Fire cycles in North American interior grasslands and their relation to prairie drought

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High-resolution analyses of a late Holocene core from Kettle Lake in North Dakota reveal coeval fluctuations in loss-on-ignition carbonate content, percentage of grass pollen, and charcoal flux. These oscillations are indicative of climate–fuel–fire cycles that have prevailed on the Northern Great Plains (NGP) for most of the late Holocene. High charcoal flux occurred during past moist intervals when grass cover was extensive and fuel loads were high, whereas reduced charcoal flux characterized the intervening droughts when grass cover, and hence fuel loads, decreased, illustrating that fire is not a universal feature of the NGP through time but oscillates with climate. Spectral and wavelet analyses reveal that the cycles have a periodicity of ≈160 yr, although secular trends in the cycles are difficult to identify for the entire Holocene because the periodicity in the early Holocene ranged between 80 and 160 yr. Although the cycles are evident for most of the last 4,500 yr, their occasional muting adds further to the overall climatic complexity of the plains. These findings clearly show that the continental interior of North America has experienced short-term climatic cycles accompanied by a marked landscape response for several millennia, regularly alternating between dual landscape modes. The documentation of cycles of similar duration at other sites in the NGP, western North America, and Greenland suggests some degree of regional coherence to climatic forcing. Accordingly, the effects of global warming from increasing greenhouse gases will be superimposed on this natural variability of drought.

charcoal | Holocene | Northern Great Plains | pollen | aridity cycles

Fire is a critical process that regulates dryland ecosystems and biodiversity. It provides a feedback that links terrestrial ecosystems to global climate through the emission of greenhouse gases and carbonaceous aerosols (1). In North America, evidence of long-term climate–fire interaction is primarily from forested ecosystems such as eastern hardwoods (2, 3), boreal forests (4, 5), coastal interior and Rocky Mountain communities (6, 7), and coastal temperate rainforests (8, 9). Nonforested ecosystems have generally received less attention, and only a few long-term fire studies are available from chaparral scrublands (10) and continental grasslands (11–14).

The Northern Great Plains (NGP) is one such continental grassland, extending north of the Nebraska Sand Hills over South Dakota, North Dakota, eastern Montana and Wyoming, and western Minnesota (Fig. 1). Its northern limit is in southern Manitoba, Saskatchewan, and Alberta in Canada. Pollen records reveal that the grasslands of the NGP developed at the start of the Holocene, when Poaceae and *Artemisia* expanded to replace widespread spruce forest (15). In the warm mid-Holocene, *Ambrosia* and Chenopodiaceae/Amaranthaceae increased in abundance, only to decrease in the late Holocene as climate cooled and modern prairie was established.

Arctic, Pacific, and tropical Atlantic air masses converge over the NGP, and, consequently, the region is climatically sensitive. An annual deficit of precipitation minus evaporation also characterizes the region (15), making it highly sensitive to changes in the moisture regime. Previous paleoclimatic investigations have documented oscillations in several disparate climate proxies, revealing a high degree of past climatic variability on the plains (13, 16–22), especially in precipitation. Such variability has been linked to solar cycles (21) and to Pacific Decadal and Atlantic Multidecadal Oscillations (23, 24). Before widespread 20th-century fire suppression, anecdotal evidence suggests that frequent fires maintained high levels of productivity and biodiversity on the plains (25), yet research into the effects of past climatic variability on the fire regimes of these expansive and economically important grasslands is still relatively nascent. In addition to natural climatic variability, the interior plains may respond adversely to greenhouse warming (26). Indeed, one of the most difficult consequences of climate change to predict in continental interiors is severe drought and its associated landscape response, mandating further investigation into prairie–climate interaction. Studies with sufficient temporal resolution and duration are necessary to provide further insight into the complexity of climate in the continental interior, as well as to detail the relation between fire and short-term climatic variability.

