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Resilience of Sandhills Grassland to Wildfire During Drought☆

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ABSTRACT

In the Nebraska Sandhills, one of the largest contiguous grassland ecoregions remaining in North America, sandy textured soils are stabilized by fine root biomass from predominantly warm-season grasses. Concerns over destabilization have led to management that aims to avoid an undesirable state change toward mobile sand dunes. In 2012, the Sandhills experienced extreme drought conditions that coincided with the worst wildfire year on state record. According to state-and-transition models and ecosystem managers, the combination of wildfire and drought conditions should cause a state transition due to a lack of recovery of grassland vegetation and a loss of sand dune stability. To test this hypothesis, we implemented a time-since-fire study to track biomass recovery of Sandhills grassland vegetation following a wildfire on The Nature Conservancy's Niobrara Valley Preserve in burned and unburned areas. Two yr following the wildfire, aboveground herbaceous biomass in burned areas had recovered to levels that did not differ from unburned areas, maintaining the stability of the sand dunes. This provides evidence that counters current land management frameworks that portray Sandhills grassland as highly vulnerable to destabilization when wildfires occur during severe drought conditions.

Introduction

Considerable uncertainty continues to surround the rangeland discipline's depiction of the role of fire and drought as drivers of vegetation change in sandy soil ecosystems. It is often suggested that sandy soil ecosystems are sensitive to destabilization when a disturbance removes aboveground plant biomass, increases bare ground, and heightens the potential for erosion (Muhs and Wolfe, 1999; Forman, 2001; Mason et al., 2004). This presumption is evident in current state-and-transition models. Both the Ecological Site Description Database (ESD, 2011) and LANDFIRE Program (LANDFIRE, 2012) depict a transition from a stable grassland state to a mobile sand dune state following wildfire in drought (Fig. 1). In addition, management in many sandy soil ecosystems like the Nebraska Sandhills—the largest stabilized sand dune in the Western Hemisphere—aims to limit disturbances, such as fire, that expose bare soil due to concerns over broad-scale destabilization (Stubbendieck 1998). This suggests that there is a prevailing hypothesis among managers that has been put into practice in sandy soil ecosystems. Specifically, vegetation will not recover following fire during drought because the combination of fire and drought has overcome the resilience of the existing grassland state and induced a transition to a new stable state characterized by a lack of vegetation and sand mobility.

While there are case studies where grassland vegetation in sandy soils has recovered following wildfire (Arterburn, 2016; Breshears et al., 2016), data have not been collected during extraordinary conditions when system thresholds have the potential to be overcome, leading to a transition to a new state (e.g., following a wildfire during an exceptionally dry period). Following a wildfire in the Nebraska Sandhills that occurred during the worst drought on modern record and which continued 6 months after the wildfire event (precipitation was 72% below the monthly mean in July 2012; HPRCC, 2015), we initiated monitoring to assess whether Sandhills grassland would recover following the wildfire and drought. Similar to other assessments of ecosystem resilience (Folke et al., 2004; Allen et al., 2005; Wonkka et al., 2016), we used biomass recovery to indicate whether the resilience of a vegetated state has been overcome. Here, we report on the recovery status of this Sandhills grassland 2 yr following the wildfire.

Methods

In July 2012, the Fairfield Creek Wildfire occurred in the north-central Sandhills of Nebraska during a 9-mo drought when precipitation levels were 72% below the historical average (HPRCC, 2015). The wildfire burned a portion of The Nature Conservancy's Niobrara Valley Preserve located 43 km northwest of Ainsworth, Nebraska. The Niobrara Valley Preserve includes a 5 217-ha west bison unit and a 3 935-ha east bison unit that have been grazed continuously by independent bison

