

Characterizing ecological sieves in urban green spaces: PCA analysis of habitat gradients and avian species-specific occupancy regressions

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Abstract

Urban green spaces in arid cities are vital for avian conservation, yet how vegetation structure, park morphology, and human disturbance interact to shape communities remains poorly understood. We surveyed bird communities across 57 parks (1.36–122.98 ha) in Isfahan, Iran, identifying 42 species with site-level richness ranging from 3 to 38, and using Sentinel-2 metrics, principal component analysis distilled 16 environmental variables into five gradients—with PC1 (vegetation quality; 44.1% variance) representing the primary habitat quality axis, dominated by NDVI (loading: 0.963) and canopy density. Single-season occupancy models revealed that woodland and edge-associated species responded strongly to this complex canopy gradient, led by *Passer montanus* ($\beta = 3.037$, $p = 0.031$), *Oriolus oriolus* ($\beta = 2.150$, $p < 0.001$), and *Muscicapa striata* ($\beta = 1.840$, $p < 0.001$); however, human presence (PC2) elicited divergent, species-specific occupancy responses, attracting *Upupa epops* ($\beta = 1.420$, $p < 0.001$) but repelling *P. domesticus* ($\beta = -1.250$, $p = 0.023$). At the community level, species richness was the most responsive metric, structured by all five PC gradients (FDR-adjusted $p < 0.05$), whereas total abundance was driven solely by PC1 ($\beta = 0.224$, $p < 0.001$). Moreover, environmental gradients explained Shannon ($R^2_{\text{adj}} = 0.851$) and Simpson ($\text{adj } R^2 = 0.827$) diversities far better than Pielou's evenness ($\text{adj } R^2 = 0.419$), highlighting strong habitat filtering on species composition rather than abundance distribution. We conclude that conserving avian biodiversity in arid urban matrices depends on maintaining structurally complex, high-density canopy networks rather than simply increasing park size.

Highlights

- Vegetation quality explained 44% of urban park environmental variance
- Occupancy of woodland species strongly linked to canopy structure
- Species richness predicted more reliably than abundance or evenness
- Human presence yielded divergent species-specific occupancy responses

1. Introduction

Urbanization constitutes one of the most profound anthropogenic drivers of global environmental change, fundamentally altering ecosystem processes and biotic communities worldwide (Urban et al., 2024). As cities grow, natural habitats become increasingly fragmented and subjected to new ecological pressures that filter species according to their functional traits (Hahs et al., 2023). Within this transformed landscape, urban green spaces, defined here as publicly accessible, purpose-managed vegetated areas within city boundaries, can serve as critical refuges for biodiversity. This role is particularly pronounced in arid urbanized regions, where these parks frequently constitute the only remaining patches of perennial vegetation, acting as last sanctuaries (Kim & Coseo, 2018). By supplying shade, moisture, and food resources otherwise largely absent from the built environment, urban parks in such settings become indispensable ecological infrastructures rather than mere amenities (Faggi & Caula, 2017). The ecological value of these green refuges, however, depends critically on their capacity

to support diverse and resilient wildlife communities. Birds are especially useful for assessing this capacity, as their high mobility and pronounced sensitivity to environmental gradients make them integrative indicators of habitat quality across multiple spatial scales (Vasquez & Wood, 2022).

The ecological literature has identified several key factors that shape bird communities in urban parks, though their relative importance and interactive effects remain context-dependent. Park size has long been considered a primary predictor, with larger areas generally supporting higher species richness and abundance by offering more diverse habitats and larger population sizes. In Bangkok, Chaiyarat et al. (2019) documented a clear positive relationship between park area and species richness, with the largest parks hosting species twice as those in smaller parks, and further demonstrated that proximity to the largest park also enhanced diversity. Similarly, Huang et al. (2022) found that park area, perimeter length, and woodland proportion positively influenced bird diversity in Fuzhou, China, while irregular park shape also benefitted resident birds. However, other studies have challenged the primacy of area. Shih (2018) reported that in Taipei's densely developed central districts, bird richness and diversity increased with greenspace size, water area, and habitat heterogeneity, but found little relationship with greenspace structure (shape, distance to nearest greenspaces, or proximity to source patches) or surrounding development intensity. This suggests that habitat quality and internal complexity may outweigh simple spatial metrics in some urban contexts.