One site in the NGP that contains a detailed record of such climatic variability, in the form of drought cycles, is Kettle Lake (Fig. 1) (16). The cycles are evident in an early Holocene section of core that dated to 8,500–7,900 calendar yr B.P. [cal B.P.; present = *anno Domini* (A.D.) 1950]. The more humid phases were marked by increases in the carbonate mineral aragonite, grass pollen, and charcoal particles, whereas the intervening droughts were characterized by elevated detrital quartz, increased *Ambrosia* pollen, and a reduction in charcoal. The record of early Holocene drought cycles at Kettle Lake indicates that the site was sensitive to centennial-scale climate variability in the recent past and is a good candidate for the possible persistence and preservation of the cycles through time. In this study, we used high-resolution sampling with four objectives: (*i*) to identify late Holocene climatic variability at Kettle Lake, with emphasis on drought-cycle detection and characterization, (*ii*) to use fossilized charcoal to profile the long-term incidence of fire at Kettle Lake, (*iii*) to document the response of fire to past climatic fluctuation, and (*iv*) to combine the results from this investigation with those detailing early Holocene climate–landscape dynamics (16) to examine secular trends throughout the Holocene. The results are then compared with other paleoenvironmental investigations in the NGP and from western North

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Abbreviations: NGP, Northern Great Plains; A.D., *anno Domini*; cal B.P., calendar years B.P. (present = A.D. 1950); LOI, loss-on-ignition; MWP, Medieval Warm Period; LIA, Little Ice Age.

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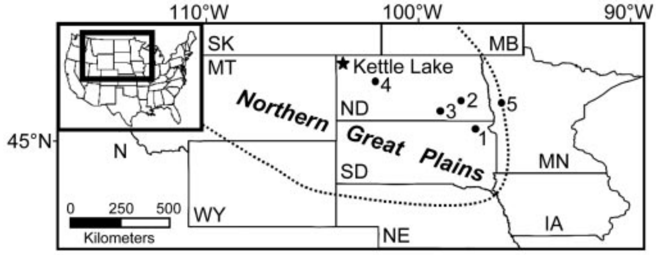

Fig. 1. Study location (*Inset*) and study site map. The dotted line defines the approximate boundary of the NGP. Kettle Lake is marked by a star. Sites numbered 1–4 correspond to other locations where aridity cycles have been detected: 1, Pickerel Lake (South Dakota) and Spring Lake; 2, Moon Lake (North Dakota); 3, Coldwater Lake; 4, Rice Lake. Location 5 is West Olaf Lake.

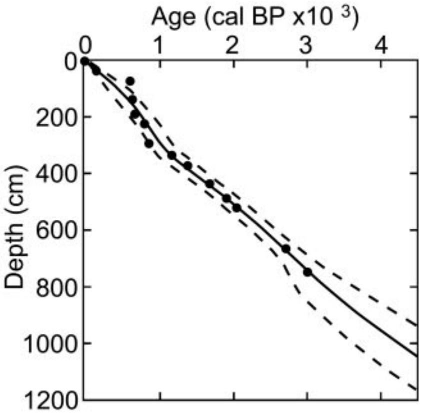

Fig. 2. Age–depth model for Kettle Lake. The dots represent the ages used in the model and are reported in Table 1. The solid line is the fitted age model; the dashed lines are standard error estimates.

America and Greenland to ascertain regional trends and to examine possible causal mechanisms.

Study Site

Kettle Lake is located at 48.61° N and 103.62° W in extreme northwestern North Dakota (Fig. 1). The lake lies in the glaciated region of the Missouri Coteau province of the Great Plains, where glacial till and moraines are ubiquitous and relief is moderate (27). Shallow pothole lakes dot the modern landscape. Kettle Lake is an unusual lake for this region, being relatively deep and small, with a surface area of 2.2 hectares and a water depth of 10 m. The lake has no inflow or outflow streams, so groundwater inflow maintains water level (16).

