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EVIDENCE OF HOLOCENE CLIMATE CHANGE IN A NEBRASKA SANDHILLS WETLAND

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ABSTRACT—The Nebraska Sandhills consist of 50,000 km^2 of dunes, currently stabilized by vegetation. Radiocarbon dates of paleosols, blocked paleovalleys, and sand beds found in interdunal wetlands suggest that the Holocene had significant periods of dune reactivation. A paleoecological investigation was conducted in Jumbo Valley, NE, in an interdunal wetland known to contain sand layers interbedded with peat. The sedimentary record in two cores is continuous, except for some loss due to surficial burns. Macrofossils indicate that the late Pleistocene was cool and wet, with current vegetation establishing around 12,000 years ago. Sand and bulk density profiles reveal significant periods of dune activity in the intervals 9200-7000, 6400-5400, 4000-3000, 2700-2300, 2100-1800, and 950-700 calendar years before present (cal yr BP). Profiles also indicate four significant wet intervals: 6900-6500, 4700-4000, 5200-5000, and 1300-1000 cal yr BP. Dune activity prior to 6000 cal yr BP was most likely caused by drought, while after 6000 cal yr BP, increased frequency and severity of fires appear to have also contributed. This study reveals that the Sandhills have experienced many droughts, including as recent as 950-700 cal yr BP, that were more severe than any experienced in the last century.

Key Words: drought, dune reactivation, fire, Holocene climate, lithology, macrofossils, paleoecology

Introduction

The Nebraska Sandhills extend over 50,000 km^2 of central Nebraska and are the largest recently active sand sea in the western hemisphere (Fig. 1). The largest dunes of the Sandhills region are up to 130 m high (Swinehart 1990) and were formed by predominantly NW–SE winds (Ahlbrandt and Fryberger 1980). Smith (1965) hypothesized that the dunes formed during late Pleistocene arid episodes, with only minor reactivation occurring during the Holocene. Ahlbrandt et al. (1983), utilizing radiocarbon dates of organic matter overlain by eolian (windblown) sand, suggested that the bulk of the extant dunes were a product of several Holocene episodes of eolian activity. Later workers provided additional radiocarbon dates from paleosols (ancient soils), interbedded lake muds and peats within the dunefield, and optically stimulated luminescence (OSL) dates on dune sand (Swinehart 1990; Loope et al. 1995; Ponte 1995; Stokes and Swinehart 1997; Mason et al. 1997; Muhs et al. 1997; Loope and Swinehart 2000; Goble et al. 2004; Mason et al. 2004). These efforts suggest the following significant periods of Holocene eolian activity in the Sandhills: 700-900, 3200-4000, and 6000-9000 cal yr BP. The timing and frequency of past eolian deposition in the Sandhills is important for understanding the sensitivity of these landforms to future climatic conditions. Currently sufficient spring and summer rainfall promotes the growth of prairie vegetation (grasses, herbs, and forbs), which stabilizes the dunes. Precipitation ranges from 406 mm/yr in the western part to 610 mm/yr on the eastern portion. Present-day winds exceed the threshold velocity for sand movement (5 m/sec) about 50% of the time (Muhs et al. 1997) and only the current vegetation cover prevents reactivation of the dunes.

In the north-central Sandhills, at least 30 groundwater-fed wetlands accumulating peat are present between the elongate dunes (Steinauer et al. 1996). As much as 7 m of peat has built up in these wetlands, with basal dates of about 12,500 cal yr BP (Ponte 1995). Beds of fine to medium sand, up to 3 m thick, are interbedded with the peat and typically extend southward from the dune margin, thinning toward the center of the wetland (Fig. 2). Based on their geometry, distribution, and sedimentary structures, these sand beds have been interpreted as products of eolian sedimentation (Loope and Swinehart 2000; Mason et al. 2004).

The climatic implications of eolian sand interbedded with peat are significant. The wind moves sand primarily by saltation, a process whereby sand grains typically bounce less than 1 m above the land surface. While the effects of vegetation on sand transport are not well known, Wasson and

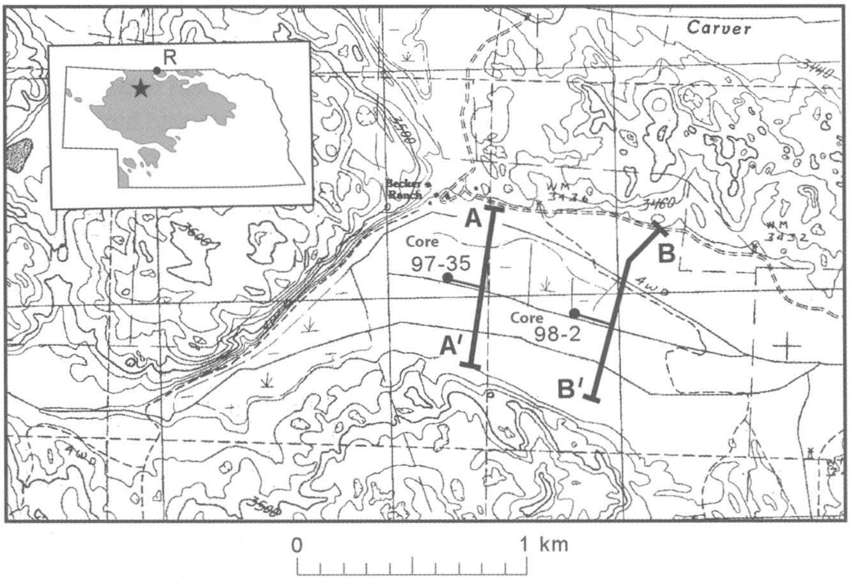

Figure 1. A topographic map of Jumbo Valley indicating core and transect locations, Insert at the top left shows the location of the Nebraska Sandhills (shaded), Jumbo Valley (star), and Rosebud (R) sites. Base map from USGS 1:24,000 Wolf Lake quadrangle. Contour interval 20 feet.

