



Research



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Author for correspondence:

Samantha Ariel McGarrigle

e-mail: samantha.a.mcgarigle@gmail.com

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Evaluating interactive effects of the Conservation Reserve Program and wind energy infrastructure on grassland bird abundance in the United States

Samantha Ariel McGarrigle¹, Ellery Vaughn Lassiter¹, Karen Maguire², Rich Iovanna³, Jay E. Diffendorfer⁴, Anthony Lopez⁵, Kyle Reed², Courtney Duchardt^{1,6} and Scott R. Loss¹

¹Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, OK 74078, USA

²US Department of Agriculture, Economic Research Service, Washington, MO 64105, USA

³Farm Production and Conservation Mission Area, US Department of Agriculture, Washington, DC 20250, USA

⁴Geosciences and Environmental Change Science Center, US Geological Survey, Lakewood, CO 80225, USA

⁵National Renewable Energy Laboratory, US Department of Energy, Golden, CO 80401, USA

⁶The University of Arizona School of Natural Resources and the Environment, Tucson, AZ, USA

SAM, 0000-0002-2018-798X

The extent of grasslands has contracted globally, leading to significant declines in grassland-obligate species, including birds. Grassland birds are threatened by multiple factors, including grassland conversion to cropland, and development, including energy infrastructure. In the USA, the federal Conservation Reserve Program (CRP) provides financial incentives for agricultural landowners to convert marginal cropland to vegetative covers, including grassland, making it a key approach to recovering grasslands. However, given the high percentage of wind turbines near Conservation Reserve Program land, it is critical to determine if wind energy and the Conservation Reserve Program interact to affect grassland birds. We used generalized additive models and community science eBird data to assess the interactive effects of wind and the Conservation Reserve Program on the abundances of 27 grassland-obligate bird species across their breeding ranges in the continental US. We found

associations between bird relative abundances and interactions involving wind and Conservation Reserve Program variables, suggesting that wind energy development near Conservation Reserve Program fields could dampen the benefits of the Conservation Reserve Program for some species. These results indicate that decisions about where to install wind energy infrastructure that incorporate information about the presence of Conservation Reserve Program land may reduce the adverse effects of wind energy on grassland birds. This study provides information that can help maximize the benefits of the Conservation Reserve Program while allowing for environmentally friendly development of renewable energy.

1. Introduction

The extent of grassland ecosystems has declined rapidly globally over the past century [1]. In North America, the Great Plains region has lost 70% of its historic grassland land cover, with tallgrass prairie regions having lost 73% of their historical extent [2], primarily to agriculture [3,4]. As a result of grassland loss through conversion to cropland, application of pesticides [4], woody plant encroachment [5,6] and climate change [7,8], grassland bird populations in North America are declining faster than any other group of birds [7–10]. To reduce carbon emissions from the electricity sector and mitigate climate change, renewable energy infrastructure, including wind and solar, is needed, but these energy sources can also negatively affect grassland birds, including through collisions with infrastructure [11] and a reduction in habitat quality [3].

Grassland birds are represented by a broad array of taxonomic groupings and have diverse life histories and a range of migratory strategies and food and habitat preferences [12]. Thus, no single conservation approach will result in population increases for all grassland bird species [7,12]. Nevertheless, addressing grassland loss, one of the greatest threats to grassland-obligate bird species, is likely to benefit this rapidly declining avian group. In the USA, non-governmental organizations and the federal government have implemented programs to help recover grassland ecosystems. One such federal program, the Conservation Reserve Program (CRP), was enacted as part of the Food Security Act of 1985. The CRP is one of the largest private lands conservation programs and the largest US Department of Agriculture (USDA) conservation program [13,14]. The CRP provides financial incentives for agricultural landowners to engage in voluntary contracts to retire cropland that is highly erodible or environmentally sensitive. Land accepted into the program is converted for periods of 10–15 years into grass, trees or other vegetation cover that provides habitat for wildlife species, erosion control or other benefits consistent with CRP goals [15]. According to the USDA, which manages the program, almost 27 million acres were enrolled in 2024, close to the CRP acreage cap [13].

Contracts for producers who enroll in CRP vary depending on the type of vegetative cover planted, the management practices required, the number of acres enrolled and the amount of financial assistance they receive. Conservation practices (CP) are a key characteristic of CRP contracts used to capture much of the variation in the type of vegetative cover used. From 2008 to 2022, CRP contracts were implemented using more than 40 different CP codes. The vegetative covers associated with each CP code were designed to address different environmental goals, including erosion control, water quality enhancement and providing wildlife habitat [13,15]. CRP land has often been shown to be positively associated with grassland bird abundance [7,16–18]; however, not all grassland bird species experience clear abundance increases owing to the implementation of the CRP [7,16,18]. The varied responses of grassland birds to the CRP are probably attributable to the wide range of habitat preferences among this wide-ranging guild of birds. Because grassland birds are declining rapidly, a thorough understanding of the effects of conservation programs, including the CRP, on populations of this avian group is needed, especially given other increasing threats to birds, including alternative energy sources, such as wind and solar energy infrastructure.

To reduce greenhouse gas emissions from the electricity sector to mitigate climate change, US state and federal policies, including the Federal Production Tax Credit and State Renewable Portfolio Standards, have provided financial incentives for renewable energy development, particularly wind and solar. This development has occurred largely in rural areas and on agricultural land [19]. Wind energy development in the USA has expanded dramatically since the 1980s, and many areas of the nation that have a relatively high share of CRP land [20] also host extensive wind energy infrastructure. While wind energy is a cleaner form of electricity production compared with traditional fossil fuels, wind energy infrastructure

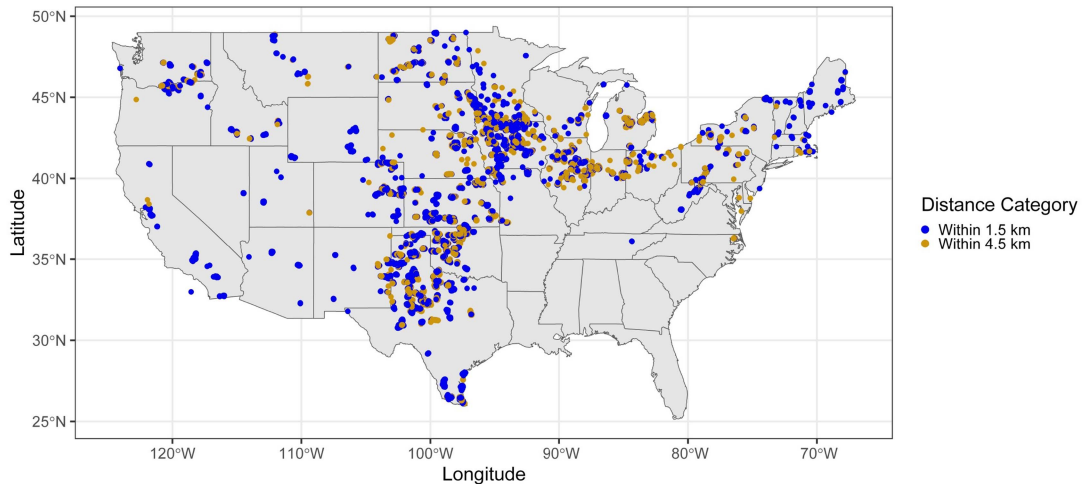


Figure 1. Map of wind turbine locations in the contiguous US that became operational prior to 2021 and that are located within 1.5 km and 4.5 km of land enrolled in the Conservation Reserve Program (CRP). Wind turbine data are from the United States Wind Turbine Database v. 5.3 [36] and CRP data are from a restricted access dataset provided by the USDA Farm Service Agency.

can negatively affect wildlife [21–25]. For birds, wind energy development can cause direct mortality owing to bird collisions with wind turbines [24,26–29], and indirect effects owing to land cover changes that alter bird movements and habitat use [23,29,30]. These factors can reduce bird abundance locally [3,21,30,31] and have the potential to contribute to larger-scale bird population declines as further wind development occurs in the future [24,32,33]. Furthermore, the above literature indicates that different bird species experience differential effects of wind energy, including the degree to which abundances are affected, the spatial scale of responses and the specific characteristics of wind energy (e.g. turbine height, turbine count) that drive responses. Carbon emission reduction is a necessary step towards reducing climate change impacts [34]; therefore, understanding the impacts of wind energy development on birds can help balance the need for a continued roll out of renewable energy with the goal of minimizing adverse effects of energy development.