Climate in the region of Kettle Lake is continental, with long, cold winters and warm summers. Annual precipitation is <400 mm, and precipitation minus evaporation is ≈ -500 mm (15). Vegetation around Kettle Lake consists of mixed prairie containing *Agropyron smithii* (western wheatgrass), *Koeleria pyramidata* (prairie junegrass), *Stipa comata* (needle-and-thread), *Bouteloua gracilis* (blue grama), *Bouteloua curtipendula* (sideoats grama), and *Schizachyrium scoparium* (little bluestem). *Artemisia frigida* (fringed sagebrush) and *Artemisia ludoviciana* (prairie sagebrush) are also common.

Materials and Methods

The deepest part of Kettle Lake was incrementally cored with a Wright square-rod piston corer in A.D. 1995 (−45 cal B.P.). Selected charcoal, plant fragments, and seeds were dated by accelerator mass spectrometry (AMS) at the Lawrence Livermore National Laboratory (Livermore, CA), and the resultant dates (Table 1) were calibrated to calendar ages (28). An age–depth model (Fig. 2) was developed by fitting a loess function to the calibrated AMS dates, as well as to the estimated immigration date of *Salsola* pollen, an introduced species, to the region (15). The *Salsola* pollen is probably from *Salsola tragus* (prickly Russian thistle), first arriving in South Dakota from Russia during the 1870s A.D. and ultimately spreading over most of the United States and much of southern Canada (29). The introduction of *Salsola collina* (slender Russian thistle) to the Central Plains in the 1920s A.D. may have contributed additional *Salsola* pollen to Kettle Lake.

Sediment vertical accretion rates (in cm·yr^{-1}) were determined according to the age–depth model. The core sections were sampled contiguously at high resolution (1 cm ≈ 3–5 yr) for both charcoal and loss-on-ignition (LOI) carbonate (30) for the interval spanning −45 to 4,500 cal B.P. Samples for pollen analysis were also collected from the core at ≈4-cm intervals. Volumetric samples (0.5 cm^3) were dried overnight at 100°C,

Table 1. Radiocarbon dates from Kettle Lake

Sample	Material dated	Core depth, cm	Radiocarbon age, ^{14}C yr B.P.	Calibrated age (50% median probability), cal B.P.
Core Top	N/A	0	N/A	−45
European Settlement	Onset of *Salsola* pollen	24	N/A	70
CAMS-41153	*Scirpus* seeds	75	570 ± 40	594
CAMS-41154	Charcoal, *Scirpus* seed	139	680 ± 50	629
CAMS-38081	Charcoal	188	720 ± 60	665
CAMS-38082	Charcoal	224	870 ± 60	790
CAMS-32010	Charcoal	294.5	960 ± 50	858
CAMS-38083	Charcoal	336	1,240 ± 70	1,159
CAMS-38084	Charcoal, *Typha* seed	372.7	1,480 ± 70	1,379
CAMS-38085	*Rosa* seed	435.5	1,770 ± 50	1,683
CAMS-32009	Charcoal, *Scirpus,* and *Chenopodium* seeds	487.5	1,960 ± 70	1,908
CAMS-38087	Charcoal	520	2,080 ± 50	2,048
CAMS-57143	Charcoal	667	2,580 ± 40	2,722
CAMS-57145	Charcoal	746	2,880 ± 50	3,009
CAMS-57140	Charcoal	1,567	7,120 ± 40	7,936*

*, Basal anchor date in age–depth model, not presented in Fig. 2.

weighed, combusted in a muffle furnace at 500°C for 1 h, weighed to determine organic-matter loss, and then combusted at 900°C for 1 h to determine carbonate content. Controls of ash-free filter paper and pure calcium carbonate were run to ensure complete combustion. An estimate of carbonate content was made by assuming that the reduction in mass at 900°C was from CO_2 lost during conversion of $CaCO_3$ to CaO (i.e., multiplying mass lost at 900°C by 2.27, the ratio of the molecular weights of $CaCO_3$ and CO_2).

