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Temporal and site-specific variations in two bird assemblages: insights from anthropized landscapes in the Isthmus of Tehuantepec, Mexico

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ABSTRACT

The increasing prevalence of anthropized landscapes, often characterized by extensive agricultural practices and artificial infrastructure developments (e.g. wind farms), can lead to complex ecological scenarios where the functional roles of species within their communities are altered. This study aims to compare bird populations at two anthropized sites (Stipa and Sureste, Mexico) over a four-year period. Given their proximity (< 5 km) and the shared characteristic of being located within wind farm areas on agricultural ground, similarities in bird species composition were expected. During the study, 88,765 birds of 178 species were recorded. The results revealed comparable species richness at both sites, with 137 species observed at Stipa and 135 at Sureste. Differences in assemblage composition were significant between sites and seasons (fall vs. summer, fall vs. spring), but not between years. The dissimilarity between the two sites seems to be mainly influenced by the presence of waterbirds associated with an irrigation canal at Stipa and raptors associated with open areas at Sureste, likely a favourable habitat to maximize hunting success. The stable species assemblage structure observed over the study years suggests constant resource availability resulting from habitat homogenization driven by expanded sorghum cultivation displacing other crops. Conversely, variations in bird composition between seasons were influenced by migratory patterns, particularly among raptors, which became more abundant over the study years. This study supports the idea that artificial water supplies can favour the presence of bird species with an affinity for aquatic habitats in anthropized habitats, such as at Stipa. This highlights the importance of designing, regulating and well-managing artificial resources in anthropized landscapes, as these can contribute to habitat restoration, increase taxonomic diversity, and help achieve long-term conservation goals.

Keywords: wind turbines, agriculture, irrigation canal, Isthmus of Tehuantepec, aquatic birds

INTRODUCTION

Anthropic perturbations such as habitat loss, resource overexploitation, and pollution, have caused detrimental effects on biodiversity (Singh et al. 2021). These disturbances are generally categorized into three types: i) direct human impacts; ii) biotic pressure (e.g. invasive species); and iii) environmental changes (e.g., abiotic conditions and habitat loss; Mouillot et al. 2013). Specifically, among the environmental changes, habitat loss is known for having negative impacts on local bird assemblages in which declining specialist species are often replaced by generalist species thus leading to the homogenization of the communities (Ibarra & Martin 2015, Callaghan et al. 2019).

Birds are highly sensitive to habitat changes, making them excellent indicators of ecosystem health (Fraixedas et al. 2020). Their presence and diversity provide crucial insights into the overall condition and sustainability of natural environments (Fraixedas et al. 2020, Chowfin & Leslie 2021). Numerous studies have demonstrated that while disturbances can sometimes increase total bird abundance (Stouffer et al. 2006, McWethy et al. 2010, Battisti et al. 2016), they often result in altered assemblage composition, with declines in species diversity (Proppe et al. 2013, Bregman et al. 2014, Rigal et al. 2023). This is particularly relevant in Mexico, where the growing prevalence of anthropized landscapes, characterized by extensive agriculture and artificial infrastructure, can lead to complex ecological scenarios that alter species' functional roles within their communities (Villegas-Patraca et al. 2012, Smith et al. 2015). While anthropogenic activities can introduce new habitat components that sometimes increase biodiversity (intermediate disturbance hypothesis; Connell 1979), they may also facilitate the dominance of human-associated birds, which can outcompete native species (Samia et al. 2015, Almeida et al. 2020, Hendershot et al. 2020, Lindenmayer et al. 2023). As a result, species richness values may remain stable despite disturbances, masking underlying effects on taxonomic, genetic, and functional diversity (Mouillot et al. 2013, Liang et al. 2019). Understanding how do bird species respond to these environmental disturbances is thus a key issue for the management and conservation of their habitats.

Bird assemblages can vary across time (within and between years), making consistent habitat management in anthropized landscapes a challenging task (Villegas-Patraca et al. 2012, Farfán et al. 2017). Nevertheless, most studies focus only on specific periods of the birds' annual cycle, namely during migration or the breeding season (Villegas-Patraca et al. 2014, Cabrera-Cruz et al. 2017). Therefore, a comprehensive understanding of the impacts on community assemblage, along with consideration of temporal variability, is essential for assessing the overall effects of human disturbance.

