Complex disturbance-driven reactivation of near-surface sediments in the largest dunefield in North America during the last 200 years

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ABSTRACT: Understanding the historical activity of desert dune systems is important for identifying both the palaeoenvironmental drivers of change and the likelihood of future reactivation. Dating dune sediments in the Nebraska Sandhills has identified regional-scale dune activity over centennial and millennial timescales during the Holocene, occurring at 9.6–6.5, 3.8 and 2.5 ka, and most recently spanning the Medieval Climatic Anomaly 1050–650 years BP. These periods have been interpreted as palaeoclimatic evidence of intense aridity lasting decadal and centennial timescales. A detailed record of dune activity in the historical period, since EuroAmerican arrival, is lacking however, yet important for interpreting the role of human agency amongst the factors influencing disturbance. Without a high-resolution record of short-term, historical, local sediment mobilization, it is not possible to distinguish the environmental factor(s) responsible for local reactivation. In this paper, the individual drivers of vegetation disturbance are reviewed and presented alongside a luminescence-dated reconstruction of dune sediment deposition ages. This allows an integrated assessment of the relationship between drivers and environmental response over a recorded period. We focused our investigation on the aeolian reactivations of surface dune sediments and blowout features around the Niobrara Valley Preserve in the northern limits of the Nebraska Sandhills. Results show a near-continuous (within uncertainties) timeline of local reactivation across the sites studied, with variation between the individual features indicating that both regional (i.e. climatic) and local (i.e. land use) forcings contribute to surface disturbance. © 2019 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd.

KEYWORDS: Nebraska Sandhills; dunefield disturbance; deposition; OSL; grazing

Introduction

The Nebraska Sandhills, currently stabilized by extensive perennial warm-season grasses (Bleed, 1998), is the largest aeolian dunefield in North America (Ahlbrandt and Fryberger, 1980; Loope and Swinehart, 2000) covering 57,000 km². Previous research, using optically stimulated luminescence (OSL) dating, has identified multiple Holocene dune reactivations in the Great Plains, including at 9.6–6.5, 4.4–3.4 and 2.3 ka, with the most recent regional-scale period spanning the Medieval Climatic Anomaly (MCA) 1050–650 years BP (see overview in Halfen and Johnson, 2013). Over millennial and centennial timescales, the regional dunefield reactivations have been interpreted as a proxy palaeoclimatic signal of decade or longer megadroughts. Over more recent timescales, localized aridity events have been identified in a range of proxies including lake sediments (Schmieder et al., 2011), tree ring records (Cook et al., 2004) and the OSL-dated reactivation profiles of aeolian sediments (Forman et al., 2005). These shorter events probably increased the extent of patchy, local reactivation of the dunes in the Sandhills (Muhs and Holliday, 1995).

Modelling studies, however, have suggested that over shorter timescales, surface sediment disturbance could be triggered by a more complex array of factors beyond precipitation reductions. Using the CENTURY ecosystem model, Mangan et al. (2004) suggested that the additive effects of fire or grazing in combination with mild drought conditions can create conditions that reduce biomass and favour aeolian disturbance of the dune surface. Stubbendieck (2008) also highlighted that a combination of factors can have a greater impact on vegetation than drought alone, emphasizing the need for a more holistic approach to assessments of disturbance, which includes anthropogenic factors (Wolfe et al., 2007). Barchyn and Hugenholtz (2013) summarize causal disturbance forces in a conceptual model that integrates both natural and anthropogenic drivers of devegetation and thus aeolian erosion. The model hypothesizes that a stabilized surface is reactivated following a disturbance event, where the term ‘disturbance’ refers...
to the rate of removal or destruction of vegetation by fire, grazing and human manipulation of the environment, as well as precipitation and drought. However, a high-resolution study with empirical disturbance datasets has not yet been used to test the role of multiple factors in influencing the sensitivity of vegetated dunes to ongoing surface activation in the Great Plains.

In principle, if we have data for both forcing factors and episodes of surface mobilization, it should be possible to connect disturbance events with an environmental response. However, the capacity to identify a coherent relationship between empirical measurements of environmental response and drivers has not fully been assessed. By studying sediment response over the recent historical period, during which detailed climatic, land use and wildfire disturbance data have been recorded, we can potentially identify the drivers of environmental change and how the site responded. As we expect drivers of environmental disturbance to change under future climates (e.g. Mangan et al., 2004), it is important to identify a method that allows us to link drivers of environmental destabilization with responses, facilitating the prediction of future reactivation potentials.

Approach

Whilst anthropogenic activity is acknowledged as a contributory driver of disturbance in dryland aeolian systems, the relative significance and quantification of human versus natural factors is understudied. In North China, a series of studies (e.g. Chun, 2018; Zhang and Huisingh, 2018; Xu et al., 2019) have looked at the relative contribution of climate change and human activities in driving changes in dune activity, but similar analyses have not been extended to other dryland environments, nor to time periods before the availability of recurrent satellite imagery in the 1970s and 1980s. In this study, we use empirical data from the sedimentary record to test relationships between disturbances and surface sediment mobilization in the Niobrara Valley Preserve and surrounding ranches in the northern Nebraska Sandhills (Figure 1).

To reconstruct a history of environmental reactivation, a chronology of surface sediment deposition is produced using intensive near-surface sediment sampling across dune blowouts, changepoint analysis (Killick and Eckley, 2014; Buckland et al., 2018) and high-resolution quartz OSL dating. Then, a record of potential disturbances in the region is gathered from climatic and land use datasets across the Sandhills. Without a direct measure of long-term vegetation cover, existing research in the Central Great Plains and prairie grasslands (e.g. Milchunas et al., 1989; Biondini et al., 1998; Forman et al., 2001; Mangan et al., 2004; Stubbendieck, 2008; Grassini et al., 2010; Mangan et al., 2004; Milchunas et al., 1989; Schmieder et al., 2011, 2012; Stubbendieck, 2008) has identified levels of historical precipitation, grazing, wildfire and land use changes as key factors that affect levels of vegetation. Records of these parameters are gathered from a range of instrumental and archival datasets providing information on precipitation, land use change, wildfire occurrence and regional drought.

In this study, we set out to use shallow ages from near-surface dune sediments in combination with data on late 19th to early 21st-century climate and disturbances to identify which combination of climatic events or disturbances was most important in initiating devegetation and sediment mobilization. However, results show that since disturbance and drought are chronic throughout the period of study, and disturbance events are short relative to the errors of dating and to the response time of the system, a near-continuous timeline of localized patchy surface reactivation is observed across the sites.

Study Site and Methods

Study area

Located on the south side of the Niobrara River in the northern limits of the Nebraska Sandhills, the southern section of the Niobrara Valley Preserve (NVP) and surrounding ranches used in this study cover an area c. 30 km² (Figure 1). The area receives c. 550 mm annual rainfall (1905 AD to present) (mean 558 mm, standard deviation 152 mm), with most of the rainfall occurring from April through to the end of August, and c. 960 mm annual snowfall occurring from October to May. Prevailing winds from the south take place during the summer months (May to September), with stronger winds from the northwest dominating in the winter. The local area has been occupied by EuroAmerican settlers since the late 19th century and the introduction of the railroad through Brown County. Prior to that, the understudied archaeological record of the region suggests Native Americans used the Sandhills primarily for hunting and gathering, although some sites in the central and eastern Sandhills contain features that suggest semi-permanent habitation and agriculture (Napier et al., 2018). Cattle ranching has remained the dominant land use in the local area since EuroAmerican occupation. A good record of recent historical events, coupled with access to existing instrumental datasets and high environmental dose rates (e.g.
Stokes and Swinehart, 1997; Goble et al., 2004; Muhs, 2004; Forman et al., 2005; Miao et al., 2007) to aid in the OSL dating of young sediments, meant that this specific location was suitable for this research study.

