Avian Community Diversity and Its Influencing Factors at Taiyangshan Wind Farm, Ningxia: Postprint

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Abstract

The northwestern desert and semi-desert grassland region of China represents a concentrated area of wind energy resources; however, the impacts of operational centralized large-scale wind farms on avian communities, and the primary influencing factors, have not yet received adequate attention. During the spring and autumn of 2024, we conducted an investigation of bird diversity and associated environmental factors at the Taiyangshan Wind Farm in Ningxia using a grid sampling approach. Results demonstrate: bird community diversity indices in wind turbine grids were lower than those in control grids; wind turbine density and rated power significantly influenced bird community diversity, with areas containing medium-rated-power (2000 kW) turbines exhibiting relatively higher bird diversity levels; noise intensity generated by turbine operation did not significantly affect bird diversity, whereas electromagnetic radiation intensity significantly influenced spring bird community evenness; distance from wind turbines was the primary factor affecting bird community diversity, with birds exhibiting avoidance behavior toward turbines; additionally, turbine size, plant richness, and vegetation height were also important factors influencing bird diversity at the Taiyangshan Wind Farm. Therefore, in the planning and construction of wind farms in desert and semi-desert grassland regions, synergistic optimization of bird diversity conservation and green energy development can be achieved by increasing inter-turbine spacing to reduce density, prioritizing medium-rated-power turbines, and targeted enhancement of vegetation richness and average height within wind farms.

Full Text

Bird Community Diversity and Influencing Factors in the Taiyangshan Wind Farm of Ningxia

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Abstract

The desert and semi-desert grassland zones in northwestern China represent regions with abundant wind energy resources, yet the ecological impacts of large-scale centralized wind farms on avian communities remain understudied. During the spring and autumn of 2024, we investigated bird diversity and associated environmental factors in the Ningxia Taiyangshan wind farm using a grid sampling approach. Our results demonstrate that bird community diversity indices in wind turbine grids were significantly lower than those in control grids. Both wind turbine density and rated power significantly influenced bird community diversity, with areas containing medium-rated-power turbines (2000 kW) exhibiting relatively higher diversity levels. While noise intensity generated by turbine operation showed no significant effect on bird diversity, electromagnetic radiation intensity significantly affected the Pielou evenness index of spring bird communities. Distance to wind turbines emerged as the primary factor influencing bird community diversity, indicating an avoidance response by birds. Additionally, turbine size, plant richness, and vegetation height were identified as important factors affecting bird diversity in the Taiyangshan wind farm. Therefore, in the planning and construction of wind farms in desert and semi-desert grassland regions, synergistic optimization of bird biodiversity conservation and green energy development can be achieved by increasing turbine spacing to reduce density, prioritizing medium-rated-power turbines, and enhancing vegetation richness and average height within wind farm areas.

Keywords: wind farm; bird diversity; environmental factors; semi-desert grassland; Ningxia

Introduction

Reconciling humanity' s growing energy demands with wildlife conservation represents a critical challenge in conservation biology. Wind energy, as a clean and renewable resource, plays a vital role in mitigating global energy shortages, climate warming, and environmental pollution, making its development a priority in many national energy policies. However, wind farm construction and operation pose potential threats to regional biodiversity, with ecological effects including habitat fragmentation and disruption of migration corridors that may impact multiple taxonomic groups, particularly bird populations. The impacts of wind power on birds primarily include direct mortality from collisions with turbines and associated infrastructure, as well as indirect effects from electromagnetic, noise, vibration, and visual disturbances during construction and operation that can degrade habitat quality and food resources, thereby altering bird community structure and stability. Previous studies have shown that avoiding important bird habitats or flight corridors during wind farm siting, optimizing turbine layout, and enhancing landscape and habitat management within wind farm areas can effectively reduce impacts on birds. Therefore, understanding the distribution patterns of birds in wind farm areas and identifying key factors influencing bird diversity provides a reliable basis for developing conservation measures.

