



RESEARCH ARTICLE

## Grassland bird community and acoustic complexity appear unaffected by proximity to a wind energy facility in the Nebraska Sandhills

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### ABSTRACT

The placement of wind energy facilities on the landscape is a potential source of direct mortality for wildlife, but indirect effects of wind facilities on natural communities are less well known. An anthropogenically altered acoustic environment may render habitat unsuitable for species that use vocalizations to communicate. We listened to sound recordings to identify the species assemblage of common breeding birds in an unfragmented grassland in the Nebraska Sandhills (USA) in the vicinity of a wind energy facility. From the recordings, we calculated the Acoustic Complexity Index (ACI), which we used to assess differences in the avian community between a reference area (>760 m from any turbines) and a treatment area (<760 m from turbines). We did not observe differences at the assemblage level using univariate metrics of diversity: mean species richness (3.48 vs. 3.25 species per recording event) and Whittaker  $\beta_w$  index (6.03 vs. 5.85 species turnover of habitat type) or the ACI (0.17 vs. 0.15). ACI increased with the progression of the breeding season and was correlated with species richness, indicating that ACI provides a useful estimate of acoustic activity of grassland songbirds. The limited habitat perforation caused by wind energy facilities and roads (1% in the area of the wind energy facility) and the low-frequency noise emitted by operational wind turbines did not appear to affect the presence or singing behavior of breeding passerine birds in this landscape.

*Keywords:* ACI, acoustic complexity, grassland songbirds, Greater Prairie-Chicken leks, indirect impacts, perforation, wind turbine noise

### Las comunidades de aves de pradera y la complejidad acústica parecen no ser afectadas por su proximidad a instalaciones de energía eólica en las colinas arenosas de Nebraska

### RESUMEN

La ubicación en el paisaje de instalaciones de energía eólica es una fuente potencial de mortalidad directa para animales silvestres, pero los efectos indirectos de las instalaciones de energía eólica en comunidades naturales son menos conocidos. Un ambiente acústico alterado antropogénicamente puede hacer que un hábitat no sea apropiado para las especies que usan vocalizaciones para comunicarse. Escuchamos grabaciones de sonidos para identificar el ensamblaje de especies comunes que se reproducen en una pradera no fragmentada en las colinas arenosas de Nebraska (EEUU) en la vecindad de una instalación de energía eólica. Con las grabaciones calculamos el índice de complejidad acústica (ICA), el cual usamos para determinar diferencias en la comunidad de aves entre un área de referencia (a más de 760 m de las turbinas) y un área de tratamiento (a menos de 760 m de las turbinas). No observamos diferencias a nivel del ensamblaje usando medidas univariadas de diversidad: la riqueza de especies promedio (3.48 vs. 3.25 especies por evento de grabación) y el índice de diversidad  $\beta_w$  de Whittaker (6.03 vs. 5.85 recambio de especies de cada tipo de hábitat) o el ICA (0.17 vs. 0.15). El ICA se incrementó a medida que progresaba la temporada reproductiva y se correlacionó con la riqueza de especies, indicando que el ICA provee un estimado útil de la actividad acústica de las aves de pradera. La perturbación limitada del hábitat causada por las instalaciones de energía eólica y las carreteras (1% en el área de las instalaciones de energía eólica) y el sonido de baja frecuencia emitido por las turbinas en funcionamiento no parecen afectar la presencia o el comportamiento de canto de las aves paserinas reproductivas.

*Palabras clave:* aves canoras de pradera, complejidad acústica, ICA, impactos indirectos, leks de *Tympanuchus cupido*, perforación, ruido de turbinas eólicas

### INTRODUCTION

Acoustic surveys are emerging as an effective method for capturing the complexity of communities and even

ecosystems (Sueur et al. 2008, Gasc et al. 2013, Fuller et al. 2015, Buxton et al. 2016), and they may be used to inform comprehensive management strategies (Blumstein et al. 2011). Several studies have demonstrated that

anthropogenic noise may reduce habitat quality (Bayne et al. 2008, Francis et al. 2009, Ware et al. 2015) by masking acoustic signals and decreasing the efficiency of communication (Brumm 2004, Brumm and Slabbekoorn 2005, Kight et al. 2012, Damsky and Gall 2017). In particular, traffic studies indicate that bird abundance, occurrence, physiology, and species richness may be negatively correlated with levels of vehicle noise (Forman et al. 2002, Peris and Pescador 2004, Halfwerk et al. 2011). However, little attention has been paid to the effects of anthropogenic noise on the activity of acoustic communities, although acoustic space may be an indicator of environmental integrity if acoustical niches reflect the ecological niches of vocal animals (Farina et al. 2011a, Kasten et al. 2012, Gage and Axel 2014, Fuller et al. 2015).

Soundscape ecology describes the potentially complex relationship between a landscape and the composition of its sound and may indicate changes in habitat conditions (Pijanowski et al. 2011a, 2011b, Gasc et al. 2017). The soundscape reflects the dynamics of community structure and function (Schafer 1977, Qi et al. 2008, Pijanowski et al. 2011a) and is created by the physical interactions between geological (e.g., wind, rain), biological (e.g., vocal animals), and anthropogenic (e.g., cars, mechanical) sounds (Pijanowski et al. 2011a, 2011b). While advances in tools to analyze soundscape recordings are ongoing (Gasc et al. 2015, 2017), acoustic indices have been developed to allow the rapid extraction of soundscape information from enormous volumes of acoustic data (e.g., the R packages ‘seewave’ [Sueur et al. 2016] and ‘soundecology’ [Villanueva-Rivera and Pijanowski 2016]). Acoustic indices used as proxy indicators of biodiversity have been applied to comparative studies of distinct habitats (Sueur et al. 2008, Kasten et al. 2012, Towsey et al. 2014, Gage et al. 2017). Most validation studies have occurred in forested systems, so the validity of acoustic indices in grasslands remains less clear (Pieretti et al. 2011, Buxton et al. 2016).

