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 char-

acterizes 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, Pickering Lake (South Dakota) and Spring Lake; 2, Moon Lake (North Dakota); 3, Coldwater Lake; 4, Rice Lake. Location 5 is West Olaf Lake.

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.).

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.

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 $\text{cm}\cdot\text{yr}^{-1}$) were determined according to the age–depth model. The core sections were sampled contiguously at high resolution ($1\text{ cm} \approx 3\text{--}5\text{ yr}$) for both charcoal and loss-on-ignition (LOI) carbonate (30) for the interval spanning -45 to $4,500\text{ cal B.P.}$ Samples for pollen analysis were also collected from the core at $\approx 4\text{-cm}$ 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 <i>Salsola</i> pollen	24	N/A	70
CAMS-41153	<i>Scirpus</i> seeds	75	570 ± 40	594
CAMS-41154	Charcoal, <i>Scirpus</i> 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	$1,240 \pm 70$	1,159
CAMS-38084	Charcoal, <i>Typha</i> seed	372.7	$1,480 \pm 70$	1,379
CAMS-38085	<i>Rosa</i> seed	435.5	$1,770 \pm 50$	1,683
CAMS-32009	Charcoal, <i>Scirpus</i> , and <i>Chenopodium</i> seeds	487.5	$1,960 \pm 70$	1,908
CAMS-38087	Charcoal	520	$2,080 \pm 50$	2,048
CAMS-57143	Charcoal	667	$2,580 \pm 40$	2,722
CAMS-57145	Charcoal	746	$2,880 \pm 50$	3,009
CAMS-57140	Charcoal	1,567	$7,120 \pm 40$	7,936*

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

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. 4c). Previous