Given the important effects of wind energy development and the CRP on grassland bird populations, evaluation of potential interactions between wind and the CRP is warranted. Wind turbines are often placed on open, flat landscapes, such as grasslands and fields, where there is consistent wind flow [35] and nearby power grid connections. In the continental US in 2023, 58.1% of wind energy facilities were located within 1.5 km of lands enrolled in the CRP, and 66.8% were within 4.5 km of CRP lands (figure 1). Because wind energy facilities and land enrolled in the CRP are often proximate to each other, there is the potential for interactive effects of these two factors on wildlife, including birds. For example, direct or indirect negative effects of wind turbines near CRP land could reduce, offset or even outweigh the benefits of the CRP to bird populations that would otherwise be accrued. Alternatively, CRP lands close to wind energy development could allow birds to use CRP land instead of areas immediately adjacent to turbines, thereby reducing the risks associated with wind energy development. It is important to determine whether and how wind energy and CRP may interact to affect grassland bird populations; the absence of this information is a critical knowledge gap for grassland bird management and conservation efforts.

Addressing this major research need, we evaluated the effects of wind energy, CRP and their interaction on the abundance of 27 grassland-obligate bird species across their breeding ranges in the continental US, and at two spatial grains, specifically, hexagonal grid cells with radii of 4.5 km and 1.5 km. To measure bird populations, we used community science data from eBird to first identify individual effects of wind energy and CRP variables, focusing on effects of the CRP as we plan to conduct a more detailed evaluation of wind energy effects in a forthcoming study. We then evaluated associations between bird abundance and interactions between the wind and CRP variables identified as important for bird abundance in the first step of analysis. We expected the potential for interactions between wind and CRP variables, reflecting the possibility that some benefits of CRP for some grassland-obligate species may be offset by wind energy infrastructure. Results from this study can be used to help maximize the

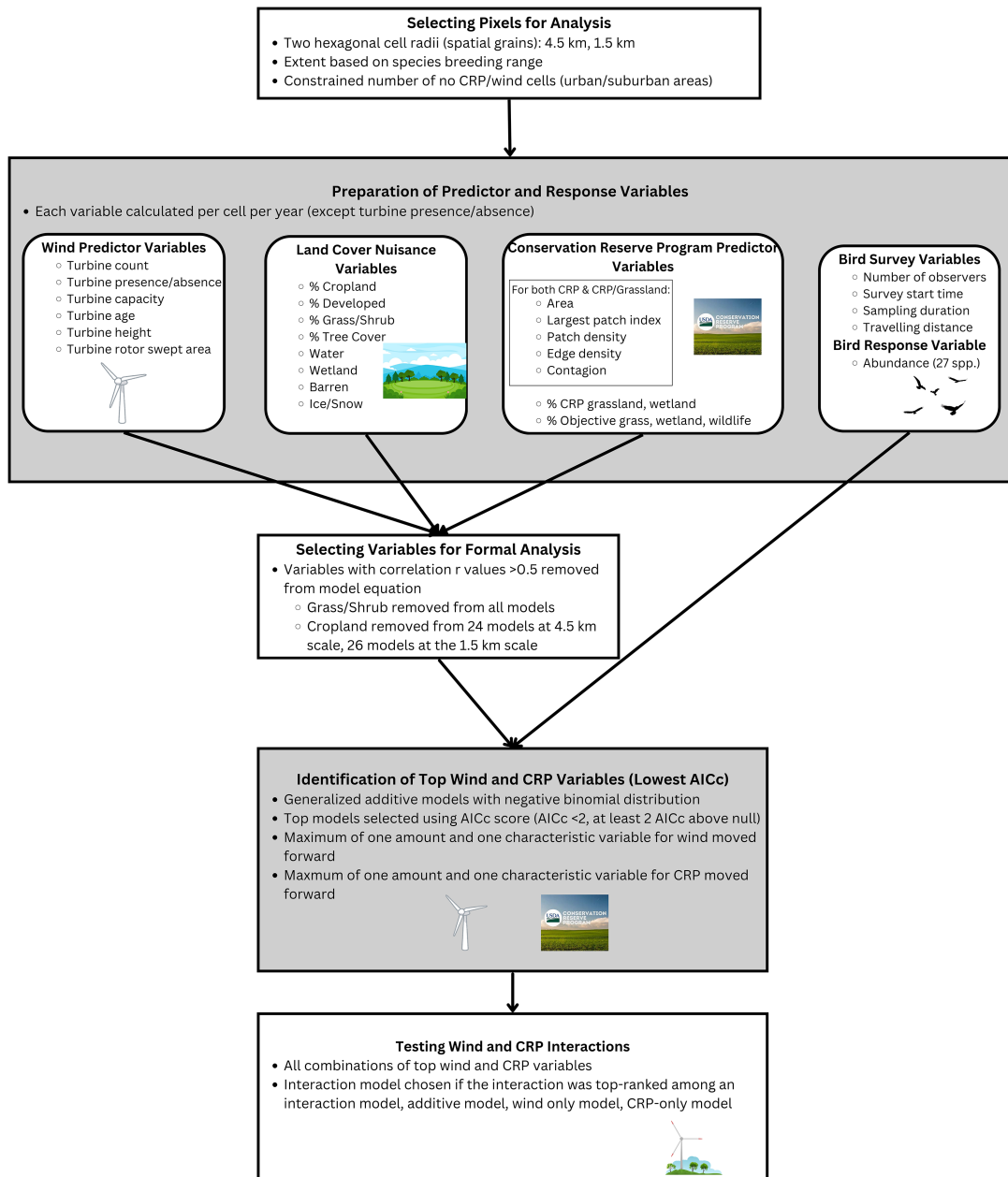


Figure 2. Diagram illustrating the workflow for statistical analysis of the associations between wind energy, the Conservation Reserve Program and breeding season abundance of grassland-obligate bird species in the contiguous US from 2012 to 2021.

benefits of both wind energy and CRP without exacerbating any potential negative effects on populations of grassland birds.

2. Material and methods

2.1. Study system and organisms

A diagram illustrating the workflow for all methods and analyses can be found in [figure 2](#). For our study, we focused on grassland and wetland CRP fields, other grasslands not in the CRP and wind energy infrastructure, within the breeding ranges of 27 grassland-obligate bird species in the continental US. This includes 25 migratory and 2 non-migratory species (see [table 1](#) for a full list of included species). We identified this set of grassland-obligate birds using classifications of Vickery *et al.* [37].