Along with Google Earth imagery from 1993 onwards, archived aerial photography for 1939, 1954 and 1968 was used as a source of time-series data on vegetation cover change and observed locations of surface sediment exposure and activity. These images provide excellent spatial coverage of all the areas included in the field sampling programme and show bare sand very clearly, indicating areas where significant sediment movement is typically occurring, given the Sandhills wind regime.

## Dunefield disturbance record

Based on historical photography and geomorphological interpretations in the field, sampling aimed to capture: aeolian landscape features representative of the wider system (i.e. the NVP region), locations with variability in land use histories (i.e. different grazing histories) and locations identified in aerial imagery as having previously been disturbed. In total, six sites were selected for sampling (Figures 1A–F). As sedimentary profiles in dunefield environments are inherently discontinuous (Bailey and Thomas, 2014), multiple sediment cores were extracted at each site for OSL dating to ensure that zones of erosion and deposition within the system were captured (Buckland et al., 2018) and a fuller chronology produced (Figure 1). At each sample point, 50-cm black opaque plastic tubing was hammered vertically into the surface sediments, retrieved and capped. The focus on sampling the upper 50 cm of sediment units was not to provide a full or long chronology of Sandhills accumulation, but to create a high temporal resolution record of activity that could be analysed alongside the proxy records of environmental disturbance. A total of 17 cores were returned to the Oxford Luminescence Dating Laboratory for analysis (Table I).

Samples were prepared and analysed under subdued orange light. The plastic tubing was split lengthwise and sediments subsampled at centimetre scale, dried and mounted onto single 8-mm diameter discs for initial changepoint analysis. Changepoint analysis, which allows significant breaks in sedimentation to be identified statistically, was applied to all subsamples from the 17 sediment cores prior to selection of subsamples for full-preparation luminescence dating (Buckland et al., 2018). With potentially up to 850 cm of sediment available for dating, a method was needed to more robustly justify the depths selected for focusing luminescence dating efforts. In sedimentary settings with high quartz content and little dose rate variability, changepoint analysis of unprepared $L_x/T_x$ measurements can be used to statistically identify locations in the depth profile where the more significant changes in the equivalent dose (i.e. a proxy for age) occur, allowing us to make a more informed decision about where to focus the dating resource (Buckland et al., 2018). This method led to a range of mid-section and end-point samples being identified from the cores as representative of dune activity phases and appropriate for full OSL dating. Sensitivity-corrected OSL $L_x/T_x$ profiles, and

### Table I. Sediment core latitude, longitude and elevation details; site description for study sites A–F

| Sediment core Latitude Longitude Elevation (m.a.s.l.) | Site description |
|-----------------------------------------------|------------------|
| NVP15/1/1 42.73510–100.03734 768 | Located on the eastern half of the NVP boundary and positioned on the upper slopes of one of the larger dune sections formed in the vicinity, on the northern edge of the Hazel Creek palaeochannel. Aerial photography from 1954 and 1968 shows site A was one of the most active blowouts in the preserve. Present vegetation cover included patchy shrubs and grasses with patches of visibly bare sand. Sediment cores NVP15/3/1 and NVP15/3/1 were extracted from the top of the blowout backwall and base of the blowout, respectively. |
| NVP15/3/1 42.73491–100.03781 757 | In the western limit of the study area, outside the NVP on the privately owned O’Kief ranch. Four vertical sediment cores were extracted along a transect from the crest (NVP16/2/1) of a choppy dune, down the SE flank (NVP16/2/2 and 3) across a livestock-disturbed interdune (no sample) and into a downslope deposition lobe (NVP16/2/4). The lobe appeared to be formed from sediment debris from the disturbed area. |
| NVP16/5/1 42.71943–100.02847 763 | A transect across a well-vegetated parabolic dune located SE of the NVP limits. Cores from the easterly facing parabolic dune (NVP16/5) include parabolic dune nose (5/1), windward-dune slope (5/2), deflation basin ahead of the dune (5/3) and from the northern arm of the parabolic dune (5/4). No active surface sands were present at the time of sampling. |
| NVP16/5/2 42.71953–100.02880 762 | Large blowout feature located north of the original homestead on the O’Kief ranch. Choppy dune/ basin feature appears to have accumulated against a fence line and copse of planted trees. Four cores taken along a transect trending NW–SE: crest of dune (NVP16/4/1), slope (NVP16/4/2), deflation basin (NVP16/4/3) and up the opposite-facing slope (NVP16/4/4). Transect was semi-vegetated with grasses and patches of bare sand found between grasses. |
| NVP16/5/3 42.71972–100.02927 755 | Fenceline dune located south of site D on the Sandhill and Sun Ranch. Site E noted as having experienced deposition in the 1930s when sediment was eroded from the adjacent prairie dog town and deposited along the boundary fence of the ranch. One vertical core (NVP15/4/1) was extracted from this site to explore the variability in the landscape when placed near sites D and F. |
| NVP16/5/4 42.72039–100.02929 758 | Selected as a comparison site to the other sampling sites as this location did not show any present evidence for recent reactivation, nor did the archived aerial photography or the ranchers’ accounts. Two vertical sediment cores were extracted from this site: crest of vegetated rolling dune (NVP16/6/1) and from a relative low point (NVP16/6/2). |
To improve the chronological resolution and reduce the uncertainty estimates, Bayesian age–depth models were created for sediment cores that identified subsamples with overlapping age estimates using the freeware OxCal software package (version OxCal 4.3) (Bronk Ramsey, 2009). The model applies a sequential order on the subsample OSL age estimates based on the depths and stratigraphic positions within the sediment core. Bayesian age–depth models were produced for sediment cores NVP15/1/1, NVP15/3/1 (site A) and NVP15/4/1 (site E) and modelled ages are presented alongside unmodelled ages in Table II (see Appendix B for Bayesian age–depth profiles).

Vegetation cover drivers

Vegetation cover acts as a protective ‘skin’ (Wolfe and Nickling, 1993), suppressing disturbance and preventing surface reactivation (Barchyn and Hugenholtz, 2013). The key determinants of cover levels include precipitation, grazing pressure, wildfire occurrence and land use changes. Data for each of these factors were used as a proxy for past vegetation cover levels, as follows.

The Palmer Drought Severity Index (PDSI) is a metric of annual historical drought conditions (Palmer, 1965). Drought occurrence and frequency affects the level of plant-available moisture, and thus levels of vegetation cover. In order to extend the range of PDSI coverage to capture multi-century timescales, we used data from the North American Drought Atlas (Cook and Krusic, 2004). The closest PDSI data point in this study, grid point 161 (42.5°N, -100°W), is based on a cumulative regional signal taken from trees in a 2.5° × 2.5° grid, ranging from 8 to 33 tree ring records from 1500 to 2003 AD. As well as the regional PDSI signal, a local tree ring index derived from ponderosa pine tree ring widths in the NVP area (Brown et al., n.d.) was used to give a local proxy of climatic conditions.