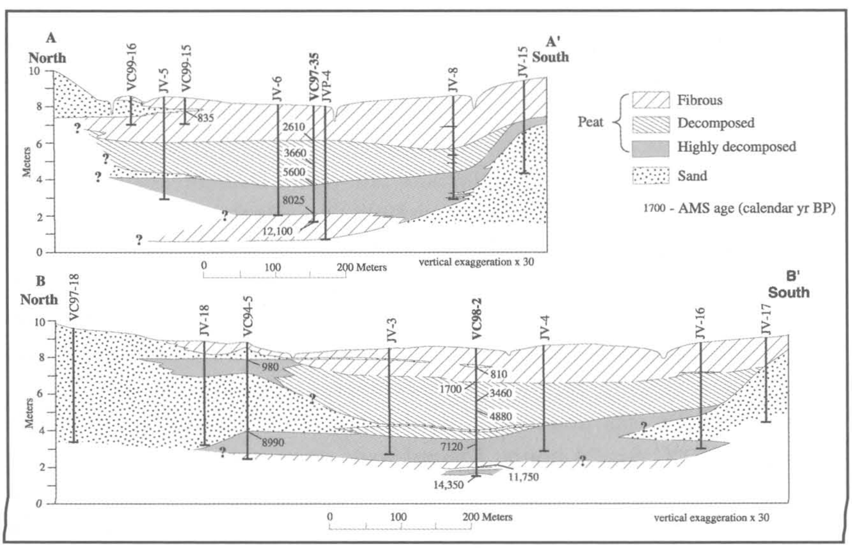

Figure 2. Jumbo Valley transects showing lithology from vibracores (VC) and selected AMS radiocarbon dates in cores 97-35 and 98-2. Radiocarbon dates in core 94-5 are from Ponte (1995). Cores 97-35 and 98-2 have been projected onto the transects.

Nanninga (1986) calculated that with more than about 40% vegetation cover, sand transport will be reduced to zero. Depending on the shape, size, and density of vegetation, there may be little sand movement with a vegetative cover as low as 30% (Cooke et al. 1993). For the sand to have spread hundreds of meters across what are now densely vegetated wetland surfaces, not only must the vegetation cover on the dunes be significantly reduced to supply the sand, but water tables must have been similarly low in the wetlands. However, water tables in these wetlands are quite stable, as they are buffered from local precipitation fluctuations by the large amount of groundwater stored under the large dunes (Bleed 1990; Harvey et al. 2001; Mason et al. 2004). A long-term drought more severe than any experienced in the last century would seem necessary for these wetland water tables to decline enough to allow sand transport by the wind. In addition, Ponte (1995) reported that some undegraded peats in Jumbo Valley contained between 20% and 60% (by weight), very fine to fine-grained sand composed primarily of quartz and feldspar. This sand must have been deposited out of suspension from nearby dune sources (Tsoar and Pye 1987; Fig. 1), rather than by saltation, given the restraints on sand movement and vegetation described above.

The objective of this research is to describe the macrofossils and lithology of two deep cores from the Jumbo Valley wetland. Our aim is to determine changes in vegetation type, peat decomposition, and amounts of sand and charcoal and relate these to paleoclimate, in particular, episodes of drought and wetness.

Methods

During the summers of 1997 and 1998 two vibracores (97-35 and 98-2) were obtained from near the center of Jumbo Valley (Fig. 2), a wetland then managed by the Nature Conservancy and Sandhills Task Force. The cores were described in the field, wrapped in plastic film, and stored at the University of Nebraska-Lincoln at 4°C. Subsamples were taken in 1998 and 1999 for bulk density, ash content, macrofossils, and radiocarbon dating. The ash content was determined by burning the sediments in a muffle furnace at 550°C for 24 hours. Macrofossils were washed with a 125 μm sieve and examined under a dissecting microscope (Nicholson 1993). Three relative estimates based on volume were taken and then averaged on the following macrofossil components: diatoms, charcoal, organic detritus, monocot tissues, bryophyte fragments, aquatic plant tissues, wood fragments, and spruce needles. Seeds were counted directly and equilibrated to

numbers found in 10 ml of sediments. Taxonomy for vascular plants follows Gleason (1968), and for mosses Ireland (1982), except *Drepanocladus*, which follows Janssens (1983). The geochronology of the cores was determined by ^{14}C accelerator mass spectroscopy (AMS) dates on a variety of materials (Table 1). Sampling for radiocarbon chronology was targeted at lithologic changes (sand beds in particular) and sampled intervals were 1 cm thick. If present, seeds and horizontal plant fragments were hand-picked for analyses; otherwise, bulk peat samples were submitted to the National Ocean Sciences AMS facility (NOSAMS) at Woods Hole. Sand percentage was determined by removing the nonmineral fraction (predominantly diatoms) from the ashed samples by wet sieving through a .062 mm sieve and treating the remaining sand fraction with 3% HF for 1 min to remove any sand-sized diatom frustules. The sample was then decanted and washed three times, dried, and sieved into very fine, fine, and medium sand-size fractions and weighed. Petrographic analyses of 30 samples showed the sand fraction consisted of about 75% quartz, 20% feldspar, and 5% chert and other rock fragments. For all analyses except AMS samples, core 97-35 was sampled at 10 cm intervals, whereas core 98-2 was sampled every 5 cm and at major changes in lithology. Organic detritus is the amorphous organic material remaining after decomposition, and the relative amounts can serve as proxy for relative rates of decomposition (Campbell and Flannigan 2000). Decomposition rates are controlled by vegetation type, fluctuations in the water table, depth to the anaerobic zone, and changes in mean annual temperature. Lowered water tables and higher temperatures will increase the rate of decomposition and thus the amount of organic detritus in the sediments. When water tables are higher, or temperatures are lower, the rate at which plant material enters the anaerobic layers is accelerated and the amount of organic detritus in the sediments becomes reduced (Ingram 1978). The relative amount of organic detritus was assessed by producing a ratio of the amount of organic detritus over the amount of decomposable material in each sample. Woody materials and the roots of woody plants were not included in the calculations because of the relatively recalcitrant nature of these substances.