This study aims to quantify differences in bird assemblages between two wind farm sites located in the Isthmus of Tehuantepec, a key area for wind energy development in Mexico (Solórzano-Tello & Portador-García 2016, Zárate-Toledo & Fraga 2016). Over a four-year period, we assessed seasonal and annual variations in birds' presence and community composition in agricultural landscapes. Given the close proximity of the sites (< 5 km) and their shared agricultural surroundings, we expected both to exhibit similar bird species assemblages, primarily composed of generalist species associated with crop environments. However, our research could not directly evaluate the impact of wind farms on avian assemblages due to the absence of control data from wind farm-free areas. Nonetheless, by examining bird communities within these sites, we provided valuable insights into the avian species inhabiting disturbed environments, thus, contributing to a better understanding of changes in bird assemblages within anthropized landscapes.

MATERIALS AND METHODS

Study area and data collection

A total of 768 diurnal sampling sessions from 8:00 AM to 12:00 PM were conducted over a four-year period (from summer 2018 to spring 2022) to count bird species and estimate richness and abundance.

These sampling sessions were conducted by the same person and were evenly distributed across seasons (24 transects in winter, spring, summer and fall) and years (96 transects). Each sampling session consisted of six one-kilometer-long transects, each with a width of 50 meters, and a duration of 90 minutes per transect. Bird species were recorded using both auditory methods, by identifying bird calls, and visual observations of individuals. Observations were conducted using Celestron UpClose G2 10×50 binoculars to ensure accurate identification and minimize errors in species detection.

The Bii Nee Stipa Wind Farm (hereafter Stipa) and Project 40 CE Sureste I, Phase II (hereafter, Sureste) are located in southeastern Oaxaca, within the Isthmus of Tehuantepec region, Mexico, and are 4.5 km apart (edge to edge; Fig. 1). The Stipa wind farm is located at an altitude of 40 m a.s.l. and has 37 wind turbines distributed over an area of 413.56 ha (1 turbine/11.17 ha). The land use is primarily agricultural (crops) interspersed with small patches of plant species characteristics of the deciduous forest, mainly from the Fabaceae family. The northern boundary of Stipa is delimited by an irrigation canal and deciduous forest, while the southern boundary is surrounded by other wind farms. The Sureste wind farm is located at an altitude of 50–70 m a.s.l. and comprises 34 wind turbines distributed over an area of 894.50 ha (1 turbine/26.3 ha). Its land use is primarily agricultural (crops), which de-

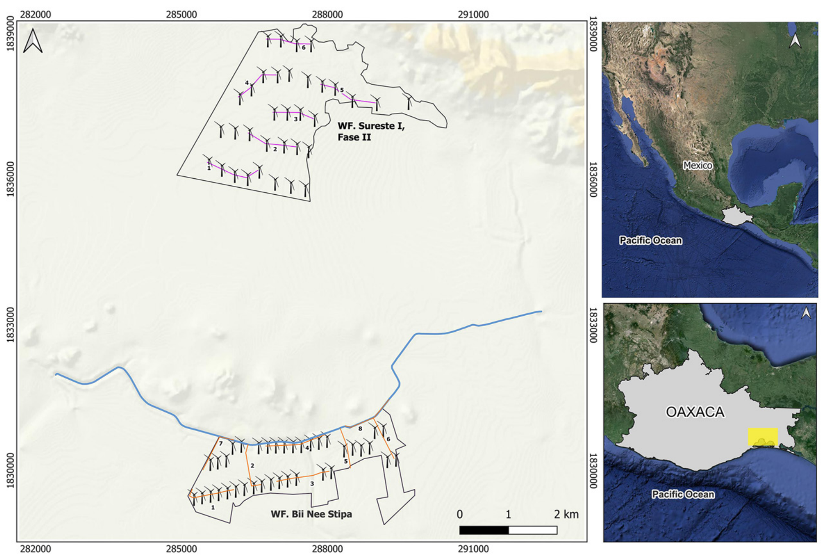

Figure 1. Distribution of bird monitoring transects in the Stipa (yellow lines) and Sureste (purple lines) wind farms. The blue line represents the irrigation canal, and the wind turbine icon represents the location of the wind turbines present at both sites.

pends on the rainy season. The site is limited to the west by thorn forest and to the north by a mountainous strip of deciduous forest, and by two urban areas, La Cueva and La Mata.