Wildfires can remove above-ground biomass, exposing the underlying sediments to aeolian processes. Precipitation levels are also linked to the likelihood of wildfire occurrence, impacting the availability of fuel for fire and determining aridity levels and the subsequent likelihood of a fire starting (Guyette et al., 2015). A wildfire history for the study site was compiled using data from the tree scar record for NVP in Guyette et al. (2011). The fire scar history of 39 tree samples spans the last 300 years and records 30 separate wildfires. To include fires relevant to the study area, only those identified in the records of at

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**Table II.** Results for all subsamples measured using full-preparation OSL dating. Subsample ages were calculated based on an overburden density 1.9 ± 0.1 g cm⁻³ and water content 3 ± 2% following the method described in Nelson and Rittenour (2015).

| Site sample. | Subsample reference | Depth (cm below surface) | Aliquots (n) | \( D_e \pm 1\sigma \) (Gy) \(^a\) | Dose rate (Gy ka \(^{-1}\)) \(^b\) | Age ± 1\(\sigma\) (years) | Date ± 1\(\sigma\) (AD) \(^c\) | Date ± 1\(\sigma\) (AD) \(^d\) |
|--------------|---------------------|--------------------------|-------------|----------------------|-------------------|-----------------|---------------|---------------|
| Site A: blowout feature | | | | 3 ± 8 | 2018 ± 8 | 2014 ± 9 |
| NVP15/1/1 | | | 1 | 25 | -0.007 ± 0.016 | 1.98 ± 0.05 | 41 ± 20 | 1974 ± 20 | 1998 ± 10 |
| NVP15/1/10 | | | 10 | 19 | 0.087 ± 0.037 | 2.13 ± 0.05 | 37 ± 17 | 1978 ± 17 | 1984 ± 8 |
| NVP15/1/20 | | | 20 | 16 | 0.08 ± 0.037 | 2.15 ± 0.05 | 37 ± 17 | 1978 ± 17 | 1984 ± 8 |
| NVP15/1/30 | | | 25 | 18 | 0.071 ± 0.033 | 2.15 ± 0.05 | 33 ± 15 | 1922 ± 15 | 1978 ± 9 |
| NVP15/1/40 | | | 30 | 22 | 0.17 ± 0.068 | 2.15 ± 0.05 | 79 ± 32 | 1936 ± 32 | 1971 ± 9 |
| NVP15/1/50 | | | 40 | 19 | 0.14 ± 0.035 | 2.15 ± 0.05 | 65 ± 16 | 1950 ± 16 | 1959 ± 10 |
| NVP15/1/60 | | | 50 | 19 | 0.12 ± 0.029 | 2.15 ± 0.05 | 56 ± 14 | 1959 ± 14 | 1948 ± 12 |
| NVP15/1/1 | | | 1 | 20 | 0.10 ± 0.044 | 1.65 ± 0.05 | 61 ± 27 | 1954 ± 27 | 1959 ± 18 |
| NVP15/3/1 | | | 10 | 21 | 0.19 ± 0.061 | 1.75 ± 0.04 | 109 ± 35 | 1906 ± 35 | 1951 ± 14 |
| NVP15/3/10 | | | 20 | 21 | 0.20 ± 0.10 | 1.76 ± 0.04 | 113 ± 57 | 1902 ± 57 | 1943 ± 12 |
| NVP15/3/25 | | | 25 | 26 | 0.11 ± 0.022 | 1.76 ± 0.04 | 62 ± 13 | 1953 ± 13 | 1939 ± 11 |

(Continues)
| Site sample. | NVP | Subsample reference | Depth (cm below surface) | Aliquots (n) | Dose rate (Gy a ± 1σ) | Age ± 1σ (years) | Date ± 1σ (AD)c | Date ± 1σ (AD)d |
|-------------|-----|---------------------|-------------------------|--------------|-----------------------|-----------------|-----------------|-----------------|
| Site B: windmill site | NVP16/2/1 | 6 | 23 | 0.20 ± 0.045 | 2.29 ± 0.05 | 87 ± 20 | 1929 ± 20 |
| | NVP16/2/2 | 25 | 18 | 0.71 ± 0.071 | 2.33 ± 0.05 | 202 ± 56 | 1844 ± 56 |
| | NVP16/2/3 | 34 | 16 | 1.03 ± 0.095 | 2.36 ± 0.05 | 437 ± 41 | 1630 ± 41 |
| | NVP16/2/4 | 45 | 55 | 0.27 ± 0.052 | 2.35 ± 0.05 | 115 ± 22 | 1901 ± 22 |
| Site C: parabolic dune | NVP16/5/1 | 7 | 18 | 0.26 ± 0.10 | 2.46 ± 0.05 | 106 ± 41 | 1930 ± 41 |
| | NVP16/5/2 | 9 | 23 | 0.27 ± 0.059 | 2.36 ± 0.05 | 116 ± 25 | 1907 ± 25 |
| | NVP16/5/3 | 39 | 16 | 1.92 ± 0.11 | 2.59 ± 0.05 | 740 ± 40 | 1276 ± 40 |
| | NVP16/5/4 | 27 | 18 | 1.91 ± 0.099 | 2.56 ± 0.05 | 747 ± 42 | 1269 ± 42 |
| Site D: homestead site | NVP16/4/1 | 5 | 17 | 0.072 ± 0.037 | 2.26 ± 0.05 | 32 ± 16 | 1984 ± 16 |
| | NVP16/4/2 | 25 | 27 | 0.13 ± 0.029 | 2.35 ± 0.05 | 55 ± 12 | 1961 ± 12 |
| | NVP16/4/3 | 3 | 21 | 0.30 ± 0.088 | 2.40 ± 0.06 | 125 ± 37 | 1891 ± 37 |
| | NVP16/4/4 | 47 | 44 | 1.84 ± 0.074 | 2.34 ± 0.05 | 788 ± 36 | 1228 ± 36 |
| Site E: 1930s dune | NVP15/4/1 | 5 | 20 | 0.14 ± 0.043 | 2.51 ± 0.06 | 56 ± 17 | 1955 ± 17 |
| | NVP15/4/10 | 10 | 20 | 0.18 ± 0.018 | 2.57 ± 0.06 | 70 ± 7 | 1942 ± 8 |
| | NVP15/4/15 | 15 | 17 | 0.30 ± 0.051 | 2.60 ± 0.05 | 116 ± 2 | 1920 ± 2 |
| | NVP15/4/20 | 20 | 19 | 0.28 ± 0.058 | 2.61 ± 0.05 | 107 ± 12 | 1905 ± 12 |
| | NVP15/4/25 | 25 | 19 | 0.38 ± 0.086 | 2.61 ± 0.05 | 146 ± 13 | 1888 ± 13 |
| | NVP15/4/30 | 30 | 19 | 0.46 ± 0.083 | 2.61 ± 0.05 | 176 ± 13 | 1873 ± 13 |
| | NVP15/4/35 | 35 | 19 | 0.44 ± 0.085 | 2.61 ± 0.05 | 169 ± 13 | 1860 ± 13 |
| | NVP15/4/40 | 40 | 19 | 0.52 ± 0.094 | 2.61 ± 0.05 | 200 ± 36 | 1815 ± 36 |
| | NVP15/4/45 | 45 | 44 | 1.41 ± 0.047 | 2.6 ± 0.05 | 158 ± 18 | 1838 ± 18 |
| Site F: old rolling dunes | NVP16/6/1 | 4 | 17 | 0.21 ± 0.041 | 2.37 ± 0.05 | 89 ± 17 | 1927 ± 17 |
| | NVP16/6/2 | 12 | 17 | 0.75 ± 0.085 | 2.61 ± 0.06 | 287 ± 33 | 1729 ± 33 |
| | NVP16/6/3 | 25 | 17 | 1.49 ± 0.14 | 2.63 ± 0.06 | 567 ± 55 | 1449 ± 55 |
| | NVP16/6/4 | 41 | 16 | 1.87 ± 0.098 | 2.59 ± 0.05 | 722 ± 41 | 1294 ± 41 |
| | NVP16/6/5 | 7 | 16 | 0.43 ± 0.037 | 2.57 ± 0.06 | 168 ± 15 | 1840 ± 15 |
| | NVP16/6/6 | 15 | 18 | 1.14 ± 0.077 | 2.65 ± 0.06 | 430 ± 30 | 1586 ± 30 |
| | NVP16/6/2 | 34 | 19 | 1.82 ± 0.088 | 2.62 ± 0.06 | 695 ± 37 | 1321 ± 37 |