Table 1. Grassland-obligate bird species (MacDonald *et al.* 2024) of the continental US used in the analysis of the effects of CRP land and wind energy infrastructure on bird relative abundance. Conservation status information is from the International Union for Conservation of Nature (IUCN) Red List and Partners in Flight regional scores within their Avian Conservation Assessment Database. The 'Models' columns refer to which model category was the best supported in our interaction analysis framework (Wind: a model containing only the wind variable; CRP: a model only containing the CRP variable; CRP + Wind: an additive model containing both the wind and CRP variable; CRP*Wind: a model including an interaction between the wind and CRP variable). Two X marks indicate that two different interaction models were best supported in their respective model comparisons for a given species at a given spatial grain.

common name	scientific name	migratory status	conservation status	models				
				spatial grain	wind	CRP	CRP + Wind	CRP *Wind
Baird's Sparrow	<i>Centronyx bairdii</i>	migratory	least concern (stable); watch list, regional concern	4.5		X		
				1.5		X		
Bobolink	<i>Dolichonyx oryzivorus</i>	migratory	least concern (decreasing); watch list, regional concern	4.5			X	
				1.5		X		
Burrowing Owl	<i>Athene cunicularia</i>	migratory	least concern (decreasing)	4.5			X	
				1.5			X	
Cassin's Sparrow	<i>Peucaea cassinii</i>	migratory	least concern (decreasing); regional concern	4.5		X		X
				1.5		X		
Chestnut-collared Longspur	<i>Calcarius ornatus</i>	migratory	vulnerable (decreasing); watch list, regional concern	4.5			X	
				1.5		X		
Dickcissel	<i>Spiza americana</i>	migratory	least concern (stable)	4.5			X	
				1.5			X	
Eastern Meadowlark	<i>Sturnella magna</i>	migratory	near threatened (declining); common bird in steep decline	4.5		X		
				1.5			X	
Ferruginous Hawk	<i>Buteo regalis</i>	migratory	least concern (increasing); regional concern	4.5				X
				1.5			X	
Grasshopper Sparrow	<i>Ammodramus savannarum</i>	migratory	least concern (decreasing); common bird in steep decline	4.5		X		
				1.5		X		
Greater Prairie-Chicken	<i>Tympanuchus cupido</i>	non-migratory	near threatened (increasing); watch list, regional concern	4.5		X		
				1.5		X		
Henslow's Sparrow	<i>Centronyx henslowii</i>	migratory	least concern (increasing); watch list, regional concern	4.5		X		
				1.5		X		

(Continued.)

Table 1. (Continued.)

common name	scientific name	migratory status	conservation status	models				
				spatial grain	wind	CRP	CRP + Wind	CRP *Wind
Horned Lark	<i>Eremophila alpestris</i>	migratory	least concern (decreasing); common bird in steep decline	4.5			X	
				1.5			X	
Lark Bunting	<i>Calamospiza melanocorys</i>	migratory	least concern (decreasing); common bird in steep decline	4.5		X		
				1.5		X		
LeConte's Sparrow	<i>Ammospiza leconteii</i>	migratory	least concern (decreasing); watch list, regional concern	4.5		X		
				1.5		X		
Long-billed Curlew	<i>Numenius americanus</i>	migratory	least concern (decreasing); regional concern	4.5		X		
				1.5			X	
Marbled Godwit	<i>Limosa fedoa</i>	migratory	vulnerable (decreasing); watch list, regional concern	4.5		X		
				1.5		X		
Mountain Plover	<i>Anarhynchus montanus</i>	migratory	near threatened (decreasing); watch list, regional concern	4.5	X			
				1.5		X		
Northern Harrier	<i>Circus hudsonius</i>	migratory	least concern (decreasing); regional concern	4.5			X	
				1.5			X	
Savannah Sparrow	<i>Passerculus sandwichensis</i>	migratory	least concern (decreasing); common bird in steep decline	4.5			X	
				1.5				X
Short-eared Owl	<i>Asio flammeus</i>	migratory	least concern (decreasing); common bird in steep decline	4.5		X		
				1.5		X		
Sharp-tailed Grouse	<i>Tympanuchus phasianellus</i>	non-migratory	least concern (increasing); regional concern	4.5			X	
				1.5				X, X
Sprague's Pipit	<i>Anthus spragueii</i>	migratory	vulnerable (decreasing); watch list, regional concern	4.5			X	
				1.5		X		
Swainson's Hawk	<i>Buteo swainsoni</i>	migratory	least concern (stable); regional concern	4.5		X		
				1.5			X	X
Thick-billed Longspur	<i>Rhynchophanes mccownii</i>	migratory	least concern (stable); watch list, regional concern	4.5		X		
				1.5		X		

(Continued.)

Table 1. (Continued.)

common name	scientific name	migratory status	conservation status	models			
				spatial grain	wind	CRP + Wind	CRP *Wind
Upland Sandpiper	<i>Bartramia longicauda</i>	migratory	least concern (increasing); regional concern	4.5	X		
				1.5	X		X
Vesper Sparrow	<i>Poocetes gramineus</i>	migratory	least concern (increasing); regional concern, common bird in steep decline	4.5			X
				1.5			X
Western Meadowlark	<i>Sturnella neglecta</i>	migratory	least concern (decreasing); regional concern, common bird in steep decline	4.5			X
				1.5		X	

2.2. Data sources

2.2.1. Bird data

We used eBird, a global community science database comprised of bird observations [38,39], to examine range-wide abundances of our study species. To generate bird abundance data, we used bird observations from the eBird Basic Dataset (EBD), which has a global spatial extent, is updated monthly (www.ebird.org/science/download-ebird-data-products), is freely accessible via the eBird online portal and can be processed using the ‘auk’ package in R [40]. Each observation is recorded in a checklist submitted by eBird users that includes the number of each bird species observed and survey metadata that include duration of observation period, distance travelled, start time of the observation period and survey protocol used (stationary or travelling) [41]. All observations and checklists in the database are validated using eBird’s data verification process [42]. Checklists are also marked as either complete, meaning all birds observed were recorded and identified to the best level of accuracy possible by the observer, or incomplete, meaning not all observed birds were included in the checklist and/or that an attempt to observe all birds was not made [43]. Following eBird best practices, only data recorded in complete checklists were used for analyses. If a checklist was complete and did not have a corresponding observation for a certain species, we inferred that the species was not detected. If the complete checklist had a corresponding observation for a certain species but did not have a count value for the observation, the species was treated as having a ‘presence-only’ value for the checklist. For all species, presence-only data were transformed to presence-absence data by combining species observations with corresponding checklists following the procedure recommended by Strimas-Mackey *et al.* [44]. We used this presence-absence data to develop estimates of relative abundance (henceforth referred to as abundance) for each species (defined as the expected number of individuals detected on an eBird checklist), because there is no way to calculate absolute detectability using eBird data.

2.2.2. Land cover data

We measured annual land cover using the US Geological Survey (USGS) Land Change Monitoring, Assessment, and Projection (LCMAP) for each year in the sample period 2012–2021 [45] to account for land cover classes that are not part of CRP characteristics. The Primary Land Cover (LCPRI) data are derived from the annual thematic land cover in the LCMAP database. Eight land cover classes are identified in the LCPRI dataset: developed, cropland, grass/shrub, tree cover, water, wetland, ice/snow and barren (see [45] for detailed definitions of each land cover class).

2.2.3. Wind energy data

To measure wind energy development, we used the US Wind Turbine Database, which includes detailed information for each large-scale, commercial wind turbine [36]. The database includes the turbine

Table 2. Description of Conservation Reserve Program (CRP) conservation practice (CP) types included in each of the CRP practice Cover Type and Objective categories. The average percentage of total CRP area was calculated by taking the average of the yearly amounts for each category. Individual CP codes can capture multiple goals; therefore, some codes were included in multiple categories.

conservation practice cover type category	CP codes included	percentage of total CRP area
cover type categories		
grassland (continuous herbaceous patch, used for cover)	1, 4, 10, 12, 18, 25, 33, 38, 42, 43, 87, 88, 90	20.26
wetland (wetland patch)	9, 23, 27, 28, 37, 39, 40, 41	2.24
objective categories		
grass cover (establish herbaceous cover to mitigate erosion, improve water quality and provide wildlife habitat)	1, 2, 10, 18, 87, 88, 90	15.26
wetland creation (create/restore wetland habitat)	23, 27, 28	1.77
wildlife (benefit wildlife through habitat protection, creation and/or enhancement (includes multiple cover types))	4, 9, 12, 25, 29, 33, 37, 38, 42, 43	5.58

location, height, capacity, rotor diameter and project. Our sample includes 74 497 turbines in 1703 wind energy projects across 45 states that were installed between 2012 and 2021.