STATISTICAL ANALYSIS

Bird assemblage structure analysis

The bird community assemblage was characterized by the number of species (species richness; S) and the total of individuals (abundance; N) and was further assessed using Bray-Curtis similarity and multivariate ordination (Clarke et al. 2014; Brabata et al. 2019). Multivariate non-metric multidimensional scaling ordination (nMDS) was used to compare bird assemblages (individual species abundance) between the two wind farm sites (Stipa and Sureste). The Hotelling's T^2 permutation test was applied to identify significant differences in bird assemblages between the two sites (Willems et al. 2002). A two-way nested analysis of similarity (ANOSIM) was used to test for differences in the bird assemblages among the four years (season within years) and to test for differences among the four seasons (months within season) of the year. The ANOSIM analysis generates a probability value P and a statistic R, which takes a value of – 1 when all elements within a group are less similar to each other than to elements in other groups, and of 1 when all elements within a group are more similar to each other than to elements in other groups. When the value of R is close to 0, the similarities of elements between and within groups are on average equal (Clarke & Warwick 2001). Pairwise ANOSIM comparisons of sample groups was applied to identify which group (i.e., Wind Farm/Year/Season) was significantly different (Clarke et al. 2014).

Similarity percentage analysis (SIMPER) was performed to determine the average similarity and dissimilarity among the wind farms (Sureste and Stipa), years, and seasons. The variability among samples (bird censuses) among the wind farms, years, and seasons of the study was compared with the index of multivariate dispersion (MVDISP) routine. For all multivariate analysis, data were fourth root transformed to reduce the influence of highly abundant taxa (Clarke et al. 2014) and calculated in R using the Vegan package (Oksanen et al. 2022).

To assess the association of bird species to each wind farm in each year and season, indicator value analysis (IndVal) was applied using the R package indicspecies (Dufrêne & Legendre 1997). The IndVal index is the result of the specificity 'A' (predictive value of the species as indicator of the site group) and fidelity 'B' (probability of finding the species in sites belonging to the site group; De Cáceres 2019). IndVal provides a quantitative measure of how strongly a species is associated with a particular site or period of time, helping to identify which species may serve as indicators of ecological conditions or habitat types. A higher IndVal value indicates stronger association, highlighting key species that may reflect environmental changes or habitat quality (Dufrêne & Legendre 1997).

Taxonomic structure analysis

In order to describe differences in taxonomic structure among the wind farms of the study (Sureste and Stipa), the index of Average Taxonomic Distinctness (AvTD; Δ+) was applied using the software PRIMER 7 (Clarke et al. 2014). The AvTD (Δ+) measures the expected taxonomic distance of the assemblage for a given number of species for a standard Linnean classification (Clarke & Warwick 1999). The hierarchical classification of the recorded bird's species (from species to order level; AOU 1998; Chesser et al. 2024) was used to calculate the values of AvTD (Δ+) and results visualized using a Funnel plot. The results were displayed in a Funnel Plot of Δ+ against m (number of species), allowing simultaneous comparison of distinctness values of each wind farm with the expected 95% probability limits.

RESULTS

Bird assemblage structure

Over the study period, a total of 88,765 individual birds from 178 species grouped in 50 families belonging to 21 orders were recorded (ESM 1). Ninety-four species (52.8 %) were identified at both wind farm sites; the species richness was comparable at both sites, with 137 species recorded in Stipa, including 43 exclusive species (those recorded only in one site), and 135 species recorded in Sureste, with 41 species being exclusive to that location. However, despite the comparable species richness, the total mean abundance of birds was 33.3 % higher at Sureste compared to Stipa (ESM 1).

The nMDS clearly separated the observed birds by wind farm site (Fig. 2a), with a dissimilarity of 68 % (Table 1). Furthermore, there were significant differences observed in the bird assemblage composition between Sureste and Stipa ($T^2 = 3.21$ df = 589, $P < 0.001$; Fig. 2a).

In the Stipa wind farm, a higher abundance of species from the families Icteridae, Columbidae, Tyrannidae, Passerellidae, Cuculidae, Ardeidae, Psittacidae, Anatidae, Mimidae and Threskiornithidae was recorded. Moreover, Stipa presented the highest number of indicator species, mainly those associated with aquatic environments such as *Charadrius vociferus*, *Aramus guarauna*, *Ardea alba*, *Butorides virescens*, *Dendrocygna autumnalis*, *Eudocimus albus*, *Spatula discors*, *Egretta thula* and *Mycteria americana* (Table 2). In contrast, at Sureste wind farm site, a higher abundance of species of the families Columbidae, Icteridae, Passerellidae, Cardinalidae, Tyrannidae, Psittacidae, Cuculidae, Laridae, Corvidae and Polioptilidae were observed (ESM 1). Here the indicator species were insectivorous, granivorous and raptor species including *Morococcyx erythropygus*, *Icterus pustulatus*, *Peucaea sumichrasti*, *Myiarchus cinerascens*, *Circus hudsonius, Falco sparverius*, *Falco femoralis*, *Falco columbarius* (Table 2).