Ningxia possesses abundant wind energy resources, particularly in desert and semi-desert grassland areas that offer favorable natural conditions for large-scale wind energy development. The Taiyangshan wind farm, located in central Ningxia' s semi-desert region, represents one of the important centralized large-scale wind power bases in northwestern China, with a total installed capacity exceeding 500 MW. This study investigates bird diversity in the Taiyangshan wind farm, analyzes the impacts of wind farm operation on birds, and reveals key environmental factors influencing bird diversity in wind farm areas, providing scientific basis and practical guidance for wind farm management and development in northwestern semi-desert grassland regions, as well as for bird conservation measure formulation.

1. Study Area Overview

The Taiyangshan wind farm (106°17 4 –106°39 58 E, 37°25 32 –37°28 3 N) covers an area of 730 km^2, situated at the junction of Lingwu City, Litong District, Hongsibao District, and Yanchi County in central Ningxia (Figure 1). The region has an elevation range of 1176–1446 m, with flat and open terrain, an average annual temperature of -1°C, extreme maximum temperature of 37.4°C, and extreme minimum temperature of -27.1°C. Average annual precipitation is 266.1 mm, and average wind speed is 3.2 $m \cdot s^{-1}$. The natural vegetation consists of desert and semi-desert grassland, with partially distributed semi-mobile crescent-shaped dunes. Vegetation is dominated by small xerophytic perennial herbs, with xerophytic semi-shrubs also comprising a significant proportion, including *Suaeda prostrata*, *Suaeda glauca*, *Lespedeza potaninii*, *Artemisia scoparia*, *Convolvulus tragacanthoides*, and *Caragana korshinskii*. The ecological environment is fragile, with animal resources dominated by species adapted to arid and semi-arid environments, including mammals such as *Spermophilus alaschanicus*, *Lepus tolai*, and *Vulpes vulpes*; reptiles such as *Phrynocephalus frontalis*, *Eremias argus*, and *Elaphe dione*; and birds including *Alaudala cheleensis*, *Galerida cristata*, and *Pica serica*.

2. Methods

2.1 Sample Plot Setup Within the study area, wind turbines were distributed across the landscape. Using ArcGIS, we divided the area into 1 km × 1 km grids and assigned numbers, with each grid containing varying numbers of wind turbines. Turbine rated power included four types: 750 kW, 1500 kW, 2000 kW, and 2500 kW. We excluded grids containing villages, photovoltaic facilities, and highways to avoid their potential impacts on bird diversity. From the remaining grids, we selected 24 grids as survey units (Figure 1). Based on the number of wind turbines within each grid, we classified the selected grids into six groups (G0-G5), with distinct turbine characteristics in each group (Table 1).

2.2 Data Collection Surveys were conducted in 2024 during spring (April-May) and autumn (September-October)—peak periods of bird activity and abundance. Each of the 24 grids was surveyed once per season to obtain data on bird diversity and associated environmental factors. To minimize the influence of environmental fluctuations during the survey period, all grid surveys in both seasons were completed within a concentrated timeframe by a trained team using standardized methodologies.

2.2.1 Bird Survey Bird surveys were conducted on clear or cloudy days with wind speeds not exceeding level 3, during peak activity periods: early morning (0.5 h before sunrise) and evening (1 h before sunset to sunset). Teams of 2-3 people equipped with toolboxes, binoculars, and cameras conducted point counts at the center of each grid, observing birds within a 250 m radius. Each point was surveyed for 30 minutes, recording bird species, abundance, and coordinate information. Each individual was counted only once; birds that left and returned to the survey point were not recounted.

2.2.2 Environmental Factor Survey Turbine-related factors included hub height (HTurb), rated power (PTurb), rotor diameter (STurb), distance from grid center to nearest turbine (DTurb), and number of turbines per grid (NTurb), from which turbine density (DWT) was calculated. Wind farm noise (Noise) and electromagnetic radiation (Electromagnetic radiation) also significantly impact birds. We measured noise using an AWA6292 sound level meter and electromagnetic radiation using an electromagnetic radiation analyzer.