*aEquivalent dose calculated using unlogged CAM (Galbraith et al., 1999).*

*bTotal dose rates calculated using DRAC (Durcan et al., 2015), with weighted averages of radionuclide concentrations used in homogenous sediment cores.*

*cDate presented in years (AD) based on sediment sampling in 2015 and 2016.*

*dBayesian modelled dates for sediment cores that showed overlapping ages between subsamples (Bronk Ramsey, 2009) (see Appendix B).*

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least two individual trees were considered as likely to have had an impact extending widely over the landscape. A large wildfire that occurred in 2012 (also an extreme drought year), burning 66 000 acres across NVP and surrounding ranches, has also been included in the analysis.

Identifying grazing pressures on the different sampling sites over the last 200 years is not possible due to data scarcity and difficulties in assessing past livestock movements in response to changing environmental conditions. For example, land management strategies, stocking rates and grazing levels will change on a variety of temporal scales in response to weather conditions such as winter blizzards and droughts. The impact of any concentration of livestock on vegetation (i.e. ‘overgrazing’) will also be affected by antecedent climate (e.g. Forman et al., 2001). Given these complexities, a coarse-scale assessment of general grazing and land use intensity was developed with a temporal resolution appropriate for the data scale of other variables.

Based on local land use and grazing pressure data, a table of ‘potential grazing pressure intensity’ was produced (Table III). Local land ownership history and land use changes have been sourced from original land patents, historical reports and interviews with local ranchers and preserve managers. Key dates associated with the regional development of the railroad, as well as homestead acts, are included in this study. Notable periods of grazing and land use pressure change were identified, with periods classified as either: 1 (low pressure), 2 (moderate grazing pressure) or 3 (high grazing pressure) based on combining data on: the level of population in the surrounding area, knowledge of ranching/agriculture strategies, land ownership chronologies and wild versus open/closed ranching levels. Together, these are used to suggest relative periods of increased and decreased pressure which can be analysed alongside the other disturbance factors. Intensity classifications and time intervals have been verified by colleagues and local ranchers, who have studied and managed pastures in the local region for many decades (Table III). Similar extrapolations of a quantitative classification index from qualitative datasets have successfully been completed in other areas of environmental science (e.g. Nicholson, 2001a,b; Grab and Nash, 2010; Nicholson et al., 2012a,b; Adamson and Nash, 2014; Nash et al., 2016) to identify variability in historical climates.

Wind erosivity potential is key in determining whether sediment will be mobilized when surfaces are bare. Wind speed data from Valentine, NE (42.88°N, −100.55°W) from 1987 to 2017 AD has shown that average daily wind speeds have exceeded the wind speed entrainment thresholds of 4.5 m s⁻¹ (Lancaster, 1988) and 5.97 m s⁻¹ (Bullard et al., 1996) for 97 and 88% of the time, respectively. Likewise, existing drift potential studies and datasets from the region have demonstrated the relatively high drift potentials experienced locally (e.g. Muhs et al., 2000; Muhs and Budahn, 2019). Given this, wind speed has not been considered a limiting factor on sediment transport when surfaces are bare and has not been included as a key controlling variable on sediment movement in this location.

**Results**

The luminescence ages for subsamples dated across the six sites are presented in Table II and Figure 2. Given the focus on near-surface sediments, OSL ages are notably younger than those usually published in the luminescence literature. A combination of technique-focusing methods (Buckland et al., 2018) and optimal mineralogical properties (Muhs, 2004) ensured that OSL methods could successfully be applied to these sediments to produce reliable age estimates <200 years with errors as low as 5%. Luminescence ages from individual subsamples are reported as calendar dates AD to allow comparison with the historical, instrumental and land use datasets.

**Dune reactivation histories**

The aim of the multiple-core sampling strategy was to ensure OSL-dated chronologies would capture the heterogeneity of the aeolian record within and between individual features, allowing both zones of erosion and accumulation to be represented in the final timeline of surface disturbance events. Capturing the variability in the record both within and between sampling sites is important in providing a fuller depositional history of the dunes, but also in developing an understanding of the variability in environmental response to a range of disturbances that act at different spatial scales. Vertical sediment profiles were typically characterized by homogenous light sands with a lack of any visible stratigraphy or organic matter; exceptions were noted at sites C and F, where notable soil layers were found overlying aeolian sand units.

Initial field assessments and observations at site A suggested sediment had been scoured from the base of a blowout by prevailing westerly winds, creating a deflation basin, and deposited on the eastern crest of the blowout. OSL results potentially support this interpretation, with older ages found at the surface of the blowout basin (NVP15/3/1) and modern sediments located at the crest of the blowout backwall (NVP15/5/1). The presence of sediments dated from 1959 ± 18 AD, 1 cm below the surface of NVP15/3/1, suggests this could be an active erosional site where a thin layer of bleached material overlies a profile that is gradually being eroded and redeposited elsewhere (e.g. at NVP15/5/1). Contrasting the 50-cm section from the crest of the backwall shows sediments dated from 1948 ± 12 AD until the present day – indicating a gradual accumulation of sediments over the last 60 years, or varying levels of bioturbated mixing in these near-surface sediments, or a combination of both (see Goble et al., 2004). The oldest near-surface sediments found at this site are dated to the end of the 19th century and agree with dune ages found at the other sampling sites, suggesting a true depositional unit.

OSL ages at site B reconstruct the history of localized sediment movement across a transect running from a dune crest, across a disturbed interdune area where a windmill water pump focuses livestock concentration, to a lobe of redeposited sediment. Site B was intentionally selected as a site with a clearly identifiable more disturbed history, allowing us to contrast the environmental response with sites (e.g. C and F) which do not have as obvious an anthropogenic influence. Based on this understanding, we would expect the first three sediment cores to represent zones of erosion whilst NVP16/2/4, shown in 1968 aerial imagery as an extending depositional lobe, is in a position of currently accumulating sand. Eleven OSL samples show the youngest ages are at site NVP16/2/4. Ages show a general increase in age down from the surface, extending back to 1901 ± 22 AD at 50 cm depth. NVP16/2/1, 2/2 and 2/3 have older surface sediments, potentially representing current sites of erosion where overlying sediments are progressively being removed and redeposited downwind. Whilst older ages could suggest zones of stability, the near-surface location of these ages could also indicate this is a zone of erosion or has been heavily bioturbated with older sediments mixed into the shallower sediments.