2.2.4. Conservation Reserve Program data

We used annual spatial data on CRP enrolment for 2012–2021 provided by the USDA Farm Service Agency to capture amounts and characteristics of land enrolled in the CRP; this dataset has restricted access owing to its inclusion of detailed location information for enrolled CRP lands. The data included the boundary of each CRP field, the year of initial land enrolment and the CP code implemented. The CP code designates the type of CRP practice implemented (e.g. CP-1: Establishment of Permanent Introduced Grasses and Legumes, CP-2: Establishment of Permanent Native Grasses, CP-3: Tree Planting). We further categorized CP codes by Cover Type to identify fields that were grasslands or wetlands. For our analysis, we included five CRP-related metrics, including area, largest patch index, patch density, edge density and a connectivity metric (hereafter referred to as contagion). Each of these metrics was calculated twice, once including only CRP land and once including CRP land combined with other grasslands not enrolled in the CRP. We focused on both grassland and wetland CRP types in analyses because some grassland birds occur in herbaceous-dominated land cover types that consistently have saturated soils and/or standing water and are thus often considered wetlands. We also categorized CP codes into Objective categories based on the goal of the practice, as explained in the CP code documentation and the expert opinion of coauthor R.I. These categories included grass cover, wetland creation and wildlife habitat. Because individual CP codes can capture multiple goals, some codes were included in multiple categories in our analysis (e.g. CP 38, categorized as grassland cover and wildlife habitat creation owing to the breadth of this conservation practice). See [table 2](#) for a comprehensive list of the CP codes included in each of the above-described categories, as well as percentages of total CRP acreage included in each category.

2.3. Data preparation

2.3.1. Spatial grains and land cover

To analyse potential bird responses to wind and the CRP at two spatial grains, we constructed hexagonal grids ('dgconstruct' function, 'dggridR' package) [46] with two radii, 4.5 km and 1.5 km, across the continental US. For each of these spatial grains, we collated annual measures of bird relative abundance,

land cover, wind energy and the CRP for the sample period 2012–2021. The 1.5 km grain is the smallest recommended buffer distance for using eBird data to analyse responses of birds to factors like land cover and infrastructure owing to the spatial precision of eBird observations [44]. The 4.5 km grain is the distance within which wind turbines were found to displace prairie grouse species in previous studies [32]. We calculated the proportion of each of the eight land cover classes in each 1.5 km and 4.5 km spatial grain in each year. Land cover composition in each hexagonal cell was included in models to account for habitat differences among eBird data locations. Also, because we focused on grassland CRP, in addition to measures of grassland proportion in each hexagonal cell, we generated measures of the joint share of the CRP and other non-CRP grasslands, and we considered both the CRP and joint CRP-grassland when evaluating habitat characteristics associated with bird abundance.

2.3.2. eBird

To restrict the sample to relevant areas for each species, we constructed samples using bird observations within the geographic range for each species in the contiguous US, with breeding seasons defined based on dates from eBird Status and Trends Models ('ebirdst' package) [47]. We also reduced the number of untreated grid cells (i.e. hexagonal cells with no CRP land and no wind turbines) that were in developed areas, because the CRP is only implemented on agricultural lands and therefore cells in predominantly developed (e.g. urban and suburban) areas do not provide an appropriate comparison group. To do this, we calculated the 65% confidence interval of per cent developed in cells with the CRP and/or wind and then randomly sampled and retained 25% of untreated cells with development values greater than the 65% CI (equivalent to 1 SD from the mean). We retained only 25% of the untreated cells, as the data were heavily zero-inflated, therefore, we reduced the number of cells that had no wind energy present and no CRP land present.

Given the semi-structured nature of eBird data, it is necessary to address sample bias, including spatial, effort and temporal biases. Specifically, bird observations are biased towards locations where birds and bird watchers are more common. As noted above, this was addressed by aggregating all observations in hexagonal cells with cell radii of 1.5 km and 4.5 km. Using all checklists within a given grid cell, we calculated the average annual breeding season relative abundance for each study species. To address birder effort and birding skill bias, we included only observations that were part of complete checklists. Further, and as recommended by Strimas-Mackey *et al.* [44], we included variables in the statistical models to account for survey effort, specifically the number of observers, start time, sampling duration and travelling distance associated with each checklist. All of these variables were averaged for each hexagonal grid cell for each year of the study. To address temporal bias associated with the dramatically increased number of eBird checklists across our study period, we standardized the number of eBird observations used to calculate yearly averages by the first year (2012) of the dataset. Specifically, for each species and spatial grain, we identified the number of checklists submitted within the US breeding range of each species in 2012, and for all successive years through 2021, we randomly selected the same number of annual checklists for inclusion in analyses.

2.3.3. Wind energy

We generated six total wind energy predictor variables for our analyses. From the wind energy dataset, we calculated total annual counts of turbines, average turbine height, average turbine rotor swept area (RSA) and total installed wind energy capacity for each data cell. These characteristics and spatial data were available for each individual turbine. Turbine height refers to the height to the top of the turbine tower where the rotor blade is mounted (sometimes referred to as the turbine nacelle), and RSA is the area through which turbine blades rotate and convert wind into mechanical energy. We also calculated the average age of turbines by subtracting the year each turbine became operational from the year of the bird data for that analysis replicate (analyses included separate replicates for each year, as described below), and then averaging these values across all wind turbines in each data cell. Finally, we also generated a turbine presence-absence variable using the average turbine count in a cell, where cells with values above 0 were categorized as 'present' and cells with values of 0 were 'absent'. All wind energy predictor variables were calculated in R v. 4.4.2 [48] using dplyr summary statistic functions [49]. All wind variables except turbine count were treated as categorical variables after calculating averages to simplify interpretation and allow us to compare to areas without turbines. Turbine variable categories were selected by evenly dividing the range of each variable into approximately equal-sized bins. This

was done because generalized additive models (GAMs) require equal-sized bins to run correctly and to minimize potential convergence issues. Turbines lacking any characteristic information were removed from the dataset used for analysis to ensure that the same set of wind turbine data was used for all models, an approach that was necessary for our model comparison methodology described below. These turbines were, therefore, not used towards turbine count values or for calculating annual averages for turbine capacity and characteristic variables. The number of cells removed owing to a lack of turbine information ranged between 1 and 448 cells and was dependent upon the spatial grain and size of a species' breeding range.

2.3.4. Conservation Reserve Program

We generated 15 total CRP predictor variables, all continuous, for our analyses. Detailed descriptions of each CRP variable are in supplementary material table S1. Habitat characteristics were calculated using landscape analysis functions from PyLandStats in Python [50]. Using the hexagonal grids described above, we generated annual measures of total CRP area and total area of CRP combined with grassland (CRP-grassland) for each year for each hexagonal cell. We also calculated eight additional spatial metrics, including four each for the CRP and CRP-grassland land cover categories—largest patch index, patch density, edge density and connectivity index (hereafter, referred to as contagion). To assess the effects of different types of CRP, we constructed five additional variables, including measures of the annual number of acres of the CRP in the habitat categories of grassland and wetland, and in the objective categories of grass cover, wetland creation and wildlife habitat.

2.4. Statistical analyses

We examined relationships between wind energy, the CRP and bird species abundances using GAMs. We used GAMs as we hypothesized nonlinear relationships between avian abundance and many of our predictor variables. Replicates were indexed by cell and year, leading to annual replicates for each hexagonal grid. Prior to conducting analyses, we generated Pearson correlation matrices for each species to examine correlations between predictor variables, including all bird survey effort, land cover, wind and CRP variables that were to be included in GAMs described below (see supplementary material table S1 for a full list of variables included and their definitions). Any land cover variables that were highly correlated ($r \geq \pm 0.5$) [51,52] with wind or CRP variables were removed from analyses, as we were more interested in evaluating the effects of wind and CRP variables. Many wind and CRP variables were correlated with each other; therefore, no models could contain more than one wind or CRP variable. For land cover variables that were correlated with one another, but not highly correlated with any wind or CRP variables, separate analyses with each land cover variable were run. We then compared results using Akaike information criteria (AIC_c) scores ('AICc' function, 'AICcmodavg' package) [53] and selected the land cover variable with the lower AIC_c score. For most species, at both spatial scales, the grassland and/or cropland land cover classes were highly correlated with multiple CRP variables, leading to the removal of grassland and/or cropland variables from models. The grassland land cover class was not included in any models while cropland was only included in four models, three at the 1.5 km spatial grain and one at the 4.5 km spatial grain. The removal of land cover variables owing to the above-described correlations means that we were not able to fully account for all land cover variation in our models, and we cover the implications of this limitation in the Discussion.