For vegetation surveys, we established 100 m × 100 m plant survey plots in each grid center, using five-point sampling to set up 5 m × 5 m shrub quadrats or 1 m × 1 m herb quadrats. We recorded plant species, abundance, and height to calculate flora diversity index, flora dominance index, flora abundance, and flora height as metrics of plant characteristics. Climate data, including monthly average temperature, humidity, and wind speed, were obtained from Worldclim (https://www.worldclim.org/). Altitude data were extracted from 30 m × 30 m digital elevation images from the Geospatial Data Cloud (https://www.gscloud.cn). Soil Adjusted Vegetation Index (SAVI) data were obtained from the National Geospatial Information Center (http://www.dsac.cn).

2.3 Data Analysis

2.3.1 Bird Community Diversity Bird abundance was measured by individual count, and species richness by species number. We used the Shannon-Wiener diversity index (H), Pielou evenness index (E), and Simpson dominance index (D) to characterize bird community diversity:

Shannon-Wiener diversity index (H):

$$H' = -\sum_{i=1}^{S} P_i \ln P_i$$

Pielou evenness index (E):

$$E = \frac{H'}{\ln S}$$

Simpson dominance index (D):

$$D = 1 - \sum_{i=1}^{S} P_i^2$$

where $P_i = n_i/N$, n_i is the number of individuals of species i, N is the total number of individuals, and S is the total number of species.

2.3.2 Statistical Analysis and Mapping We used IBM SPSS Statistics 27 for data analysis. The Kolmogorov-Smirnov test assessed normal distribution. Wilcoxon rank-sum tests analyzed differences in bird community diversity between wind turbine grids and control grids. Generalized Linear Models (GLM) examined effects of turbine-related parameters, noise, and electromagnetic radiation on bird community diversity. Spearman correlation analysis explored relationships between electromagnetic radiation and spring bird evenness index. Redundancy Analysis (RDA) using CANOCO 5.0 examined relationships between bird community diversity and environmental factors. ArcMap 10.8 was used for mapping.

3. Results

3.1 Bird Species Composition A total of 31 bird species were recorded in the study area, comprising 2,123 individuals. Spring surveys recorded 17 species (1,234 individuals), while autumn surveys recorded 22 species (889 individuals). Seven nationally protected second-class bird species were recorded: *Circaetus gallicus*, *Hieraaetus pennatus*, *Buteo hemilasius*, *Falco tinnunculus*, *Falco amurensis*, *Falco subbuteo*, and *Alauda arvensis*. Passeriformes had the most species (15 species, 48.39% of total). The dominant species were *Alaudala cheleensis* and *Galerida cristata*. Among non-Passeriformes, raptors (Accipitriformes and Falconiformes) comprised the highest proportion (7 species, 22.58%). Resident birds were the dominant residency type (14 species, 45.16%), and the Palaearctic realm was the primary zoogeographic type (22 species, 70.97%) .

3.2 Impact of Wind Turbines on Bird Community Diversity In wind turbine grids, both spring and autumn bird communities showed decreasing abundance and richness with increasing turbine numbers (Figure 2). Bird community diversity indices in turbine grids were significantly lower than in control grids ($P < 0.05$). Spring bird abundance in grids with $ $4 turbines was significantly lower than in control grids (Z = -2.107, P = 0.035), and autumn bird abundance in grids with $ $3 turbines was significantly lower (Z = -2.316, P = 0.021), indicating significant negative impacts of wind turbines on bird community diversity.