Mineral suites were also obtained from a short section of the core (2,630–2,850 cal B.P.) by x-ray diffraction (XRD) using a PW-1800 diffractometer (Panalytical, formerly Philips, Eindhoven, The Netherlands) with Cu-Kα radiation so that aragonite content could be specifically determined. XRD samples were air-dried, crushed, filtered through a 100-μm mesh, and mounted on 40-mm chemplex disks in a thin ($<$1 mm) layer for analysis. The results were quantified with calibrated reference intensity ratios, yielding a measurement of percent mineral constituent relative to the total crystalline fraction of the sample. Mineral percentages were adjusted for total sediment weight using the LOI results, with carbonate minerals (calcite, dolomite, and aragonite) normalized to the total LOI carbonate value.

Pollen preparation followed standard techniques (31), with samples being analyzed until a minimum of 300 pollen grains from upland taxa were tabulated. To reconstruct the incidence of past fire, the sediment was gently sieved at 180 μm, and the coarse fraction was examined for charcoal under a dissecting microscope at 20× magnification. The microscope was fitted with a video mount and networked to a computer containing specialized NIH IMAGE software so that each charcoal fragment could be measured for length, width, and total area. Charcoal flux (in $mm^2 \cdot cm^{-2} \cdot yr^{-1}$) was determined for each sample by multiplying charcoal concentration (in $mm^2 \cdot cm^{-3}$) by the vertical accretion rate.

Anomalies of charcoal flux, carbonate content, and percentage of grass pollen were calculated by a square-root transformation of the raw data and subtraction of the mean. Fourier power spectral analysis was used to assess the dominant frequency of charcoal deposition in the core. Charcoal flux was analyzed with REDFIT, which fits a first-order autoregressive process to unevenly spaced data, thus avoiding the introduction of interpolation bias (32). Power spectra are reported as relative power spectral densities (variance/frequency) plotted against frequency. Cross-spectral analysis (33) was used to determine the coherence of frequency between charcoal and grass, charcoal and carbonate, and grass and carbonate. A shortcoming of Fourier power analysis, however, is that it yields an integrated estimate of variance for the entire time series. Therefore, wavelet power spectral analysis (34) was used to identify the dominant frequencies in the charcoal, grass, and carbonate series and to examine how those frequencies varied throughout the late Holocene.

Results and Discussion

LOI carbonate and x-ray diffraction results were combined with similar mineralogical estimates from an early Holocene section of the core (16) to examine the relationship between LOI carbonates and aragonite (Fig. 3). It is hypothesized that aragonite is the only authigenic carbonate that precipitated in Kettle Lake throughout the Holocene, because it is prevalent in both the early and late Holocene. Aragonite is formed during the humid phases of the drought cycles as higher rates of groundwater inflow increase the amount of dissolved Ca and alkalinity entering the lake, ultimately precipitating out as aragonite during summer (16, 35). Comparison between LOI carbonate and aragonite content reveals a strong linear relationship when aragonite comprises $>$35% of the crystalline fraction, corroborating that high values of LOI carbonate indicate more humid conditions. Deviations from the linear trend at aragonite concentrations $<$35% are attributed to a relative increase in allogenic calcite and dolomite supply to the basin during times of drought.

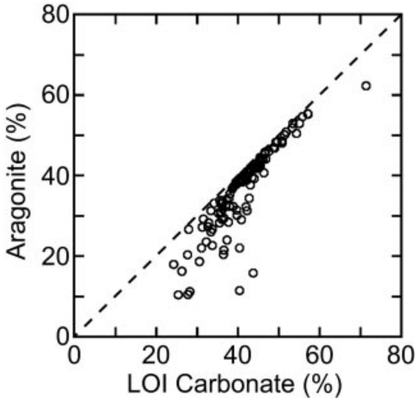

Fig. 3. Scatter diagram of LOI carbonate versus x-ray diffraction aragonite percentage, showing a strong, direct linear relationship at values $>$35%.