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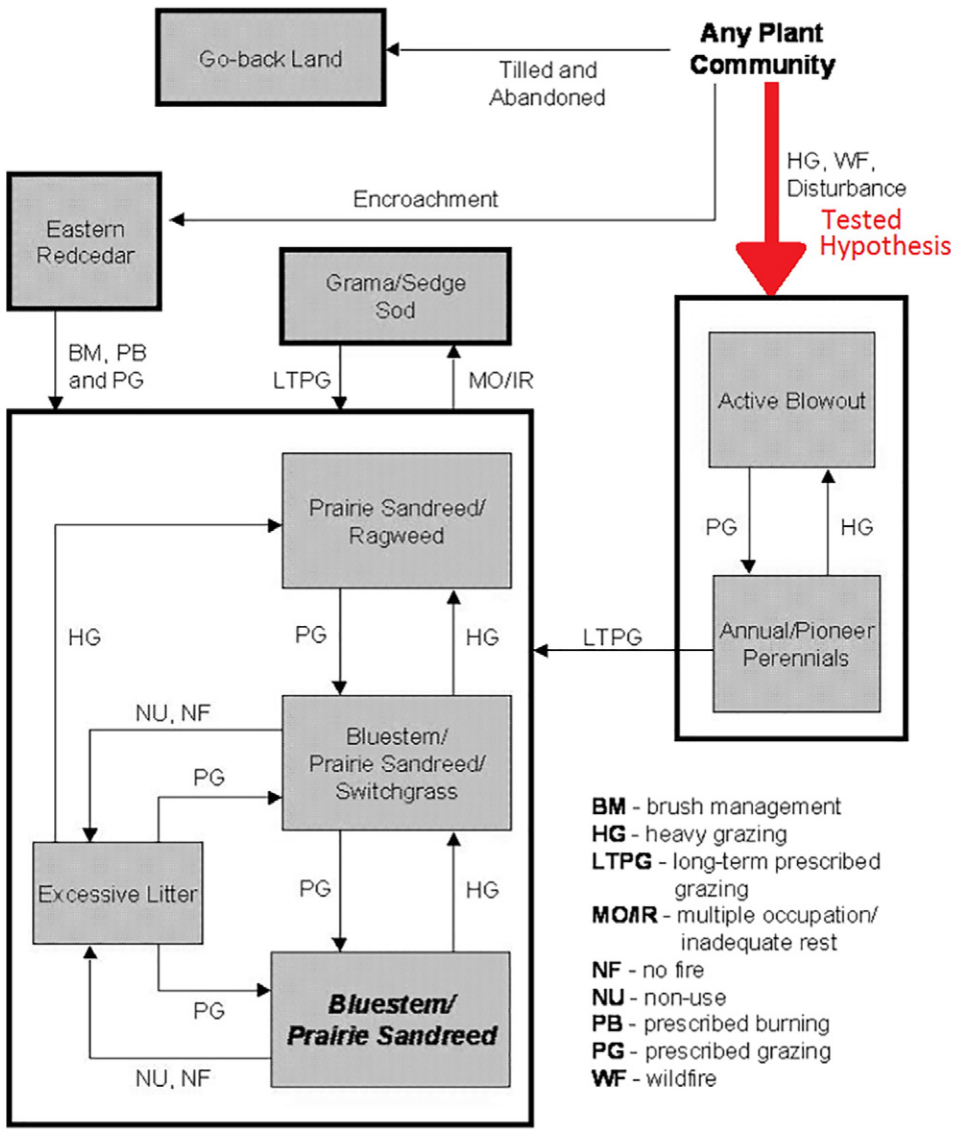

Figure 1. State-and-transition models characterize fire as a disturbance that causes destabilization and a shift to an eroded, sand dune stable state in sandy soil ecosystems. Shown here is an example of a typical state-and-transition model with a transitional pathway from a stabilized grassland state to a mobile sand dune state following wildfire (Sands Medium P.Z. 17 − 22; MLRA 065-Nebraska Sandhills from the USDA Ecological Site Description Database; ESD, 2011).

herds since 1988 and 1986, respectively. The stocking rate of both units has historically targeted 1 animal unit month (AUM) · ha^{-1} (Pfeiffer and Steuter, 1994), which is low relative to a moderate Sandhills stocking rate of 1.8 AUM · ha^{-1}. Mean annual precipitation for the area is 591 mm, and mean annual temperature is 10°C, ranging from − 3°C in January to 24°C in July (HPRCC, 2015). Soils are classified as Valentine fine sands (mixed, mesic Typic Ustipsamments) featuring a low water-holding capacity and a high risk of wind erosion. Upland vegetation at the site is characterized as Sandhills prairie that is dominated by perennial grasses, including sand bluestem (*Andropogon hallii* Hack.), little bluestem (*Schizachyrium scoparium* [Michx.] Nash), and prairie sandreed (*Calamovilfa longifolia* [Hook.] Scribn.).