The year 2021/2022 exhibited the highest richness and abundance compared to the others, with 135 species and 30,238 individuals recorded. In contrast,

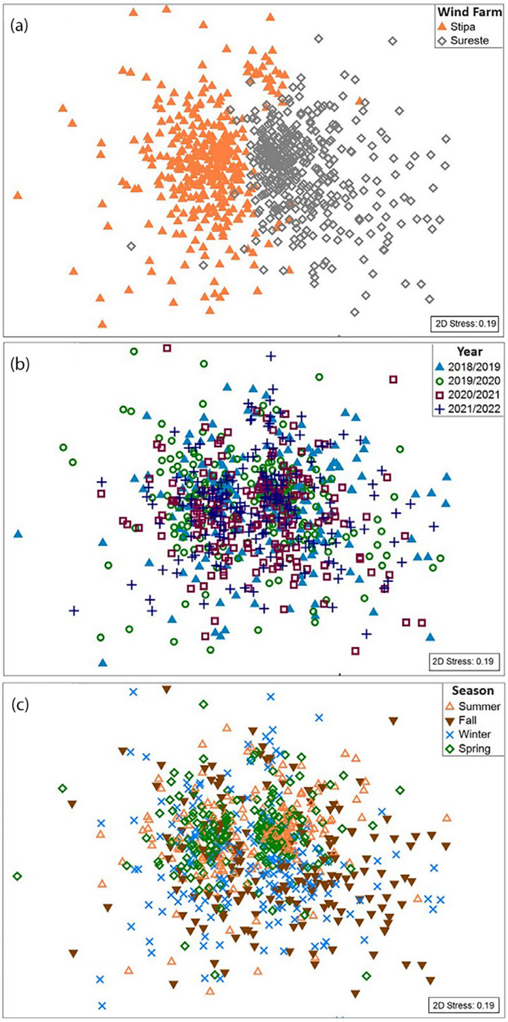

Figure 2. Non-metric multidimensional scaling (nMDS) plots based on species abundances obtained from 768 diurnal sampling sessions illustrating differences across: a) wind farms; b) years, and c) seasons. The nMDS represents sample similarities in a reduced-dimensional space, with points closer together indicating more similar species compositions. The degree of correspondence between the distances among points is quantified by a stress value (0.0: perfect, 0.1: excellent, 0.2: good, and 0.3: poor).

the lowest richness value was obtained for 2019/2020, while the lowest abundance occurred in 2018/2019. Nevertheless, the differences in the bird assemblage among years were not significant (ANOSIM, R = – 0.027, P = 0.262; Fig. 2b).

With respect to the seasons, the highest number of species was observed during autumn and summer, with 135 and 131 species, respectively. Conversely, winter and spring recorded the lowest richness values with 118 and 116 species, respectively. Regarding the abundance of individuals, the largest count was in spring with 30,394 individuals, while the lowest counts were recorded in winter (17,780 individuals) and summer (17,125 individuals). Furthermore, differences in bird assemblage between seasons were only significant between fall and spring (ANOSIM, R = 0.237, P= 0.014, Fig. 2c), and between fall and summer (ANOSIM, r = 0.171, P = 0.037; Fig. 2c).

Taxonomic structure

The Sureste Wind Farm site exhibited the lowest value of recorded species and the lowest values of AvTD (Δ+) compared to Stipa, indicating a narrower range of taxonomic groups (Fig. 3). In contrast, the high value of Δ+ index at Stipa indicates that the species are unevenly distributed along the phylogenetic tree, suggesting that there is a large taxonomic distance between them. Concerning temporal patterns, both the spring season and the year 2019/2020 recorded the fewest number of bird species. However, despite the low-

Table 1. Similarity percentage analysis (SIMPER) and multivariate dispersion (MVDISP) values within and between the factors (Wind Farms, Years, Seasons) of the study. Higher values of dissimilarity indicate lower similarity between samples. Higher values of multivariate dispersion indicate more variability among bird samples within each factor

