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Taxonomic and functional alteration of bird communities in photovoltaic power plants

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Abstract

The construction of photovoltaic (PV) power plants induces habitat conversion and degradation, which consequently affect species communities and ecosystem functioning. However, the impacts of PV power plants on species diversity remain poorly understood. This study investigates the effects of a PV power plant on taxonomic and functional composition of bird communities. We conducted bird surveys in PV power plants located in the Qinghai-Tibet Plateau (QTP) of China, which encompasses two major microhabitat types – *Caragana*-dominated shrubland and *Stipa-Achnatherum* steppe, along with adjacent natural habitats. Our findings demonstrate: (i) bird taxonomic diversity remained stable but functional diversity increased within PV power plants; (ii) The PV power plants selectively attracted smaller species, herbivores and understory foragers while filtering out larger species, granivores and ground foragers, it also attracted species with weak dispersal abilities, likely due to spatial and resource changes induced by artificial structures; (iii) These impacts were similar across both microhabitat types but exhibited variations due to their ecological characteristics. Notably, PV power plants within the *Caragana*-dominated shrubland supported less vertebrate-consuming species, while PV effects within *Stipa-Achnatherum* steppe were more pronounced on granivores and ground dwellers. With a more comprehensive analysis of functional traits, our results unravel the underlying process driving PV-induced community-level alteration in avian assemblages, which has rarely been explored in previous studies. It also highlights the need to investigate the spatiotemporal trajectory of PV induced impacts on avian diversity.

Introduction

As part of the global shift from fossil fuels to renewable energy, the rapid expansion of photovoltaic (PV) power plants (Rehbein et al. 2020) has raised concerns about biodiversity impact. PV installations are often located on ecologically valuable land (Taylor 2019; Rehbein et al. 2020), leading to habitat loss, fragmentation, and alteration (Gasparatos et al. 2017). They also require substantial water, intensifying stress on water-scarce ecosystems (Cameron et al. 2012; Grippo et al. 2015). Moreover, herbicides and dust control chemicals used to maintain panel efficiency may drive soil erosion and pollution (Lovich and Ennen 2011; Grippo et al. 2015). Quantifying these impacts on biodiversity is essential for sustainable PV deployment (Hernandez et al. 2015).

PV power plants affect wildlife through direct and indirect mechanisms (Gasparatos et al. 2017). At the individual level, smooth PV panels reflect polarized light, which aquatic insects, birds, and bats may mistake for water bodies, increasing mortality risk (Greif and Siemers 2010; Horváth et al. 2010; Greif et al. 2017). Concentrated PV panels can also act as ecological traps, attracting breeding insects but reduce breeding success (Horváth et al. 2009; Horváth et al. 2010; Kagan 2014). At the community level, PV installations alter species richness and composition through habitat loss and alteration (Dwyer et al. 2018). However, the effects of PV power plants on bird communities appeared to vary regionally. For instance, studies in North America and South Africa reported lower bird species richness in PV power plants than adjacent natural or semi-natural habitats, but higher abundance (DeVault et al. 2014; Visser

et al. 2019). Conversely, research in European agricultural landscapes found that PV power plants supported higher bird species richness and abundance, with shifts in community composition towards invertebrate feeders (Jarčuška et al. 2024). These divergent outcomes suggest species-specific responses to PV power plants shaped by the spatial and resource needs of individual species (Harrison et al. 2017). For instance, PV arrays may benefit small passerines by providing perches but deter raptors (DeVault et al. 2014). Similarly, ground-nesting birds might use PV power plants as shelter (Smith et al. 2010), although patterns differ among sites (Montag et al. 2016).

Key research gaps of PV impact on wildlife remain. First, most studies emphasize individual-level outcomes (e.g., reproduction, mortality) rather than community-level effects (e.g., species richness, abundance). Second, few studies have quantified trait-based responses, despite functional traits being central to predicting community dynamics to habitat change (Si et al. 2016; Harrison et al. 2017). Third, the role of microhabitat heterogeneity, which likely mediates species responses, has rarely been tested. To address these gaps, we examined the taxonomic and functional effects of PV power plants on bird communities in 2 alpine meadow microhabitats (*Caragana*-dominated shrubland and *Stipa-Achnatherum* steppe) in northwestern China, where PV expansion is extensive. We chose bird as a study system because they are widely used as bioindicators (Sekercioglu et al. 2004) and play critical ecological roles (Bosc et al. 2018; Estes et al. 2011). Specifically, we compared bird taxonomic diversity (species richness, α & β diversity), functional diversity (Functional Dispersion), and functional structure (trait composition) between PV power plants and natural habitats to answer the following questions: (i) How do PV power plants alter bird community taxonomically and functionally? (ii) Do they filter or favor species with particular traits? and (iii) Are these effects consistent across microhabitats?

Methods

Study sites

The Qinghai-Tibet Plateau (QTP) in western China is characterized by alpine landscapes, low precipitation, and high solar radiation (> 6,500 MJ/m^2 annually, the highest in China; Zhou et al. 2010). These conditions make the QTP a priority region for solar energy development, with the potential to contribute 45.6% of China's total solar capacity (Zhuang et al. 2021). However, the QTP supports a unique yet fragile alpine ecosystem (Nagy 2012; Cunningham and Beazley 2018), raising concerns about habitat degradation from large-scale PV expansion.

Our study site, the Longyangxia PV power plants (36.11741393°N, 100.55255243°E, WGS84; elevation: 2915m), located at Gonghe town, Qinghai Province. Since its first installation in 2015, the power plants have expanded to 345 km^2, ranking among the largest PV installations nationwide (National Energy Administration 2022). The plants have applied sheep grazing instead of conventional herbicides to control vegetation growth between panels, minimizing chemical inputs. The PV power plants we studied span 2 native microhabitats: (i) *Caragana*-dominated shrubland (dominant species: *Caragana & Artemisia Spp.*); (ii) *Stipa-Achnatherum* steppe (dominant species: *Stipa* & *Achnatherum Spp.*). To assess PV

impacts on bird diversity, we established 8 sample plots (4 per microhabitat). Within each microhabitat, we set 2 plots inside PV power plants and 2 in adjacent natural habitats. Each plot covered 7–15 km² (side length: 1–5 km), spaced at least 1 km apart to reduce potential interference among bird communities (Fig. 1).

Bird surveys

We used line transects (Bibby et al. 2000) to survey bird species richness and abundance. 2 sets of paired plots (1 PV plot and 1 natural plot) across the 2 microhabitats were sampled in 2022, and another 2 sets were sampled in 2023. All surveys were conducted in late June to early July, aligning with the delayed breeding onset of high-altitude birds due to resource and climatic constraints (Li 2013; Liu 2014; Boyle et al. 2016; Xiao et al. 2017; Coe et al. 2021), ensuring high detectability. Within each plot, we established 6 1-km transects, perpendicular to the arrangements of solar panels if within the PV plots, with transect widths extending across two sets of solar panels on each side (Fig. 1A). In addition, we recorded raptors in a larger observation radius of 250 m on each side to provide a more comprehensive assessment of the community. Transects were spaced 300–500 m apart between the larger radius boarders to avoid potential counting repetition. All surveys were conducted twice (≥ 7-day intervals) during peak bird activity (06:00–09:00 and 16:00–19:00) under suitable weather conditions (avoiding strong wind or rain) at a slow walking pace. All birds seen or heard within the observation radius were recorded by 2 experienced observers together. To minimize potential bias caused by incidental observations, flyovers without confirmed take-off points were excluded.

