastern Nebraska. The color index was compared to an SST reconstruction for the eastern tropical Pacific based on the Mg/Ca ratio from ocean cores (V21–36, 1°13S, 89°41W, Koutavas et al., 2002). Anomalously low SST values should correspond to persistent "La Niña-like" conditions, although there are some discrepancies between this SST record and reconstructions of El Niño variability from other proxies (e.g. Rein et al., 2005).

Color index values in Bignell Loess vary through the Holocene in a pattern broadly similar to that of eastern Pacific SST (Fig. 5). Lower (more negative) color index values, indicative of higher primary productivity and/or slower aeolian dust accumulation, coincide with relatively high SST during Brady Soil formation developed around 13,000 to 10,000 years ago. Independent evidence also suggests frequent El Niño events in this interval (Rittenour et al., 2000; Rein et al., 2005). In contrast, the early to mid-Holocene was marked by high (less negative) color index and low SST (Fig. 5), and was also a time of reduced El Niño frequency (Rodbell et al., 1999; Rein et al., 2005). The late Holocene is marked by a return to generally low color index, indicating higher primary productivity and/or slower dust sedimentation, and high eastern Pacific SST.

When considered in more detail, however, comparison between the color index proxy at Wauneta and eastern Pacific SST reveals important discrepancies that conflict with the proposed teleconnection. The dry episode recorded in the color index and centered at about 2500 years ago coincides with low SST, consistent with the teleconnection, but dry conditions centered at 3800 years ago occurred when the eastern tropical Pacific SST was intermediate to high (Fig. 5). Neither has been identified as a time of low El Niño frequency (Rein et al., 2005). The arid period indicated by a high color index began at a time closely coinciding with dropping SST, but ended by about 6500 years ago, well before SST rose again in the late Holocene.

These discrepancies do not rule out a teleconnection between persistent La Niña-like conditions in the tropical Pacific, more specifically the cooling of the eastern equatorial Pacific, and aridity on the Great Plains. On the other hand, our results strongly suggest that other mechanisms must also be important in controlling wet–dry climate variation on the Plains. It is worth noting that other hypothesized mechanisms for Holocene climate change in this region are also difficult to reconcile with the proxy record from the Wauneta site. For example, if direct or indirect effects of summer insolation control are responsible for early to mid-Holocene aridity (Kutzbach, 1987; COHMAP, 1988; Harrison et al., 2003), it is difficult to explain why the largest wet to dry shift in the Wauneta record, at the end of Brady Soil formation, occurred just after a peak of summer insolation.

3.6. Time series analysis on color and $\delta^{13}C$ data

Because color and $\delta^{13}C$ data provide useful information about climate and vegetation change, we performed

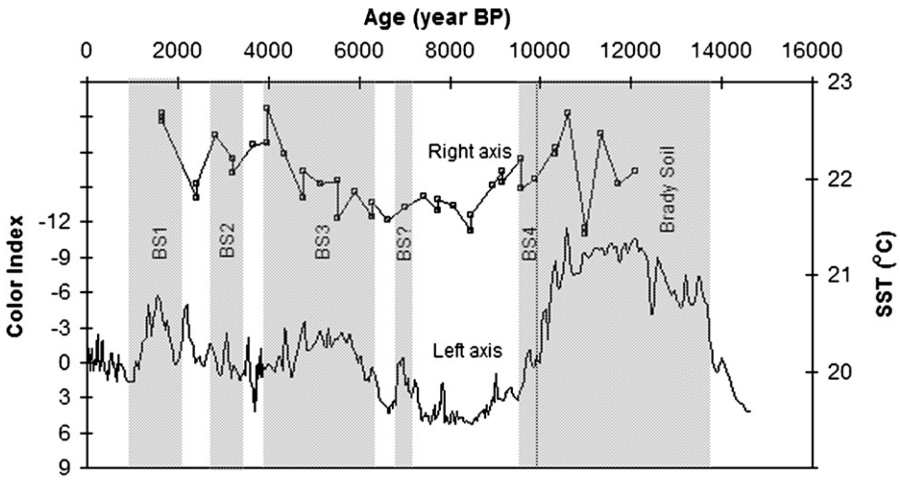

Fig. 5. Color index (generated from *L***a***b* after statistical normalization) at Wauneta compared to SSTs in the Eastern Tropical Pacific (V21–36, 1°13S, 89°41W, Koutavas et al., 2002). Statistical normalization simply converts data of any distribution into Standard Normal distribution, *N* (0,1), with the range of about −3 to +3 (99% coverage); color index, after sum of three normalized date sets at the same age, ranges from about −9 to 9. Gray bands indicate positions of the buried soils (BS).