The rate of sediment accretion in Kettle Lake has been rather consistent during the late Holocene, averaging 0.24 $cm \cdot yr^{-1}$. The only noticeable departure from this trend occurs circa the Medieval Warm Period (MWP) (≈900–550 cal B.P.) when accretion increased to 0.34 $cm \cdot yr^{-1}$ (Fig. 2). By contrast, charcoal flux is highly variable, exhibiting distinct episodes of high charcoal accumulation separated by intervals of little or no charcoal deposition (Fig. 4*a*). This sequence reveals that the incidence of fire was intermittent during the last 4,500 yr, alternating between fire-prone intervals and intervals when fire was not an important landscape process. This patterning implies that perdurable fire cycles have persisted on the northern plains for millennia. LOI carbonate content and percentage of grass pollen also fluctuate down-core, covarying with charcoal (Fig. 4 *a* and *b*). Combined, these synchronous oscillations comprise a 4,500-yr record of climate–fuel–fire cycles on the NGP.

The covariation in LOI carbonates, grass, and charcoal during the late Holocene demonstrates that drought cycles were not limited to just the early Holocene (16); rather, they were a principal factor shaping this grassland ecosystem until the time of European settlement. High charcoal accumulation coincident with high LOI carbonate content indicates that fire was a dominant process during moist periods, likely in response to increased fuel load, as evidenced by high grass content (Fig. 4 *a* and *b*). Similarly, grass pollen and fuel loads were also positively correlated with moisture availability at Kettle Lake in the early Holocene, synchronously tracking short-term moisture availability (16). A comparable climate–fuel–fire relationship has also been observed at West Olaf Lake in Minnesota (14), where in the mid-Holocene, both charcoal and grass pollen increased concomitant with a long-term decline in moisture deficit. Reduced LOI carbonate content is contemporaneous with drought, signifying decreased groundwater input of dissolved Ca and alkalinity to the lake as well as increased clastic input associated with the loss of grass biomass and vegetation cover. During droughts, charcoal production decreased in response to the reduction in fuel load. Concurrently, regional dune activation and increased aeolian sediment transport (17, 36) may have replaced fire as the dominant landscape processes. These observations suggest that the NGP are characterized by dual landscape modes governed by short-term climatic variability, regularly switching between domains.

Efforts have recently been made to portray the climatic conditions of the NGP during specific late Holocene periods