Functional traits

We selected 5 functional traits to quantify functional diversity: body mass, foraging stratum, diet, hand-wing index (HWI), and migration. Body mass reflects resource demand, extinction risk, and niche occupancy (Gaston and Blackburn 1995) and is broadly considered informative of ecological roles (Brown 1995). Foraging stratum (ground, understory, mid-high, air) and diet (invertebrate, vertebrate, fruit, plant organism) describe resource use (Schipper et al. 2016). HWI and migration indicate species mobility and dispersal capacity. All trait data were extracted from AVONET (Tobias et al. 2022) and the Avian Diet database (Hurlbert et al. 2021).

Data analysis

An individual-based rarefaction curve and a sample coverage curve were generated to assess the sampling completeness of our observation data. Each survey replicate at the transect level was retained, and abundance data were aggregated by plot to construct per-plot species matrices. Analyses were performed using the R package iNEXT (Chao et al. 2014) with 999 bootstrap replications to estimate 95% confidence intervals. We used q = 1 (Shannon diversity) and compared expected species richness across treatments at standardized sample coverage.

To account for imperfect detection in bird counts, we applied a hierarchical multi-species N-mixture model (Royle 2004) to adjust our raw observation data. Species recorded in only a single replicate visit across the dataset were excluded to ensure model convergence, resulting in the exclusion of 5 species. Given the substantial overdispersion observed present in the raw counts (variance-to-mean ratio = 6.42 at the observation level and 5.69 at the site level), we compared model fits between Negative Binomial (NB) formulation with a Zero-Inflated Negative Binomial (ZINB) formulation. The zero-inflated negative binomial (ZINB) model exhibited severe convergence issues (maximum $\hat{R}$ = 2.04), indicating weak identifiability of the zero-inflation component under the observed data structure, likely due to the sparsity and strong count heterogeneity of the alpine bird community data. Consequently, we adopted the more parsimonious Negative Binomial distribution, implemented via a Poisson–Gamma mixture, to model latent species abundance at the transect level. This approach preserved model parsimony while adequately addressing overdispersion in the data.

Bird abundance at the transect level was modeled as a function of treatment (natural/PV), microhabitats (Caragana/Stipa), their interaction, and survey year. Observed counts from replicate visits were modeled as binomial outcomes conditional on latent transect-level abundances (*N*) and detection probabilities (*p*). Detection probability was modeled simultaneously as a function of survey time (morning/afternoon), with transect included as a random effect. Species-level parameters were modeled as random effects drawn from common community-level distributions, thus parameter estimates for individual species were informed by the overall community, improving estimates for species with limited observations. We assigned weakly informative priors to all model parameters: regression coefficients were assigned normal priors (Normal (0, σ^2 = 100)), variance parameters were assigned weakly informative half-Student-t priors (df = 3) truncated at zero. The dispersion parameter of the negative binomial distribution was assigned a uniform prior between 0.1 and 20. Posterior distributions of latent abundance calculated by the N-mixture model were used for further community analyses.

We then employed Monte Carlo integration by repeatedly drawing samples from the posterior distributions. For each posterior draw, we calculated *α* diversity (Shannon index) and functional diversity (Functional Dispersion, FDis). Community functional structure was quantified using Community Weighted Means (CWM) of bird functional traits. Functional distances among species were calculated using Gower distance to accommodate mixed trait types. To test the effects of PV power plants on bird communities across different microhabitats, we fitted a linear model to estimate the effects of PV and its interaction with microhabitat types for each Monte Carlo iteration on posterior samples. This constitutes a two-stage approach propagating posterior uncertainty from the N-mixture model into community-level inference. Effects were summarized as posterior medians with 95% credible intervals.

β diversity was quantified using Bray–Curtis dissimilarity based on posterior estimates of species abundance. We descriptively interpreted differences in community composition between treatments within each microhabitat using permutational multivariate analysis of variance (PERMANOVA) via the “adonis2()” function in R (Oksanen 2015). Rather than relying on single *p*-values, we quantified uncertainty by applying PERMANOVA across multiple posterior draws of the community matrix.

Community composition was visualized using non-metric multidimensional scaling (NMDS) based on Bray–Curtis dissimilarity of posterior mean abundance, implemented with the “metaMDS()” function (Oksanen 2015). NMDS was used as a two-dimensional ordination tool to summarize patterns in community composition among treatments.

All models were implemented in R 4.2.1 using the “rjags” (Plummer et al. 2014) and “coda” packages (Plummer et al. 2006). We assessed model convergence using the Gelman-Rubin statistic ($\hat{R}$) and visual inspection of Markov Chain Monte Carlo (MCMC) chains. The adequacy of model fit was evaluated via posterior predictive checks (PPC) by comparing observed and simulated data from the posterior predictive distribution. We further examined model adequacy by evaluating zero frequencies and variance structure in the observed and simulated data, and by conducting residual diagnostics using the “DHARMa” package (Hartig 2022).

Results

Species composition

A total of 2,760 individuals representing 23 species were recorded during the survey. The rarefaction accumulation curve flattened with the accumulation of sampling effort, while sample coverage was between 0.9 and 1.00 for all groups, suggesting an adequate sample size for both microhabitats (Fig. 2a; Fig. 2b). After filtration for at least 1 occurrence in transect replicates, 2,753 individuals representing 18 species were included in the model (Table 1). The estimated negative binomial dispersion parameter was consistently low (median = 0.8, 95% credible interval (CrI): 0.65–0.98), indicating substantial heterogeneity in latent abundance and consistent with overdispersion in the count process. Gelman-Rubin diagnostics indicated generally adequate mixing for all key fixed-effect, including treatment, habitat, their interaction, and year ($\hat{R} \leq 1.05$). Across all monitored parameters, 20% exceeded the conventional threshold of $\hat{R} = 1.1$, with a maximum value of 1.13 (Online Resource 1), primarily associated with latent abundance and variance components. Posterior predictive checks also showed proper agreement between observed and simulated data (Online Resource 2). Residual diagnostics using DHARMa indicated moderate overdispersion (dispersion = 1.73) and slight zero inflation (ratio = 1.05), consistent with inspection of zero frequencies (zero proportion = 79.7%) and variance structure (Variance-to-mean ratio = 6.42) in observed data.

Table 1
Bird species included in the analysis and their total observed abundance. *"*Caragana*" and "PV_C" represent *Caragana*-dominated shrubland's natural plots and PV plots, "*Stipa*" and "PV_S" represent *Stipa-Achnatherum* steppe's natural plots and PV plots.

Common name	**Scientific name**	***Caragana***	**PV_C**	***Stipa***	**PV_S**	**Total**
Daurian partridge	*Perdix dauurica*	3	5	5	10	23
Common hoopoe	*Upupa epops*	3	15	3	8	29
Eurasian Kestrel	*Falco tinnunculus*	8	4	3	0	15
Gray-backed shrike	*Lanius tephronotus*	4	3	0	0	7
Horned lark	*Eremophila alpestris*	103	159	273	262	797
Eurasian tree sparrow	*Passer montanus*	40	67	34	35	176
Mongolian lark	*Melanocorypha mongolica*	16	0	73	0	89
Lesser whitethroat	*Curruca curruca*	6	0	0	0	6
Isabelline wheatear	*Oenanthe isabellina*	126	9	99	20	254
Oriental magpie	*Pica serica*	11	2	0	8	21
Oriental skylark	*Alauda gulgula*	12	40	150	16	218
Asian short-toed lark	*Alaudala cheleensis*	175	36	137	22	370
Hill Pigeon	*Columba rupestris*	8	11	13	7	39
Black Redstart	*Phoenicurus ochruros*	8	205	14	326	553
Little Owl	*Athene noctua*	1	0	1	0	2
Twite	*Linaria flavirostris*	1	11	4	36	52
Brown Accentor	*Prunella fulvescens*	0	21	0	72	93
Rock Sparrow	*Petronia petronia*	0	0	3	6	9
Total species richness	-	16	14	14	13	18
Total abundance	-	525	588	812	828	2753

PV effect was not statistically significant on estimated species richness in both *Caragana*-dominated shrubland (median PV effect = -0.58, 95% CrI: -1.92 to 0.67) and *Stipa-Achnatherum* steppe (median PV effect = -0.83, 95% CrI: -2.25 to 0.58). Estimated bird abundance was relatively stable between PV plots and natural plots in the 2 microhabitats, with a median PV effect of -10.73% (95% CrI: -33.93% to 13.89%) in *Caragana*-dominated shrubland and − 13.88% (95% CrI: -33.43% to 11.49%) in *Stipa-Achnatherum* steppe. There were also no statistically significant differences between PV power plants and natural habitat for Shannon diversity in either microhabitat (*Caragana*-dominated shrubland: median PV effect =

0.15, 95% CrI: -0.07 to 0.44; *Stipa-Achnatherum* steppe: median PV effect = -0.04, 95% CrI: -0.18 to 0.13; Fig. 2c).