time series analysis using REDFIT 3.8 (Schulz and Mudelsee, 2002). The program is specifically designed for unevenly spaced paleoclimatic data and can test whether peaks in the spectrum of a time series are significant against the red-noise background or above certain confidence intervals. $\delta^{13}C$ spectra show periodicities of 103–118 years cycle (above 95% confidence interval, Monte Carlo test, peaks at 116 and 106 years) from $\delta^{13}C$ (Fig. 6). Peaks at 61 and 53 years, close to the maximum temporal resolution of sampling, have limited implications. The analysis also reveals 103 years cycle (above 90% confidence interval) from color index.

Previous spectral analysis suggest 100–130 years drought cycles during arid mid-Holocene and no pronounced cycles during wetter late Holocene from Kettle Lake of North Dakota (Clark et al., 2002). A more recent study on the same lake reveals 160 years periodicity in the last 4500 years and possible cycles ranging between 80 and 160 years during the early to mid-Holocene (Brown et al., 2005). Yu and Ito (1999)

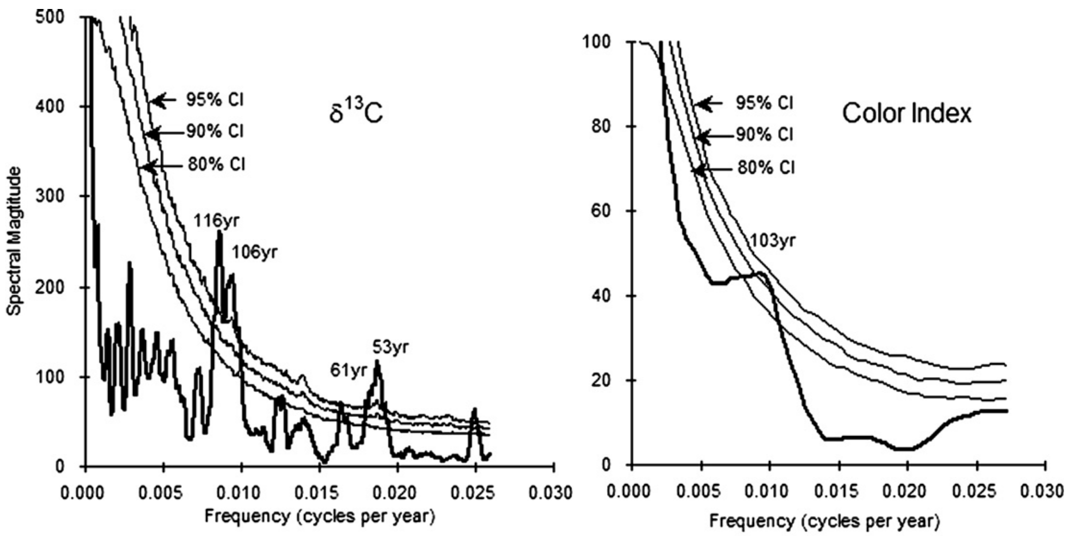

Fig. 6. Power spectral analysis of $\delta^{13}C$ (Fig. 3) and color index (Fig. 5) from Wauneta by REDFIT3.8 (Schulz and Mudelsee, 2002). Spectra show periodicities of 103–118 years (above 95% confidence interval, Monte Carlo Test) from $\delta^{13}C$, 103 years (above 90% confidence interval) from color index.

noted statistically significant periodicities of about 400, 200, 130 and 100 years in Mg/Ca ratios from Rice Lake, which they interpreted as possible solar forcing.