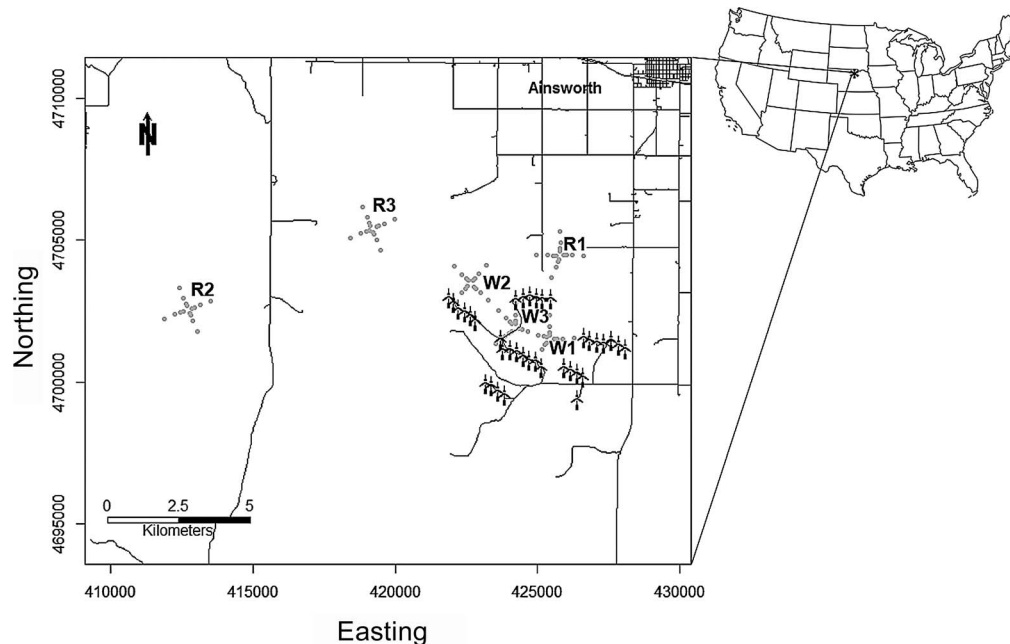
Because wind energy development is encroaching on fairly intact grassland habitats, an understanding of how the presence of wind energy facilities, and their associated noise, affects grassland bird communities has become important (Langston and Pullan 2003, Bennett et al. 2014, Hale et al. 2014, Smith and Dwyer 2016). The first stage of habitat loss and fragmentation that accompanies wind energy development is habitat perforation, which involves the disruption of otherwise continuous habitat through direct loss by creation of spatial gaps (Forman 1995). Habitat perforation is not limited to physical habitat loss because noise pollution of the natural soundscape perforates otherwise intact three-dimensional acoustic space used by organisms for communication (Brumm and Slabbekoorn 2005, Kight et al. 2012, Buxton et al. 2017).

To date, comparative investigations of the acoustic activity of bird communities in the vicinity of wind energy facilities have not occurred. Wind energy production has the potential to significantly elevate ambient sound levels through propagation of low-frequency noise (i.e. below 1.0 kHz for most large wind turbines; Møller and Pedersen 2011) to distances of >1 km (Van den Berg 2004). Zwart et al. (2016) demonstrated that an increase of low-frequency song elements in response to territorial intrusion was absent for European Robins (*Erithacus rubecula*) exposed to low-frequency wind turbine noise, indicating that wind turbine noise may affect their ability to deter an intruder. This exemplifies the potential impacts of wind turbine noise infiltrating wildlife habitat, which has begun to gain attention as an aspect of environmental protection (Brown et al. 2013, Ritts et al. 2016).

Here, we analyze the spring soundscape of a wind energy facility in the Nebraska Sandhills, the largest intact grassland in the Great Plains of North America (~5,076,400 ha; Bleed and Flowerday 1998). The recordings we analyzed were made at Greater Prairie-Chicken (*Tympanuchus cupido pinnatus*; hereafter “prairie-chicken”) leks that were part of a concurrent study (Harrison et al. 2017, Whalen et al. 2017). Our aims for the soundscape analysis were to (1) quantify species diversity at the community assemblage level between grassland sites with and without wind turbines (Magurran et al. 2011); (2) assess the correlation of a commonly used acoustic index (ACI; Pieretti et al. 2011, Towsey et al. 2014) with grassland bird richness; and (3) compare the acoustic complexity of these community assemblages in space and time using a regression framework. We predicted that (1) the presence of wind facility infrastructure in unfragmented grasslands would alter the spatial and structural assemblage of the breeding bird community and (2) the machinery-produced noise in the wind-energy-facility environment would influence the diurnal acoustic activity of the bird community by increasing the soundscape’s acoustic complexity (Pieretti and Farina 2013, Duarte et al. 2015).

## METHODS

Our study was centered on a preexisting 1,620 ha wind energy facility owned and operated by the Nebraska Public Power District, ~10 km south of Ainsworth, Brown County, Nebraska, USA (42.4571°N, 99.9142°W; Figure 1). The facility, built in 2005, consists of 36 wind turbines that occupy 20.2 ha of the property with associated infrastructure (Nebraska Public Power District; <http://www.nppd.com/about-us/power-plants-facilities/wind-generation/ainsworth-facts-and-figures/>; accessed June 10, 2016). Each 1.65 MW capacity turbine stands 70 m tall, has 40 m long blades, and covers a 0.4 ha footprint.



**FIGURE 1.** Locations of 6 sampling transects (gray dots) in 2 grassland habitats—W sites, within  $\sim 770$  m of wind turbines (black wind turbine symbols); and R sites, without wind turbines—at the Nebraska Public Power District wind energy facility near Ainsworth, Brown County, Nebraska, USA, in May 2013.

Other infrastructure at the facility included gravel roads, an electrical substation, high-tension power lines and towers, and maintenance buildings. The fieldwork was carried out between May 2 and 27, 2013, as part of a larger study of the acoustic ecology of prairie-chicken leks (Whalen 2015). Prairie-chicken leks are usually located on hilltops covered with short grass, where adult males congregate in spring to attract females.