PERMANOVA results revealed remarkably consistent effects of PV on *β* diversity across posterior draws in both microhabitats. In *Caragana*-dominated shrubland, PV effect explained a median of 36.2% (min-max R^2: 28.1%–45.6%) of the community dissimilarity. In *Stipa-Achnatherum* steppe, PV effect was more pronounced, which explained a median of 46.5% (min-max R^2: 36.8%-59.6%) of the variation. Across posterior draws, PERMANOVA tests indicated robust evidence for PV-associated community differences (median $p \approx 0.001$; 100% p-value < 0.05). The NMDS ordinations illustrated clear separation (Fig. 3), with a stress value of 0.136, indicating a proper fit of the data. Yet this ordination was based on posterior mean abundance and should be interpreted as a central tendency of community structure rather than a full representation of posterior uncertainty.

Functional diversity

Bird communities in PV power plants exhibited higher functional diversity than those in natural habitats, as the functional dispersion (FDis) was significantly higher in both *Caragana*-dominated shrubland and *Stipa-Achnatherum* steppe (Table 2, Fig. 4).

Functional structure

The PV power plants affected the functional structure of bird communities in specific aspects (Table 2).

1. Body size

Bird body sizes were significantly smaller in PV power plants than in natural habitat in both *Caragana*-dominated shrubland and *Stipa-Achnatherum* steppe (Table 2, Fig. 5).

1. Diet composition

In both microhabitats, fruit and plant-organism feeders were significantly more abundant in PV power plants, while seed feeders were less abundant. The trend was more pronounced in *Stipa-Achnatherum* steppe (Table 2, Fig. 5). In *Caragana*-dominated shrubland, PV power plants supported lower proportion of vertebrate feeders than natural plots, whereas no statistically significant effects were observed on invertebrate feeders (Table 2, Fig. 5a); In *Stipa-Achnatherum* steppe, no statistically significant effects were observed on vertebrate or invertebrate feeders between PV plots and natural plots (Table 2, Fig. 5b).

1. Foraging Stratum

In both microhabitats, ground-foragers were significantly more abundant in natural plots, while understory-foragers were more abundant in PV plots, especially in *Stipa-Achnatherum* steppe (Table 2,

Fig. 5b). In *Stipa-Achnatherum* steppe, the proportion of mid-high and aerial foragers was higher in PV power plants (Table 2, Fig. 5b), which did not demonstrate significant changes in *Caragana*-dominated shrubland (Table 2, Fig. 5a).

1. Mobility

In both microhabitats, birds have significantly lower hand-wing index in PV power plants, yet no significant difference of migration level found between natural and PV plots (Table 2, Fig. 5).

Table 2 Summary of Bayesian hierarchical models evaluating the effects of PV power plants on bird functional diversity and community-weighted mean (CWM) traits across the 2 microhabitats.

* “Mass” represents estimated community weighted mean of log-transformed bird body mass (g), “HWI” represents estimated community weighted mean of log-transformed bird hand-wing index; “Migration” represents estimated community weighted mean of bird migration level; “Diet.Invertebrate”, “Diet.Vertebrate”, “Diet.Seed”, “Diet.Fruit”, “Diet.PlantO” represent estimated community weighted mean of invertebrate, vertebrate, seed, fruit and plant organism dietary component (%), respectively; “ForStrat.ground”, “ForStrat.understory”, “ForStrat.midhigh”, “ForStrat.aerial” represent estimated community weighted mean of bird forage primarily on ground, in understory, at midhigh-layer and aerially (%), respectively. “Microhabitat x PV” represents the differential impact of PV between the 2 microhabitats;

“*” indicates a significant effect, where the 95% credible interval (CrI) does not overlap zero; estimates with absolute value < 0.01 are presented in scientific notation (e.g., 3.12 x 10 − 3) to preserve precision.

Response	Microhabitat	PV effect (median)	Lower 95% CrI	Upper 95% CrI
FDis	**Caragana***	**0.79**	**0.51**	**1.04**
	Stipa-Achnatherum*	**1.03**	**0.86**	**1.22**
	Microhabitat x PV	0.24	-0.05	0.6
Diet.Fruit	**Caragana***	**0.09**	**0.06**	**0.12**
	Stipa-Achnatherum*	**0.12**	**0.08**	**0.15**
	Microhabitat x PV*	**0.02**	**0.01**	**0.04**
Diet.Invertebrate	*Caragana*	-0.01	-0.04	0.01
	Stipa-Achnatherum	3.12×10^{-3}	-0.02	0.02
	Microhabitat x PV	0.01	-0.01	0.03
Diet.PlantO	**Caragana***	**0.01**	**8.95×10^{-4}**	**0.01**
	Stipa-Achnatherum*	**0.01**	**4.04×10^{-3}**	**0.02**
	Microhabitat x PV	0.01	4.04×10^{-3}	0.02
Diet.Seed	**Caragana***	**-0.05**	**-0.10**	**-0.01**
	Stipa-Achnatherum*	**-0.12**	**-0.16**	**-0.06**
	Microhabitat x PV*	**-0.07**	**-0.10**	**-0.04**
Diet.Vertebrate	**Caragana***	**-0.03**	**-0.06**	**-0.01**
	Stipa-Achnatherum	-0.01	-0.02	0.01
	Microhabitat x PV*	**0.02**	**4.95×10^{-3}**	**0.06**
ForStrat.aerial	*Caragana*	-8.17×10^{-3}	-4.18×10^{-3}	6.87×10^{-4}
	Stipa-Achnatherum*	**8.04×10^{-4}**	**1.44×10^{-4}**	**2.88×10^{-3}**
	Microhabitat x PV*	**1.69×10^{-3}**	**2.33×10^{-4}**	**0.01**
ForStrat.ground	**Caragana***	**-0.14**	**-0.18**	**-0.09**
	Stipa-Achnatherum*	**-0.18**	**-0.21**	**-0.12**
	Microhabitat x PV*	**-0.04**	**-0.07**	**-0.01**
ForStrat.midhigh	*Caragana*	4.90×10^{-3}	-0.01	0.01

Response	Microhabitat	PV effect (median)	Lower 95% CrI	Upper 95% CrI
	Stipa-Achnatherum*	**0.01**	**2.59×10^{-3}**	**0.02**
	Microhabitat x PV	4.76×10^{-3}	-0.01	0.02
ForStrat.understory	**Caragana***	**0.13**	**0.09**	**0.17**
	Stipa-Achnatherum*	**0.16**	**0.11**	**0.20**
	Microhabitat x PV*	**0.03**	**0.01**	**0.06**
HWI	**Caragana***	**-0.06**	**-0.11**	**-6.41×10^{-4}**
	Stipa-Achnatherum*	**-0.13**	**-0.19**	**-0.08**
	Microhabitat x PV*	**-0.07**	**-0.11**	**-0.04**
Mass	**Caragana***	**-0.18**	**-0.28**	**-0.06**
	Stipa-Achnatherum*	**-0.28**	**-0.39**	**-0.16**
	Microhabitat x PV	-0.10	-0.19	0.01
Migration	*Caragana*	-0.10	-0.20	0.04
	Stipa-Achnatherum	-0.09	-0.19	0.04
	Microhabitat x PV	0.02	-0.11	0.12

Discussion

The PV power plants we studied supported similar levels of bird species richness and abundance to adjacent natural habitats. Although *α* diversity did not differ significantly, *β* diversity analysis revealed distinct community composition between PV power plants and natural habitats. Functional diversity was consistently higher in PV plots, accompanied by shifts in functional trait distributions across both *Caragana*-dominated shrubland and *Stipa-Achnatherum* steppe. Together, these results indicate alteration both taxonomically and functionally of bird communities in PV environments.