Results

AMS Radiocarbon Dates

Both cores are well dated, with 22 AMS radiocarbon dates taken from core 98-2, and 11 from core 97-35 (Table 1; Fig. 3). Two out-of-sequence

TABLE 1
AMS RADIOCARBON DATES FOR CORES 98-2 AND 97-35

Core 98-2

Depth (cm)	Lab no.	Material dated	Radiocarbon age (^{14}C yr BP)	Calibrated age range (2 sigma)
128	OS-25451	Roots/seeds	880 ± 30	710-910
129	OS-25452	Peat	870 ± 35	690-910
207	OS-24453	Peat	1770 ± 40	1570-1820
208	OS-25018	Peat	1920 ± 60	1710-2000
219	OS-25455	Roots/seeds	2840 ± 45	2460-2780
305	OS-25456	Peat	3170 ± 60	3230-3550
305	OS-25457	Roots/seeds	3230 ± 40	3360-3560
324	OS-25458	Roots/seeds	3340 ± 45	3470-3690
326	OS-25459	Peat	3300 ± 45	3410-3640
341	OS-25525	*Scirpus* seeds	4300 ± 65	4640-5120
445	OS-26160	Peat	4830 ± 35	5470-5640
468	OS-27009	Peat	5050 ± 95	5610-5990
512	OS-26054	Roots	6210 ± 40	6990-7240
549	OS-26055	Roots	7560 ± 85	8180-8530
574	OS-26056	Roots	8370 ± 60	9150-9520
624	OS-26057	Roots	10050 ± 100	11250-12250
629	OS-26412	Monocot roots	10200 ± 60	11500-12350
659	OS-26384	Sedge/ grass / bryophytes	11600 ± 85	13150-15050
662	OS-25460	Wood/seeds	11800 ± 65	13450-15150
674	OS-25461	*Salix* bract /seeds/*Picea* needles	11950 ± 65	13650-15250
675	OS-26639	*Picea* needles	11850 ± 160	13450-15250
714	OS-25524	Wood/seeds	10700 ± 85	12350-13000

Core 97-35

Depth (cm)	Lab no.	Material dated	Radiocarbon age (^{14}C yr BP)	Calibrated age range (2 sigma)
99	OS-26163	Roots/seeds	100 ± 45	0-270
209	OS-26164	Sedge seeds	2560 ± 40	2470-2760
289	OS-26821	Roots/seeds	3150 ± 40	3260-3470
319	OS-26822	Peat	3410 ± 40	3500-3820
339	OS-25485	Roots/seeds	3570 ± 45	3710-3990
449	OS-27012	Peat	4830 ± 110	5300-5900
450	OS-25487	Peat	4860 ± 50	5480-5710
479	OS-28228	Peat	5410 ± 110	5940-6410
539	OS-26654	Peat	6060 ± 120	6600-7250
604	OS-25490	Peat	7230 ± 90	7850-8260
649	OS-25491	Peat	10250 ± 80	11550-12650

Note: AMS dates were calibrated sing Oxcal V3.5 (Ramsey 1998).

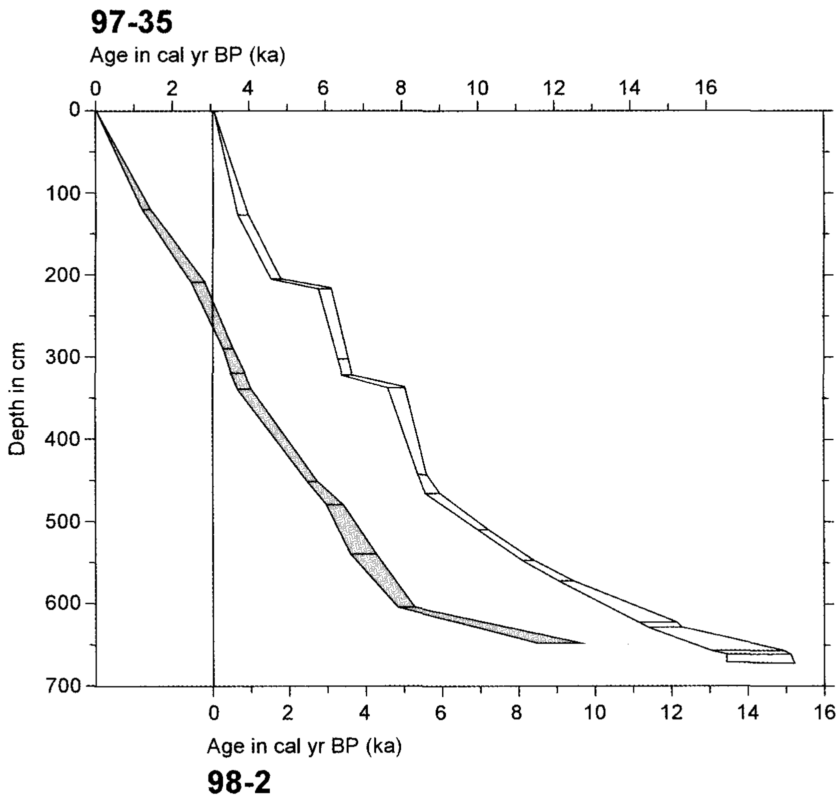

Figure 3. Age models for the cores derived from linear interpolation between calibrated ages.

dates were rejected, one from 98-2 (714 cm) and one from 97-35 (99 cm). To compare dates obtained on different materials, two sets of AMS dates (one on peat and one on roots and seeds) were determined for each of two intervals (219 and 305 cm) in core 98-7. Although the ^{14}C dates don't overlap at the 95% (2 sigma) level for the 219 cm interval, they do come closer when calibrated. The 305 cm samples overlap at the 65% (1 sigma) level for both uncalibrated and calibrated dates. As another check on AMS dating, successive 1 cm intervals were sampled from four intervals (128-129, 207-208, 324-326, and 674-675 cm of core 98-2; Table 1). Intervals 128-129, 324-326, and 674-675 overlap at 1 sigma, and 207-208 overlaps at 2 sigma.