The study area (785–830 m above sea level; Figure 1) in the Nebraska Sandhills was dominated by grass species, including little bluestem (*Schizachyrium scoparium*), switchgrass (*Panicum virgatum*), and prairie sandreed (*Calamovilfa longifolia*). Land use was primarily cattle ranching (80% land cover); hay production (10%); and cultivated crops, including corn (*Zea mays*), soybean (*Glycine max*), and alfalfa (*Medicago sativa*), that are supported by irrigation (5%); human development accounted for the remaining 5% of land cover (Bleed and Flowerday 1998). On average, wind speeds exceed  $8.5 \text{ m s}^{-1}$  at 80 m above ground (average height of a wind turbine hub).

We estimated dominant land-cover type (grassland, wetland, developed, and forest) from the 2011 National Land Cover Database (Homer et al. 2012) within a 1,000 m radius of the center of each lek using ArcGIS 10.3 Spatial Analyst extension (ESRI 2011). Each of our recording sites, a circle with a radius of  $\sim 800$  m centered on a prairie-chicken lek, was placed within grassland, with sub-irrigated meadows or wetlands as a secondary land-cover

component (Table 1). Overall, the mean Euclidean distance between the recording transects (wind facility and reference sites) was 2,050 m (range: 397–5,409 m). The mean distance between reference sites and the nearest wind turbine was 4,000 m (range: 763–8,348 m), and the mean distance between wind facility sites and the nearest wind turbine was 167 m (range: 86–321 m) (Table 1).

We recorded the soundscape by positioning 8 digital recorders (SM2+; Wildlife Acoustics, Maynard, Massachusetts, USA) along 2 perpendicular lines running east to west and south to north, which was repeated at 3 grassland leks within 760 m of the wind energy facility and 3 leks  $\geq 760$  m away from the wind farm during each week in May 2013 (Figure 1). Along each transect, audio recorders were placed at distances of 100, 200, 400, and 800 m from the edge of an active prairie-chicken lek. Eight audio recorders were used to simultaneously record sound on 2 of the 4 transects (e.g., north-south or east-west) during one visit to a lek site. Sound was recorded at the other 2 transects within a week of the last visit.

We recorded sound at 3 two-minute periods within a morning: approximately 1 hr before sunrise (early), sunrise (mid), and 1 hr after sunrise (late) to capture the dawn chorus in the study area (about 0530–0730 hours CDT; Figure 2). Sound was recorded at each site once per week during optimal conditions (sunny, low wind [ $< 24$  kmh], no rain) to minimize the impact of weather on the acoustic performances of the birds and on the soundscape measurements (i.e. wind and rain; Pijanowski et al.

**TABLE 1.** Euclidean distances (m) from center of wind energy facility and nearest turbine to nearest recording location, elevation (m a.s.l.), and percent cover of dominant land-cover types within a 1,000 m radius of the center of each recording location in May 2013 at the Nebraska Public Power District wind energy facility near Ainsworth, Brown County, Nebraska, USA.

Variable	Reference				Wind facility			
	1	2	3	$\bar{X}$	1	2	3	$\bar{X}$
Distance to turbine	1,587	11,121	6,513	6,407.7	948	1,000	757	901.7
Nearest distance	763	8,349	2,891	4,001.0	91	86	211	129.3
Elevation	786	821	798	801	802	799	802	801
Percent grassland	90.6	89.6	90.1	90.1	98.8	94.5	97.1	96.8
Percent wetland	2.8	10.3	8.3	7.2	1.0	5.4	2.8	3.1
Percent hardwood	2.9	0	1.6	1.5	0.02	0	0	0.00
Percent developed	3.6	0	0	1.2	0	0	0	0.001

2011b), thus allowing us to record primarily avian acoustic activity. Each recorder was fixed on a post at 25 cm (height of a prairie-chicken; Schroeder and Robb 1993) above the ground, with the 2 lateral microphones clear of any surface that could be an obstacle to sound. Each microphone was fitted with 2 windscreens to reference for wind distortion in the recordings (Wildlife Acoustics windscreen; Windtech 600 series windscreen, Olsen Audio Group, Scottsdale, Arizona, USA). The recorders were set at 44.1 kHz/16 bit/stereo mode and stored data in WAV file format.

The first 2 min of each hour in the 3 hr dawn recording window totaled 618 two-minute files (20.6 hr). To determine how energy was distributed across the spectrum in every 2 min WAV file, a fast Fourier transformation of 512 points was performed, which equated to 256 classes of frequencies available for processing using a 5 s temporal step,  $j$ . To assess the complexity of the soundscape, we employed the Acoustic Complexity Index (ACI) developed by Pieretti et al. (2011). On the basis of a matrix of the intensities extrapolated from the spectrogram (divided into temporal steps and frequency bins), the index extracts a measure of acoustic information from audio recordings based on the absolute difference ( $d_k$ ) between 2 adjacent

values of intensity,  $I_k$  and  $I_{(k+1)}$ , in a single frequency bin ( $\Delta f_j$ ):

$$d_k = |I_k - I_{(k+1)}| \tag{1}$$

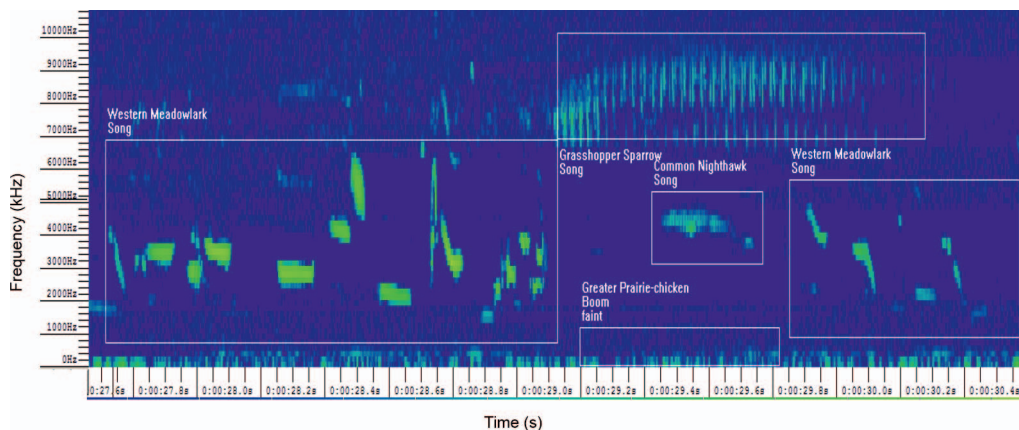
The index then adds together all the  $d_k$  encompassed in the first temporal step of the audio recording ( $j$ ; e.g., 5 s, 30 s...):