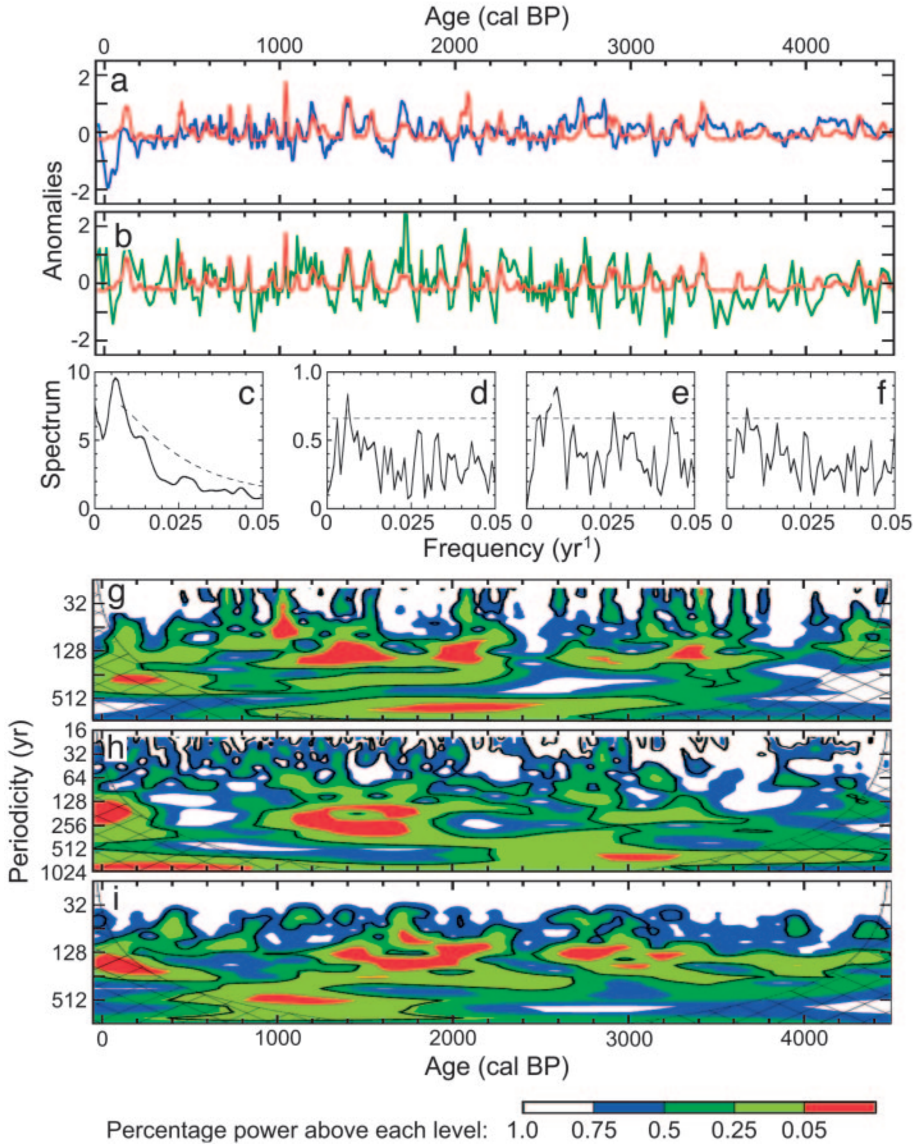

Fig. 4. Kettle Lake core characteristics. (*a* and *b*) Down-core trends in charcoal (red line) and LOI carbonate content (blue line) (*a*) and charcoal (red line) and percentage of grass pollen (green line) (*b*). The anomalies are presented as 5-point moving averages. (*c*) Fourier power spectrum showing a dominant periodicity of ≈160 yr for the charcoal time series. (*d–f*) Cross-spectra for charcoal and carbonates (*d*), charcoal and grass (*e*), and carbonates and grass (*f*) showing coherency at ≈160 yr. The dashed lines in *c–f* are 95% confidence intervals. (*g–i*) Charcoal, carbonate, and grass pollen wavelets, respectively, where the contours show regions with >90% confidence intervals relative to red noise, and the hatched areas show those regions where edge effects caused by zero padding are significant.

such as the MWP and the Little Ice Age (LIA) (≈450–100 cal B.P.), as well as during decadal droughts of the 19th to 20th centuries, such as the Dust Bowl (19–21, 37). Although hydrologically variable, two distinct periods of drought have been identified during the MWP, whereas prolonged dry conditions have been suggested for the LIA (19–21). At Kettle Lake, high sedimentation rates are accompanied by several oscillations in carbonate mineral content, grass pollen, and charcoal flux during the MWP (Fig. 4 *a* and *b*), suggesting that climate was variable at that time, alternating between wet and dry intervals. In contrast, conditions during the LIA are more difficult to discern. Overall lower carbonate content during the LIA (i.e., −0.4 anomaly values) suggests that dry conditions generally prevailed at this time. However, fluctuations in carbonate content are still noted during this interval, implying variability in the moisture regime. Grass pollen also oscillates throughout the LIA, with no obvious difference from earlier cycles. However, a reduction in charcoal flux is evident during the LIA, illustrating that fires were rare during this period. These observations suggest that a somewhat dry, although variable, climate characterized by reduced fire prevailed during recent centuries. The dramatic decline in carbonates at Kettle Lake since A.D. 1850 is highly anomalous compared with the preceding 4,400 yr. Charcoal is also rare post-A.D. 1850. These low values are probably not related solely to decadal droughts that have been catalogued since settlement but are related to agricultural activities and fire suppression efforts, suggesting that anthropogenic landscape modifications have greatly affected the recent stratigraphic record.