Greater sedimentological variability at site C, coupled with the presence of a visually identified overlying organic unit (NVP16/5/2 and NVP16/5/3), implies less current activity at this
Table III. Land use, settlement and assumed grazing history based on archival records and oral histories of Brown County, NE.

| Period   | Comments/supporting evidence | Intensity ‘score’ |
|----------|------------------------------|-------------------|
| Pre-1870s | • Prior to 1870, bison grazing intensity on all sites was probably in the range of 2–3 due to the value of the Niobrara River and its tributaries as a reliable source of water throughout the year.  
• Year-long bison herds roaming and grazing in the nearby Niobrara River area would have made use of the available forage in this part of the Sandhills.  
• During the 1870s, cattlemen came to Brown County ahead of the railroad, attracted by the abundant prairie grasslands. Early ranching operations used a system of ‘open range’ – cattle roamed free.  
• By the late 1870s, the bison had been cleared from the region, settlements and military forts were established (Baltsengperger, 1985). | 2 |
| 1870–1880 | • Winter of 1880/81 is recorded as one of the most severe ever known – ranchers suffered heavy losses and left the area, leaving the prairies open to settlement by farmers who arrived in the mid-1880s with the development of the railroad through Brown County.  
• Years 1884–1885 were marked by a rush of new settlers to the Brown County region, however, few cattle ranches located in the Sandhills as grass covering was sparse; ranchers focused on grazing in the valleys.  
• Original EuroAmerican settlers were only given 160 acres and settlers were unsuccessful in attempts to farm the plots. Plots in the nearby area were heavily over-farmed and led to high levels of land degradation and damage to the surface vegetation.  
• Low level of grazing pressure on the immediate study location, but a higher score would be used for the surrounding areas which were heavily farmed and degraded during this period.  
• Many cattle died during the severe winter of 1885/86, dry summer the following year and severe winter of 1888 (Perry and Stubbendieck, 1976).  
• Crops failed following the previous dry years, farms were deserted and the population of Brown County halved from 1890 to 1895.  
• 1890: Sample sites E and F were bought and homesteaded.  
• 1900 onwards: A new system of ranching operations was adopted – a transition from open range to controlled ranching (Miller, 1998). | 1 |
| 1880–1904 | • Sites A, B, C and D: Intensity score 2. Sites E and F: Intensity score 3.  
• Following the Kinkaid Act (1904) which gave families 640 acres of land, population increased in the Sandhills.  
• Numerous small ranches sprang up in the Brown County area containing not only grazing cattle, but also wheat and dairy cattle. Percentage of regional Sandhills Cattle Ranching Area used for ranching pastures doubled from 42.4% in 1909 to 80.3% in 1928 (Hedges and Elliott, 1930).  
• 1904: Sample site B bought and homesteaded. Groundwater pump found at site B, likely installed soon after purchasing. Site B groundwater pump is a site of persistent heavy trampling by cattle and thus has been graded 3 from this point forward.  
• 1914: Sample sites A and C were bought and homesteaded.  
• 1915: Sample site D bought and homesteaded. Original homestead is located c. 50 m southeast of site D sample transect. Non-naturally occurring tree species found at site D, likely planted by one of the early homesteaders to create a wind break across the prairies. | 2–3 |
| 1904–1930 | • Peak population in the Sandhills is noted from 1904 to 1920.  
• Population fell in the wider area during the Great Depression as Kinkaiders left the region, however, reductions in cattle herds in the Sandhills were less severe than in the rest of the state. Reports suggest that cattle were moved into the Sandhills from surrounding states (Miller, 1998).  
• As Kinkaiders left, ranchers acquired more land and grazing would have increased in the local area.  
• Less conservative (than present) grazing strategies used.  
• 1945: Change in ownership of sample site B – pasture purchased by current family. | 3 |
| 1930–1940 | • Sites A, C, D, E and F: Intensity score 2. Site B: Intensity score 3.  
• Less conservative (than present) grazing strategies used.  
• 1940: Sample sites A, C, D, E and F: Intensity score 2. Site B: Intensity score 3. | 2–3 |
| 1940–1970 | • Anecdotally, specific sites are noted to have been overgrazed during this period, prior to the establishment of the Niobrara Valley Preserve.  
• Sites A, B and C: Intensity score 3. Sites D, E and F: Intensity score 2.  
• Conservative grazing strategies used post-1980 (e.g. rotation of pastures).  
• 1945: Change in ownership of sample site A – pasture purchased by The Nature Conservancy and establishment of the Niobrara Valley Preserve.  
• 1981: Change in ownership of sample site D – pasture purchased by current family.  
• 1985: Bison reintroduced to sample site A.  
• Site B, D, E and F used as moderately grazed commercial grazing operations. | 2–3 |
| 1970–1980 | • Sites A, B and C: Intensity score 3. Sites D, E and F: Intensity score 2.  
• 1980: Change in ownership of sample sites A, C and F: subplots purchased by The Nature Conservancy and establishment of the Niobrara Valley Preserve.  
• 1981: Change in ownership of sample site D – pasture purchased by current family.  
• 1985: Bison reintroduced to sample site A.  
• Site B: Intensity score 3. | 1–3 |
| 1980 onwards | • Sites A and C: Intensity score 1. Sites D, E and F: Intensity score 2. Site B: Intensity score 3.  
• 1985: Bison reintroduced to sample site A.  
• Sites B, D, E and F used as moderately grazed commercial grazing operations. | 1–3 |