$$D = \sum_{k=1}^n d_k \quad \text{for: } j = \sum_{k=1}^n \Delta t_k; \quad n = \text{number of } \Delta t_k \text{ in } j \tag{2}$$

where  $D$  is the sum of all the  $d_k$  contained in  $j$ . To obtain the relative intensity and to reduce the effect of the distance of the birds from the recording microphone, this result is then divided by the total sum of the intensity values in  $j$ :

$$ACI = \frac{D}{\sum_{k=1}^n I_k} \tag{3}$$

where the ACI is calculated in a single temporal step ( $j$ ) and in a single frequency bin ( $\Delta f_j$ ), which results in all  $\Delta f_j$  for  $j$  in the entire recording being summed (Pieretti et al.



**FIGURE 2.** Representative spectrogram of the sounds produced by grassland birds on our study area at the Nebraska Public Power District wind energy facility near Ainsworth, Brown County, Nebraska, USA, in May 2013.



2011). This algorithm results in a unitless value that is correlated with the number of bird vocalizations (Bobryk et al. 2016).

We extracted ACI values from the 1.5–22.05 kHz frequency band (mainly occupied by vocalizing passerines; Farina et al. 2011b) using the “acoustic\_complexity” function in the “soundecology” package in R 3.1.1 (Ligges et al. 2016, R Development Core Team 2016, Villanueva-Rivera and Pijanowski 2016). The threshold of 1.5 kHz was chosen because most of the energy from anthropogenic noise (e.g., wind turbines and traffic) and prairie-chicken vocalizations are primarily concentrated under 2 kHz (Sparling 1983, Møller and Pedersen 2011). This 2 kHz threshold was lowered 0.5 kHz to prevent us from excluding important avian vocalizations that were just above 1.5 kHz, such as those of Western Meadowlarks (*Sturnella neglecta*) (Figure 2; Pieretti and Farina 2013). We intended to evaluate the acoustic expression primarily of songbirds using this threshold (Pieretti et al. 2011, Pieretti and Farina 2013), which is set above wind turbine noise. However, the presence of low-frequency noise can interfere with behavior such as vocal communication, thus resulting in altered acoustic activity of birds (Slabbekoorn and Ripmeester 2008, Pieretti and Farina 2013) and altered community structure (Francis et al. 2009).

When detected in surveys of the 2 min sound files, we characterized the anthropogenic noise (e.g., wind turbines) by analyzing the power spectrum using Raven Pro 1.5 (Bioacoustics Research Program 2014). These noise events were described by measuring their minimum, maximum, and peak frequencies and their duration. Mean maximum frequency of wind turbine noise was divided by the full spectrogram bandwidth (22.5 kHz) to provide an estimate of how much acoustic space might be occupied by wind turbine noise (Duarte et al. 2015).

We calculated species richness and community composition for each site by identifying species using Raven Pro 1.5, to evaluate community-level differences between the recording sites close and far from the wind energy facility. Sounds produced by amphibians, birds, and mammals were identified by E.J.R. in every 2 min file, totaling 972 analyzed minutes (486 files); 163 files were removed from the index estimation when birds were heard using the recorder as a singing perch and filling the spectrogram with a single loud vocalization; this left 323 two-minute files for ACI estimation.

At the assemblage level, for each of the 6 sets of recording transects (Figure 1), we obtained the number of species; this parameter corresponded to an  $\alpha$ -diversity measure (i.e. the number of species referred to a single sampling transect; Whittaker 1972, Magurran 2013). For each habitat type, within and outside the wind energy facility, we obtained the following community parameters:

(1) total number of species ( $S$ ), a measure of  $\gamma$ -diversity for the relative habitat type (Whittaker 1972); and (2) mean number of species (a normalized metric of richness;  $S_{\text{mean}}$ ), as the ratio between the number of species identified at each recording transect and the number of recordings days. To assess the habitat heterogeneity of each habitat type, we calculated the Whittaker  $\beta_w$  index (Whittaker 1960) as

$$\beta_w = S/S_{\text{mean}} \quad (4)$$

where  $S$  is a measure of  $\gamma$ -diversity and  $S_{\text{mean}}$  is a measure of averaged  $\alpha$ -diversity values among recording events. This index indirectly estimates bird-related habitat heterogeneity by assessing the species turnover among transects (assuming that the higher the species turnover, the higher the habitat heterogeneity; Magurran 2013).

We used Pearson’s product-moment correlation to verify a relationship between ACI and bird species richness. A linear mixed-effects model (Bates et al. 2015) was used to evaluate the dawn chorus ACI near or far from wind turbines in relation to times of day (early, middle, and late morning) and number of days since May 1. Treatment type (reference or wind facility) was a categorical independent variable, which did not constrain us to assume a priori that the relationship between breeding-bird acoustic activity and distance to nearest turbine would be linear (Hale et al. 2014, Powell et al. 2017). The time period of recording and days since May 1 were used as independent variables (as fixed effects) while recording location nested within lek site was used as a random effect. We log transformed variables where appropriate to meet the criteria of normality for parametric statistical analyses. We report exact  $P$  values to distinguish between significant effects ( $P < 0.05$ ) and marginally significant effects that may warrant attention ( $0.05 < P < 0.1$ ).

## RESULTS

### Wind Turbine Noise Characterization

A total of 32 occurrences of wind turbine noise were detected in the 486 recordings. Wind turbine noise was absent from 98.5% of reference site recordings and was absent from 84% of the recordings at the wind facility sites. Only 2 recordings at the reference site R1 contained wind turbine noise, while wind turbine noise was not heard at reference sites R2 and R3. Wind turbine noise was present in 10, 7, and 13 recordings at wind facility sites W1, W2, and W3, respectively. Wind turbine noise lasted the duration of these 2 min recordings. The mean ( $\pm$  SD) maximum frequency of this noise was  $0.731 \pm 0.239$  kHz, meaning that the noise occupied 3.3% of the full spectrogram bandwidth (22.05 kHz). Mean peak and

**Table 2.** Detected common breeding bird species and mean species occurrence ( $\pm$  SE) per recording at reference and wind facility sites in May 2013 at the Nebraska Public Power District wind farm near Ainsworth, Brown County, Nebraska, USA.