Bird species richness and abundance demonstrated similar levels between PV power plants and natural habitats, which contrasted with previous findings. Studies in the USA and South Africa (DeVault et al. 2014; Visser et al. 2019) reported lower richness but higher abundance within PV power plants, whereas research in European farmland (Jarčuška et al. 2024) reported higher bird species richness. Such inconsistency likely reflected differences in habitat context (Harrison et al. 2017). Shannon diversity remained similar, but we noticed the rarity of some species in specific treatment (e.g. *Melanocorypha mongolica* in PV plots, *Prunella fulvescens* in natural plots). Consistent with this, PERMANOVA analysis revealed clear separation of species community composition between PV power plants and natural

habitats. These results indicate species turnover through the filtration of native species and colonization of new species (Harrison et al. 2017; Visser et al. 2019), leading to altered community structure (DeVault et al. 2014; Jarčuška et al. 2024).

Functional diversity patterns reinforced this community alteration. Higher functional dispersion (FDis) in PV plots across both microhabitats suggested greater functional niche differentiation (Mouillot et al. 2013). This could likely be facilitated by artificial structures in PV power plants that created novel space and resources (Barnagaud et al. 2017). In contrast, natural habitats with harsher conditions likely promoted niche overlaps and clustered trait distribution (Petchey and Gaston 2002; Mason et al. 2005; Song et al. 2014; Ding et al. 2021).

To explore the process contributing to these differences in functional diversity, we conducted trait-based analysis which revealed potential selective filtering and attraction on traits. Both microhabitats exhibited similar patterns in functional alteration: in PV power plants, the proportion of frugivorous birds and plant-organism feeders largely replaced that of granivorous birds. Meanwhile, foraging activity shifted from the ground to the understory layers, compared to adjacent natural habitats. These changes likely indicate that PV power plants have modified vegetation structure due to microclimate changes (Hernandez et al. 2014), and also altered resource utilization patterns from artificial perch availability (Pidgeon et al. 2014; Montag et al. 2016). Species unable to adapt to these changes were likely replaced by those capable of utilizing them. Additionally, birds in PV power plants generally had lower hand-wing index (HWI), which represented weaker dispersal ability, while migratory tendencies remained unchanged. This suggests PV structures may provide shelter for weaker flyers from predators or harsh environment (DeVault et al. 2014; Sheard et al. 2020). However, in our study system, PV power plants had not yet become an advantageous habitat for migratory species.

Differences in functional composition also existed between the 2 microhabitats. In natural-*Caragana*, bird community consisted of higher proportion of vertebrate-consuming species, likely due to the open habitat supporting predator species (Montag et al. 2016). In contrast, in *natural-Stipa*, PV effects were generally more pronounced on the shift from granivores to plant and fruit feeders, and from ground foragers to understory and mid-high foragers in the community, indicating a more significant filtration on open grassland dwelling species like larks. Notably, Jarčuška et al. (2024) reported contrasting functional changes, indicating that the utilization of space and resource in PV power plants may converge within a landscape, but diverge across landscapes due to variation in ecological niches (Schoener 1974; Turner 1989). It further calls for investigations on PV effects on landscape scales.

Notably, although the N-mixture model corrected for imperfect detection and accounted for overdispersion using a Negative Binomial formulation, the model residuals still indicated a moderate level of overdispersion and slight zero inflation. This is likely due to sparsity and aggregation of the bird communities we studied, which could lead to inflated estimates of absolute abundance. Yet the hierarchical structure of our model ensures that uncertainty in latent abundance is fully propagated into the effect size estimates, leading to conservative credible intervals that mitigate over-interpretation of

the data. Additionally, due to limitations of access permission and study design, we did not acquire pre-construction community information for PV power plants in the region, limiting our analysis to a snapshot comparison. Also noted that, the PV plots sampled in 2022 have been operating for 5 years in *Caragana*-dominated shrubland and 6 years in *Stipa-Achnatherum* steppe, respectively, while PV plots sampled in 2023 have been operating for 3 and 9 years, respectively, and our sample design was difficult to separate the effect of operation time from plot. Yet, PV power plants may have profound impacts in the long term (Hernandez et al. 2014; Kraft et al. 2015), which may bias our estimates on PV effect. Future research incorporating temporal scales to investigate on the trajectory of PV-induced community assembly should be essential.

In general, by quantifying multiple functional traits related to survival, we provided a more comprehensive assessment of resource utilization in PV power plants. Results support previous hypotheses that PV impacts are species-specific and depend on spatial and resource requirements (Harrison et al. 2017; Jarčuška et al. 2024). It is important to note that, due to the limited number of PV power plants in different microhabitats, the number of plots surveyed were limited, a larger sample size could lead to higher accuracy. In future research, a spatiotemporal framework, that considers year of operation and different landscapes, to explore the trajectory of PV-induced community assembly should be essential for sustainable PV planning.

Declarations

Ethics Approval

This study involved purely observational research on free-living wild birds, and was conducted with no physical interaction, capture, or disturbance to the animals or their habitats. Fieldwork was supported by National Forestry and Grassland Administration, with permission granted by Gonghe County Bureau of Agriculture and Technology.

Competing interests

All authors declare no conflict of interest.

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Author Contribution

All authors contributed to the study conception and design. Material preparation and data collection were performed by L.G., P.L.,L.P. and Y.L., data analysis was performed by L.G. and P.L.. The first draft of the manuscript was written by L.G. and all authors commented on previous versions of the manuscript. W.D. revised the draft critically for important intellectual content. All authors approved the version to be published and agree to be accountable for all aspects of the work in respect of accuracy or integrity.