Close examination of the age model for core 98-2 suggests two disconformities or breaks in peat sedimentation. The youngest occurs between 208

and 219 cm, or about 1700 and 2900 cal yr BP, and is preceded by one between 326 and 340 cm, or about 3500 and 4900 cal yr BP. These breaks may reflect a local decrease in organic matter accumulation or possibly removal of peat by fire. Charcoal is present in both layers, suggesting that the peat surface may have burned at least twice in the history of this wetland. Since core 97-35 was not dated using as close a spacing as core 97-2, these breaks in sedimentation are not obvious. However, burnt seeds of wetland plants were found in core 97-35 at a depth of 311 cm (about 3500 cal yr BP), suggesting that fire may have destroyed some peat in the wetland at this time. Fire is known to remove surface peat (Turetsky and Wieder 2001), particularly in wetlands with low water tables, but burn patterns in any given fire can be patchy.

The age models (Fig. 3) show that peat accumulation between 0 and 475 cm (the last 5800 years) was about 80 cm/1000 yr. Below 475 cm the accumulation rate drops to about 30 cm/1000 yr, despite a significant amount of mineral sand accumulation. The rate below 475 cm has probably been reduced by peat degradation and compaction.

Botanical Profiles

Core 98-2. Basal sediments, between 662 and 715 cm depth (13,450-15,250 cal yr BP), contain abundant spruce needles, wood, bryophyte fragments (*Calliergon, Drepanocladus*), and seeds of the following genera: *Menyanthes, Lycopus, Ranunculus, Typha, Eleocharis*, and *Scirpus* (Fig. 4). This indicates that a wetland with some open patches of water existed, surrounded by spruce trees. From 662 to 640 cm, fewer spruce needles are present and fossils of aquatic plants such as *Dulichium, Najas, Potamogeton, Carex*, and *Eleocharis* are numerous. Above 640 cm *Drepanocladus* is the dominant macrofossil along with *Carex* and grass remains, an assemblage more typical of a boreal fen. The most common macrofossils preserved in this profile are roots of various sedges and grasses (monocots). Monocot roots were not an abundant macrofossil in the basal sediments. Abundance increases above 700 cm, declines significantly from 600 to 440 cm, then gradually increases again above 400 cm. Currently, the abundance of this macrofossil in surface layers is reduced compared to older sediments (100 to 400 cm deep). Contemporary wetland vegetation appeared above 620 cm (11,250-12,250 cal yr BP). Macrofossil remains of the current vegetation are the roots of sedges and grasses (monocots), seeds of *Typha, Scirpus*, and *Eleocharis*, and less abundantly, wetland herbs (*Ranunculus, Mentha, Sagittaria*, and *Viola*).

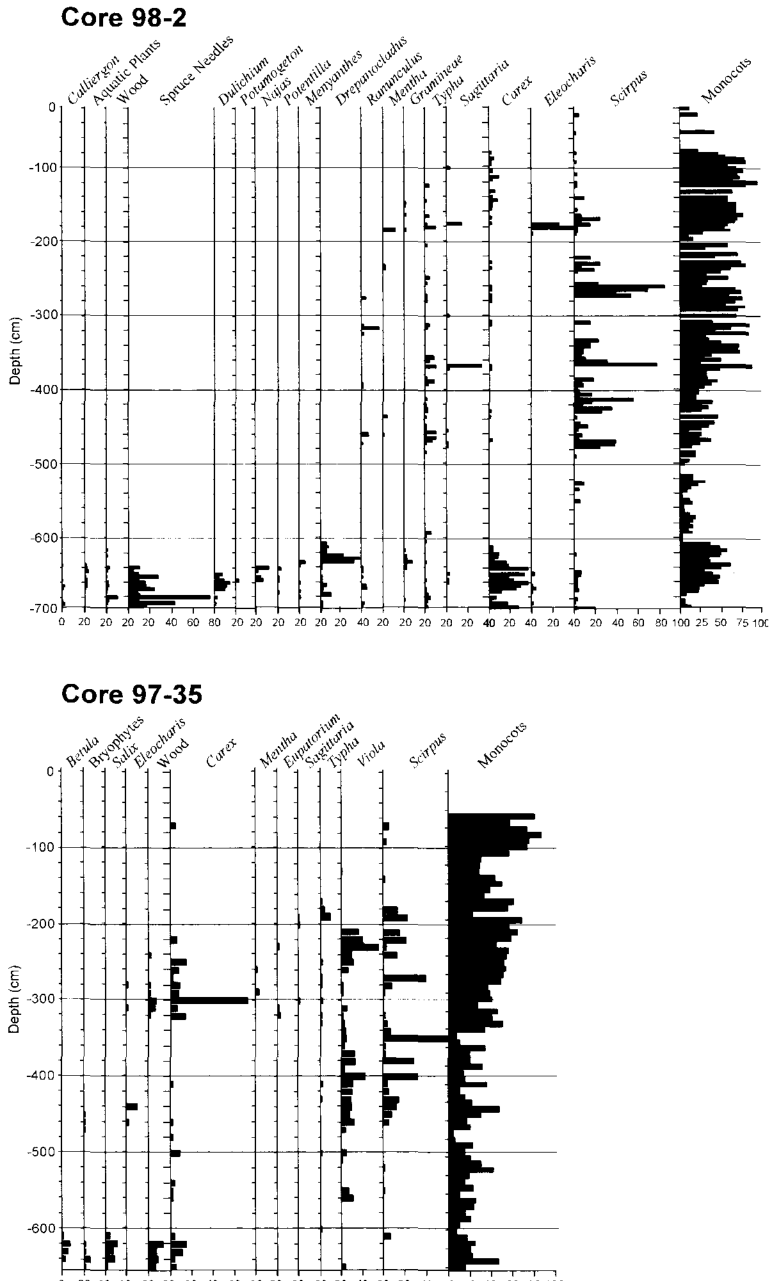

Figure 4. Macrofossil profile of cores 98-2 and 97-35. *Calliergon*, aquatic plants, wood fragments, spruce needles, bryophytes, *Drepanocladus*, and monocot roots and tissue, are relative percentages by volume of macrofossil material. All other macrofossils are absolute counts of seeds or fragments preserved in 10 ml of peat.