Species	Reference			Wind facility		
	1	2	3	1	2	3
American Goldfinch ( <i>Spinus tristis</i> ) <sup>a</sup>						X
Lark Sparrow ( <i>Chondestes grammacus</i> )	X	X		X	X	X
Grasshopper Sparrow ( <i>Ammodramus savannarum</i> )	X	X	X	X	X	X
Bobolink ( <i>Dolichonyx oryzivorus</i> )	X		X		X	
Eastern Meadowlark ( <i>Sturnella magna</i> ) <sup>a</sup>			X			
Western Meadowlark ( <i>Sturnella neglecta</i> )	X	X	X	X	X	X
Red-winged Blackbird ( <i>Agelaius phoeniceus</i> )	X	X	X	X	X	X
Brown-headed Cowbird ( <i>Molothrus ater</i> )	X		X		X	X
Common Grackle ( <i>Quiscalus quiscula</i> ) <sup>a</sup>			X			
Common Yellowthroat ( <i>Geothlypis trichas</i> ) <sup>a</sup>			X			
Yellow Warbler ( <i>Setophaga petechia</i> )	X		X			X
Blackpoll Warbler ( <i>Setophaga striata</i> ) <sup>a</sup>			X			
Dickcissel ( <i>Spiza americana</i> ) <sup>a</sup>			X			
Canada Goose ( <i>Branta canadensis</i> )	X	X	X	X	X	X
Mallard ( <i>Anas platyrhynchos</i> )	X	X	X	X	X	X
Ring-necked Pheasant ( <i>Phasianus colchicus</i> )	X			X	X	X
Greater Prairie-Chicken ( <i>Tympanuchus cupido</i> )	X	X	X	X	X	X
Mourning Dove ( <i>Zenaidura macroura</i> )	X	X	X	X	X	X
Common Nighthawk ( <i>Chordeiles minor</i> )		X	X	X	X	X
Killdeer ( <i>Charadrius vociferus</i> )	X		X	X	X	X
Upland Sandpiper ( <i>Bartramia longicauda</i> )	X	X	X	X	X	X
Wilson's Snipe ( <i>Gallinago delicata</i> )	X		X		X	X
Spotted Sandpiper ( <i>Actitis macularia</i> ) <sup>a</sup>			X			
Northern Flicker ( <i>Colaptes auratus</i> )	X		X			
Eastern Kingbird ( <i>Tyrannus tyrannus</i> )	X		X	X		X
American Crow ( <i>Corvus brachyrhynchos</i> ) <sup>a</sup>				X		
Horned Lark ( <i>Eremophila alpestris</i> )	X	X	X	X	X	X
Tree Swallow ( <i>Tachycineta bicolor</i> ) <sup>a</sup>						X
Barn Swallow ( <i>Hirundo rustica</i> ) <sup>a</sup>	X					
House Wren ( <i>Troglodytes aedon</i> )	X		X			X
American Robin ( <i>Turdus migratorius</i> )	X		X			
Brown Thrasher ( <i>Toxostoma rufum</i> ) <sup>a</sup>			X			
European Starling ( <i>Sturnus vulgaris</i> ) <sup>a</sup>	X					
Total breeding bird species	20	11	19	13	16	18
Species per recording	4.1 (0.2)	3.5 (0.2)	4.6 (0.2)	3.5 (0.2)	3.8 (0.2)	3.7 (0.2)

<sup>a</sup> Species not included in diversity analyses.

minimum frequency were  $0.170 \pm 0.015$  and  $0.052 \pm 0.033$  kHz, respectively.

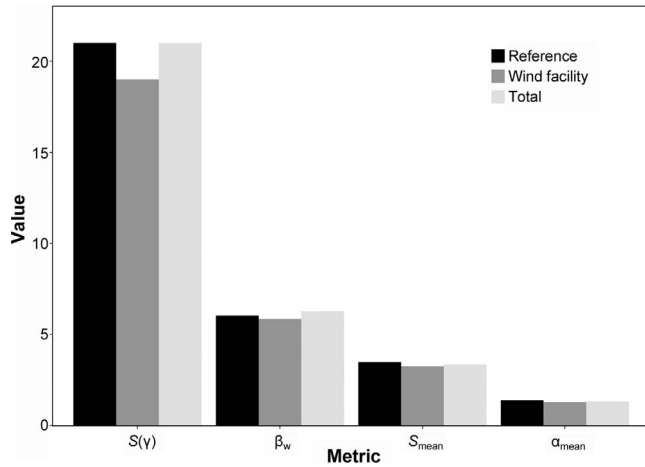
### Characterization of Fauna

We detected 33 bird species, including nonbreeding species, single detections, and long-distance Neotropical migrants (Table 2). Twenty-one breeding grassland bird species were identified ( $S(\gamma) = 21$  in reference and 19 in wind turbine areas). Overall, species composition within wind facility and reference habitat was identical, with the exception of Northern Flicker (*Colaptes auratus*) and American Robin (*Turdus migratorius*), which were detected at reference sites R1 and R3. These sites lie near the town of Ainsworth, a source of habitat for these arboreal species. Species rarefaction curves reached an asymptote for each habitat type, indicating that additional sampling

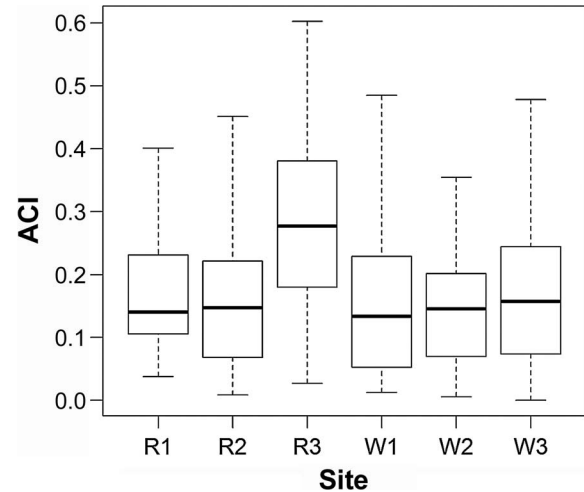
would likely not yield any other species within the study area (Appendix Figure 6). At the community level, differences for  $S_{\text{mean}}$  or  $\alpha_{\text{mean}}$  were not significant when comparing reference and wind facility areas (Mann-Whitney  $U$ -test;  $P > 0.1$ ; Figure 3). The Whittaker  $\beta_w$  index did not show differences between reference and wind facility areas (Figure 3).