The 103–118 years periodicity in our record is generally similar to these cycles observed from lake studies. Although the mechanisms responsible for these periodicities are not clearly understood, such century-scale oscillations appear to be a common component of proxy records derived from a variety of sites across the northern and central Great Plains, and may have a common origin in the interaction of climatic and ecosystem dynamics. Among all the proposed origins, solar variability seems to be always on the top, often the only one, of the list.

The proposed drought mechanisms of SST (persistent La Niña condition) and the centennial scale 103–118 years periodicity observed in our record are not exclusive. They can interact with each other at different time scales. One of the best examples of their superimposition is the aridity during the early to mid-Holocene, when the SST hypothesis is applicable to the long-term drought condition, and these centennial scale periodicities are also pronounced under the overall arid climate from our color and $\delta^{13}C$ data and lake-sediment record (Clark et al., 2002).

4. Conclusions

Four major conclusions can be drawn from this study:

1) Organic carbon content and *L*a*b*** color variations are the most sensitive proxies to detect weakly developed soils and estimate the degree of the soil development for Bignell Loess, consequently they provide valuable information for reconstructing climate change. In contrast, grain size characteristics and magnetic susceptibility do not provide very useful paleoclimatic information for the central Great Plains.
2) High-resolution $\delta^{13}C$ data from SOC suggest that the C_3-dominated vegetation recorded in the Peoria Loess shifted dramatically to a C_4-dominant habitat in the Brady Soil, and then progressively shifted to nearly pure C_4 vegetation in the late Holocene loess and soils. Landscape disturbance may have played a more important role than surface temperature in determining the C_3–C_4 vegetation ratio during the Holocene interval.
3) The comparison between the color changes of the Bignell Loess at the Wauneta section and the eastern tropical Pacific SSTs allows evaluation of a teleconnection recently proposed to explain droughts in the central Great Plains. The two records are broadly similar, but differ in significant details, including the timing of one major late Holocene dry episode and the end of early to mid-Holocene aridity. Teleconnection with the tropical Pacific can possibly explain some Holocene dry episodes on the Great Plains, but other mechanisms must be responsible for drought at other times.
4) Time series analysis reveals a 103–118 years periodicity from $\delta^{13}C$ data, and a 103 years periodicity from color during the Holocene. These cycles are similar to previously reported drought cycles derived from North Dakota lakes, although the physical mechanisms are as yet unclear. These centennial scale periodicities may have interacted with the possible ocean temperature forcing, particularly in the arid early to mid-Holocene.

Acknowledgements

This work was funded by the National Science Foundation (DEB-0322067; EAR-9709742, BCS-0079252, BCS-0352683, BCS-0352748), and a grant from the UW-Madison Graduate School and KU General Research Fund. We thank W. Zanner (University of Minnesota) and K. Willey (University of Kansas) for their field assistance, A. Feggestad (University of Wisconsin) for improving the earliest version of the manuscript, W. Balsam (University of Texas) and anonymous reviewer for critical review and helpful comments on the manuscript.

References

Ahlbrandt, T.S., Swinehart, J.B., Maroney, D.G., 1983. The dynamic Holocene dune fields of the Great Plains and Rocky Mountain basins, U.S.A. In: Brookfield, M.E., Ahlbrandt, T.S. (Eds.), Aeolian Sediments and Processes, 11th International Association of Sedimentologists Congress. Elsevier Sci. Publ. Co., Amsterdam, Netherlands, pp. 379–406.

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., Johnson, W.C., 1998. Late-Quaternary landscape response to environmental change in south-central Kansas. Association of American Geographers Annals 88, 125–146.

Balsam, W.L., Ji, J.F., Chen, J., 2004. Climatic interpretation of the Luochuan and Lingtai loess sections, China, based on changing iron oxide mineralogy and magnetic susceptibility. Earth and Planetary Science Letters 223, 335–348.

Birkeland, P.W., 1999. Soils and Geomorphology, 3rd ed. Oxford University Press, pp. 1–24.