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Data Availability

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

References

1. Barnagaud JY, Gaüzère P, Zuckerberg B, Princé K, Svenning JC (2017) Temporal changes in bird functional diversity across the United States. Oecologia 185:737–748. https://doi.org/10.1007/s00442-017-3967-4
2. Bibby CJ, Burgess ND, Hill DA, Mustoe S (2000) Bird census techniques, 2nd edn. Academic, London
3. Bosc C, Roets F, Hui C, Pauw A (2018) Interactions among predators and plant specificity protect herbivores from top predators. Ecology 99:1602–1609. https://doi.org/10.1002/ecy.2377
4. Boyle WA, Sandercock BK, Martin K (2016) Patterns and drivers of intraspecific variation in avian life history along elevational gradients: a meta-analysis. Biol Rev 91:469–482. https://doi.org/10.1111/brv.12180
5. Brown JH (1995) Macroecology. The University of Chicago Press, Chicago
6. Cameron DR, Cohen BS, Morrison SA (2012) An approach to enhance the conservation-compatibility of solar energy development. PLoS ONE 7:e38437. https://doi.org/10.1371/journal.pone.0038437
7. Chao A, Gotelli NJ, Hsieh TC, Sander EL, Ma KH et al (2014) Rarefaction and extrapolation with Hill numbers: a framework for sampling and estimation in species diversity studies. Ecol Monogr 84:45–67. https://doi.org/10.1890/13-0133.1
8. Coe SJ, Purcell KL, Rotenberry JT (2021) Modeling phenological reaction norms over an elevational gradient reveals contrasting strategies of dusky flycatchers and mountain chickadees in response to early-season temperatures. Ornithology 138:ukab056. https://doi.org/10.1093/ornithology/ukab056

9. Cunningham C, Beazley K (2018) Changes in human population density and protected areas in terrestrial global biodiversity hotspots, 1995–2015. Land 7:136. https://doi.org/10.3390/land7040136
10. DeVault TL, Seamans TW, Schmidt JA, Belant JL, Blackwell BF et al (2014) Bird use of solar photovoltaic installations at US airports: implications for aviation safety. Landsc Urban Plan 122:122–128. https://doi.org/10.1016/j.landurbplan.2013.11.017
11. Ding Z, Hu H, Cadotte MW et al (2021) Elevational patterns of bird functional and phylogenetic structure in the central Himalaya. Ecography 44:1403–1417. https://doi.org/10.1111/ecog.05660
12. Dwyer JF, Landon MA, Mojica EK (2018) Impact of renewable energy sources on birds of prey. Birds of prey: biology and conservation in the XXI century. Springer, Cham, pp 303–321
13. Estes JA, Terborgh J, Brashares JS, Power ME, Berger J et al (2011) Trophic downgrading of planet Earth. Science 333:301–306. https://doi.org/10.1126/science.1205106
14. Gasparatos A, Doll CNH, Esteban M, Ahmed A, Olang TA (2017) Renewable energy and biodiversity: implications for transitioning to a green economy. Renew Sustain Energy Rev 70:161–184. https://doi.org/10.1016/j.rser.2016.08.030
15. Gaston KJ, Blackburn TM (1995) Birds, body-size and the threat of extinction. Philos Trans R Soc B 347:205–212. https://doi.org/10.1098/rstb.1995.0022
16. Greif S, Siemers BM (2010) Innate recognition of water bodies in echolocating bats. Nat Commun 1:107. https://doi.org/10.1038/ncomms1110
17. Greif S, Zsebok S, Schmieder D, Siemers BM (2017) Acoustic mirrors as sensory traps for bats. Science 357:1045–1047. https://doi.org/10.1126/science.aam7817
18. Grippo M, Hayse JW, O'Connor BL (2015) Solar energy development and aquatic ecosystems in the southwestern United States: potential impacts, mitigation, and research needs. Environ Manage 55:244–256. https://doi.org/10.1007/s00267-014-0384-x
19. Google (2023) Shanghai, China [Satellite image]. Google Earth Pro (7.3.6.10201). Retrieved April 23, 2025, from https://www.google.com/earth/
20. Harrison C, Lloyd H, Field C (2017) Evidence review of the impact of solar farms on birds, bats and general ecology. Natural England, UK
21. Hartig F (2022) DHARMa: residual diagnostics for hierarchical (multi-level/mixed) regression models. R package version 0.4.6
22. Hernandez RR, Easter SB, Murphy-Mariscal ML, Maestre FT, Tavassoli M et al (2014) Environmental impacts of utility-scale solar energy. Renew Sustain Energy Rev 29:766–779. https://doi.org/10.1016/j.rser.2013.08.041
23. Hernandez RR, Hoffacker MK, Murphy-Mariscal ML, Wu GC, Allen MF (2015) Solar energy development impacts on land cover change and protected areas. Proc Natl Acad Sci USA 112:13579–13584. https://doi.org/10.1073/pnas.1517656112

24. Horváth G, Kriska G, Malik P, Robertson B (2009) Polarized light pollution: a new kind of ecological photopollution. Front Ecol Environ 7:317–325. https://doi.org/10.1890/080129
25. Horváth G, Blahó M, Egri A et al (2010) Reducing the maladaptive attractiveness of solar panels to polarotactic insects. Conserv Biol 24:1644–1653. https://doi.org/10.1111/j.1523-1739.2010.01518.x
26. Hurlbert AH, Olsen AM, Sawyer MM, Winner PM (2021) The avian diet database as a source of quantitative information on bird diets. Sci Data 8:260. https://doi.org/10.1038/s41597-021-01049-9
27. Jarčuška B, Gálffyová M, Schnürmacher R, Baláž M, Mišík M et al (2024) Solar parks can enhance bird diversity in agricultural landscape. J Environ Manage 351:119902. https://doi.org/10.1016/j.jenvman.2023.119902
28. Kagan RA, Viner TC, Trail PW, Espinoza EO (2014) Avian mortality at solar energy facilities in southern California: a preliminary analysis. National Fish and Wildlife Forensics Laboratory
29. Kraft NJB, Adler PB, Godoy O et al (2015) Community assembly, coexistence and the environmental filtering metaphor. Funct Ecol 29:592–599. https://doi.org/10.1111/1365-2435.12345
30. Li S (2013) Cooperative breeding system of ground tits in the northeast Tibetan Plateau [□□□

28:1291–1301. https://doi.org/10.1111/cobi.12291

41. Plummer M, Best N, Cowles K, Vines K (2006) CODA: convergence diagnosis and output analysis for MCMC. R News 6:7–11
42. Plummer M, Stukalov A, Denwood M (2014) rjags: Bayesian graphical models using MCMC. R package version 3–13
43. Rehbein JA, Watson JEM, Lane JL, Sonter LJ, Venter O et al (2020) Renewable energy development threatens many globally important biodiversity areas. Glob Change Biol 26:3040–3051. https://doi.org/10.1111/gcb.15067
44. Royle JA (2004) N-mixture models for estimating population size from spatially replicated counts. Biometrics 60:108–115. https://doi.org/10.1111/j.0006-341X.2004.00142.x
45. Schipper AM, Belmaker J, de Miranda MD, Navarro LM, Böhning-Gaese K et al (2016) Contrasting changes in the abundance and diversity of North American bird assemblages from 1971 to 2010. Glob Change Biol 22:3948–3959. https://doi.org/10.1111/gcb.13292
46. Schoener TW (1974) Resource partitioning in ecological communities. Science 185:27–39. https://doi.org/10.1126/science.185.4145.27
47. Sekercioglu ÇH, Daily GC, Ehrlich PR (2004) Ecosystem consequences of bird declines. Proc Natl Acad Sci USA 101:18042–18047. https://doi.org/10.1073/pnas.0408049101
48. Sheard C, Neate-Clegg MHC, Alioravainen N et al (2020) Ecological drivers of global gradients in avian dispersal inferred from wing morphology. Nat Commun 11:2463. https://doi.org/10.1038/s41467-020-16313-6
49. Si X, Baselga A, Leprieur F, Song X, Ding P (2016) Selective extinction drives taxonomic and functional α and β diversities in island bird assemblages. J Anim Ecol 85:409–418. https://doi.org/10.1111/1365-2656.12478
50. Smith RK, Pullin AS, Stewart GB, Sutherland WJ (2010) Effectiveness of predator removal for enhancing bird populations. Conserv Biol 24:820–829. https://doi.org/10.1111/j.1523-1739.2009.01421.x
51. Song Y, Wang P, Li G, Zhou D (2014) Relationships between functional diversity and ecosystem functioning: a review. Acta Ecol Sin 34:85–91. https://doi.org/10.1016/j.chnaes.2014.01.001
52. Taylor R, Conway J, Gabb O, Gillespie J (2019) Potential ecological impacts of ground-mounted photovoltaic solar panels: an introduction and literature review. BSG Ecology, Oxford
53. Tobias JA, Sheard C, Pigot AL, Devenish AJM, Yang JY et al (2022) AVONET: morphological, ecological and geographical data for all birds. Ecol Lett 25:581–597. https://doi.org/10.1111/ele.13898
54. Turner MG (1989) Landscape ecology: the effect of pattern on process. Annu Rev Ecol Syst 20:171–197. https://doi.org/10.1146/annurev.es.20.110189.001131
55. Visser E, Perold V, Ralston-Paton S, Cardenal AC, Ryan PG (2019) Assessing the impacts of a utility-scale photovoltaic solar energy facility on birds in the Northern Cape, South Africa. Renew Energy