GAMs were constructed using the 'gam' function in the 'mgcv' package [54]. Following the recommendation of Lee & Skripnikov [55] for GAMs we specified knots as five for all bird survey effort, land cover, wind and CRP variables, except for the survey effort variable mean start time, which had a knots value of seven owing to the cyclic nature of the variable. All continuous predictor variables were standardized prior to modelling. To select the model specifications for each species, we first determined the distribution which was the best fit for the abundance data. Specifically, we ran a base model, with species abundance as the dependent variable and longitude and latitude as the independent variables (to account for spatial variation not captured in other variables, and to help account for potential spatial autocorrelation), using Poisson, zero-inflated Poisson, negative binomial and zero-inflated negative binomial specifications. We selected negative binomial as the best fitting distribution for the abundance data for all species as it consistently had the lowest AIC_c score among analyses run for all species and both spatial scales. Next, we added a single survey effort, land cover, wind or CRP variable to the base

model one at a time in individual models. This was done to determine whether relationships between abundance and each predictor variable were linear or nonlinear. Variables with effective degrees of freedom (e.d.f.) scores less than two were classified as linear while those with e.d.f. scores greater than two were classified as nonlinear; a smoothing spline was used for the nonlinear variables.

After determining the best-fitting distribution for the abundance data and determining whether each predictor variable should be modelled linearly or nonlinearly, we constructed models that included latitude, longitude, bird survey effort variables, land cover variables, and a single wind or CRP variable. We did not evaluate models containing more than one wind or CRP variable owing to strong correlations among these predictor variables as discussed above. To assess support for each predictor variable, we conducted two separate AICc model comparisons: one for wind variables and one for CRP variables. For each species, we used AICc values to identify up to two strongly supported wind variables, one measuring the amount of wind energy infrastructure (e.g. turbine count) and the other measuring a turbine characteristic (e.g. turbine height), and up to two strongly supported CRP variables, one measuring the amount of CRP or CRP/Grassland (e.g. CRP area), and the other a CRP characteristic (e.g. CRP edge density) (see supplementary material table S1 for a list of all variables capturing wind energy and CRP amounts and characteristics). Models were considered strongly supported if they had $\Delta\text{AICc} \leq 2$ and at least two above the null model. In the results section and in supplementary tables, we present results of analyses evaluating the independent effects of wind and CRP variables, as this information provides crucial context for the interaction analyses. However, in the Discussion, we do not include in depth coverage of results from the analyses that only included wind energy variables, as we plan to conduct a more focused evaluation of the independent effects of wind energy on grassland birds in a forthcoming companion paper.

Using strongly supported wind and CRP variable(s) identified in the individual effect model comparisons, we next evaluated potential interactions between these best-supported wind and CRP variables. Specifically, for each species at each spatial scale, we tested up to four two-way combinations of CRP and wind variables, comparing all possible combinations of interactive and additive relationships between the best-supported wind amount, wind characteristic, CRP amount and CRP characteristic variables. We only considered interaction models for species and spatial grains for which there were strongly supported models in both the CRP and wind energy model comparisons. There were also instances where either an amount or characteristic variable, but not both types of variables, were supported above the null model, and in these cases, we only conducted interaction analyses for combinations of best-supported variables. For example, if a wind amount and a CRP characteristic variable each received support, but no wind characteristic or CRP amount variables received support, we only tested the interaction between the supported wind amount and CRP characteristic variable. For each analysed two-way interaction between wind and CRP variables, we conducted an additional AICc model comparison to identify the best-supported of four models: (1) a single-variable model with the wind variable, (2) a single-variable model with the CRP variable, (3) an additive model with both the wind and CRP variables, and (4) a model with the interaction between the wind and CRP variable. We concluded there was support for an interaction only when the interaction model was top-ranked; otherwise, we concluded there was no support for such an interaction.

3. Results

3.1. Comparisons of models containing only wind or Conservation Reserve Program variables

Comparison of models containing only a single wind variable indicated at least one wind amount and/or characteristic variable was supported for 14 of 27 species, but often there was only support for a wind variable at one of the two spatial grains (table 1; supplementary material, tables S2 and S5). Among wind amount and characteristic variables, turbine capacity and turbine height, respectively, were the most frequently supported variables (seven species each; supplementary material, tables S2 and S5).

Comparison of models containing only a single CRP variable indicated that at least one CRP amount and/or characteristic variable was supported for all species at both 4.5 km and 1.5 km spatial grains (table 1; supplementary material, tables S2 and S5). Among CRP amount variables, CRP/Grassland area (i.e. combined area of CRP-enrolled land and other non-CRP grasslands) was supported most frequently (19 species), while CRP/Grassland contagion (a metric capturing degree of fragmentation of the CRP and other grasslands) and CRP/Grassland largest patch index (the proportional cover of the largest

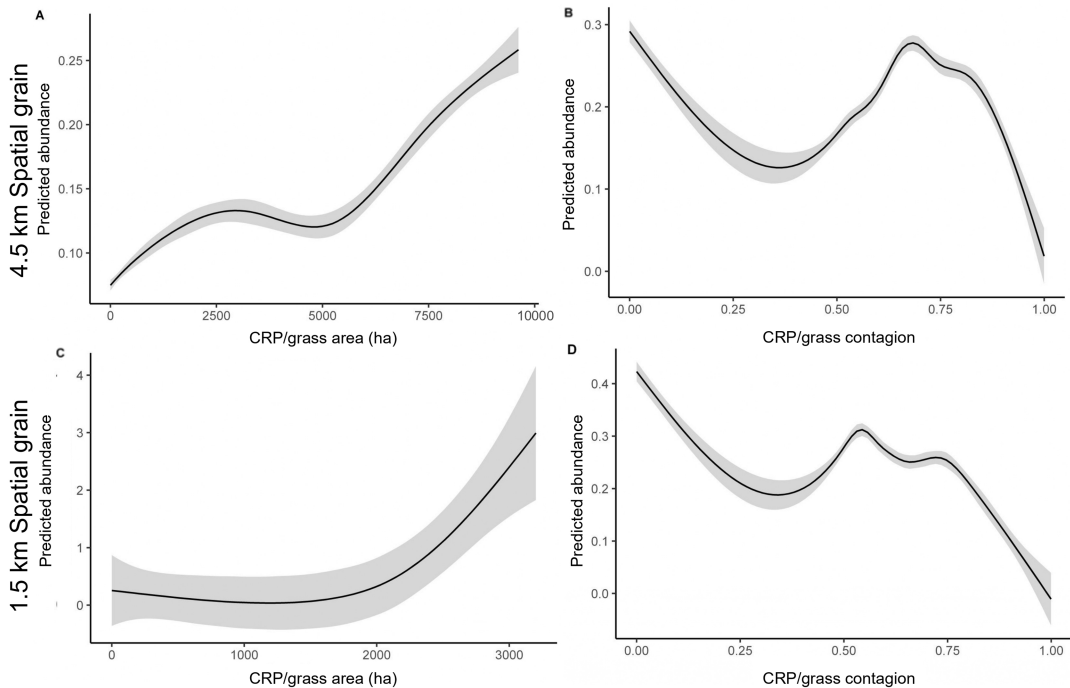


Figure 3. Smooth line plots displaying relationships between well-supported Conservation Reserve Program (CRP) variables and predicted bird relative abundance based on comparisons of models containing single CRP variables, including for: (A) Grasshopper Sparrow at the 4.5 km spatial grain, (B) Eastern Meadowlark at the 4.5 km spatial grain, (C) Greater Prairie-Chicken at the 1.5 km spatial grain and (D) Bobolink at the 1.5 km spatial grain. Shaded regions represent the model-estimated 95% confidence intervals around the predicted relationship.

patch of the CRP and other grassland in the cell) were the most-supported CRP characteristic variables (eight and seven species, respectively; supplementary material, tables S2 and S5). In general, models for which CRP/Grassland area and CRP/Grassland largest patch index were supported indicated that bird abundance increased with increases in values of these variables, although in a nonlinear fashion (figure 3). Relationships between bird abundance and CRP/Grassland contagion were not as straightforward, as some species exhibited abundance declines with increasing CRP/Grassland contagion, others increased with increasing contagion, and still others increased in abundance up to a certain threshold of contagion before decreasing and then increasing again (see figure 3 for examples of these patterns). One of the three CRP objective variables (i.e. Percent Objective Wetland; supplemental material tables S3, S7) was supported for six species. There was better support for variables capturing both CRP land and other grassland, compared with variables only capturing the CRP, demonstrating the general importance of both CRP grasslands and other types of grasslands for our study species.