Boutton, T.W., 1996. Stable carbon isotope ratios of soil organic matter and their use as indicators of vegetation and climate change. In: Boutton, T.W., Yamasaki, S. (Eds.), Mass Spectrometry of Soils. Marcel Dekker, Inc., New York.

Brown, K.J., Clark, J.S., Grimm, E.C., Donovan, J.J., Mueller, P.G., Hansen, B.C.S., Stefanova, I., 2005. Fire cycles in North American interior grasslands and their relation to prairie drought. Proceedings of the National Academy of Sciences 102, 8865–8870.

Cerling, T.E., Quade, J., Wang, Y., Bowman, J.R., 1989. Carbon isotopes in soils and paleosols as ecologic and paleoecologic indicators. Nature 341, 138–139.

CIE, Commission Internationale de l'Eclairage, 1978. Recommendations on Uniform Color Space, Color-Difference Equations and Psychometric color Terms, Supplement No. 2 Publication CIE No. 15 (E-1.3.1), /(TC-1.3), Paris: Bureau Central de la CIE.

Clark, J.S., Grimm, E.C., Donovan, J.J., Fritz, S.C., Engstrom, D.R., Almendinger, J.E., 2002. Drought cycles and landscape responses to past aridity on prairies of the Northern Great Plains, USA. Ecology 83, 595–601.

COHMAP members, 1988. Climatic changes of the last 18,000 years: observations and model simulations. Science 241, 1043–1052.

Cole, J.E., Overpeck, J.T., Cook, E.R., 2002. Multiyear La Niña events and persistent drought in the contiguous United States. Geophysical Research Letters 29 (13). doi:10.1029/2001GL013561.

Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., Stahle, D.W., 2004. Long-term aridity changes in the western U.S. Science 306, 1015–1018.

Dearing, J., Dann, R., Hay, K., Lees, J., Loveland, P., Maher, B., O'Grady, K., 1996. Frequency-dependent susceptibility measurements of environmental materials. Geophysical Journal International 124, 228–240.

Ehleringer, J.R., Monson, R.K., 1993. Evolutionary and ecological aspects of photosynthetic pathway variation. Annual Review of Ecology Systematics 24, 411–439.

Feggestad, A.J., Jacobs, P.M., Miao, X.-D., Mason, J.A., 2004. Stable carbon isotope record of Holocene environmental change in the Central Great Plains. Physical Geography 25, 170–190.

Feng, Z.D., Johnson, W.C., 1995. Factors affecting the magnetic susceptibility of a loess-soil sequence, Barton County, Kansas. Catena 24, 25–37.

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.

Geiss, C.E., Zanner, W.C., Banerjee, S.K., Minott, J., 2004. Signature of magnetic enhancement in a loessic soil in Nebraska. Earth and Planetary Science Letters 228, 355–367.

Goble, R.J., Mason, J.A., Loope, D.B., Swinehart, J.B., 2004. Optical and radiocarbon ages of stacked paleosols and dune sands in the Nebraska Sand Hills, USA. Quaternary Science Reviews 23, 1173–1182.

Grimley, D.A., Follmer, L.R., McKay, E.D., 1998. Magnetic susceptibility and mineral zonations controlled by provenance in loess along the Illinois and central Mississippi River valleys. Quaternary Research 49, 24–36.

Grimm, E.C., 2001. Trends and paleoecological problems in the vegetation and climate history of the northern Great Plains, USA. Biology and Environment: Proceedings of the Royal Irish Academy 101B, 47–64.

Grüger, J., 1973. Studies on the Late Quaternary vegetation history of northeastern Kansas. Geological Society of America Bulletin 84, 239–250.

Harrison, S.P., Kutzbach, J.E., Liu, Z., Bartlein, P.J., Otto-Bliesner, B., Muhs, D., Prentice, I.C., Thompson, R.S., 2003. Mid-Holocene climates of the Americas: a dynamical response to changed seasonality. Climate Dynamics 20, 663–688. doi:10.1007/s00382-002-0300-6.

Heller, F., Liu, T.S., 1986. Palaeoclimate and sedimentary history from magnetic susceptibility of loess in China. Geophysical Research Letters 13, 1169–1172.