Maximum variance in the late Holocene charcoal series from Kettle Lake occurs at a frequency of 0.0062 yr^{-1}, corresponding to an ≈160-yr periodicity (Fig. 4*c*). Previous

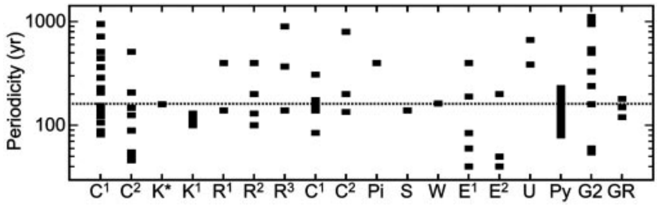

Fig. 5. A comparison of prominent periodicities identified at selected sites. The dotted line is the 160-yr periodicity horizon. Abbreviations are as follows, with references in parenthesis: C^1, atmospheric $^{14}CO_2$ record (38); C^2, atmospheric $^{14}CO_2$ (39); K*, Kettle Lake (this study); K^1, Kettle Lake (16); R^1, Rice Lake (13); R^2, Rice Lake (21); R^3, Rice Lake (13); C^1, Coldwater Lake (13); C^2, Coldwater Lake (13); Pi, Pickerel Lake (17); S, Spring Lake (40); W, Waubay Lakes complex (South Dakota) (40); E^1, Elk Lake (Minnesota) (41); E^2, Elk Lake (42); U, Upper Pinto Fen (Alberta, Canada) (43); Py, Pyramid Lake (Nevada) (44); G2, Greenland Ice Sheet Project 2 (45); GR, Greenland Ice Core Project (46).

work at Kettle Lake indicated that the drought cycles in the early Holocene were 100–130 yr in duration (16). However, the time control for the short section of core (8,500–7,900 cal B.P.) previously studied is based on only three radiocarbon dates, and within the 2σ errors of the dates, the periodicity could be 80–160 yr. Thus, it remains difficult to identify any secular trends in the cycles at Kettle Lake because it is not known whether the periodicity has remained static or doubled during the past 8,500 yr.

Cross-spectral analysis reveals a correlation among charcoal, LOI carbonates, and grass at a periodicity of ≈160 yr (Fig. 4 *d–f*), suggesting that all three proxies at Kettle Lake were responding to the same environmental forcing. Several other proxy records from sites distributed widely over the NGP also have prominent periodicities that are somewhat similar in duration to those at Kettle Lake (Table 2, which is published as supporting information on the PNAS web site; see also Fig. 5). For example, a 130- to 140-yr cycle has been identified at Rice Lake in North Dakota during the latest Holocene from oscillations in both Mg/Ca ratios and charcoal (13, 21). Similarly, fluctuations in Mg/Ca ratios at Spring Lake in South Dakota correspond to a 140-yr cycle (40), whereas fluctuations in charcoal during the last millennium at Coldwater Lake in North Dakota reveal dominant periodicities ranging between 140 and 175 yr (13). Although the above-mentioned lacustrine records clearly show century-scale periodicity, the subtle variations in the duration of the periodicities may be related to several factors, including sampling resolution, the degree of chronological control, and basin-specific characteristics that govern site sensitivity and responsiveness to environmental forcing. In contrast to the variations noted in the lacustrine records, a high-resolution dendrochronological investigation from nearby South Dakota reveals a 163-yr fluctuation in lake level during the past few centuries (40), yielding a periodicity identical to that observed at Kettle Lake. Combined, these records not only illustrate that short-term climatic variability is a recurrent phenomenon in the continental interior, but also that the periodicity has regional coherence.