Vegetation structure and physiological vigor have emerged as powerful determinants of urban bird diversity, often operating through mechanisms of resource availability and microhabitat provisioning. Kotsiotis et al. (2025) demonstrated that spectral indices of vegetation, particularly the Normalized Difference Vegetation Index (NDVI), were the most important proxies positively related to taxonomic and functional diversity across multiple spatial scales in Kavala. Leveau and Isla (2021) further established that vegetation patterns derived from NDVI explained more than half of the variation in taxonomic and functional diversity in Mar del Plata, Argentina, and that models constructed in one city could adequately predict diversity in other nearby cities, highlighting the transferability of vegetation-based predictive frameworks. This approach has recently been extended to broader climatic contexts; for instance, Fairbairn et al. (2025) demonstrated that both NDVI and vegetation volume serve as robust positive predictors of taxonomic and functional diversity in urban bird communities, reinforcing the utility of remote sensing metrics across different city types. Xiong et al. (2022) added a landscape-context dimension to this modeling by comparing hillside versus riverside parks in Guangzhou, China, and found that plant traits (tree evenness, habitat diversity, water area) were positively associated with bird diversity, while surrounding building coverage was negatively related. Their work also underscored that species composition differed markedly between park types, with certain species favoring hillside habitats and others riverside settings, indicating that local environmental filtering operates at fine scales.

Despite these advances, significant gaps remain. First, the vast majority of studies have been conducted in temperate or tropical humid climates, whereas arid metropolitan regions, characterized by extreme temperatures, scarce rainfall, and intensive irrigation-dependent landscaping, remain severely understudied. The ecological filters in such environments may be qualitatively different, as water

availability and vegetation stress become overriding constraints (Alghanimi & Asgarian, 2026). Second, while many studies focus on a single predictor set (e.g., vegetation indices or park area), few have simultaneously integrated multiple axes such as the combination of vegetation structure, park morphology, human usage to partition their relative contributions to community metrics. Third, there is growing recognition that species richness, abundance, and evenness may respond to environmental gradients in non-parallel ways, yet most research emphasizes richness, leaving the drivers of abundance and evenness poorly resolved. For instance, Korňan (2023) observed that bird assemblage stability and species turnover in urban parks show inconsistent patterns with park size, and that total assemblage density tended to decrease with increasing park size which is a counterintuitive result that highlights the complexity of abundance dynamics. Finally, human disturbance in parks is often assumed to be uniformly negative, but recent evidence suggests that certain adaptable species may benefit from human presence (Alghanimi & Asgarian, 2026), while others are deterred, implying a species-specific niche-partitioning effect that merits explicit testing.

The present study addresses these gaps by examining avian community structure within 57 urban parks spanning a pronounced gradient in size up to 120 ha in the arid metropolitan area of Isfahan, Iran. This system was selected because its extreme climatic conditions and heavily urbanized matrix offer a natural experiment to disentangle the relative importance of park morphology, vegetation, surrounding land-use context, and human recreational intensity. Systematic point-count surveys during the spring breeding season were combined with high-resolution environmental characterization derived from Sentinel-2 imagery and field observations. Principal component analysis was then employed to synthesize an array of environmental variables into orthogonal gradients. Occupancy models and systematic regression frameworks were subsequently used to assess the drivers of species-specific occupancy, species richness, abundance, and community evenness. Specifically, the aims of this study were (1) to determine whether vegetation structural complexity dominates predictions of both species richness and occupancy of non-synanthropic species, outweighing park area and shape; (2) to determine whether human presence elicits divergent species-specific responses; and (3) to examine whether environmental gradients more strongly regulate species richness than abundance or evenness, the latter being subject to greater stochasticity. By quantifying these relationships, the present study aimed to provide actionable insights for urban planning and green space management in arid cities, where conserving avian biodiversity requires evidence-based prioritization of limited resources.

2. Material and methods

2.1. Study parks

This study is carried out in Isfahan City, the third most populous metropolitan area in Iran (32° 32' 40" – 32° 40' 50" N and 51° 49' 60"–52° 26' 30" E). The region is characterized by an arid to semi-arid climate, with a mean annual temperature of 15.2 °C and an average annual precipitation of less than 150 mm (Asgarian et al., 2018). Historically, Isfahan has developed a robust network of urban green infrastructure

(Tashakor et al., 2023), and currently, approximately 10% of the total municipal area is dedicated to urban parks and public green spaces (Tashakkor et al., 2020). For this study, 57 urban parks were selected to represent a gradient of urban ecological conditions across the city (Fig. 1). The sampled parks exhibited significant heterogeneity in size, with areas ranging from 1.36 ha to 122.98 ha. The spatial distribution of these parks was relatively dispersed, with a mean inter-park distance of 2,575 m, ensuring a broad representation of the urban matrix. The vegetation structure within the selected parks was characterized by a pronounced dominance of a limited number of taxa. Ground cover was overwhelmingly dominated by Lawn grass (Poaceae), which significantly influenced the overall abundance patterns and ecological texture of the sites. In contrast, the woody strata (shrubs and trees) displayed a more even distribution across recorded taxa. Among the woody species, *Platanus orientalis* and *Nerium oleander* exhibit high frequencies, followed by evergreen species such as *Pinus eldarica* and *Cupressus sempervirens*. This composition reflects a managed urban landscape where traditional Persian garden elements (e.g., Plane trees) are integrated with drought-tolerant species suited to the regional climate.