The Fairfield Creek Wildfire burned major portions of the west (2 281 ha; 43.7%) and east (3 203 ha; 81.4%) bison units in late July 2012, resulting in both burned and unburned areas in each bison unit. At the time of the fire, local weather stations reported temperatures reached 43°C, relative humidity was as low as 13%, and wind gusts were recorded up to 50 km · hr^{-1}. Precipitation levels were 75% below average for the 60 d before the wildfire (HPRCC, 2015). Following the wildfire, departures from the mean annual precipitation in 2013, 2014, and 2015 were − 1.73%, − 11.48%, and 0.55%, respectively (HPRCC, 2015). Bison continued to have access to burned and unburned areas immediately following the fire at reduced stocking rates of 0.69 AUM · ha^{-1} and 0.49 AUM · ha^{-1}, in west and east bison units, respectively, before increasing to 1.09 AUM · ha^{-1} and 1.12 AUM · ha^{-1} in 2015.

Vegetation Sampling

In 2014, we collected aboveground herbaceous biomass at 3-m intervals along a 300-m, north/south transect, resulting in 100 samples per burned/unburned patch in each bison unit (400 samples total). This sampling was repeated at different locations along the same transect in 2015; however, The Nature Conservancy conducted a prescribed burn that included the unburned portion of the east bison unit, so those samples were not included in our 2015 analysis (resulting in 200 samples in burned areas and 100 in unburned areas in 2015). Transect locations were randomly selected but excluded minor components of the landscape (e.g., patches of trees and shrub islands). While transect sampling can reduce the spatial distribution of the sample, the length of transect used here ensured that the sampling covered a diversity of topoedaphic conditions occurring in the Sandhills. Transects were 10 356 m apart, on average (range: 291 − 22 687 m). Herbaceous vegetation was clipped at ground level within a 0.1-m^2 quadrat near peak aboveground herbaceous biomass in late July/early August each year and sorted to live, standing dead, and litter. Herbaceous standing dead biomass and herbaceous litter biomass consisted of previous years' growth, differentiated by attachment to the soil or not, respectively. Samples were oven-dried at 60°C for a minimum of 48 hr to remove all moisture.

Data Analysis

We tested for differences in aboveground herbaceous biomass between burned and unburned areas with linear mixed-effect models. Models tested for differences in total herbaceous biomass, live herbaceous biomass, total dead herbaceous biomass, standing dead biomass, and herbaceous litter biomass. Dead herbaceous biomass is an aggregate of herbaceous standing dead biomass and herbaceous litter biomass. Fixed effects for fire (burned vs. unburned), year (2014 vs. 2015), and their interaction were included in each model, as well as a random intercept for bison unit and a random intercept for plot nested in bison unit to account for random site effects and repeated measures. Degrees of freedom and *P* values were derived using a Satterthwaite approximation (Satterthwaite, 1946). We controlled the false-discovery rate using the algorithm derived by Benjamini and Hochberg (1995). Models were created using the lme4 package for the R statistical computing environment (R Core Team, 2014; Bates et al., 2015). The comparison between burned and unburned areas was used to infer whether aboveground herbaceous biomass in burned areas recovered to levels similar to those observed in unburned areas. We assumed burned and unburned areas were similar before the wildfire based on close proximity and similar management and topography, which is consistent with other postwildfire assessments (Fule et al., 2004). Like other wildfire studies, samples ($n = 200$) were pseudoreplicated because only one wildfire event occurred on the landscape (Hurlbert, 1984; Wiens and Parker, 1995; Laughlin and Fule, 2008).

Results and Discussion

Our study provides evidence that counters the perspective prevalent in management frameworks for the region that Sandhills grassland is highly vulnerable to destabilization when wildfires occur during severe drought conditions. Aboveground herbaceous biomass recovered to levels similar to unburned areas within 2 yr following wildfire (estimates for total and live herbaceous biomass in burned plots did not differ from unburned plots; Table 1), indicating that the resilience of Sandhills grassland to the combination of wildfire and drought was not overcome (Fig. 2). Total herbaceous biomass and live herbaceous biomass in burned areas did not differ from unburned areas after 2 yr. Dead herbaceous biomass in burned areas was significantly lower than in unburned areas 2 yr after the fire (2014) but had recovered and was similar to unburned areas 3 yr following the fire (2015; see multiple comparisons for dead herbaceous biomass from Table 1). This difference in 2014 was the result of a significant difference in litter in 2014 that was also no longer apparent in 2015 (multiple comparisons for litter from Table 1). Standing dead biomass was not different in burned and unburned areas after 2 yr.