*In addition to those cited in the text, data sources include Kay et al. (1989), Stubbendieck (1998), Nebraska Genealogy website (accessed December 2017) and conversations with Doug Kuhre (NVP Ranch Manager). Time brackets, commentary and intensity scores have been discussed with local grassland ecologist Dr Al Steuter (commercial ranch owner and previous NVP Ranch Manager). Classification scores reflect: 1 – low pressure, 2 – moderate grazing pressure, 3 – high grazing pressure. Variation in intensity scores between sampling sites is demonstrated in Figure 3.*
Figure 2. Aerial photograph showing location of transects and sediment cores taken at each of the six sites. Site transects, elevation profile, sedimentary logs and OSL results are presented for each sediment core. Dashed lines represent breakpoints in \( L/T \) measurements according to changepoint analysis. (A) Two cores were extracted at site A – blowout feature: NVP15/1/1 (42.7351°N, 100.0373°W) and NVP15/3/1 (42.7349°N, 100.0378°W). Homogenous light sands dominated both cores with no lithostratigraphic structure or significant changes in chronostratigraphy identified either visually or algorithmically. (B) Four cores were extracted at site B – windmill site: NVP16/2/1 (42.7273°N, 100.1454°W), NVP16/2/2 (42.723°N, 100.1448°W), NVP16/2/3 (42.7271°N, 100.1446°W) and NVP16/2/4 (42.7265°N, 100.1432°W). Like site A, homogenous light sands dominated all four sediment cores at site B. (C) Four cores were sampled at site C – parabolic dune: NVP16/5/1 (42.7194°N, 100.0285°W), NVP16/5/2 (42.7195°N, 100.0288°W), NVP16/5/3 (42.7197°N, 100.0293°W) and NVP16/5/4 (42.7304°N, 100.0293°W) with a combination of organic-rich units and aeolian sands found amongst the cores. (D) Four cores were extracted at site D – homestead site: NVP16/4/1 (42.7444°N, 100.1046°W), NVP16/4/2 (42.7444°N, 100.1045°W), NVP16/4/3 (42.7442°N, 100.1042°W) and NVP16/4/4 (42.7438°N, 100.1040°W). All four sediment cores taken at site D comprise homogenous light aeolian sands with active sands noted at the surface of NVP16/4/3 during field sampling. (E) One core was sampled at site E – 1930s dune: NVP15/4/1 (42.7372°N, 100.0919°W) from a fenceline dune that anecdotally was active during the 1930s. (F) Two cores were extracted at site F – old rolling dunes: NVP16/6/1 (42.7391°N, 100.1036°W) and NVP16/6/2 (42.7393°N, 100.1033°W). Like profiles found at site C, both NVP16/6/1 and NVP16/6/2 showed upper organic-rich layers, overlying homogenous light sands. Changepoint analysis and noted lithological variability across all sediment cores was used to guide subsample selection for OSL dating. Satellite imagery courtesy of © 2017 Google Earth Pro, Landsat/Copernicus. [Colour figure can be viewed at wileyonlinelibrary.com]
mid-14th century; (3) late 19th/early 20th century. The unit encompassing 1890–1900 AD is commonly found across other sampling sites.

Site D is located at an old homestead site and has evidence of significant landform disturbance in the form of a large blow-out feature. Sediment appears to have been scoured from the...
basin by the dominant northwesterly winds and deposited on adjacent dune slopes. Near-surface OSL ages span the late 20th century to the 1st century AD, with common units appearing in multiple cores: (1) the deepest units in both slopes (NVP16/4/2 and NVP16/4/4) extend back from the early 16th century; and (2) the middle unit in NVP16/4/3 and the uppermost unit in NVP16/4/4 capture reactivation in the early 18th century. As expected, the upper crestal region (NVP16/4/1) is dominated by recent sediments.

OSL ages from NVP15/4/1 (site E) show periods of sand activity from the mid-19th century until the late 20th century, with ages in the 1890s and 1950s in agreement with those at other sites (Figure 2E). The changepoint model for this core required a high level of model sensitivity, since a relatively short time period was covered in the sediment core; identified breaks are structurally less significant and may be influenced by noise within the coarse OSL profile or due to bioturbation and mixing of grains in the near-surface sediments. Site E is located adjacent to a prairie dog town and the potential for mixing is arguably higher than that found at the other study sites.

Site F ages capture a series of reactivation events from 1927 ± 17 to 1291 ± 41 AD in the sediment profiles (Figure 2F). Breakpoints in the chronology determined by changepoint analysis, coupled with the OSL ages, show distinct activity phases where one-sigma age errors do not overlap. The ages of the deepest units in each core are within errors of each other, suggesting an episode of activity in the late 13th/early 14th century with subsequent periods of deposition preserved in the overlying horizons. There is a distinct lack of post-1927 AD reactivation events recorded at this site, although successive surface disturbances may have been eroded from the landscape.

Integrating deposition and driver profiles

Deposition profiles for each site are shown in Figure 3, alongside site-specific and regional-scale disturbance datasets from 1840 AD to the present. The regional PDSI record identifies multiple periods of drought in the mid- and late 19th century, followed by episodic drought conditions during the 1930s, 1950s and more recently in the late 20th century (Figure 3a). The PDSI record is broadly in agreement with the local tree ring record (Brown et al., n.d.), which provides a more localized drought signal, with periods of below-average growing conditions noted in the 1870s, 1890s, 1920s, 1930s and 1960s. Wildfire occurrences (Figure 3c) have decreased in the 20th century, following a peak from the mid-1870s to the early 20th century. This peak in wildfire occurrence coincides with the advent of EuroAmerican settlement and railroad construction through the Sandhills. Only study site A was located inside the boundary of the extensive wildfire in 2012, with sites D and C within 0.5–1 km of the fire boundary.

Notable socioeconomic events, land use changes and a history of grazing pressure and strategy are presented in Figures 3e and 4 and explained in detail in Table III. A shift from unorganized territory and open-range ranching occurred in the late 19th century, followed by a boom in immigration as settlers arrived in Brown County with the development of the railroad (post-1883). Whilst pressure on the land was high, with initial settlers degrading the surface on the small plots they farmed, a gradual improvement in grazing strategy and land management practices has taken place over the last 70 years. All six sites sampled in this study are currently used for cattle grazing (site A has been used for bison grazing since 1985), and have been occupied from the late 19th to the early 20th centuries, but have experienced varying levels of grazing pressure history over the last 170 years (Figure 3e).

Combined, potential disturbance factors produce a continuous sequence of conditions that could have driven near-surface reactivation events within the local area. The earlier period of interest (1840–1900 AD) is dominated by episodes of either regional or local drought with superimposed clusters of wildfires, whilst the latter half (1930s onwards) has less frequent episodes of reduced moisture availability and the intervening period (1900–1930s AD), despite no measured sign of drought, coincides with the period of heaviest grazing pressure in the region. As such, the combined disturbance record has potentially produced conditions conducive to sediment movement throughout the time period of interest.

Figure 3f presents the environmental response as captured in the OSL record and also noted from historical aerial imagery. The one-sigma age uncertainties on the OSL ages restrict the capacity to identify individual episodes of surface deposition, with the results potentially interpretable as indicating quasi-continuous sediment movement through the period of analysis (Figure 3f). Figure 3f shows OSL dates to be randomly distributed across the timeline studied, but with a slight reduction at some sites in frequency prior to the 1890s and since the 1970s. Visually, the results show that all sites have recorded evidence of surface disturbance and mobilization between the period 1890–1960, with either one or many OSL dated units.

Aerial photographs from 1939, 1954 and 1968 and Google Earth imagery (1993 to present) provide a high spatial resolution of vegetation cover change across the sample sites and wider region (see Appendix D). Orange and red bars in Figure 3f demonstrate periods of ‘almost bare’ and ‘completely bare’ vegetation cover, respectively, for individual sample sites. Images show that site D has had almost no vegetation cover in all the photographs assessed, with periods of completely bare surface coverage in the mid-20th century, and more recently when the wider environment has equally shown reduced vegetation cover.

Discussion

The analysis of stacked OSL ages from each sample site allows for reactivation timings to be compared against disturbance datasets (Figure 3f). A multicore strategy with stacked ages for each site ensures a more complete chronology of deposition events is produced for each localized feature. Comparing the results from each site allows us to identify the variability between the response of the geomorphological features where some forcings affect all sites (e.g. climate) but others are site-specific (e.g. grazing pressure). Through integrating age and observational data from the field, proxy records of environmental drivers and local oral histories, we can attempt to disentangle the complexities between surface aeolian responses to environmental drivers.