3.2. Evaluation of interactions between wind and Conservation Reserve Program variables

At the 4.5 km spatial grain, interactions were evaluated for the 14 species that had a supported wind and CRP variable (table 1; supplementary material, table S3). Of these 14 species at the 4.5 km spatial grain, an interaction model was top-ranked for four species, indicating support for an interactive effect of wind and CRP variables (supplementary material, tables S3 and S4). There was no support for wind–CRP interactions at the 4.5 km scale for the other 10 species, as either the additive model was top-ranked (nine species; supplementary material, figure S2) or models containing only the wind or CRP variable were top-ranked (one species; table 1; supplementary material, figure S4 and table S3).

Among the four species for which an interaction model was supported (Cassin's Sparrow, Ferruginous Hawk, Vesper Sparrow and Western Meadowlark), turbine height was included in the interaction for two species (Vesper Sparrow and Western Meadowlark), while the most common CRP variables included in supported interactions were the CRP/Grassland largest patch index and CRP/Grassland area (two species each). The best-supported models for Vesper Sparrow and Western Meadowlark included

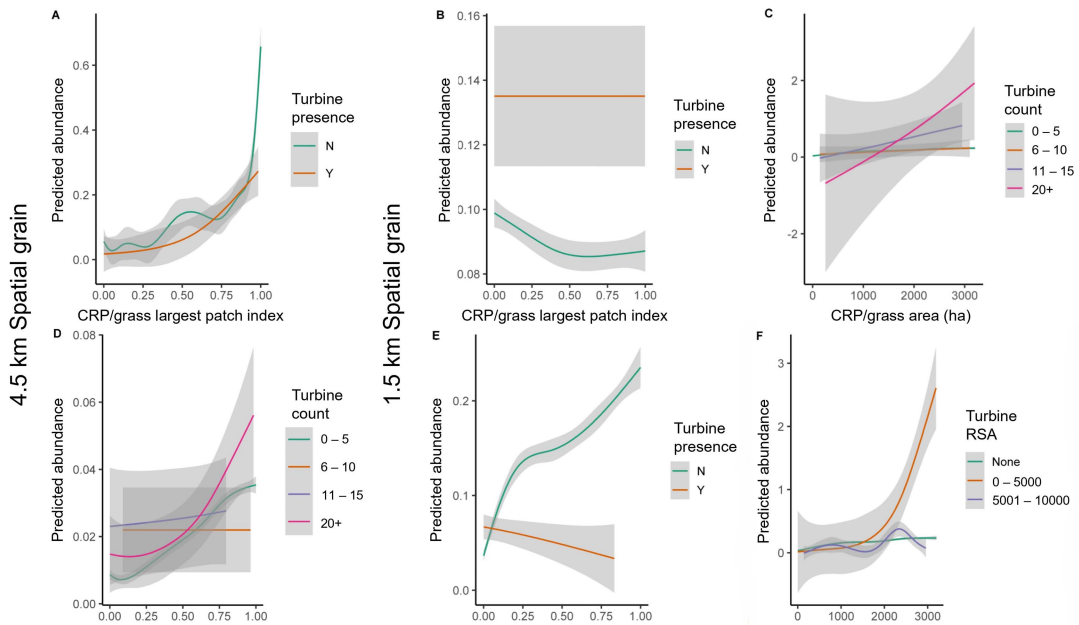


Figure 4. Smooth line plots displaying a subset of supported interactive effects of wind and CRP variables on bird relative abundance, including for: (A) Cassin's Sparrow at the 4.5 km spatial grain, (B) Swainson's Hawk at the 1.5 km spatial grain, (C) Sharp-tailed Grouse at the 1.5 km spatial grain, (D) Ferruginous Hawk at the 4.5 km spatial grain, (E) Upland Sandpiper at the 1.5 km spatial grain and (F) Sharp-tailed Grouse at the 1.5 km spatial grain. RSA represents turbine rotor swept area. Shaded regions represent the model-estimated 95% confidence intervals around the predicted relationship.

an interaction between wind turbine height and CRP/Grassland total area (supplemental material figure S1A/B). Models for both of these species indicated that, as the combined area of CRP and other non-CRP grasslands increased, abundance also increased; however, this effect was moderated by turbine height, as the increase with increasing CRP/Grassland area was somewhat dampened in areas with taller turbines—except for areas with turbines in the 41–60 m range, for which the increase with CRP/Grassland area was greater (supplementary material, figure S1A/B). For Cassin's Sparrow and Ferruginous Hawk, abundances increased as the CRP/Grassland largest patch index increased (figure 4A,D). However, for Cassin's Sparrow, the presence of wind turbines dampened this positive effect of CRP and other grasslands (figure 4A). For Ferruginous Hawk, there was a similar pattern as for Cassin's Sparrow, except in areas with 20 or more turbines present, where the positive effect of the CRP was much greater (figure 4D).

At the 1.5 km spatial grain, we evaluated interactions for the 14 species that had at least one well-supported wind and CRP variable, with Upland Sandpiper, Swainson's Hawk, Mountain Plover and Sharp-tailed Grouse having multiple well-supported wind or CRP variables that were carried forward into the combined wind and CRP models. Of these 14 species, at least one interaction model was top-ranked for five species. There was no support for wind–CRP interactions for the remaining nine species, either the additive model was top-ranked (eight species, not including Swainson's Hawk, for which both an interaction and an additive model were supported, see supplementary material, figure S3) or models containing only the wind or CRP variable were top-ranked (two species, with Sprague's Pipit having a supported CRP-only model while Upland Sandpiper had a supported interaction model and CRP-only model, see supplementary material, figure S4; table 1; supplementary material, tables S6 and S7). For Sharp-tailed Grouse, there were two combinations of wind and CRP variables for which the interaction models were top-ranked in their respective model comparisons (table 1; supplementary material, table S7).

For the supported interactions between wind and CRP variables at the 1.5 km grain, relationships with abundance were relatively consistent across species. Specifically, abundance tended to increase with increasing CRP/Grassland area and the CRP/Grassland largest patch index (figure 4; supplementary material, figure S4). For Upland Sandpiper, these positive associations with CRP and non-CRP grasslands were greater when wind energy infrastructure was absent (figure 4E), but the reverse pattern occurred for Swainson's Hawk (figure 4B). For Upland Sandpiper, as the CRP/Grassland largest patch index

values approached 1.0 (their maximum value), predicted abundance in cells without turbines was double the predicted abundance in cells where turbines were present (figure 4E). Savannah Sparrow and Vesper Sparrow had supported interactions between turbine height and two different CRP variables, CRP/Grassland area and the CRP/Grassland largest patch index, respectively. Savannah Sparrow abundance decreased with increasing CRP/Grassland area where turbines averaged 41–60 m and 81+ m in height, increased with increasing CRP/Grassland area where turbines averaged 21–40 m in height and showed a nonlinear response to CRP/Grassland area where turbines averaged 61–80 m in height, with abundance rapidly increasing as CRP/Grassland increased up to approximately 1000 ha then decreased for larger areas (supplementary material, figure S1D). Vesper Sparrow abundance slightly decreased as the CRP/Grassland largest patch index increased for the shortest and tallest wind turbine height categories, whereas for the middle two height categories, abundance increased as the CRP/Grassland largest patch index increased (supplementary material, figure S1C). For Sharp-tailed Grouse, interactions were supported between CRP/Grassland total area and two separate wind variables. First, abundance remained close to zero as CRP/Grassland area increased for all values of turbine count, except when there were more than 20 turbines, in which case abundance increased exponentially with CRP/Grassland area (figure 4C). Second, abundance increased slightly with increasing CRP/Grassland area where RSA averaged 5000–10000 m², and where no turbines were present, and increased exponentially with CRP/Grassland area where RSA averaged 0–5000 m² (figure 4F).