Wavelet analyses show that the drought cycles identified at Kettle Lake were not uniformly present throughout the late Holocene. Century-scale cycles of charcoal deposition were weak or absent between 4,000 and 3,800 and 2,600 and 2,400 cal B.P. (Fig. 4*g*). Further, a shift to shorter cycles occurred between 1,000 and 600 cal B.P., possibly in response to MWP climatic conditions. A similar pattern is observed in the LOI carbonate series, where the cycles are poorly defined before 3,600 cal B.P. and between ≈2,800 and 2,400 and 900 and 300 cal B.P. (Fig. 4*h*). Muted cycles are also evident in the percentage of grass wavelet at 2,500–2,300 and 1,200–600 cal B.P. (Fig. 4*i*). These results show that although century-scale drought cycles generally epitomize the plains, they can be modified or muted for short periods, adding further to the complexity of climate on the plains. The wavelet analysis also suggests an integrated landscape response to environmental forcing because both upland and lacustrine proxies experienced muting at similar times. Finally, the wavelets also show power at high periodicities, suggesting the existence of a low-frequency cycle of >500 yr at Kettle Lake. However, a longer time series with appropriate chronological control and sampling resolution is needed to fully discern such a cycle.

On a larger spatial scale, an ≈150-yr drought cycle has also been described at Pyramid Lake in Nevada (44), located ≈1,500 km to the west (Table 2 and Fig. 5). The periodicity at Kettle Lake is also highly consistent with the signal noted in the Holocene sections of the Greenland Ice Sheet Project 2 (GISP2) and Greenland Ice Core Project ice cores, located ≈4,000 km to the east. Periodicities of 155–164 yr and 150 yr are identified in the $\delta^{18}O$ records from both ice cores, respectively (45, 46), suggesting continental scale climatic forcing. The recognition of century-scale cycles from several sites across North America and Greenland suggests some degree of hemispheric correspondence, possibly related to the effects of solar modulation (21). Indeed, prominent century-and-a-half periodicities are evident in the highly precise $\Delta^{14}C$ record that is often used as a solar proxy (38, 39). Further, the good agreement between the $\delta^{18}O$ record from GISP2 and the $\Delta^{14}C$ record during the last millennia (47) provides additional evidence supporting the concept of solar climate forcing. Accordingly, solar forcing may be responsible for the century-scale aridity cycles noted at many sites in North America, including the climate–fuel–fire cycles observed at Kettle Lake. If so, it is likely that Kettle Lake will continue to experience recurrent short-term climatic variability with substantive landscape response in the future, particularly pertaining to vegetation composition, landscape stability, water availability, and disturbance regime.

Conclusions

This study reveals that climate–fuel–fire cycles have persisted on the NGP for most of the last 4,500 yr. Our results show that fire has not been a constant process on the prairies through time; rather, it has oscillated with short-term climatic cycling. Fire is more prevalent during moist periods, when grass cover is extensive, compared with drier intervals with less dense vegetation cover. Although the late Holocene was typified by ≈160-yr climate–fuel–fire cycles, there were periods when the cycles were muted or absent, further complicating the dynamics of climate on the plains. However, the general persistence of aridity cycles in the late Holocene, coupled with those previously documented in the early Holocene (16), reveals that such cycles are inherent to the NGP and have characterized the region for at least 8,500 yr and possibly longer, although secular trends remain difficult to identify. Documentation of similar cycles at other sites in the NGP suggests a regional response to environmental forcing that is possibly related to solar variability, ultimately culminating in dual landscape modes. This revelation implies that the continental interior is susceptible to climatic change not only from increasing atmospheric greenhouse gas content (26), but also from natural climatic variability.

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