Core 97-35. The oldest sediments (about 12,550 cal yr BP) contain a fossil assemblage of *Betula*, bryophytes, *Salix*, *Carex*, *Viola* seeds, wood fragments, and monocot roots, suggesting a shrub- and *Carex*-dominated community (Fig. 4). Wetland vegetation above 600 cm (7850-8260 cal yr BP) resembles the modern community and consists of *Eleocharis*, *Carex*, *Mentha*, *Eupatorium*, *Sagittaria*, *Typha*, *Viola*, and *Scirpus* seeds mixed with abundant monocot roots, and some wood. An increase in *Carex* seeds occurs between 220 and 320 cm, while *Viola* and *Scirpus* seeds reach their highest from 190 to 300 cm and from 340 to 460 cm. Monocot roots increase in abundance toward the surface.

Throughout the last 12,000 years, core 97-35 reflects a relatively drier site than that of core 98-2. It does not contain as many seeds or as many species indicative of higher water levels such as *Typha*, *Sagittaria*, *Eleocharis*, and *Scirpus*.

Lithologic/Sediment Profiles

To be classified as a histosol, a peaty soil must contain more than 20%-40% organic matter or less than 60%-80% ash (U.S. Department of Agriculture 1975). The sediments in these cores typically contain over 60% ash (Fig. 5), most of which is due to the abundance of mineral sand and siliceous diatom frustules. Core 98-2 contains more than 80% ash in the lower portion of the core, between 6000 and 12,000 cal yr BP, while core 97-35 has more than 80% ash between 3200 and 4000 and between 5500 and 10,000 cal yr BP. Charcoal fragments, probably originating from local upland fires, add to the ash content of the material and are more abundant after 6000 cal yr BP in both cores. The organic detritus ratio in core 98-2 suggests higher rates of decomposition occurring at the surface, and an extremely high peak occurs just before 12,000 cal yr BP. In core 97-35 the interval between 4000 and 6500 shows the highest decomposition of peat.

Discrete sand layers and sandy peat intervals were targeted for AMS dating (Figs. 3 and 5). In core 98-2, the first significant sand layer occurs between 128 and 135 cm and is dated at between 690 and 910 cal yr BP. This sand layer was studied in detail by Mason et al. (2004), who concluded, based on more than 20 AMS dates, that the sand layer was deposited between 650 and 950 cal yr BP. The next significant sandy interval dates from about 1800-2100 cal yr BP. Below the first hiatus in the core there is a major sandy interval dating between 3000 and 4000 cal yr BP. This is a minimum age, as the second hiatus occurs from 4000 to 4700 cal yr BP. Another sandy

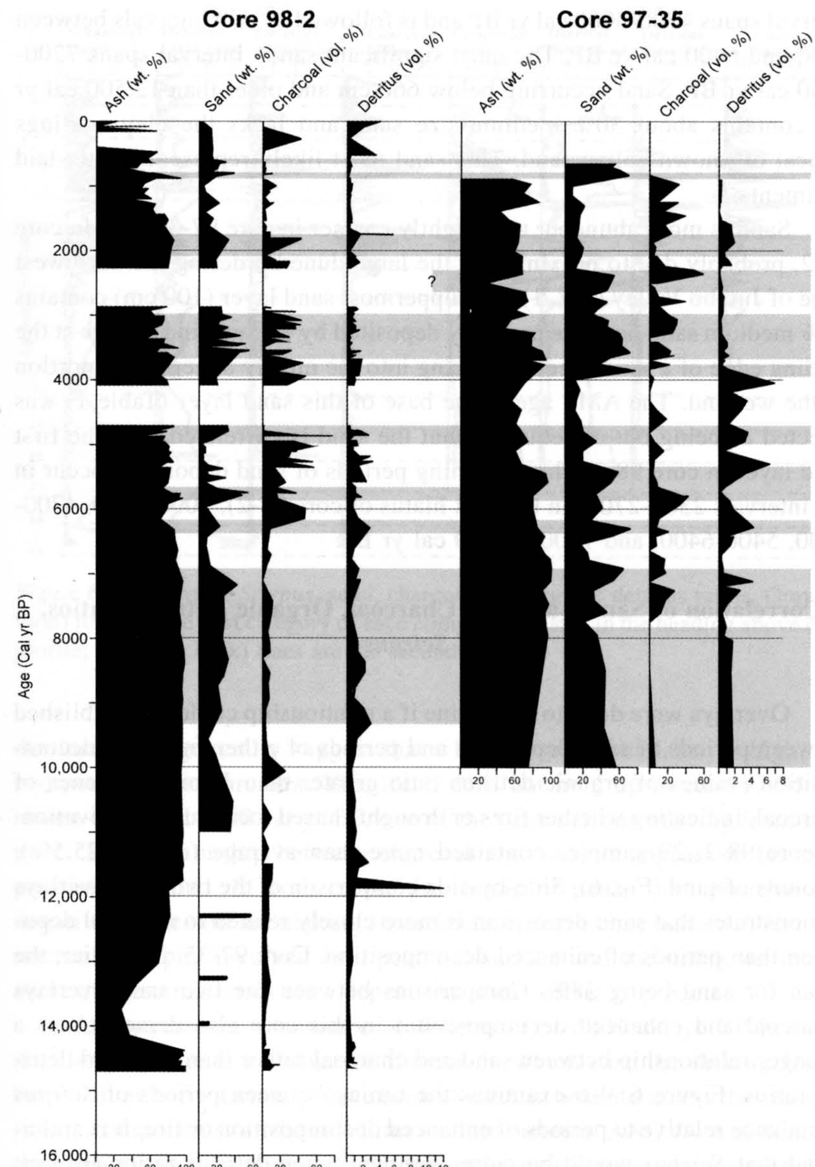

Figure 5. Lithological profiles of cores 98-2 and 97-35, showing amounts of ash, sand, charcoal, and organic detritus ratios plotted against calibrated radiocarbon age derived from the age models. Ash and sand are percentages by weight. Charcoal and organic detritus ratios are relative measures based on the volume of macrofossil material present in the core.