4. Discussion

This study represents the first large-scale evaluation of the potential interactive effects of wind energy development and CRP on the abundances of grassland-obligate birds. For four bird species at the 4.5 km spatial grain and five species at the 1.5 km spatial grain, we found evidence for an interactive effect of wind and CRP on avian abundance, suggesting that wind energy development within 1.5 or 4.5 km from CRP fields could dampen the benefits of the CRP for some grassland bird species. When considering independent effects of the CRP, we also found that CRP variables were associated with abundances of all 27 bird species and at both spatial grains analysed. Furthermore, although patterns varied among species and scales, there was a recurring pattern that variables that combined both CRP land and non-CRP grasslands, particularly CRP/Grassland area and the CRP/Grassland largest patch index, received the greatest support in explaining variation in bird abundance, and these variables also appeared most frequently in supported wind–CRP interactions. Thus, the total amount of available grasslands, not solely CRP land *per se*, is crucial for supporting high bird abundances. However, in many regions, CRP land comprises a large amount of the total grassland area, emphasizing the crucial contribution of this conservation program to bird conservation efforts. Given the known benefits of CRP for grassland-obligate birds [7,16,17,56] and the known negative effects of wind development on bird species [23,24,26–32], the knowledge gained in this study is needed to maximize the benefits of the CRP while still allowing for environmentally friendly roll out of renewable energy development.

4.1. Evidence for interactive effects of wind energy and the Conservation Reserve Program on grassland bird abundance

The positive associations between bird abundance and CRP variables were sometimes dampened by the presence of wind energy infrastructure. The presence of wind turbines, a variable that was included in two supported CRP–wind energy interaction models, had a negative effect on abundance for three of five species for which this variable was supported in the initial model selection exercise for wind energy variables. This apparent negative effect of wind power is consistent with a previous study completed in North Dakota and South Dakota, USA, which found that several species of breeding grassland birds, including Upland Sandpiper and Savannah Sparrow, had lower abundance within 100–300 m of wind turbines [32]. The only other study evaluating the interaction between CRP land and wind turbine presence, conducted in southwest Minnesota, USA, found that CRP grassland without turbines supported greater densities of grassland birds, especially area-sensitive species such as Bobolink and Savannah Sparrow, compared with CRP lands with installed turbines [57]. However, Leddy *et al.* [57] did not draw inferences about the mechanisms driving wind turbine-related reductions in bird abundance because they only considered the presence of both CRP land and wind turbines, not other variables capturing the amount or characteristics of the CRP or wind energy. Although we are uncertain what mechanisms

underlie the apparent negative effects of wind energy that we documented in this analysis, including the apparent reduction or offsetting of positive CRP effects on bird abundance, past research suggests there are direct effects of wind energy owing to bird collisions with wind turbines, and/or indirect effects through changes to habitat or creation of movement barriers [11]. It seems improbable that direct collision mortality would be solely responsible for bird abundance reductions at the 1.5 and 4.5 km spatial grains that we assessed, and indirect habitat-related effects may be more likely for most species. However, additional finer-scale research that evaluates abundance responses in relation to these interactions between wind and CRP variables, such as localized before-after-control-impact (BACI) studies on species of conservation interest, is needed to identify the relative role of specific mechanisms for driving abundance responses of individual species and at particular spatial scales.

As the interactive associations that we documented among wind energy, the CRP and bird abundance are complex, with nonlinear responses of bird abundance and species- and scale-dependent effects, the mechanisms behind these interactions are probably equally complex. We are also uncertain which mechanisms underlie the somewhat surprising pattern that wind energy variables interacted positively with CRP variables for some species, such as Swainson's Hawk and Sharp-tailed Grouse, suggesting that wind enhanced the benefits of the CRP. However, we advise caution in interpreting these patterns, as it is possible that other confounding factors underlie these relationships. For example, at the 4.5 km spatial grain, Ferruginous Hawk abundance increased as the CRP/Grassland largest patch index increased, and the strength of this positive effect of the CRP increased as the number of wind turbines increased. The fact that wind energy infrastructure appeared to enhance the positive effect of the CRP for this species may arise simply as an artefact of the disproportionate placement of wind turbines in areas with heterogeneous land cover [58,59], in which Ferruginous Hawks prefer to nest [59]. Further, there is evidence that Ferruginous Hawks can tolerate some disturbance to habitat, as a past study at a smaller spatial grain indicated higher abundance of this species near wind turbines [60], which is consistent with findings for other Accipitriformes [31]. This explanation is also consistent with the pattern observed for Swainson's Hawk at the 1.5 km spatial grain. While there is evidence that Swainson's Hawk nest success does not decrease in the presence of wind turbines [60], responses of Ferruginous Hawk nest success have been mixed [60,61]. Additionally, there is evidence for indirect effects of wind on fledgling survival in multiple raptors [61], suggesting the potential for an ecological trap, whereby birds are attracted to areas near wind turbines and experience negative fitness effects associated with this pattern of habitat use.

Some species-level effects we observed, particularly the positive association between the abundance of Sharp-tailed Grouse and wind turbine count and RSA, were inconsistent with previous studies. Previous research illustrates instances of direct collision mortality of Sharp-tailed Grouse at wind turbines [62] as well as the potential for avoidance behaviour in response to wind energy [63], which is consistent with the responses of other grouse species to wind energy [63,64]. Nest-site selection of Sharp-tailed Grouse is primarily driven by vegetation structure and composition [65]; because our study focused on breeding season abundance, the nesting preference of this species for larger amounts of grassland could explain the pattern of increasing grouse abundance with increasing area of CRP and non-CRP grassland, as was observed in Stevens *et al.* [66]. The positive relationship between Sharp-tailed Grouse abundance and wind turbine presence could also be related to nest-site selection. Wind farms can lead to high levels of disturbance at local scales, which can, in turn, result in increased forb coverage, as is observed following fires in grassland habitats [67]. This might suggest that wind energy development creates more favourable Sharp-tailed Grouse nesting habitat across the relatively large spatial scales that we studied, and this effect could be further amplified by the benefits of the CRP and other areas of grassland. However, we highlight that smaller-scale negative effects of wind energy could still occur, such as displacement or avoidance of Sharp-tailed Grouse at distances more proximal to wind turbines and at scales smaller than those we assessed in this study. Other variables may also be at play, and studies that simultaneously evaluate habitat use and survival are necessary to comprehensively determine effects on this species.

4.2. Independent effects of the Conservation Reserve Program on grassland bird abundance

When considering the effects of the CRP independent of wind energy, variables that captured land both in CRP and non-CRP grasslands were more frequently supported than variables that only captured CRP land. This suggests that while the CRP is undoubtedly beneficial to many grassland-obligate birds [7,17,18,56], landscapes composed of large amounts of both CRP land and non-CRP grassland may play

a larger role than the CRP alone, especially in regions where extensive grassland habitat remains in the landscape. However, because one goal of the CRP is to restore grasslands through some of the specific CRP practice types, this program contributes greatly to the availability of grassland in regions that have experienced dramatic losses of this land cover type and have very few native grasslands remaining, such as the corn and soybean belt of the northern Great Plains and upper Midwest of the US. For some species of grassland-obligate birds, such as Sprague's Pipit [18], the presence of CRP land does not influence abundance [18,55]. Most CRP acreage is not managed using practices that replicate ecological disturbances, which may explain the lack of response among species that are disturbance-dependent shortgrass specialists (e.g. Burrowing Owl and Sprague's Pipit). The apparent lack of CRP effect for Sprague's Pipit in Pavlacky *et al.* [18] contrasted with our results that indicated Sprague's Pipit abundance peaks in cells where the CRP/largest patch index was below 0.1. The difference in results between this and the previous study may be related to the varying spatial extents of the two studies. The Pavlacky *et al.* [18] analysis included the western portion of the Sprague's Pipit's breeding range in the USA and Canada, while our study covered the entire breeding range of Sprague's Pipit within the continental US. Our finding demonstrates the importance of considering range-wide effects of wind and the CRP, along with results of local-scale assessments, for species of conservation concern.