Reactivation events at site A coincide with the date of original homesteading in the early 20th century, increased ranching pressures and the severe blizzard of 1948/49. These events also overlap with droughts identified in the historical record, while a lack of disturbances from the 1980s corresponds to the decommissioning of commercial ranches and the establishment of the NVP. A peak in reactivation at site B from 1900 to 1930 AD occurs at the same time as the installation of the groundwater pump found at this site, which would have led to livestock concentrations in this area and increased environmental pressures. The reactivation history at site C shows a slightly earlier peak in activity, with ages in the late 19th/early 20th century coinciding with identifiable droughts in the PDSI record as well as notable blizzards. Site D OSL ages and uncertainties span the length of the period investigated, however, unlike other sites, there does not appear to be a peak in ages.
associated with the increase in settlement and ranching in the region. Given the persistently limited vegetation cover at this sample site, it is likely that a series of erosional events has left a complex and potentially incomplete record at site D. Site E also shows a near-continuous accumulation record from the mid-19th to the mid-20th century, but here peaks in accumulation can be identified in the 1900s and 1940s, which follow notable droughts recorded in the historical and PDSI records. Site F produces the fewest recent near-surface OSL ages, with no evidence for reactivation since the early 20th century.

Figure 3. Individual forcing factors and OSL ages stacked for each of the six study sites from 1840 to 2020 AD. (a) Annual PDSI (dashed) and 5-year running average PDSI (solid) values taken from Cook and Krusic (2004). (b) Annual tree ring growth index compiled using multiple ring width from ponderosa pines in the vicinity of the NVP (Brown et al., n.d.). (c) Wildfires found in two or more fire scar records taken from the data presented in Guyette et al. (2011). (d) Notable blizzards mentioned in historical records or referred to in oral histories. (e) Grazing pressure ‘intensity’ and history for each of the six sample sites based on the qualitative information detailed in Table III. (f) OSL ages with uncertainties stacked for each of the six sample sites. Red and orange bars refer to evidence from aerial photographs for ‘bare’ and ‘very bare’ dune vegetation cover, respectively. Combined aerial photography bars refer to the state of the wider region as opposed to individual sample sites – orange bars do not refer to ‘bare’ dunes but are used when dune crests are bare and blowouts have visibly increased in size. Episodes corresponding to PDSI < −1 have been shaded as yellow bars; < 986 (long-term average) tree ring index has been shaded as blue bars; and clusters of two or more frequent fire events have been shaded as red bars, to aid interpretation of the figure. [Colour figure can be viewed at wileyonlinelibrary.com]
The thin depositional units identified across the sites are a common feature in the settings of local disturbance that have been sampled in this study (i.e. blowout margins), and clear trends of younger 19th to 20th-century ages are only found in the sites which tend to have experienced episodic deposition in recent times. Whilst we prefer to interpret these ages as a reflection of episodes of deposition during surface mobilization, we cannot rule out the effects of bioturbation and the potential to impact luminescence ages when measured at the aliquot scale.

Evidence for the role of individual disturbance factors

The relationship between individual drivers and resultant surface reactivation can be assessed by comparing the timing of identified periods of deposition in the OSL chronologies with notable periods of extreme drought, increased wildfire frequency and heightened land use pressure. However, the errors in the OSL ages also do not allow individual disturbance events to always be linked to specific forcing factors.

For example, based on PDSI and local tree ring records, periods of activation from all sites do and do not overlap with notable drought periods, suggesting a complex role of drought in impacting the surface vegetation and facilitating sediment transport by the wind. We might not expect the OSL ages and drought records to overlap perfectly accounting for a lagged response of the vegetation and root networks prior to sediment remobilization. Figure 3a also suggests that whilst drought might be accountable for a portion of the reactivation events, many episodes occur decades after a drought event. Not all disturbances occur following droughts, indicating the importance of other agencies of disturbance and the potential for individual features to be more susceptible or resilient to particular forms of disturbance.

Given that wildfires are relatively short-lived events, coupled with the age range of the OSL dates, periods of deposition across the study sites are overlapping within errors of wildfire events. However, a reduction in wildfire occurrence in the 20th century is countered with OSL ages overlapping with the 1940s across nearly all sample sites studied, suggesting wildfire alone is unlikely to initiate sediment remobilization. Recent work by Artz et al. (2018) also suggests that wildfires do not necessarily lead to surface reactivation due to the rapid recovery of herbaceous biomass in grassland ecosystems. Future analysis should seek to identify the recovery time required following a wildfire and the resilience of below-ground root networks.

Another difficulty with ascribing evidence to wildfire-driven dune reactivation is the limited spatial extent of the disturbance. Wildfires can be extremely localized and based on Bragg’s (1985) original account of the fire scar tree records used (Bragg’s 1985 dataset is referred to in Guyette et al., 2011), we know that whilst many of the trees are located within the study region, we do not know the size of the individual fires, or whether they affected any of the study sites.

Finally, identifying the role of grazing pressure on destabilizing surface sediments is complicated for three reasons. Firstly, calculating levels of grazing pressure over long periods is very difficult due to technological and strategical advances in grazing management, land ownership changes and variability in scale (i.e. ‘pressure’ on the underlying surface from grazing can vary on a subreach scale due to cattle grouping around features in the landscape). Secondly, grazing pressure is technically a biotic factor, but influenced and managed by humans (Barchyn and Hugenholtz, 2013). Land management strategies will change in response to climatic factors (Helzer, 2010), and the nonlinear response of humans cannot be captured in this basic representation of grazing pressure. For example, at what level of drought would ranchers choose to reduce the size of the herd, or alternate rotations between pastures? There is no single management system that will be appropriate for all needs of ranching on the grasslands; management strategies are adapted as conditions change (Helzer, 2010). Thirdly, the response of individual animals to environmental conditions cannot be predicted. For example, herds typically shelter from the strong winds across the open prairie by grouping behind dune crests (Cunter and Waiser, 2016), protecting themselves from the wind and eroding the surface vegetation, resulting in the formation of blowouts from the heavy localized trampling. Likewise, heavy trampling occurs around groundwater pumps, as found at site B. These examples suggest that intense grazing strategies are not necessarily required to exert localized grazing pressure on the landscape. Thus, whilst the summary in Table III goes some way to demonstrating broad-scale changes in land use and grazing pressure across the sites during the last 150 years, it is not able to completely capture the nuances in grazing pressure over this period which may contribute to localized devegetation and sediment mobilization.

Evidence to suggest the potential role of land use and grazing pressure on the vegetative cover is found across all sites except site F. Reactivation ages found at sites A–E are all overlapping with ranch establishment dates, suggesting that a shift from open grazing to closed range ranching and settlement initiated...
more intensive land use. Equally, as demonstrated in Figure 3, whilst climatic and wildfire pressures subside during the period 1900–1920 AD, OSL deposition dates still occur during this period of most intense grazing pressure. At site B, the downwind depositional lobe accumulated between 1904 and 1930, following construction of the water pump and drinking trough for livestock. Aerial photograph evidence and cattle tracks in the field suggest there is an inability for the surface vegetation to recover, likely driven by heavy trampling of cattle around this water hole. A lack of identifiable reactivations since the 1980s shows that despite periods of recent drought, and extensive wildfires (e.g. 2012), the sediment has not been reactivated. Meanwhile, the reintroduction of native bison – coupled with more conservative grazing strategies – has arguably reduced the likelihood for reactivation, demonstrating a lack of commercial grazing pressure resulting in surface stability. However, the reintroduction of bison will have a complex overall outcome on the future surface stability, since the disturbance effects of bison may be key in developing active sand dune habitats and restoring threatened vegetation species associated with active sites (Fox et al., 2012).