133:1285–1294. https://doi.org/10.1016/j.renene.2018.08.106

56. Xiao Y, Zhao C, Liu W, Wu Y, Ran J (2017) Reproduction ecological traits and adaptation of Fulica atra in Zoige Plateau wetland [□□□□□□□□□□□□□□□□□□□□]. Sichuan J Zool 36:217–222. https://doi.org/10.11984/j.issn.1000-7083.20160248
57. Zhou X, Wang F, Fan J, Ochieng RM (2010) Performance of solar chimney power plant in Qinghai-Tibet Plateau. Renew Sustain Energy Rev 14:2249–2255. https://doi.org/10.1016/j.rser.2010.04.017
58. Zhuang MH, Lu X, Peng W, Wang YF, Wang JX et al (2021) Opportunities for household energy on the Qinghai-Tibet Plateau in line with United Nations' sustainable development goals. Renew Sustain Energy Rev 144:110982. https://doi.org/10.1016/j.rser.2021.110982

Figures

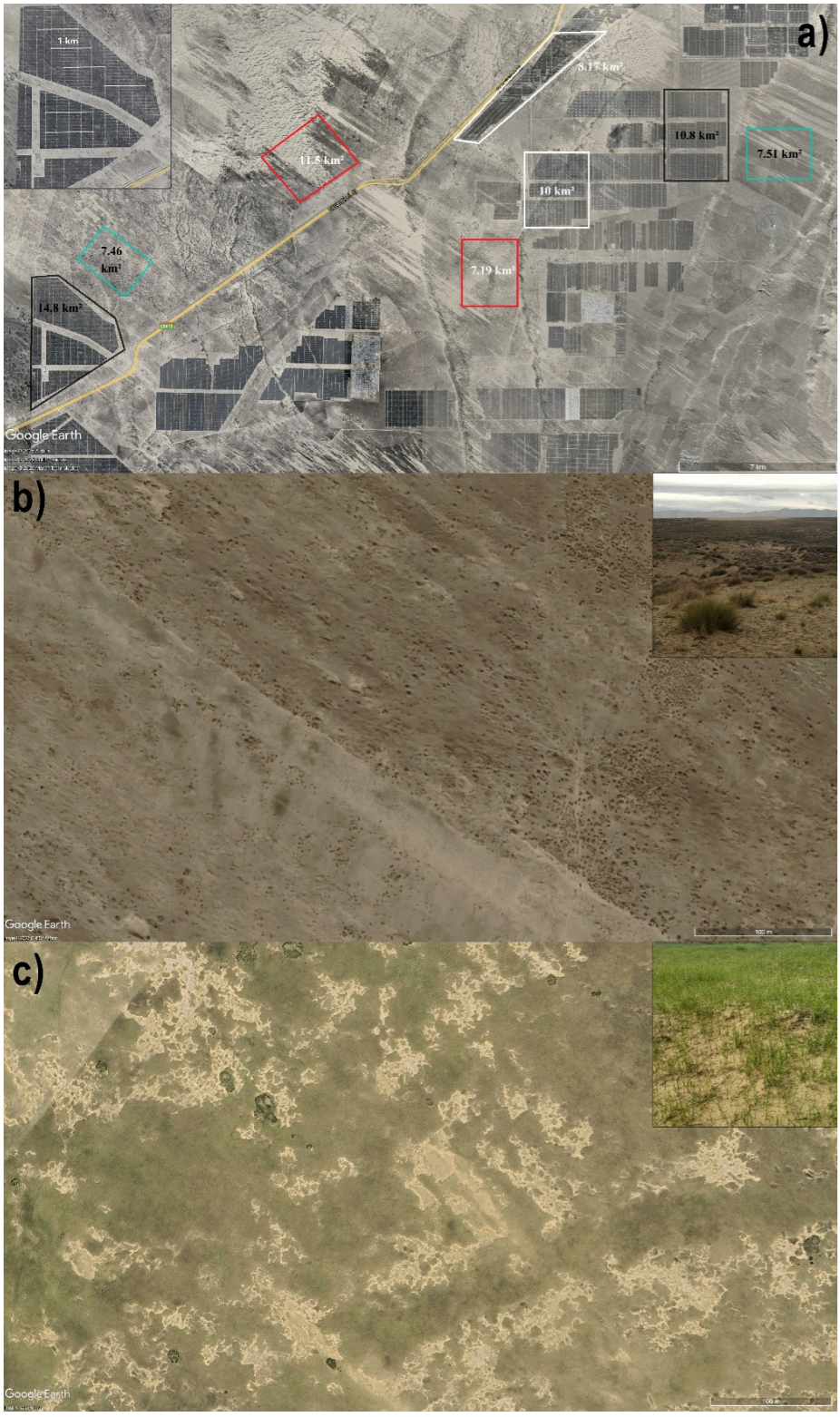

Figure 1

Sampling design in the study site. (a) PV plots (in *black*), natural plots (in *light blue*) in *Caragana*-dominated shrubland, and PV plots (in *white*), natural plots (in *red*) in *Stipa-Achnatherum* steppe, inserted picture shows an example of transect setting in a PV plot of *Caragana*-dominated shrubland; (b) *Caragana*-dominated shrubland, details as inserted; (c) *Stipa-Achnatherum* steppe, details as inserted. Satellite images obtained from Google Earth Pro (Google, 2023).