### Soundscape Dynamics

We analyzed 133 and 190 two-minute files from the month of May for ACI at reference and wind facility sites, respectively. The ACI of the acoustic morning activity increased with increasing days since May 1 (Pearson's product-moment correlation,  $t_{1,321} = 6.8$ ,  $P < 0.001$ ,  $r = 0.35$ ). A weaker, but significant, correlation between ACI and species richness per 2 min recording was evident



**FIGURE 3.** Total number of common vocal species ( $S(y)$ ), mean number of visit-weighted species in each habitat ( $S_{mean}$ ), mean visit-weighted recording transect diversity ( $\alpha_{mean}$ ), and Whitaker  $\beta_w$  index of breeding bird assemblages from our study sites at the Nebraska Public Power District wind energy facility near Ainsworth, Brown County, Nebraska, USA, in May 2013.



**FIGURE 4.** Box-whisker plots of Acoustic Complexity Index (ACI) for each study site at the Nebraska Public Power District wind energy facility near Ainsworth, Brown County, Nebraska, USA, in May 2013. Box-whisker plots are lower and upper quartiles (hinges). Black horizontal line is median. For definition and location of R and W sites, see Figure 1.

( $t_{1,321} = 4.4, P < 0.001, r = 0.24$ ). The number of species detected within each recording was greater at reference sites (mean  $\pm$  SE =  $4.07 \pm 0.1$ ) than at wind facility sites ( $3.70 \pm 0.1$ ) ( $t$ -test,  $t = 2.3, P = 0.02$ ; Table 2). In particular, the reference grassland site supporting 2% woodland cover, R3, had greater species richness within recordings and higher ACI values than all other sites (Tukey’s HSD,  $P < 0.05$ ; Figure 4). Our linear mixed model analysis with recorder location nested within site as a random effect revealed that grassland sites near or far away from the wind facility did not differ in ACI, although acoustic activity increased as the morning and the breeding season progressed (Table 3; Figure 5A, 5B). A significant interaction ( $P = 0.01$ ) between days since May 1 and treatment indicated that ACI increased at a greater rate at reference sites than at wind facility sites over the study period (Figure 5C), likely a result of active acoustic space being filled to a greater extent by vocalizing species at reference sites as the season progressed.