Hoerling, M., Kumar, A., 2003. The perfect ocean for drought. Science 299, 691–694.

Holliday, V.T., 2001. Stratigraphy and geochronology of upper Quaternary aeolian sand on the Southern High Plains of Texas and New Mexico, United States. Geological Society of America Bulletin 113, 88–108.

Hopkins, H.H., 1951. Ecology of the native vegetation of the loess hills in central Nebraska. Ecological Monographs 21, 125–148.

Jacobs, P.M., Mason, J.A., 2004. Paleopedology of soils in thick Holocene loess, Nebraska, USA. Revista Mexicana de Ciencias Geologicas (Mexican Journal of Geological Sciences) 21, 54–70.

Jacobson Jr., G.L., Webb III, T., Grimm, E.C., 1987. Patterns and rates of vegetation change during the deglaciation of eastern North America. In: Ruddiman, W.F., Wright Jr., H.E. (Eds.), North America During Deglaciation. The Geology of North America, DNAG v. K3. Geological Society of America, pp. 277–288.

Ji, J.F., Balsam, W.L., Chen, J., 2001. Mineralogic and climatic interpretations of the luochuan loess section (China) based on diffuse reflectance spectrophotometry. Quaternary Research 56, 23–30.

Johnson, W.C., Willey, K.L., 2000. Isotopic and rock magnetic expression of environmental change at the Pleistocene–Holocene transition in the central Great Plains. Quaternary International 67, 89–106.

Kelly, E.F., Blecker, S.W., Yonker, C.M., Olson, C.G., Wohl, E.E., Todd, L.C., 1998. Stable isotope composition of soil organic matter and phytoliths as paleoenvironmental indicators. Geoderma 82, 59–81.

Ketterings, Q.M., Bigham, J.M., Laperche, V., 2000. Changes in soil mineralogy and texture caused by slash-and-burn fires in Sumatra, Indonesia. Soil Science Society of America Journal 64, 1108–1117.

Koutavas, A., Lynch-Stieglitz, J., Marchitto, T.M., Sachs, J.P., 2002. El Niño-like pattern in Ice Age tropical Pacific sea surface temperature. Science 297, 226–230.

Kukla, G., Heller, F., Liu, X., Xu, T., Liu, T., An, Z., 1988. Pleistocene climates in China dated by magnetic susceptibility. Geology 16, 811–814.

Kutzbach, J.E., 1987. Model simulations of the climatic patterns during the deglaciation of North America. In: Ruddiman, W.F., Wright Jr., H.E. (Eds.), North America and Adjacent Oceans During the Last Deglaciation. DNAG Geology of North America, vol. K-3, pp. 425–447.

Lu, H.Y., Van Huissteden, K., An, Z.S., Nugteren, G., Vandenberghe, J., 1999. East Asian winter monsoon changes on millennial time scale before the last glacial–interglacial cycle. Journal of Quaternary Science 14, 101–110.

Mason, J.A., Kuzila, M.S., 2000. Episodic Holocene loess deposition in central Nebraska. Quaternary International 67, 119–131.

Mason, J.A., 2001. Transport direction of Peoria Loess in Nebraska and implications for loess sources on the central Great Plains. Quaternary Research 56, 79–86.

Mason, J.A., Jacobs, P.M., Hanson, P.R., Miao, X.D., Goble, R.J., 2003a. Sources and paleoclimatic significance of Holocene Bignell Loess, central Great Plains. Quaternary Research 60, 330–339.

Mason, J.A., Jacobs, P.M., Greene, R.S.B., Nettleton, W.D., 2003b. Sedimentary aggregates in the Peoria Loess of Nebraska, USA. Catena 57, 377–397.

Miao, X.D., Sun, Y.B., Lu, H.Y., Mason, J.A., 2004. Spatial pattern of grain size in the Late Tertiary 'Red Clay' deposits (North China) indicates transport by low-level northerly winds. Palaegeography, Palaeoclimatology, Palaeoecology 206, 149–155.