interval spans 4700-5000 cal yr BP and is followed by two intervals between 5700 and 6400 cal yr BP. The most significant sandy interval spans 7200-9200 cal yr BP. Sand occurring below 660 cm and older than 12,500 cal yr BP contains about 30% medium-size sand and lacks the clay coatings typical of known eolian sand. This sand most likely represents water-laid sediments.

Sand is more abundant and slightly coarser in core 97-35 than in core 98-2, probably due to proximity to the large dune bordering the northwest edge of Jumbo Valley (Fig. 1). The uppermost sand layer (100 cm) contains 10% medium sand and was probably deposited by eolian wind ripples at the leading edge of a sand sheet advancing into the mostly unvegetated portion of the wetland. The AMS age at the base of this sand layer (Table 1) was rejected as being out of sequence, but the sand is correlated with the first sand layer in core 98-2. The remaining periods of sand deposition occur in the intervals 2300-2700 (in the first hiatus of core 98-2), 3000-4000, 4700-5000, 5400-6400, and 7000-10,000 cal yr BP.

Correlation of Sand Layers to Charcoal, Organic Detritus Ratios, and *Scirpus*

Overlays were done to determine if a relationship could be established between periods of sand deposition and periods of either enhanced decomposition (values of organic detritus ratio greater than 1) or occurrence of charcoal, indicating whether fires or drought caused local dune reactivation. In core 98-2, 29 samples contained more than average (mean = 25.5%), amounts of sand (Fig. 6). Side-by-side comparison of the two sand overlays demonstrates that sand deposition is more closely related to charcoal deposition than periods of enhanced decomposition. Core 97-35, is sandier, the mean for sand being 38%. Comparisons between the two sand overlays (charcoal and enhanced decomposition) in this core also demonstrates a stronger relationship between sand and charcoal rather than sand and detritus ratios. Figure 6 also examines the timing between periods of *Scirpus* abundance relative to periods of enhanced decomposition or fire. It is anticipated that *Scirpus* would be more abundant when detritus ratios are low, indicating periods of reduced decomposition suggesting cooler, wetter climate, and raised water levels in the wetland. Charcoal abundance may be positively related to *Scirpus* because of increased vegetation growth providing fuel and hence a source of the charcoal, or negatively through increased drought and higher fire frequencies. In both cores, the overlays of *Scirpus* to

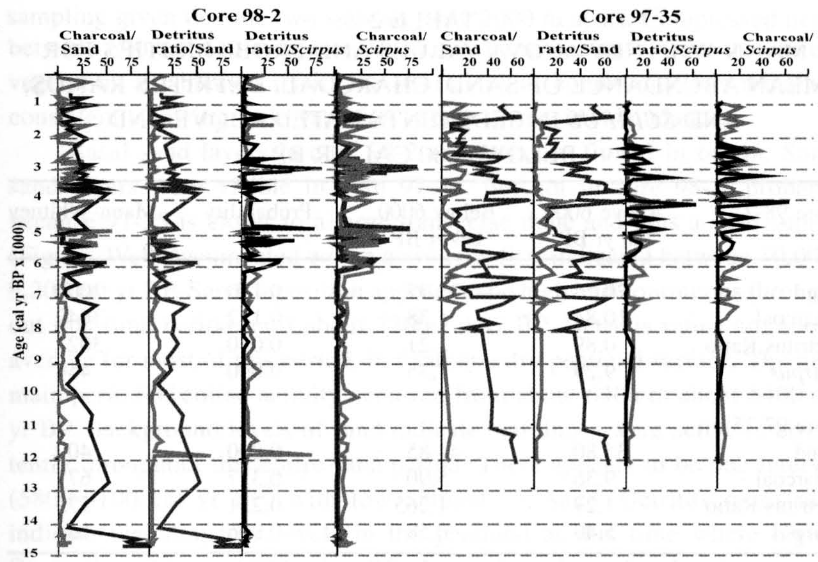

Figure 6. Overlays of *Scirpus*, sand, charcoal, and organic detritus ratios. Gray (or light) lines are the first category of each comparison listed in the heading above each profile; black (or dark) lines are the second.

detritus ratios generally suggest that when *Scirpus* abundance is high, decomposition rates are low. This trend does not hold up in core 97-35 between 4000 and 5500 cal yr BP, one of the time periods missing from core 98-2. The relationship between charcoal and *Scirpus* appears to be more positively related. In both cores, the timing of peaks both positive and negative is often offset, making statistical correlation impossible. Given the microtopography involved in a peatland surface and the unknown movement of these materials after deposition, some offset is expected.