Factor		Average Similarity	Multivariate Dispersion	Average dissimilarity									
				Stipa	Sureste	2018/ 2019	2019/ 2020	2020/ 2021	2021/ 2022	Winter	Spring	Summer	Fall
Wind Farm	**Stipa**	37.02	1.066	-	68	-	-	-	-	-	-	-	-
	Sureste	41.54	0.933	68	-	-	-	-	-	-	-	-	-
Year	**2018/2019**	39.13	0.997	-	-	-	62.67	62.05	64.28	-	-	-	-
	2019/2020	37.36	1.033	-	-	62.67	-	62.17	64.25	-	-	-	-
	2020/2021	39.84	0.931	-	-	62.05	62.17	-	63.12	-	-	-	-
	2021/2022	36.48	1.041	-	-	64.28	64.25	63.12	-	-	-	-	-
Season	**Winter**	36.73	1.07	-	-	-	-	-	-	-	61.60	64.45	67.10
	Spring	43.68	0.769	-	-	-	-	-	-	61.60	-	60.31	65.91
	Summer	38.44	0.966	-	-	-	-	-	-	64.45	60.31	-	67.56
	Fall	33.85	1.204	-	-	-	-	-	-	67.10	65.91	67.56	-

Table 2. Indicator species analysis (IndVal) comparing Wind Farms, Years, and Seasons of the study. The IndVal index combines specificity (A) and fidelity (B) to assess a species' association with a site group, indicating its value as a habitat indicator. Higher values denote stronger associations. Only species with significant values ($p < 0.05$) are listed

Factor	Sample Group	Species	Specificity A	Fidelity B	IndVal Stat*	P value
Wind Farm	Stipa	*Tyrannus melancholicus*	0.85914	0.75521	0.806	0.0001
		Charadrius vociferus	0.97804	0.43750	0.654	0.0001
		Aramus guarauna	1.00000	0.38021	0.617	0.0001
		Campylorhynchus humilis	1.00000	0.38021	0.617	0.0001
		Myiozetetes similis	0.96377	0.39323	0.616	0.0001
		Ardea alba	0.87633	0.35938	0.561	0.0001
		Sturnella magna	1.00000	0.29948	0.547	0.0001
		Leptotila verreauxi	0.84477	0.32552	0.524	0.0001
		Butorides virescens	1.00000	0.24219	0.492	0.0001
		Turdus grayi	0.98611	0.23958	0.486	0.0001
		Coragyps atratus	0.80000	0.29427	0.485	0.0001
		Dendrocygna autumnalis	0.98845	0.20052	0.445	0.0001
		Eudocimus albus	0.94626	0.19271	0.427	0.0001
		Agelaius phoeniceus	1.00000	0.18229	0.427	0.0001
		Spatula discors	1.00000	0.17969	0.424	0.0001
		Dives dives	0.79386	0.21354	0.412	0.0001
		Nannopterum brasilianum	1.00000	0.16146	0.402	0.0001
		Rostrhamus sociabilis	1.00000	0.16146	0.402	0.0001
		Zenaida macroura	0.75090	0.21354	0.400	0.0001
		Rupornis magnirostris	0.77465	0.20052	0.394	0.0001
		Icterus spurius	0.83051	0.18229	0.389	0.0001
		Cassiculus melanicterus	1.00000	0.15104	0.389	0.0001
		Jacana spinosa	1.00000	0.15104	0.389	0.0001
		Egretta thula	0.99259	0.14844	0.384	0.0001
		Chondestes grammacus	0.85714	0.15885	0.369	0.0001

(Continues)

Table 2. (Continued)