Miao, X.D., Mason, J.A., Goble, R.J., Hanson, P.R., 2005. Loess record of dry climate and aeolian activity in the early to mid-Holocene, central Great Plains, North America. The Holocene 15, 339–346.

Miao, X.D., Wang, X.L., Mason, J.A., 2006. Isolation of the syndepositional magnetic susceptibility signals from loessic paleosols of China. Journal of Asian Earth Sciences 27, 684–690.

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

Muhs, D.R., Bettis III, E.A., 2000. Geochemical variations in Peoria loess of western Iowa indicate paleowinds of Midcontinent North America during last glaciation. Quaternary Research 53, 49–61.

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

Nelson, D.M., Hu, F.S., Tian, J., Stefanova, I., Brown, T.A., 2004. Response of C3 and C4 plants to middle Holocene climatic variation near the prairie-forest ecotone of Minnesota. Proceedings of the National Academy of Sciences 101, 562–567.

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

Palmer, T.N., Brankovic, C., 1989. The 1988 U.S. drought linked to anomalous sea surface temperature. Nature 338, 54–57.

Parton, W.J., Schimel, D.S., Cole, C.V., Ojima, D., 1987. Analysis of factors controlling soil organic levels of grasslands in the Great Plains. Soil Science Society of America Journal 51, 1173–1179.

Porter, S.C., 2000. High-resolution paleoclimatic information from Chinese aeolian sediments based on grayscale intensity profiles. Quaternary Research 53, 70–77.

Pye, K.A., 1987. Aeolian Dust and Dust Deposit. Academic Press, London.

Pye, K.A., Winspear, N.R., Zhou, L.P., 1995. Thermoluminescence ages of loess and associated sediments in central Nebraska, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 118, 73–87.

Rein, B., Lückge, A., Reinhardt, L., Sirocko, F., Wolf, A., Dullo, W.C., 2005. El Niño variability off Peru during the last 20,000 years. Paleoceanography 20, PA4003. doi:10.1029/2004PA001099.

Rittenour, T.M., Brigham-Grette, J., Mann, M.E., 2000. El Niño-like climate teleconnections in New England during the late Pleistocene. Science 288, 1039–1042.

Rodbell, D.T., Seltzer, G.O., Anderson, D.M., Abbott, M.B., Enfield, D.B., Newman, J.H., 1999. A 15,000-year record of El Niño-driven alluviation in southwestern Ecuador. Science 283, 516–520.

Schubert, S.D., Suzrez, M.J., Pegion, P.J., Koster, R.D., Bacmeister, J.T., 2004a. On the cause of the 1930s dust bowl. Science 303, 1855–1859.

Schubert, S.D., Suzrez, M.J., Pegion, P.J., Koster, R.D., Bacmeister, J.T., 2004b. Causes of long-term drought in the U.S. Great Plains. Journal of Climate 17, 485–503.

Schultz, C.B., Stout, T.M., 1945. Pleistocene loess deposits of Nebraska. American Journal of Science 243, 231–244.

Schulz, M., Mudelsee, M., 2002. REDFIT: estimating red-noise spectra directly from unevenly spaced paleoclimatic time series. Computers & Geosciences 28, 421–426.

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

Trenberth, K.E., Guillemot, C.J., 1996. Physical processes involved in the 1988 drought and 1993 floods in North America. Journal of Climate 9, 1288–1298.

Vandenberghe, J., Zhisheng, A., Nugteren, G., Lu, H.Y., Huissteden, K., 1997. New absolute time scale for the Quaternary climate in the Chinese loess region by grain-size analysis. Geology 25, 35–38.

Wang, H., Follmer, L.R., Liu, J.C.-L., 2000. Isotope evidence of paleo-El Niño-Southern Oscillation cycles in loess-paleosol record in the central United States. Geology 28, 771–774.

Wang, H., Hughes, R.E., Steele, J.D., Lepley, S.M., Tian, J., 2003. Correlation of climate cycles of Middle Mississippi Valley loess and Greenland ice. Geology 31, 179–182.

Yu, Z.C., Ito, E., 1999. Possible solar forcing of century-scale drought frequency in the northern Great Plains. Geology 27, 263–266.