Broad-scale destabilization of sandy soil ecosystems is more likely to be associated with long-term drivers that change the amount of root biomass, such as long-term changes in precipitation or long-term overgrazing rather than short-term or stochastic events such as fire (Pfeiffer and Steuter, 1994; Miao et al., 2007). In a recent experimental manipulation aimed at understanding destabilization in the Sandhills, continual herbicide applications were required for 5 yr before belowground root biomass declined to a level sufficient to trigger destabilization (Hartman, 2015; Wang et al., 2015). Destabilization only occurred earlier than 5 yr when continual herbicide application was combined with shallow disking and raking that removed both aboveground and belowground plant material. Our study supports these findings. Two yr following wildfire, aboveground herbaceous biomass in burned areas had recovered to levels that did not differ from unburned areas (see Fig. 2), maintaining the stability of the sand dunes. Findings from our study extend previous findings, providing evidence that fire does not cause destabilization even when it occurs during drought conditions. Scientific evidence thus indicates that fire, by itself or in combination with drought, does not create the type or severity of disturbance to belowground plant components necessary to trigger a shift to a destabilized state. Indeed, megadroughts spanning a decade or more, not fire, have been shown to be the primary driver of broad-scale destabilization in the past (Mason et al., 2004; Miao et al., 2007; Schmeisser et al., 2009).

After recovery of herbaceous biomass, a secondary consideration is whether the plant community has undergone a shift from native to exotic species dominance or to less preferred forage species and changes in how disturbance regimes function in the future. Diversity has been

Table 1
Summary of fixed effects derived from linear mixed-effects models exploring grassland biomass recovery following wildfire. The intercept represents the reference condition (unburned, 2014), and the estimate for fire shows the difference in biomass between burned and unburned plots. The interaction estimate, as well as multiple comparisons between burned and unburned plots within years, was only included if the interaction was significant

Response variable	Fixed effects	Biomass estimate (g/m^2)	Standard error	Satterthwaite Approximated df	*T* value	FDR-adjusted *P* value
Total Herbaceous	Intercept	303.5	33.2	1.2	9.14	0.098
	Fire	−22.4	16.2	497.6	−1.39	0.199
Live Herbaceous	Intercept	162.0	8.3	7.8	19.56	0.004
	Fire	7.3	11.5	487.1	0.63	0.574
Dead Herbaceous	Intercept	141.5	27.4	1.1	5.17	0.147
	Fire	−29.7	8.5	514.7	−3.52	0.004
	Fire · yr	33.3	13.8	515.4	2.42	0.038
Standing Dead	Intercept	62.5	12.9	1.2	4.86	0.147
	Fire	−3.3	5.97	510.1	−0.55	0.584
Litter	Intercept	79.0	14.8	1.1	5.33	0.147
	Fire	−26.4	6.47	518.1	−5.27	0.004
	Fire · yr	29.2	8.2	519.8	3.56	0.012

Multiple comparisons	Estimate	Standard error	*Z* value	FDR-adjusted *P* value
Dead herbaceous				
Wildfire vs. unburned 2014	−29.7	8.5	−3.52	0.003
Wildfire vs. unburned 2015	−3.59	10.9	0.33	0.987
Litter				
Wildfire vs. unburned 2014	−26.4	5.02	−5.27	0.002
Wildfire vs. unburned 2015	2.7	6.5	0.42	0.995

FDR, False Discovery Rate.