4.3. Study limitations

Our study, while unprecedented in its scope of evaluation of the interacting effects of wind energy and the CRP using the eBird community science platform, is characterized by several limitations that should be considered when interpreting results. For example, although we were able to investigate associations between bird abundance, wind energy and the CRP across the entire US breeding ranges of grassland-obligate species, we were unable to address differences in responses between range cores and edges that are known to occur for some species [68]. At range edges, habitat quality can be poorer and/or species may be at the limit of their climate tolerances [68–70], which can lead to lower abundance at range edges compared with range cores. While we included latitude and longitude as fixed effects in all models, this and other types of natural spatial variation in abundance can lead to a potential confounding effect of abundance decline at the edge of a species range.

There are also additional large-scale sources of variation that we did not capture in our models that may contribute to patterns we observed. Abundances of some species (e.g. Bobolink, Dickcissel) are known to be positively associated with the amount of grassland in the landscape, and siting of wind energy facilities often occurs in these same landscapes owing to the open environments that favour the wind flow necessary for efficient electricity generation. Therefore, the positive response of birds to grasslands and a disproportionate installation of wind turbines in landscapes with large amounts of grasslands could lead to an apparent positive effect of wind on bird abundance when no direct mechanism for this effect exists.

Another limitation is that, despite the use of eBird data across species' US ranges, our results are correlational and do not necessarily imply cause-and-effect relationships between bird abundance and wind and CRP variables. Further study is needed to confirm these relationships and to determine if they are causal or coincidental. A BACI study design—which involves measuring whether the change in values of a response variable from a before to an after period differs between experimental units that receive and do not receive a treatment—can be a particularly rigorous approach to evaluate causal effects of a disturbance on wildlife, including birds. For example, McNew *et al.* [71] conducted a BACI study that included before and after assessment of sites that did and did not have wind turbines installed; using this approach, they found that prairie-chicken nest site selection was influenced more by rangeland management and vegetation characteristics than it was by wind energy development. Future research could incorporate BACI designs to evaluate effects of wind, the CRP and their interaction on bird abundance, for example by using big data sources like eBird and the North American Breeding Bird Survey (for example, [22]) to compare changes in abundance in areas that are converted to the CRP, that experience wind energy development, or both, to areas that experience one or neither of these two changes. Researchers could also validate the patterns we observed by conducting studies that combine such big data sources with field-collected data from wind energy facilities that are located both near and distant from CRP-enrolled land.

4.4. Management implications and future research

The lack of interactive effects among variables capturing wind energy, the CRP and other grassland types on abundance of most of our focal bird species may mean that the impacts of wind energy and the benefits of CRP can be considered separately during the development of conservation strategies and management plans for many grassland bird species. However, we did find evidence for interactive effects of wind and CRP, including potential reduction and/or offsetting of CRP benefits for four and five species at 4.5 km and 1.5 km spatial grains, respectively. Therefore, decisions about the placement of wind energy infrastructure that incorporate information about the presence of CRP land may reduce the adverse effects of wind energy on grassland-obligate birds. On the other hand, considering the presence of current or future wind energy installations in decisions about the distribution of CRP contracts may also be appropriate if the goal is to maximize the benefits of the CRP to grassland birds.

Variables capturing both CRP land and non-CRP grasslands were frequently supported in our analyses, indicating the general importance of grasslands regardless of whether they occur in CRP-enrolled properties and consistent with previous research [7,9]. Nevertheless, the Conservation Reserve Program in itself is still critical for bird conservation efforts, as it has been shown to partially offset declines in grassland bird populations caused by agricultural conversion [18], and because it provides a large proportion of natural land cover in regions with few other remaining grasslands. Although land directly within the footprint of wind energy infrastructure is not eligible for CRP payments, infrastructure can currently be installed near CRP land, and wind energy installation is one of the more popular alternatives to CRP enrolment among agricultural landowners [72]. This could partially explain why 66.8% and 58.1% of wind farms occur within 4.5 km or 1.5 km of CRP land, respectively. Other than voluntary guidance provided by the US Fish and Wildlife Service [73] to aid wind energy developers in siting wind facilities in ways that reduce adverse effects on wildlife, as well as similar guidance by some states (e.g. California and New York) [74,75] and non-governmental organizations (e.g. [76]), guidance is currently limited on what ecological factors to consider when selecting sites for new wind energy development. Our results provide additional general considerations that could be incorporated into such wind energy infrastructure guidance to minimize the effects of wind energy on birds and to allow the maximum benefits of the Conservation Reserve Program to be provided.

Although our study focused only on avian relative abundance, future research could formally evaluate the manner in which avian traits, such as migratory, foraging and nesting strategies moderate the effects of wind, the CRP and their interactions. Future research that seeks to identify key traits associated with different types of responses to wind and the CRP could allow improved prediction of the way birds respond to these factors, thus aiding decisions about wind energy siting and CRP enrolment. Our inferences only extend to the breeding season, therefore consideration of additional periods of the annual cycle is needed to fully understand demographic responses of birds to wind energy and CRP, especially because factors operating during stationary non-breeding [7,9,77,78] and migration periods [23,28] are thought to contribute to declines in grassland bird populations.

5. Conclusion

We completed the first large-scale evaluation of the potential interactive effects of wind energy and the CRP on abundances of grassland-obligate birds. We found that four bird species at the 4.5 km spatial grain and five species at the 1.5 km spatial grain had well-supported associations between abundance and interactions containing wind and CRP variables, suggesting that wind energy development within 1.5 and/or 4.5 km from CRP fields could dampen the benefits of the CRP for some grassland bird species, such as Cassin's Sparrow and Upland Sandpiper. When examining the independent effects of CRP, we found that all 27 species, at both spatial grains, had associations with CRP variables. Our work provides a starting point for additional research that can evaluate the interactive effects of wind energy and CRP land on additional species and during different periods of the annual cycle, including migration and stationary non-breeding periods. The CRP is a crucial piece of conservation efforts for grassland birds; therefore, understanding how interactions with stressors like wind energy affect the program's success can maximize its positive outcomes.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. The datasets supporting this article are already publicly available (eBird: [79], LCMAP: [80], turbine database: [81]) except for the Conservation Reserve Program data, which is not available and cannot be shared owing to privacy rights of the individual landowners; the spatial calculations for LCMAP, wind turbines, and the CRP were completed primarily using ArcGIS. The averages per hex cell per year were calculated for each dataset individually. A readme file and an example of the eBird data extraction, data frame combination, and our modelling approach can be found at: https://github.com/smcgarrigle725/ecological_data_science/tree/main/CRPWindInteraction. The same eBird data extraction approach was applied to all species individually with breeding range dates adjusted for each species. The entire workflow was completed for all 27 species at both spatial grains, changing object names accordingly.

Supplementary material is available online [82].

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. S.A.M.: data curation, formal analysis, methodology, visualization, writing—original draft, writing—review and editing; E.V.L.: data curation, formal analysis, methodology, visualization, writing—original draft; K.M.: conceptualization, data curation, funding acquisition, writing—review and editing; R.I.: conceptualization, writing—review and editing; J.E.D.: conceptualization, writing—review and editing; A.L.: conceptualization, writing—review and editing; K.R.: data curation, methodology, writing—review and editing; C.D.: conceptualization, funding acquisition, methodology, supervision, writing—original draft, writing—review and editing; S.R.L.: conceptualization, funding acquisition, methodology, supervision, writing—original draft, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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