**DISCUSSION**

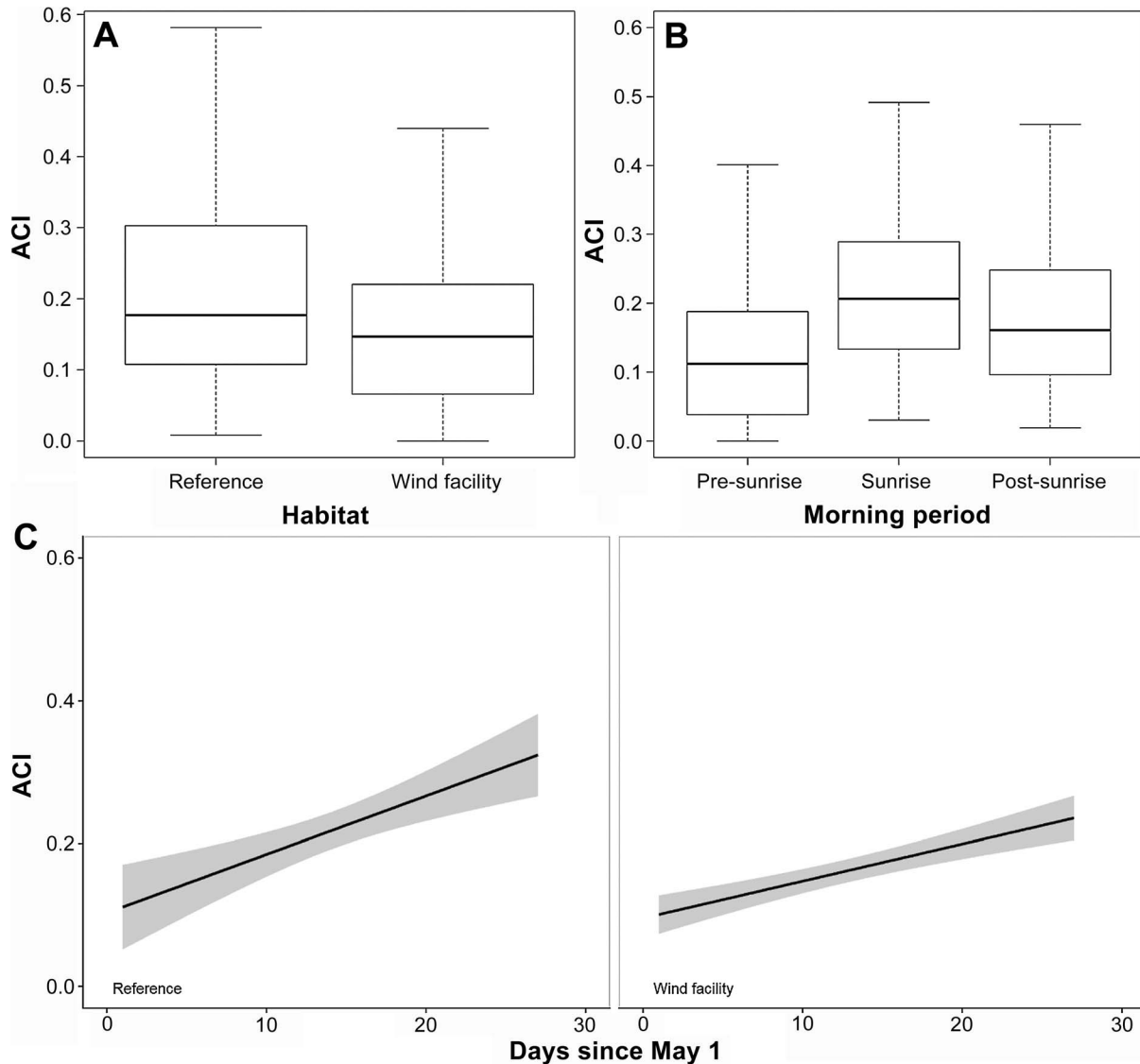
**Avian Soundscapes**

Using surveys of audio recordings, we found that the assemblages of grassland bird species between wind facility and reference sites were similar in community structure. Estimates derived from audio recordings revealed that acoustic complexity was not affected by the presence of the wind energy facility. Within the morning, ACI peaked around sunrise. A weak but significant correlation in ACI and days since May 1 indicated that acoustic complexity increased as the early breeding season progressed. These results indicate that ACI can be used to assess within-day and across-season songbird activity and coarse-scale shifts in songbird phenology in grasslands.

Apparently, the low level of impact and perforation caused by wind turbine noise and related infrastructures did not affect the response in breeding bird richness at the assemblage level. Our expectation that wind facility sites would have greater acoustic complexity than reference

**TABLE 3.** Linear mixed model results for effects of environmental factors on variation in Acoustic Complexity Index of vocal species in May 2013 at the Nebraska Public Power District wind energy facility near Ainsworth, Brown County, Nebraska, USA.

Factor	$\beta$	SE	df	$t$	$P$
Intercept	8.11	0.007	224	1,178.97	<0.001
Days since May 1	0.002	0.0003	224	6.38	<0.001
Mid-morning	0.02	0.004	224	5.04	<0.001
Late morning	0.02	0.005	224	4.01	<0.001
Treatment	0.0005	0.0008	4	1.32	0.26
Treatment*mid-morning	-0.008	0.006	224	-1.38	0.17
Treatment*late morning	-0.01	0.007	224	-1.56	0.12
Treatment*days since May 1	0.0001	0.00004	224	-2.58	0.01



**FIGURE 5.** Box-whisker plots of (A) Acoustic Complexity Index (ACI) at habitat types; (B) ACI values based on morning acoustic activity, considering all localities and recording sessions; and (C) ACI  $\pm$  SE, spanning May 2013 at reference and wind facility sites at the Nebraska Public Power District wind energy facility near Ainsworth, Brown County, Nebraska, USA. Box-whisker plots as in Figure 4.

sites was not apparent in our analyses. Although these areas exhibited more occurrences of wind turbine noise in our recordings, the noise levels were not constant and were of low frequency (<0.8 kHz); thus, the bird community did not show statistically significant differences in its acoustic expression when compared to reference sites. However, our analysis did not examine potential vocal adjustments or signal plasticity of each species (i.e. peak amplitude of vocalizations occurring at higher frequencies at wind facility sites than for individuals inhabiting reference sites; Brumm and Slabbekoorn 2005, Fernández-Juricic et al. 2005, Patricelli and Blickley 2006). Because vocal adjustments to escape the masking effects of

turbine noise may result in alterations to individual energy budgets (Brumm 2004), we urge further research to identify mechanisms responsible for settlement in noisy areas and the potential trade-offs associated with living in noisy conditions, such as feeding rates (Quinn et al. 2006) and resulting body condition (Ware et al. 2015, McClure et al. 2017).

Our study area, the unfragmented Nebraska Sandhills grasslands, hosts breeding bird assemblages typical of highly homogeneous prairie landscapes (Johnsgard 2000, Sharpe et al. 2001, Mollhoff 2016). The number of bird species identified (33) was lower than the species richness of 63 birds reported in more vertically structured



woodlands dominated by oaks (*Quercus* spp.) or red cedar (*Juniperus virginiana*) along the Niobrara River just north of our study area (Frost and Powell 2011). However, identification of 23 songbird species in our recordings was not substantially lower than the 28 species detected during 2 seasons of point-count surveys in a similar Nebraska Sandhills grassland habitat (Sliwinski 2017). Our approach was not designed to estimate abundance of individual species, yet it did describe habitat-specific avian associations within intact and human-altered grasslands. For example, we found greater acoustic activity and species richness at a primarily grassland site with slight (<2%) woodland cover. This result mirrors studies using ACI in agricultural and suburban systems, where high acoustic activity was related to the recording stations' position (Pieretti and Farina 2013, Bobryk et al. 2016). To our knowledge, this study is the first auditory inventory of bird species reported in a region of the Nebraska Sandhills. This area, in particular the sub-irrigated meadows and upland prairies, provides important nesting habitat (e.g., prairie-chicken and Sharp-tailed Grouse [*Tympanuchus phasianellus*]) and migration stopover habitat for grassland songbirds and waterbirds along the Central Flyway (Fargione et al. 2012, Gregory et al. 2012).

### Habitat Fragmentation

The location and placement of wind turbines cause habitat fragmentation and dissection by service roads, both of which can affect bird densities and community structure (Fischer and Lindenmayer 2007, Fargione et al. 2012). The effect of perforation due to wind energy activities is mostly unexplored. An investigation of avian communities via point-count surveys at 3 wind facilities in North and South Dakota revealed that 7, 1, and 1 of 9 grassland songbird species were displaced, unaffected, and attracted to or by habitat perforation, respectively (Shaffer and Buhl 2016). A before-after-control-impact (BACI) design (Manly 2000) enabled Shaffer and Buhl (2016) to distinguish whether species exhibited immediate effects (displacement within 1 yr after wind facility construction), delayed effects (displacement beyond the first year after construction), and sustained effects (displacement continuing from 1 to 5 yr after construction).