An increase in abundance of *Scirpus* after 6000 cal yr BP in these profiles may signal a change in climate, in which case the driving forces behind dune activation may have been altered. In order to assess the changes in key components, a Mann-Whitney nonparametric ANOVA was done on the amounts of sand, charcoal, detritus ratio, and *Scirpus* above and below 6000 cal yr BP (Table 2). In core 98-2, the amount of detritus and *Scirpus* are significantly different (probability 0.01 and 0.000, respectively) between the two time periods, with higher decomposition below (mean = 1.21 below, 0.89 above) and more *Scirpus* above 6000 cal yr BP (mean = 1.35 below, 9.29 above). In core 97-35, sand and *Scirpus* values differ (probability =

TABLE 2
MANN-WHITNEY ANOVA VALUES AND PROBABILITIES FOR MEAN ABUNDANCE OF SAND, CHARCOAL, DETRITUS RATIOS, AND *SCIRPUS* IN SEDIMENTS DATED ABOVE AND BELOW 6000 CAL YR BP

Core 98-2	Above 6000 cal yr BP	Below 6000 cal yr BP	Probability	Mann-Whitney
Sand	20.25	35.37	0.140	2000
Charcoal	10.84	5.38	0.182	3649
Detritus Ratio	0.89	1.21	0.010	3021
Scirpus	9.29	1.35	0.000	454
Core 97-35				
Sand	35.80	44.85	0.000	409
Charcoal	9.36	5.90	0.357	671
Detritus Ratio	1.27	1.265	0.251	575
Scirpus	5.40	0.58	0.006	164

0.000, and 0.006, respectively), sand being more abundant below 6000 cal yr BP (mean = 44.85% below, 35.80% above) and *Scirpus* more abundant above (mean = 0.58 below, 5.40 above). Charcoal levels are not significantly different above or below 6000 yr BP in either core.

Discussion

Vegetation changes seen in the cores from Jumbo Valley parallel macrofossil changes found by Watts and Wright (1966) and Wright et al. (1985) at Rosebud in the north-central part of the Sandhills (Fig 1). A shallow-water reed-swamp (*Carex*, *Sparganium*, and *Myriophyllum*) community developed during the early Holocene (12,600 ^{14}C yr BP), which was followed by a wetter phase (*Najas*, *Typha*, *Potamogeton*, *Ranunculus*, and *Utricularia*) before the onset of prairie conditions occurred at 9000 ^{14}C yr BP. At Jumbo Valley, basal macrofossils contain *Picea* and *Carex*, suggesting a wet forested meadow that became wetter, supporting aquatic plants with more northern species such as *Menyanthes* and *Drepanocladus*. A floral community similar to that at present appears to have been established around 10,500 cal yr BP (600 cm) for core 98-2, and a little later at core 97-35 (620 cm, ~9000 cal yr BP). This time difference may be an artifact of

sampling given that the two sites are only 2000 m apart. Compressed peats between 600 and 650 m in core 97-35 may be responsible. Once the current vegetation established itself, the overall plant community has remained consistent, showing little variation except in species abundances.

Basal sand layers in core 98-2 are probably fluvial in origin. Some sand layers were visible in core 97-35, but not in core 98-2, probably because 97-35 is closer to a large transverse dune and thus a sand supply (Fig. 1). Well-documented eolian activity is first indicated between 10,000-9,200 cal yr BP. Sand deposition appears to be high and continuous throughout this time period until about 7200 cal yr BP. Detritus ratios are above average for most of this period, indicating a dry peatland surface. The next main period of eolian activity occurred from about 6400 to about 5400 cal yr BP. Background levels of sand indicate that dunes were active intermittently throughout this entire time period. There appears to be one interval (5800-6100 cal yr BP) with low amounts of sand. Detritus ratios also indicate that moisture levels in the peatland at this time where highly fluctuating. Prior to 6000 cal yr BP, charcoal levels are low but decomposition is high (core 98-2), indicating that drought played a large role in dune reactivation at this time. From 6000 cal yr BP onward, lower decomposition (core 98-2) and the presence of *Scirpus* suggest that water levels in the peatland became higher. Several intervals (1000-1300, 4000-4700, 5000-5200, and 6500-6900 cal yr BP, in particular), have two out of the three following combinations: low sand percentages, low detritus ratios, and a peak in *Scirpus*. *Scirpus* is a species that is an emergent macrophyte requiring drought and exposed sediments to germinate, but afterwards withstands submersion in up to 80 cm deep water. Under these conditions it will vegetatively reproduce (Gates 1948; van der Valk 1978; Welling et al. 1988). Subsequent periods of drought exposing the rhizomes of the plant after germination will cause rapid decline of this species (Gates 1948). Thus, the intervals 1000-1300, 4000-4700, 5000-5200, and 6500-6900 may represent periods when moisture was abundant and the dunes stable and heavily vegetated.

The interaction between climate, fire, and vegetation is a complex three-way relationship. Although an increase in warm, dry weather may lead to an increase in fire frequency, so may an increase in vegetation by providing fuel (Campbell and Flannigan 2000). In addition, most fires occur during the few days with extreme fire weather conditions during either a wet or dry season, and not all vegetation provides the same amount of fuel. Flannigan and Harrington (1988) found that the frequency of dry

spells, not total precipitation, was the most significant meteorological factor promoting fires, while Campbell and Flannigan (2000) found evidence for increased fire frequency with either moist or dry conditions. In sediments younger than 6000 cal yr BP in Jumbo Valley, it is likely that moister climate led to greater vegetation growth, providing more fuel, which subsequently increased the frequency and intensity of local burns during dry spells. Conversely, the lack of *Scirpus* in sediments older than 6000 cal yr BP probably represents a period of greater aridity, with less moisture to support *Scirpus* or provide fuel for repeated fires.

Only two methods exist for determining the frequency of fire through the assay of charcoal, a chemical assay method (Winkler 1994) or direct counts or measurements of charcoal fragment size. Small pieces of charcoal (fine fraction) are thought to reflect regional activity and larger charcoal fractions represent local fires (Campbell and Flannigan 2000). The charcoal in this study was counted with a dissection microscope and is probably of local rather than regional origin and represents a fire history of nearby areas.