Factor	Sample Group	Species	Specificity A	Fidelity B	IndVal Stat*	P value
		Chordeiles minor	0.97849	0.09375	0.303	0.0001
		Actitis macularius	1.00000	0.08333	0.289	0.0001
		Tachybaptus dominicus	1.00000	0.08333	0.289	0.0001
		Ardea herodias	0.96875	0.07292	0.266	0.0001
		Tachycineta albilinea	0.97947	0.07031	0.262	0.0001
		Euphonia affinis	0.97436	0.06510	0.252	0.0001
		Mycteria americana	0.98462	0.04167	0.203	0.0002
		Heliomaster constantii	1.00000	0.02865	0.169	0.0008
		Sporophila minuta	1.00000	0.02865	0.169	0.0011
		Turdus rufopalliatus	1.00000	0.02865	0.169	0.0017
		Glaucidium brasilianum	0.83333	0.03385	0.168	0.0073
		Megaceryle alcyon	1.00000	0.02604	0.161	0.0022
		Tachycineta thalassina	1.00000	0.02344	0.153	0.0046
	Sureste	*Morococcyx erythropygus*	0.77485	0.50521	0.626	0.0001
		Icterus pustulatus	0.91040	0.41146	0.612	0.0001
		Peucaea sumichrasti	0.98734	0.29688	0.541	0.0001
		Falco sparverius	0.83673	0.29948	0.501	0.0001
		Geococcyx velox	0.97059	0.20573	0.447	0.0001
		Myiarchus cinerascens	0.92647	0.15625	0.380	0.0001
		Geranoaetus albicaudatus	0.98718	0.13542	0.366	0.0001
		Circus hudsonius	0.83607	0.12500	0.323	0.0001
		Streptopelia decaocto	1.00000	0.08073	0.284	0.0001
		Molothrus ater	0.97288	0.08073	0.280	0.0001
		Polioptila caerulea	1.00000	0.07812	0.280	0.0001
		Mimus polyglottos	0.73810	0.09635	0.267	0.0015
		Spiza americana	0.93831	0.07552	0.266	0.0006
		Archilochus colubris	0.85057	0.08073	0.262	0.0002

(Continues)

Table 2. (Continued)

Factor	Sample Group	Species	Specificity A	Fidelity B	IndVal Stat*	P value
		Myiarchus nuttingi	0.88889	0.07292	0.255	0.0002
		Passerina caerulea	0.98361	0.04688	0.215	0.0001
		Cardellina pusilla	1.00000	0.04427	0.210	0.0002
		Tityra semifasciata	1.00000	0.02865	0.169	0.0011
		Columbina talpacoti	1.00000	0.02604	0.161	0.0019
		Myiarchus tyrannulus	0.90000	0.02865	0.161	0.0052
		Fregata magnificens	0.84615	0.02604	0.148	0.0300
		Falco femoralis	1.00000	0.01823	0.135	0.0143
		Vireo gilvus	0.93333	0.01823	0.130	0.0310
		Empidonax minimus	1.00000	0.01562	0.125	0.0311
		Falco columbarius	1.00000	0.01562	0.125	0.0294
Season	Summer	*Volatinia jacarina*	0.63636	0.03646	0.152	0.021
	Fall	*Tyrannus forficatus*	0.91429	0.57812	0.727	0.001
		Archilochus colubris	0.80460	0.14583	0.343	0.001
		Polioptila caerulea	0.61905	0.10938	0.260	0.001
		Tityra semifasciata	1.00000	0.05729	0.239	0.001
		Falco femoralis	1.00000	0.03646	0.191	0.002
		Falco columbarius	1.00000	0.03125	0.177	0.002
		Accipiter cooperii	1.00000	0.02083	0.144	0.022
		Buteo platypterus	0.93333	0.02083	0.139	0.037
	Winter	*Spatula discors*	0.6891	0.2031	0.374	0.001
	Spring	*Dendrocygna autumnalis*	0.68360	0.23438	0.400	0.001
		Momotus mexicanus	0.72549	0.12500	0.301	0.001
		Chordeiles minor	0.68817	0.11979	0.287	0.001
		Coccyzus minor	0.64286	0.03646	0.153	0.049
Year	2019/2020	*Vireo gilvus*	0.93333	0.03646	0.184	0.002
	2020/2021	*Ammodramus savannarum*	0.60976	0.05729	0.187	0.032

(Continues)

Table 2. (Continued)

Factor	Sample Group	Species	Specificity A	Fidelity B	IndVal Stat*	P value
	2021/2022	*Polioptila caerulea*	0.84524	0.11458	0.311	0.001
		Cardellina pusilla	0.85294	0.07292	0.249	0.001
		Tityra semifasciata	1.00000	0.05729	0.239	0.001
		Coccyzus minor	0.85714	0.05208	0.211	0.001
		Falco femoralis	1.00000	0.03646	0.191	0.001
		Columbina talpacoti	0.73333	0.03646	0.164	0.008
		Falco columbarius	0.88889	0.02604	0.152	0.011
		Falco peregrinus	1.00000	0.02083	0.144	0.020