3.3 Impact of Turbine-Related Parameters on Bird Community Diversity Turbine density and rated power significantly affected bird community diversity ($P < 0.05$). Turbine density significantly influenced spring bird Pielou evenness index (^{2} = 10.225, P = 0.006) and Simpson dominance index (^{2} = 12.502, P = 0.014), with Pielou evenness index in areas with $ 4*turbines* · *km*^{-2}$ significantly lower than other density areas ($P < 0.05$). Rated power significantly affected autumn bird richness, Shannon-Wiener diversity index, Pielou evenness index, and Simpson dominance index ($P < 0.05$). Areas with 2000 kW turbines showed significantly higher bird richness than other power categories ($P < 0.05$), and significantly higher Shannon-Wiener diversity index, Pielou evenness index, and Simpson dominance index than 750 kW turbine areas ($P < 0.05$) [Figure 3: see original paper].

3.4 Impact of Noise and Electromagnetic Radiation on Bird Community Diversity Spring and autumn noise intensities were 42.52 ± 9.03 dB and 41.68 ± 8.62 dB, respectively. Electromagnetic radiation intensities were 0.89 $\pm$ 0.43 $mA \cdot m^{-1}$ and 0.99 $\pm$ 0.79 $mA \cdot m^{-1}$, respectively. Noise intensity was affected by distance to the nearest turbine (spring: ^{2} = 10.225, P = 0.006; autumn: ^{2} = 12.502, P = 0.014), decreasing significantly with distance ($P < 0.05$). Electromagnetic radiation intensity was affected by turbine density (spring: ^{2} = 5.745, P = 0.017). In spring surveys, Pielou evenness index in areas with $ 4*turbines* · *km*^{-2}$ was significantly lower than in areas with 1 turbine · km^{-2} ($P < 0.05$), and electromagnetic radiation intensity in $ 4*turbines* · *km*^{-2}$ areas was significantly higher than in 1 turbine · km^{-2} areas. Pielou evenness index showed a significant positive correlation with electromagnetic radiation intensity (r = 0.248, P = 0.001), increasing gradually with radiation intensity. In autumn surveys, electromagnetic radiation intensity in turbine grids was significantly higher than in control grids ($P < 0.001$). However, noise intensity showed no significant effect on bird community diversity.

3.5 Key Factors Influencing Bird Community Diversity in Wind Farm Areas Redundancy Analysis of bird community diversity and environmental factors revealed that the first two axes explained 40.79% and 67.91% of cumulative variance in spring and autumn, respectively, effectively representing the influence of environmental factors on bird community diversity. Distance to the nearest turbine (DTurb) was the primary factor affecting bird community diversity, with explanation rates of 42.4% in spring ($F = 53.8$, $P = 0.002$) and 53.8% in autumn ($F = 12.2$, $P = 0.028$), showing strong positive correlation with bird abundance. Additionally, climate temperature ($F = 4.5$, $P = 0.034$), hub height (HTurb) ($F = 12.2$, $P = 0.010$), plant richness ($F = 4.5$, $P = 0.048$), rotor diameter (STurb) ($F = 12.2$, $P = 0.003$), plant dominance ($F = 4.5$, $P = 0.044$), and plant height ($F = 4.5$, $P = 0.044$) significantly affected spring bird community diversity. Plant richness and height were also significant factors for autumn bird community diversity [Figure 5: see original paper].

4. Discussion

The desert and semi-desert grassland ecosystem of the Taiyangshan wind farm is characterized by harsh climate conditions, simple ecological structure, and vulnerability, resulting in low bird diversity. This study recorded only 31 bird species, accounting for 7.40% of Ningxia' s total bird species. Passeriformes dominated in species number and abundance, with strong adaptability to the arid environment. Dominant species included *Alaudala cheleensis* and *Galerida cristata*, which are adapted to dry and semi-dry conditions and nest primarily on the ground. Raptors, with strong flight capabilities, benefit from the open landscape for hunting. Research indicates that concentrated prey distribution and updrafts generated by turbine operation can attract raptors. Consequently, raptors comprised the highest proportion of non-Passeriformes, and all recorded raptors are nationally protected species. The presence of migratory species such as *Apus apus*, *Ichthyaetus ichthyaetus*, and *Sterna hirundo* confirms the area lies on bird migration routes. Therefore, conservation efforts should focus on Passeriformes, raptors, and migratory birds.