At the spatial and temporal scale of our study, the 1% habitat perforation (20 ha on a 1,620 ha wind energy facility) was likely not enough to disrupt the assemblage structure and singing activity. The effects of habitat perforation on bird assemblages may only be evident at higher thresholds (>10%; Fahrig 1998, With and King 1999). Using  $\beta$ -diversity as an indicator, we did not observe differences between the reference and wind energy facility sites, which suggests that bird assemblages responded to these 2 habitat types as having similar levels of patchiness, complexity, and disturbance.

We surmise that changes in heterogeneity due to the presence of the wind energy facility were too limited in extent (i.e. they are below a threshold in area or noise infiltration) and the related disturbances too low in magnitude to induce significant effects at the assemblage level (White and Pickett 1985) or acoustic community level (Bayne et al. 2008, Francis et al. 2012). However, it is possible that acoustic expression between the treatments was similar because avian communities within the wind energy facility may sing more loudly or use higher frequencies than communities in reference grasslands to mitigate acoustic masking by low-frequency noise, as observed in city-dwelling Eurasian Blackbirds (*Turdus merula*; Nemeth and Brumm 2009); such adjustments could also be the outcome of more intense vocal interaction in a more densely populated yet habitat-fragmented wind facility–grassland matrix. These potential scenarios emphasize the need for experimental studies in wind facility–grassland matrices to clarify a possible causal link between wind facility acoustics and acoustic expression of grassland birds.

To our knowledge, the present study is the first to assess the possible control-treatment effects in vocal grassland bird assemblages impacted by a wind energy facility. However, we recognize some shortcomings of this study: (1) we tested possible control-treatment differences only in one season; (2) we analyzed only the structural patterns of assemblages and did not consider more complex interactions, dynamics, and consequences due to habitat perforation (e.g., increase of edge habitats and consequently nest predation; Renfrew et al. 2005); (3) the auditory point-count method focused only on a set of common breeding birds, and our conclusions are limited to these easily detectable species and not their density, which may be affected by proximity to noise (Forman et al. 2002, Peris and Pescador 2004, Francis et al. 2009, Summers et al. 2011); and (4) our study was carried out in spring 2013, 8 yr after construction of the wind energy facility. We cannot exclude that community structure may change in the short- and medium-term post-construction periods (delayed or lag effect; Kupfer and Franklin 2009, Masden et al. 2010).

The use of prairie-chicken leks as sampling sites may have biased our findings toward grassland bird species that prefer that habitat type. In our study area, prairie-chicken leks are located in large, lowland meadows (Powell et al. 2014), areas that attract a diversity of species and the majority of those breeding in the Sandhills grasslands. Our results are derived from recordings made during low wind conditions, which allowed us to detect species without interruption from windy (noisy) conditions (Ortega and Francis 2012). While this may have biased our data (more species identifiable in recordings than in windy conditions), we believe that it provides a consistency to the data and our analyses.

### Future Considerations

Our results provide insight into the avian soundscape of relatively intact grasslands and grasslands where the acoustic space is exposed to wind turbine noise. Our surveys revealed that wind turbine noise was present in this landscape during the passerine morning chorus. Subsequent acoustic analysis revealed that the maximum frequency bandwidth of this noise ( $\leq 0.730$  kHz) occupies the operative frequencies of prairie grouse lek-advertisement vocalizations:  $< 0.30$  kHz for Greater Prairie-Chicken (Figure 2; Whalen 2015),  $0.50$ – $1.0$  kHz for Lesser Prairie-Chicken (*Tympanuchus pallidicinctus*; Sharpe 1968), and  $\sim 0.30$  kHz for Sharp-tailed Grouse (Sparling 1983). Further investigation of this potential interaction between prairie grouse acoustic ecology and wind turbine noise is warranted.

From an ecological perspective, we encourage studies focused on the effects of wind facilities on different taxonomic guilds (e.g., aerial predators; Hunt and Watson 2016) and vocal species, not evaluated in this study, that operate at the lower end of the acoustic power spectrum (e.g., gallinaceous birds). Species that can adjust vocalizations to higher frequencies may thrive in noisy habitats and experience lower interspecific competition for resources (Francis et al. 2009), while predation risk may be reduced for species in noisy habitats when compared to habitats not disrupted by anthropogenic sound (Francis et al. 2011, Smith et al. 2016). We suggest a precautionary approach and encourage further studies on wind-energy habitat perforation and concomitant anthropogenic noise at broader spatial and temporal scales.

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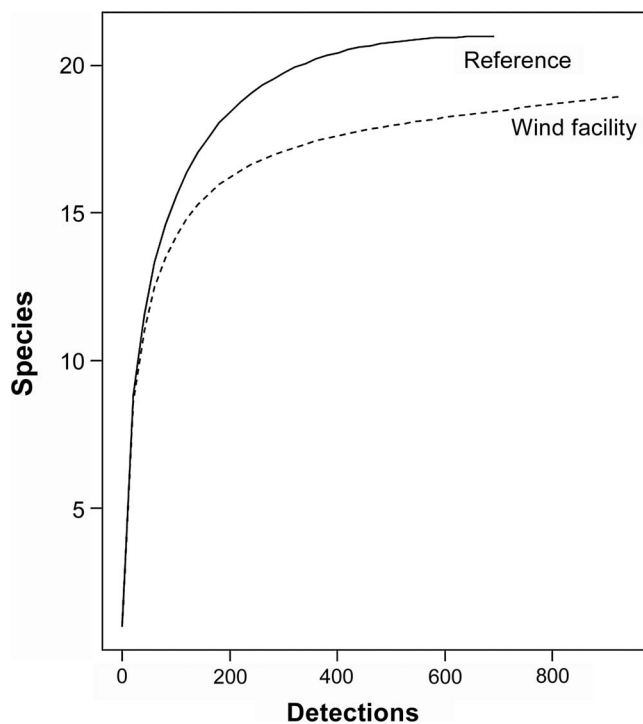
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**APPENDIX FIGURE 6.** Rarefaction curves for reference and wind-facility-site aural censuses predict the rate of accumulation of species with increasing numbers of bird detections from data for the number of detections of each species in the original sample.