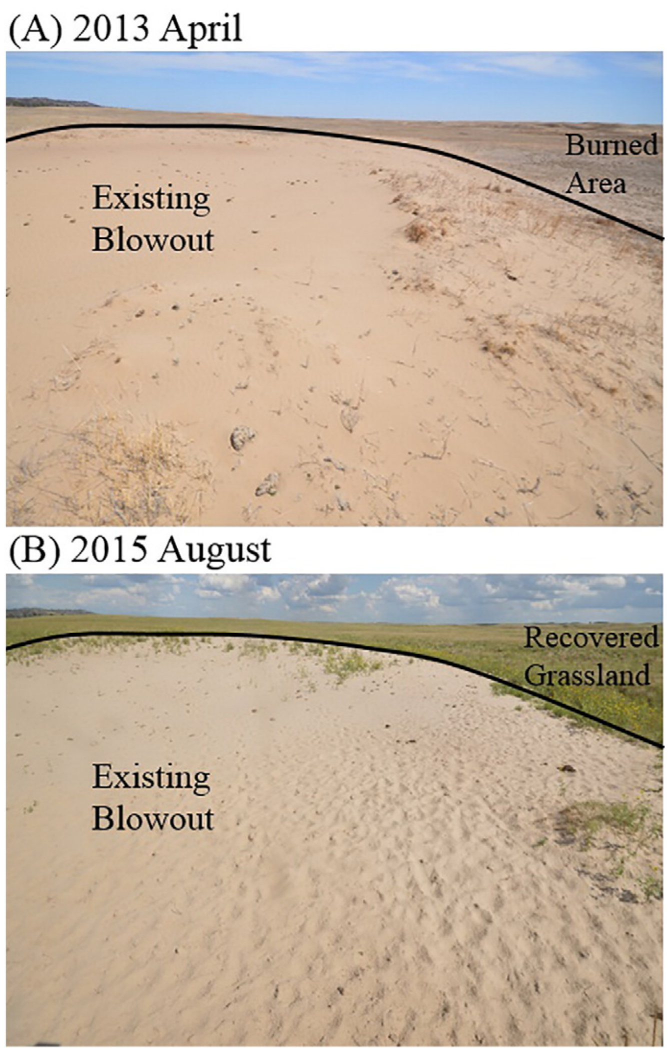

Figure 2. A, Existing blowout next to burned grassland 9-mo after the 2012 wildfire and before the start of the growing season. **B**, Recovery of Sandhills grassland 3 yr after the wildfire. Time-lapse video showing more rapid recovery is available at https://www.youtube.com/watch?v=YqMMIvAKuf0.

shown to play a critical role in the resilience of Sandhills grasslands (Fay et al., 2015). Like previous studies, we did not observe differences in plant community composition between burned and unburned areas 2 and 3 yr following the wildfire (Arterburn, 2016). Other postwildfire studies conducted in Sandhills found fire during drought did not result in long-term shifts in the plant community (Pfeiffer and Steuter, 1994; Steuter et al., 1995; Volesky and Connot, 2000). Additionally, studies in other regions of the Great Plains show no large changes in plant community composition following fire during drought (Ansley et al., 2010; Rideout-Hanzak et al., 2011; Taylor et al., 2011; Towne and Kemp, 2008; Twidwell et al., 2012).

Like other grasslands around the world, the Sandhills grassland consists of fuels that readily support fire (Guyette et al., 2012). A major concern given findings in our study is that policies and statutes that exaggerate, without scientific evidence, concerns over destabilization are promoting fire prevention to avoid conversion to an alternative ecosystem state (active sand dunes). However, prevention is unnecessary to prevent destabilization and might actually contribute to the emergence of an undesirable ecosystem state that often emerges in the absence of fire in grasslands—woody plant invasions (e.g., Sandhills grassland conversion to juniper woodland; Eggemeyer et al., 2006). This is a major concern given that since European settlement, anthropogenic influences have decreased the occurrence of fire in the Sandhills and increased potential for expanding *Juniperus virginiana* invasion (Steinauer and Bragg, 1987; Eggemeyer et al., 2006).

Implications

Our study adds to mounting evidence that fire, as an infrequent event during drought, does not cause destabilization of Sandhills grassland. Multiple lines of evidence show a well-established and diverse Sandhills grassland readily recovers following fire (Morrison et al., 1986; Pfeiffer and Steuter, 1994; Bragg, 1998; Volesky and Connot, 2000). Instead, broad-scale destabilization in the past has been linked to megadroughts and the removal of belowground fine root biomass (Miao et al., 2007). Given the empirical evidence and prevailing consensus that fire initiates feedbacks that act to stabilize grasslands in the Great Plains (e.g., Twidwell et al., 2013), we recommend that state-and-transition models within LANDFIRE and the US Department of Agriculture Ecological Site Description Database be modified to remove transitional pathways that assume the combination of wildfire and drought trigger a state transition to nonvegetated, mobilized sand dunes. Potential trade-offs regarding ecosystem services and unexpected transformations to undesirable states (e.g., woody invasion as a result of fire exclusion) can result from overemphasizing a transition that has no empirical support.

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