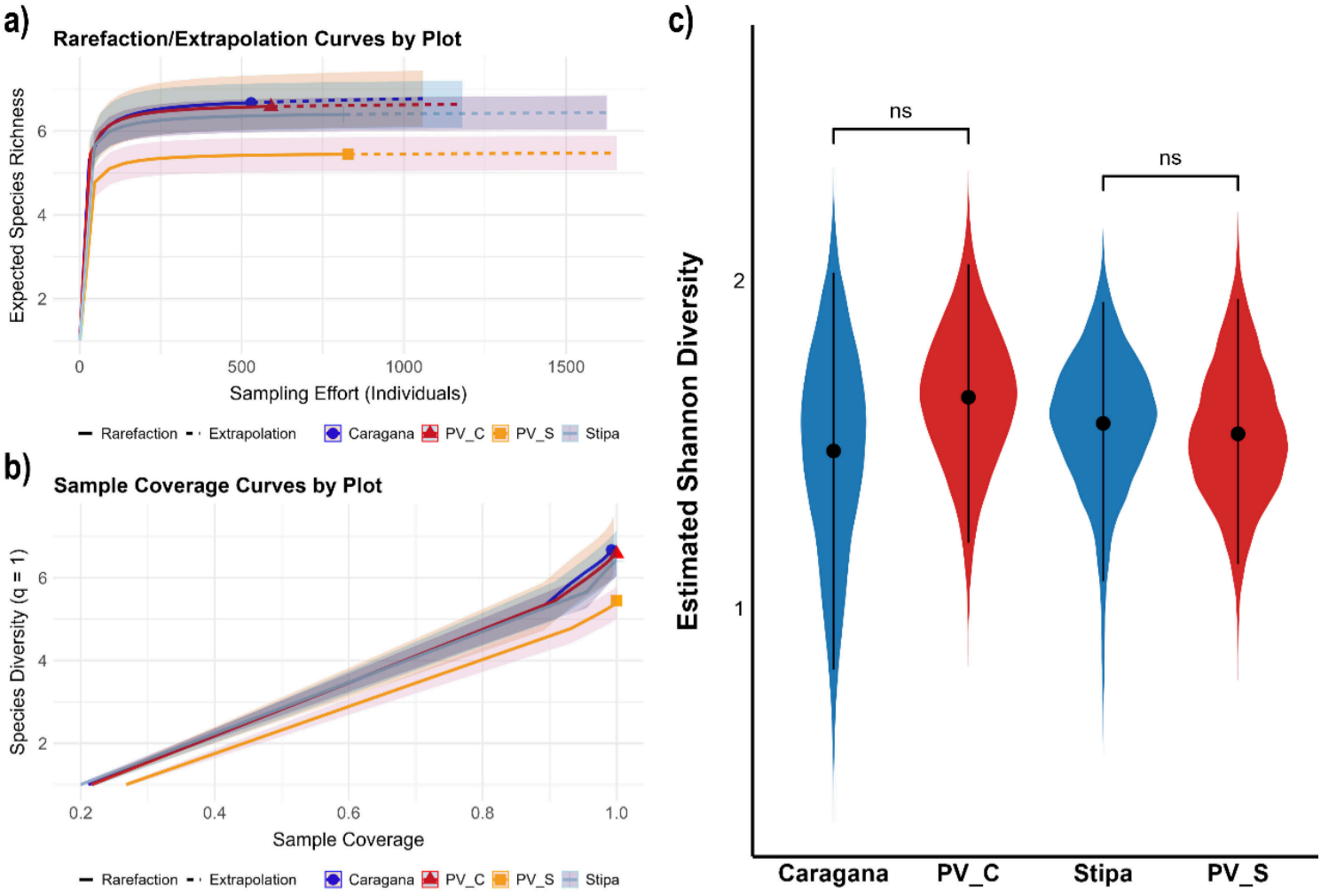

Figure 2

Sample completeness test and estimated effects of PV power plants on bird *α*diversity across the 2 microhabitats. (a) Sample-based rarefaction and extrapolation for species richness; (b) Sample coverage for Shannon diversity (q = 1); (c) Estimated Shannon diversity of PV power plants and adjacent natural habitats. Violin plots represent the posterior distributions of Shannon diversity estimated from the Bayesian N-mixture models. Within each violin, the central point indicates the posterior mean, and the whiskers represent the 95% Bayesian credible intervals (CrI).

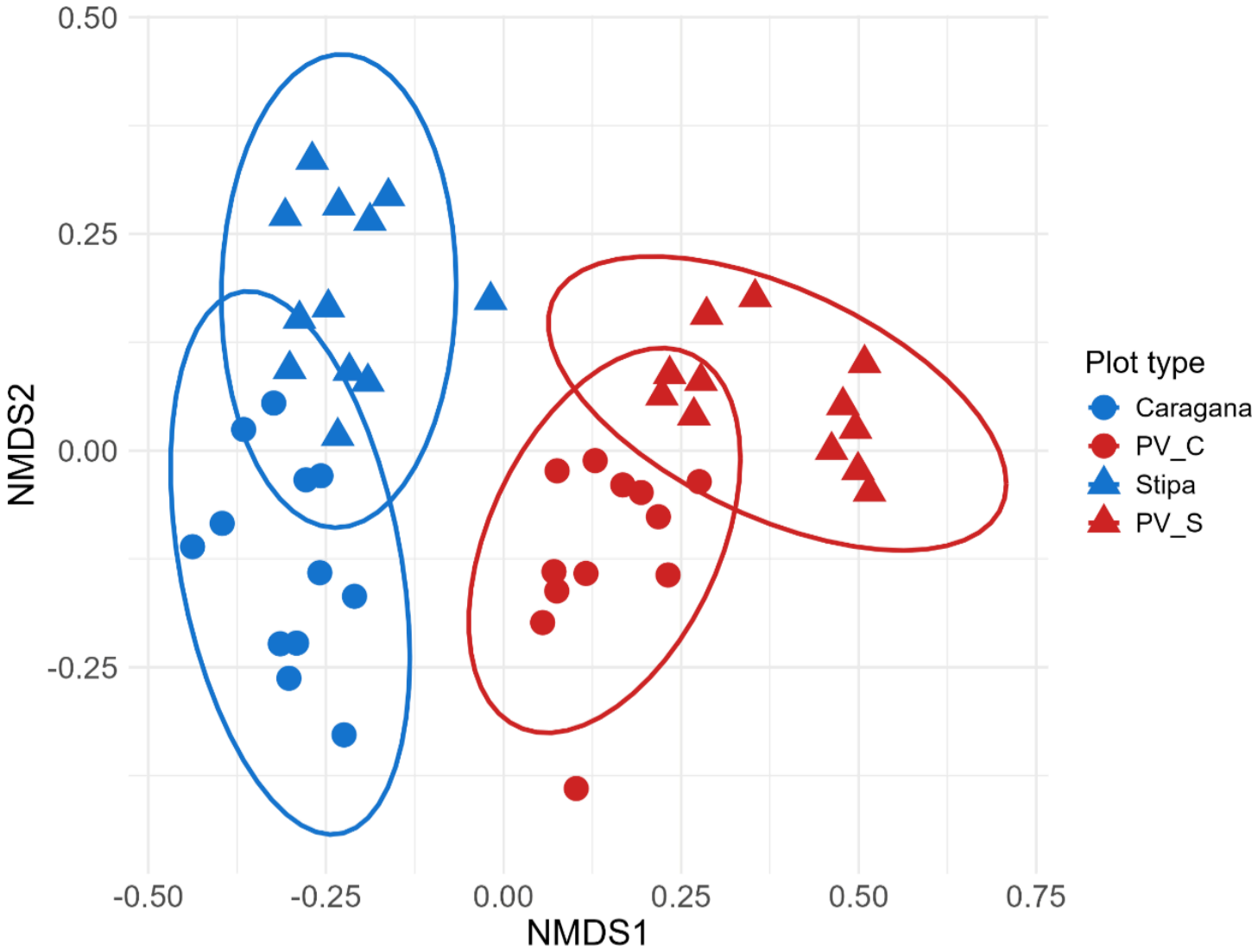

Figure 3

Bray-Curtis NMDS ordination showing bird taxonomic composition in PV power plants and adjacent natural habitats. Ordination was derived from the estimated species abundance (*N*) obtained from Bayesian N-mixture models. Points represent transect-level samples, with different shapes indicating microhabitats (circles for *Caragana*-dominated shrubland and triangles for *Stipa-Achnatherum*grassland). Ellipses encompass the 95% confidence interval for each group.