Researchers have suggested that dune reactivation in western North America occurred during the late Pleistocene and in the early to mid-Holocene (Holliday 1989; Wells et al. 1990; Spaulding 1991; Loope et al. 1995; Stokes and Swinehart 1997) in response to warmer, drier climates (Barnosky 1989; Wells et al. 1990; Haynes 1991; Loope et al. 1995). Some studies have also demonstrated a significant period of sand dune reactivation around 3000 cal yr BP (Wells et al. 1990; Muhs et al. 1997), as well as around 700-950 cal yr BP (Ahlbrandt et al. 1983; Muhs et al. 1997; Goble et al. 2004; Mason et al. 2004). This study is somewhat unique in that it provides a nearly continuous record of dune activation and stability over the past 10,000-13,000 cal yr BP in the Sandhills, allowing a perspective not available in other studies. It appears that eolian activity, not inactivity, is characteristic of the Holocene, with significant episodes occurring about 9200-7000, 6400-5400, 4000-3000, 2700-2300, 2100-1800, and most recently 950-700 cal yr BP (Fig. 7). A coarse image of the magnitude and duration of dune activity spanning the entire Holocene has been presented by Stokes and Swinehart (1997). Our study gives finer resolution to the emerging picture of Holocene eolian activity, presenting evidence that in total, roughly 6,000 of the past 10,000 years have been dominated by dune activity. In addition, four major wet periods occur in the intervals 6900-6500, 5200-5000, 4700-4000 and 1300-1000 cal yr BP. These time periods are marked by a noticeable lack of sand in the peat and macrofossils indicative of higher water levels in the wetland. The only other study from the region describing eolian activity spanning the Holocene is a quartz dust

profile from Elk Lake, MN (Bradbury et al. 1993; Clark et al. 2002). Two major periods of dry and windy conditions are interpreted to have occurred; the first from 8400 to 5500 ka and the second from 4800 to 4400 ka. Two shorter periods at around 9000 and 900 ka are also suggested by the quartz data. The Elk Lake data also indicate that eolian dust transport in the north-central United States during the postclimatic optimum (younger than 4000 cal yr BP) was much lower overall than prior time periods. In both profiles there is evidence that finer cycles are imbedded in periods of high dune activity. Clark et al. (2002) calculated a 100-130 yr periodicity for these finer cycles from Kettle Lake, ND. Millennial-scale rhythms (1450 yr periodicity) have been described for peatlands in western Canada (Campbell, Campbell, et al. 2000) where dry periods occur approximately every 2000 years beginning with the present. These intervals are not synchronous with suggested dry periods in this study.

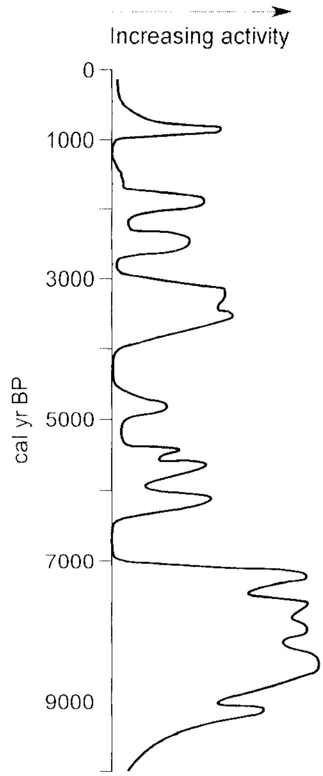

Figure 7. Qualitative interpretation of eolian activity and inactivity in the Holocene based on data from Jumbo Valley cores.

Miao et al. (in press) describe a loess (windblown silts) record from western Nebraska and Kansas that spans the early to middle Holocene. They infer that the major Holocene dunefield activity upwind from the loess deposits occurred from about 9500 to 6500 cal yr BP based on a zone of coarse-textured loess with minimal paleosol development. This agrees well with our data from Jumbo Valley.

Fire is a major initiator of dune activity. Fire frequency and severity is related to both climate and fuel loading. Drought-related fires have been shown to initiate dune activity in the tropics and in Quebec (Filion 1984). Fire frequency can, however, either decrease or increase in relationship to changes in vegetation. Most often under abundant vegetation, reduced moisture or drought will increase the frequency of fire (Brown and Sieg 1999), or flux quantities of charcoal (Camill et al. 2003). However, when fires are fuel limited such as in xeric grasslands, dry periods have been known to reduce

the grassland productivity, further reducing fire frequency as fuel loads are low and discontinuous (Clark et al. 2002; Umbanhowar 2004). In contrast, woodland expansions have been demonstrated to either increase (Campbell, Last, et al. 2000; Camill et al. 2003) or decrease (Clark et al. 2001) the fire regimes, depending upon the interplay between fuel and moisture. Umbanhowar (2004) examined the fuel-limited hypothesis by comparing a 11,000-year profile of charcoal and ostracod Ca/Mg ratios from mixed-grass prairie lakes in North Dakota. His results did not support a tight connection between climate and charcoal, but suggests that a strong link occurs. Plausible reasons given by Umbanhowar for the lack of a significant correlation are shifts in the relative composition of C_3 and C_4 grasses, ambiguities in the relationship between charcoal and ostracod Ca/Mg ratios, and the impact grazers have on fuels. Mangan et al. (2004) modeled drought, fire, and grazing impacts on dune stability in the Nebraska Sandhills using the Century model, and found that a decrease in plant productivity occurred only when fire, grazing, and mild drought occurred simultaneously.

Conclusions

Six major periods of eolian activity are recorded in the sediments of Jumbo Valley during the last 10,000 years. Fire and drought are likely to both be contributors to dune reactivation during the Holocene, either separately or in concert depending on variations in climate and weather. From this study it appears that moister climates in the latter part of the Holocene (after 6000 cal yr BP) may have increased fire frequency by adding fuel. Drought appears to have been a more significant causal agent during the early Holocene (before 6000 cal yr BP). There have been four significant wetter and/or cooler periods resulting in dune stabilization and a reduction in the levels of sand transported into Jumbo Valley by suspension.

The relationship between climate, vegetation, drought, and fire frequency is complex, and researchers are now beginning to recognize that fire frequency can increase with either lower or higher amounts of moisture depending upon the relationship with fuel. Our study suggests that the relationship between climate, vegetation, and fire has shifted during the Holocene with drought playing a greater role in the late Holocene and biomass productivity in the early Holocene. As with Umbanhowar (2004), correlations between charcoal and measures of drought, or charcoal and dune activity, are not significant because of the complexity of the relation-

ship and the shifting environmental conditions that have occurred during the Holocene.

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