*The species are listed in descending order based on the IndVal Stat value

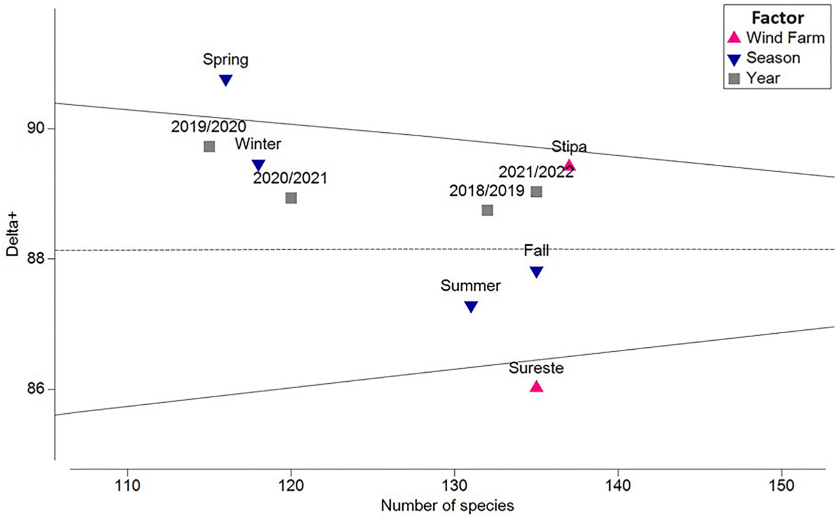

Figure 3. Average Taxonomic Distinctness (Δ+) calculated for bird species across Wind Farms, Years and Seasons. The results were presented in a Funnel Plot, with Δ+ plotted against m (the number of species), allowing for the comparison of distinctness values across wind farms, seasons and years. The solid lines indicate the 95% confidence interval, while the dashed line represents the expected mean.

er species richness, these periods also exhibited the highest values of taxonomic diversity, suggesting that the recorded species belonged to more distantly related taxonomic groups (Fig. 3).

DISCUSSION

Bird species are generally believed to exhibit lower overall species richness within anthropogenic environments such as wind farms (Fernández-Bellon et al. 2019, Rehling et al. 2023). However, our study presents a different point of view. Although we could not directly assess the impact of wind farms on bird assemblages due to the lack of control areas, our findings indicate high richness and abundance of birds in anthropized landscape with wind farms. This was an unexpected result, particularly because other areas in the region, such as the Important Bird Conservation Area of the Isthmus of Tehuantepec, have recorded up to 172 bird species (Berlanga et al. 2008). Notably, our study sites accounted for approximately 53% of the total bird species (N= 335) present in the entire Isthmus of Tehuantepec region (Herrera-Alsina et al. 2013).

The use of wind farms by birds can be influenced by several variables related to human activities and the associated infrastructures, such as turbines, irrigation systems, heavy machinery, and rural roads (Villegas-Patraca et al. 2012, Rahman et al. 2022). In our study, the bird assemblages in the agricultural landscapes surrounding the wind farms exhibited a consistent pattern, being dominated by generalist species (González-Salazar et al. 2014). This pattern aligns with broader trends in agricultural settings, where intensified farming practices and the reduction of natural landscape elements drive habitat homogenization favouring a limited range of dominant species (Hendershot et al. 2020, Turkovska et al. 2021).

In this study, the most abundant species in both wind farm areas are synanthropic species (e.g., *Quiscalus mexicanus*, *Zenaida asiatica*, *Pitangus sulphuratus*, *Peucaea ruficauda*) that benefit from human settlements and structures associated with agricultural fields where they find food and nesting sites (Olvera-Vital et al. 2020, Gómez-Moreno et al. 2023). Conversely, endemic species such as *Peucaea sumichrasti*, *Ortalis poliocephala* and *Trogon citreolus* are more vulnerable to land-use changes, experiencing reductions in population densities (McAndrews et al. 2008, Monroy-Ojeda et al. 2018). Therefore, anthropic activities such as agriculture and urbanization, have not only altered the composition of species within ecosystems but may have also led to the establishment of novel communities at both study sites (Andrade et al. 2021). For example, changing species abundance and relative frequencies thereby resulting in uni-variate diversity metrics.

The species composition observed between the two wind farms showed significant differences, with waterfowl (e.g., *Nannopterum brasilianum*, *Tachybaptus dominicus*, *S. discors*), shorebirds (e.g., *Hesperoburhinus bistriatus*, *C. vociferus* and *Actitis macularius*) and riparian birds (e.g., *A. guarauna*, *E. albus* and *Rostrhamus sociabilis*) contributing to increase the taxonomic diversity. Such diversity was largely influenced by the presence of an irrigation canal within the Stipa area. This result emphasizes the significant role of local water bodies in structuring the habitat composition and subsequently the bird community assemblage. Furthermore, it has been documented that small irrigation canals can act either as partial replacements for lost natural habitats or as biodiversity hotspots in agricultural landscapes (Rohwer et al. 2015, Giralt et al. 2021). However, the irrigation canal at Stipa Wind Farm is privately owned by farmers and is managed primarily to improve crop yields and meet irrigation needs rather than for conservation purposes. Therefore, conservation strategies should point to addressing the needs of both, agricultural activities and bird communities conservation in order to achieve mutually beneficial outcomes with implication to reducing conflicts between stakeholders (Decker et al. 2012).