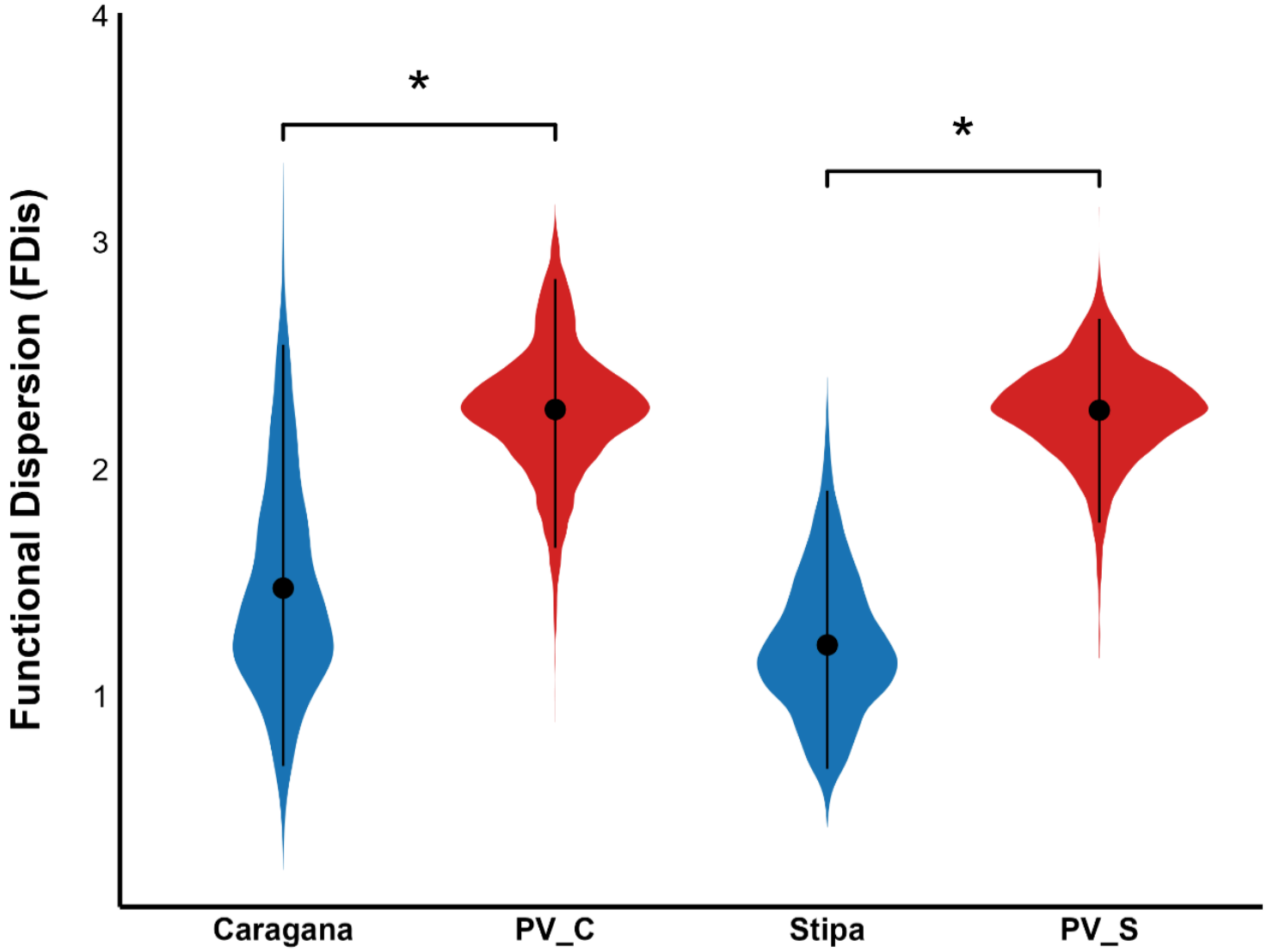

Figure 4

Estimated Functional Dispersion (FDis) of bird communities in PV power plants and adjacent natural habitats across the 2 microhabitats. Violin plots represent the posterior distributions of functional dispersion estimated from the Bayesian N-mixture models. Within each violin, the central point indicates the posterior mean, and the whiskers represent the 95% Bayesian credible intervals (CrI).

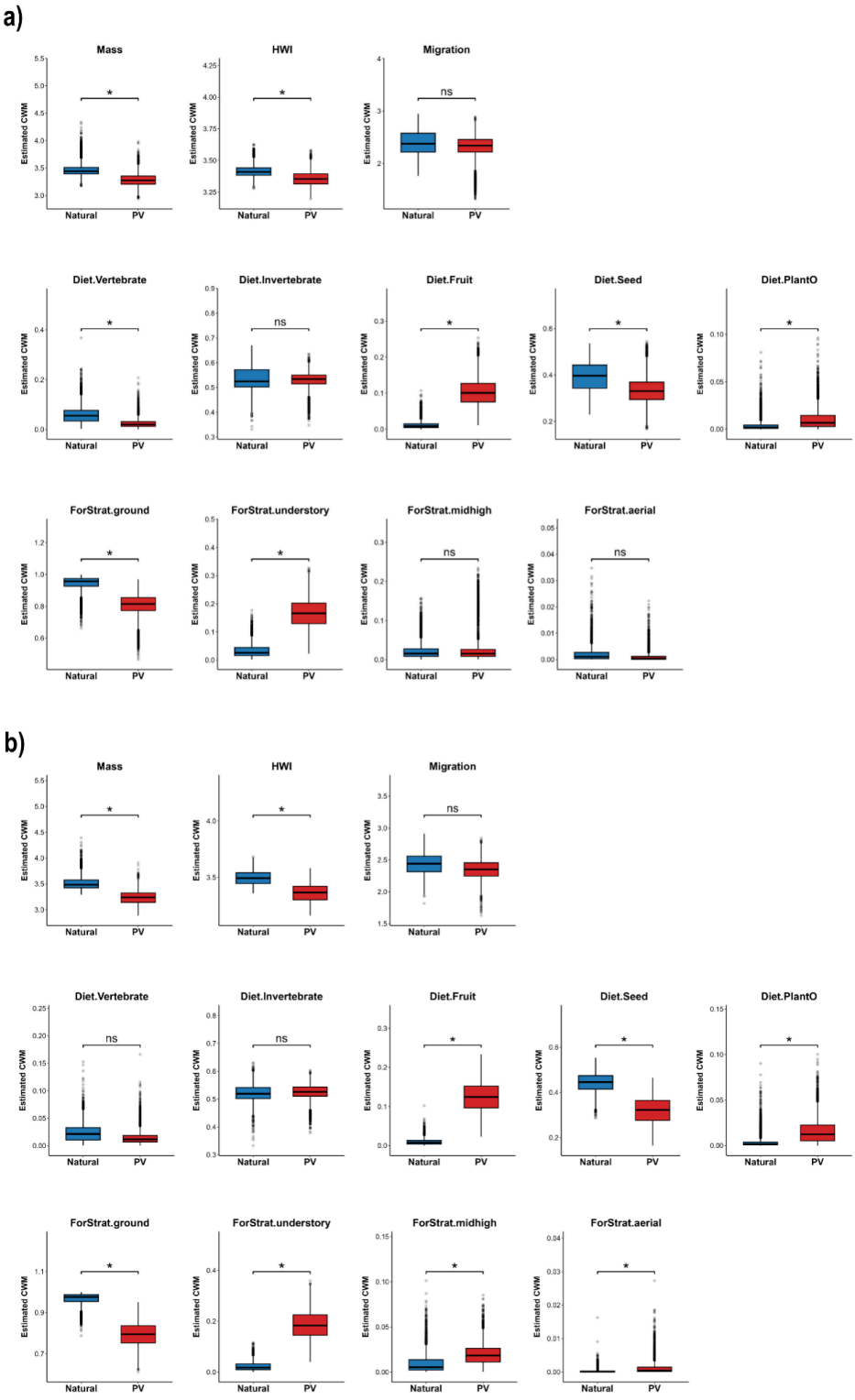

Figure 5

A comparison of bird functional traits between communities of PV power plants and adjacent natural habitats in: (a) *Caragana*-dominated shrubland; (b) *Stipa-Achnatherum*steppe.

Supplementary Files

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