Wind farm construction and operation cause regional climate change, habitat destruction, and anthropogenic disturbance, while turbines themselves create visual, noise, and vibration impacts that drive birds away. This study' s comparison between turbine grids and control grids demonstrates significant adverse effects on bird distribution and composition. Different ecological groups responded differently: only Passeriformes showed significantly lower richness and abundance in turbine grids ($P < 0.05$), while raptors showed no significant changes ($P > 0.05$). High turbine density compresses bird living space and increases collision risk, causing avoidance behavior in sensitive species. However, avoidance responses vary by species, with some attracted to or adapting to wind farms. High-density turbine layouts reduce inter-turbine distances, intensifying bird avoidance. This study also found that turbine rated power affects community structure. Rated power correlates positively with hub height and rotor diameter, and larger turbines generally have greater negative impacts. However, medium-rated-power (2000 kW) turbine areas showed the highest bird diversity, likely because this configuration balances the negative effects of higher density and larger turbine size.

Noise and electromagnetic radiation pollution adversely affect bird growth, physiology, behavior, and reproductive success. Wind farm noise originates primarily from aerodynamic noise of rotating blades and mechanical noise from gears and bearings. This study found noise intensity decayed with distance from turbines but showed no significant relationship with bird community diversity indices, possibly indicating adaptation to chronic low-frequency noise. Electromagnetic radiation from generators, transformers, and power transmission equipment was significantly higher in turbine grids and increased with turbine density. Electromagnetic radiation can interfere with cellular redox balance, cause genetic damage, and affect behavior and physiology. According to the Intermediate Disturbance Hypothesis, electromagnetic radiation as a moderate anthropogenic disturbance may suppress dominant species overpopulation, thereby increasing community evenness. The significant positive correlation between electromagnetic radiation intensity and spring Pielou evenness index supports this mechanism, where tolerant generalist species dominate under low-level radiation, leading to more balanced population distribution.

Distance to turbines was the key factor influencing bird community diversity in both seasons, consistent with other studies showing bird avoidance of turbines. Seasonal differences in bird requirements meant that primary influencing factors varied between seasons. Spring temperature increases may facilitate expansion of broadly distributed species, leading to dominance by a few species and reduced diversity. During autumn migration, large turbines increase collision risk, causing stronger avoidance and reduced diversity in those areas. Higher plant richness in autumn supports more complex insect communities, providing abundant food resources, while vegetation height increases concealment and reduces predation risk. Thus, plant richness and height positively affected autumn bird abundance.

5. Conclusions

This study used grid analysis to investigate impacts of wind farm operation on bird community diversity and key environmental factors in desert and semi-desert grassland regions. The main conclusions are:

1) Bird community diversity indices in wind turbine grids were significantly lower than in control grids, indicating that wind farm construction and operation negatively affect bird community diversity in desert and semi-desert grassland regions.

2) Turbine density and rated power significantly influenced bird commu-

nity diversity. Increased turbine density reduced Pielou evenness index. Medium-rated-power (2000 kW) turbine areas showed higher bird diversity, as this configuration balanced negative impacts from higher density and larger turbine size.

3) Turbine operation was the primary source of wind farm noise and electromagnetic radiation. Noise intensity did not significantly affect bird community diversity, while electromagnetic radiation intensity showed significant positive correlation with spring bird Pielou evenness index, suggesting that electromagnetic interference may enhance community evenness through niche substitution mechanisms.

4) Distance to wind turbines was the primary environmental factor influencing bird community diversity, with birds showing significant avoidance behavior. Turbine size, plant richness, and vegetation height were also important factors affecting bird diversity in wind farms.

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Note: Figure translations are in progress. See original paper for figures.