Additionally, water bodies in croplands can serve as refuges for insects and invertebrates, which in turn, attract farmland birds (Bretagnolle et al. 2019, Pustkowiak et al. 2021) such as *Sturnella magna*, *Agelaius phoeniceus, Campylorhynchus humilis*, *Turdus rufopalliatus*, *Tachycineta thalassina* that were present at Stipa contributing to increase the diversity of bird assemblage at the site. Moreover, vegetation along irrigation canals is known to enhance habitat heterogeneity in croplands, providing favorable foraging and nesting conditions for bird species such as *I. pustulatus*, *P. sulphuratus* and *R. sociabilis* (Schaldach et al. 1997, Berlanga et al. 2008). This body of evidence underscores the importance of preserving water supply systems in anthropized landscapes to support bird assemblages, as species diversity may also be influenced by feeding strategies (Mariano-Neto & Santos 2023), habitat use (De Bonilla et al. 2012) and the spatial characteristics of the vegetation surrounding water bodies (Almeida et al. 2020). However, further research is needed to determine whether the presence of artificial water systems near wind farms increases the risk of turbine collisions for species with aquatic affinities (May et al. 2021, Reid et al. 2023).

The differences in seasonal bird assemblages arise from the geographical location of both wind farms within the Isthmus of Tehuantepec, a vital stopover site and on the migratory route of several Nearctic-neotropical migratory birds in spring and fall months, with peak migration commonly observed in mid-October (Cabrera-Cruz & Villegas-Patraca 2016, Cabrera-Cruz et al. 2017b). Previous studies (Villegas-Patraca et al. 2012, Villegas-Patraca et al. 2014, Cabrera-Cruz & Villegas-Patraca 2016) have proposed that raptors migrating through the southern Isthmus of Tehuantepec have adapted their flight patterns to avoid wind farms. Conversely, our field observations provided contrasting evidence indicating that during fall, raptor species (e.g., *F. femoralis*, *F. columbarius*, *F. peregrinus*, *F. sparverius*, *C. hudsonius*, *Coragyps atratus*, *Caracara plancus*) use areas in close proximity to wind turbines for foraging. Raptors often favour open areas that facilitate hunting, enabling them to locate prey from the air and increase capture success (Negro & Galván 2018). The Sureste Wind Farm site, with is twice the size of Stipa, provides favourable conditions (i.e., open space) for species from the families Accipitridae (e.g., *G. albicau-*

datus, *C. hudsonius*, *Buteo platypterus*) and Falconidae (e.g., *F. sparverius*, *F. femoralis*) to maximize hunting success for birds and small mammals (Rojas & Stappung 2004, González-Salazar et al. 2014). Raptors are known to select habitats based on patterns of landscape composition and configuration (Mirski et al. 2024), which strongly correlate with prey abundance and diversity (Väli et al. 2023).

Agricultural activity remains constant throughout the year at both wind farms. However, Stipa is characterized by irrigated agriculture, while farming at Sureste relies on the rainy season (INECOL 2012). In recent years, both sites have experienced a significant expansion of sorghum cultivation, replacing crops such as peanuts, beans, corn, and chili (INECOL 2012, Santini et al. 2022). This shift has led to significant habitat homogenization, potentially promoting resource stability and therefore explaining the limited variation in the most abundant bird species observed over time.

Our findings show that a wide variety of bird species utilize wind farm sites across different seasons, with the bird assemblages being influenced by the surrounding habitat. This highlights the importance of carefully designing, regulating and managing artificial structures, such as wind farms and irrigation canals, in anthropized landscapes. When managed effectively, such resources may have the potential to increase species diversity and contribute to achieving long-term species conservation goals. In addition, the high number of birds observed near the wind farms underscores the need to conduct future monitoring studies with control areas, which could provide valuable insights into the implications of these artificial habitats on bird assemblages and collisions.

Data Avalaibility Statement

Data used for this research are available inside the paper and in the supplementary files attached.

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