### Synergies between disturbance factors

A near-continuous overall disturbance history, coupled with a near-continuous OSL record of patchy sediment movement, suggests that it is likely that a combination of disturbance factors is important in inducing the conditions suitable for landscape reactivation (Mangan et al., 2004; Stubbenbeck, 2008). The suggestion that synergies are a key part of the overall disturbance–response relationship is supported by the age profiles demonstrating that geomorphological features in the landscape have responded to different disturbance drivers, evidenced by between-site age profile differences. Features that demonstrate recent geomorphic activity in the field, or sparse vegetation cover, coincide with sites of recent reactivation ages (e.g. A, B, D and E). Meanwhile, sites with only older reactivation ages correspond to more rolling topography, upper soil horizon development and denser vegetation cover. The heterogeneity in response records demonstrates that drought alone is not the only cause of surface activity.

When multiple agents act on the landscape simultaneously, there is a greater likelihood of damage to the vegetation layer and susceptibility to reactivation. When grazing pressure is coupled with drought, their synergies reduce the threshold for each individual factor. For example, wildfire likelihood and extent (fuel availability) are both connected to precipitation (Guyette et al., 2015), and cattle feeding behaviour adjusts in conditions of drought. Wildfire and grazing pressure are also inextricably connected. Analysis of historical bison behaviour suggests that herds congregated on recently burned grasslands (Pfeiffer and Steuter, 1994; Biondini et al., 1999; Helzer, 2010). A reduction in above-ground biomass, due to intense grazing, can also reduce the level of fuel available for wildfires not only to start, but also spread. The management of wildfires has increased in recent decades, meaning that the impact of these naturally occurring disturbances in the landscape has reduced (Forman et al., 2001). We can suggest potential periods of combined forcing factor pressure, but visually are unable to identify the synergies between drivers in this multivariate dataset. Computational-based algorithms and models are needed to quantify the relationships between the drivers and the environmental response within this dataset (Buckland et al., 2019a).

### Assessing the utility of the luminescence record

Given that this study makes an unusual application of OSL data – to recent landscape disturbances – it is appropriate to evaluate this approach, since it is possible to test the results against other known records of disturbance. For example, the knowledge that the early settlers in the late 19th century heavily degraded the land, in addition to the widely cited 1930s ‘dust bowl’, provides two specific phases when surface reactivation was known and documented. OSL chronologies have successfully identified episodes of sediment reactivation during these periods across the six study sites, suggesting that the reactivation response was recorded in the geomorphology and sufficiently sampled in the method used.

The results from the stacked chronologies also highlight the benefits of a multi-core sampling strategy in the field. This approach shows how localized disturbance and sediment movement can be (e.g. the depositional lobe NVP16/2/4 that forms downwind of the groundwater pump at site B), and how a single sampling location would not alone capture the spatial complexity of localized sediment movement, nor its association with specific landscape features.

Large gaps in age profiles, however, may not indicate that deposition of surface sands is infrequent in this feature, and thus large periods elapse between new deposits. High levels of overturning in the near-surface sediments may erode underlying sedimentary units, repeatedly reworking sediment and removing a signal from the OSL record. As discussed by Bailey and Thomas (2014), the likelihood of an incomplete record is almost inevitable in these dynamic environments, and therefore it would be erroneous to assume there had not been any aeolian activity in the periods between the OSL ages. Equally, given the environment these sediments were extracted from, it is important to consider that the luminescence ages presented may be a combination of the ages of surface sediment deposition and those influenced by the mixing of grains during post-depositional bioturbation. However, since insects, rodents and pocket gophers of the Sandhills are likely transporting individual grains through the sedimentary profile, as opposed to whole sedimentary units, the overall impact on the age estimation of deposition is not considered substantial. Through analysis of the small-aliquot OSL dose distribution profiles (see Appendix A), it could be argued that wider dose distribution profiles are the result of bioturbated sediments, where grains from both younger and older sedimentary layers are mixed within the sampled layer. However, calculating ages using the unlogged CAM helps reduce any bias associated with individual aliquots/grains. Nevertheless, since this study has focused on near-surface sediments, it is important to consider that some of the ages presented in the seemingly aggrading profiles (e.g. NVP15/5/1/1, NVP15/3/1 and NVP15/4/1) could represent a combination of both near-surface continuous mobilization and low-level bioturbation in the upper sediments (see Goble et al., 2004). Future analysis could seek to identify further evidence of bioturbation through analysis of micromorphological structures in the sedimentary profile, coupled with single-grain luminescence dates. In sum, it is likely that these sediments have experienced various levels of post-depositional bioturbation, but the overall impact on the OSL ages is likely low and is not considered to have resulted in a systematic over- or underestimation of the deposition event age estimates.

### Older deposition events

Deposition events identified prior to 1840 AD have not been discussed in detail, as they fall outside the period well
documented in the climatic and disturbance datasets. However, the results from this study are in broad agreement with existing studies, suggesting periods of aeolian activity centred on ~100, ~300, ~500 and ~700 years ago (Figure 5). This synchronicity in regional reactivation, coupled with a minimal human occupation impact on the landscape, suggests that long-term climatic factors are likely a key driver behind earlier reactivations; 5-year rolling average PDSI values equally show periods of notable drought occurring within errors of luminescence dates produced in this study. Nevertheless, this study has focused solely on the upper 50 cm of dune sediments, creating a reactivation record focusing on localized movement of surface sediments as opposed to dune-building phases. Deeper sediment cores (especially at sites A and E) capturing older episodes of reactivation would improve the longer-term remobilization record at the NVP, and the comparison with other records from within the region.

Conclusions

Identifying the appropriate scale and tools to analyse spatially complex land surface responses to multiple disturbance drivers is a challenging task, especially at timescales that fall between the usual age ranges of suitable chronometric dating techniques and the availability of repeat observational data. In this study we have applied a novel set of approaches in an attempt to develop a methodological approach that can fill this data gap, in this case for the last ~200 years in the Nebraska Sandhills, which embraces evidence of multiple natural disturbance drivers and a time of changing human engagement with the landscape. OSL ages from near-surface dune sediments have produced a high-resolution history of sediment deposition events in the recent past in the northern limits of the Nebraska Sandhills. The use of a multi-core sampling strategy has successfully captured a more complete history of sediment mobilization across individual features and the wider landscape than that which would be produced from individual core methods.

A near-continuous aeolian deposition record, coupled with varying disturbance driver profiles, highlights a complex relationship between both climatic and anthropogenic parameters and geomorphological response. The variability found in the deposition profiles between sampling sites suggests that no single factor is solely responsible for the low-level reactivation history of the near-surface sediments. Whilst this study has focused on a single site within the northern Nebraska Sandhills, this is in agreement with existing studies (Mangan et al., 2004; Stubbendieck, 2008; Miao et al., 2007; Hanson et al., 2009; Mason et al., 2011; Schmieder et al., 2011; Halfen et al., 2012). Future research could seek to identify the leads, lags and synergies between the driving forces and environmental response within this multivariate dataset by using alternative computer-based analysis and modelling techniques.

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