2.2. Avian data collection

Avian communities were sampled across the 57 urban parks during the breeding season in the spring of 2024. Prior to the field surveys, a central sampling point was designated for each park using GIS. The coordinates of these centroids were then transferred to a handheld GPS unit to ensure precise location in the field. Upon arrival at each site, the survey point was established at the predefined centroid; however, in cases where the exact center was inaccessible or obstructed, the nearest point that maintained a clear 50-m radius within the park's boundaries was selected to ensure that all sampling stations were consistent in their environmental context and representative of the park's interior habitat, thereby minimizing edge-effect biases and sampling errors. At each station, a fixed-radius point-count method was employed, focusing on all birds seen or heard within a 50-m radius (Mulvaney & Cherry, 2020). To ensure a robust estimation of occupancy and detection probabilities, each site was surveyed across three distinct replicates conducted on separate days (excluding weekends). To minimize the risk of double-counting and provide a standardized sampling effort, each survey lasted exactly 15 minutes per replicate (Bonthoux & Balent, 2012). Surveys were restricted to the first three hours after sunrise, coinciding with the peak of avian vocal activity (Maseko et al., 2020). To account for potential temporal bias, the timing of each replicate at a given site was systematically rotated across different hours within the sampling window. Sampling was strictly conducted under favorable weather conditions, characterized by high visibility, no precipitation, and low wind speeds. All surveys were performed by a consistent two-person team including a primary observer specialized in regional bird identification and a secondary assistant responsible for data recording and distance estimation.

2.3. Landscape and environmental metrics

To characterize the structural, vegetational, and spatial context of the 57 urban parks, 16 environmental variables were quantified to describe park geometry, vegetation condition, internal habitat composition, surrounding land-cover matrix, and anthropogenic activity (Table 1). All remotely sensed vegetation

metrics were derived from Sentinel-2 imagery at 10 m spatial resolution for late winter and spring 2026, using Google Earth Engine (GEE) (Amani et al., 2020) as the primary cloud-processing platform. Sentinel-2 scenes were screened to minimize cloud contamination, and image composites representing the target seasonal window were used for index calculation. Spatial summaries were then linked to park polygons and park centroids in a GIS/Python workflow.

Variables describing park size and configuration were included because patch area and shape are among the most consistent predictors of habitat availability, edge effects, and the amount of interior refuge available to urban birds (Jasmani et al., 2017). Park Area (ARA) was calculated as the total area of each park polygon in ha from the mapped park boundaries. Shape Index (SHI) and Compactness (COM) were derived from the same polygon geometry to quantify how each park deviated from a simple compact form and how elongated or fragmented its footprint was.

Vegetation-condition metrics were derived from spectral indices because bird communities in urban parks were recognized to respond not only to the presence of vegetation, but also to its density, vigor, and internal heterogeneity (Chang & Lee, 2016). Mean NDVI (MND), Standard Deviation of NDVI (SND), and the 90th percentile of NDVI (P90) were calculated from Sentinel-2 reflectance composites within each park polygon. NDVI was generated using the standard normalized difference between near-infrared and red bands, and zonal statistics were then used to summarize pixel values across each park. Mean Normalized Difference Red Edge Index (MNR) was calculated in a similar way, using the red-edge and near-infrared bands to provide a complementary measure of vegetation vigor and chlorophyll-related canopy condition, particularly useful where NDVI may become less sensitive under relatively dense vegetation of some selected parks (Kesić et al., 2026). To describe habitat composition within parks, Vegetation Fraction (VFR), Tree Fraction (TFR), and Grass Fraction (GFR) were also estimated as the proportional area occupied by general vegetation, tree-dominated cover, and grass-dominated cover, respectively, as birds were known to often respond differently to broad vegetation cover, woody structure, and herbaceous ground layers, which provide distinct nesting, foraging, and shelter opportunities (Safran, 2026).

Because structural arrangement was considered as important as total cover, NDVI Texture (NTX) was included to represent local spatial variation and fine-scale patterning of vegetation. Texture metrics were regarded as useful in urban ecological studies because two parks with similar mean greenness may differ substantially in patch arrangement, canopy clustering, and microhabitat complexity. NTX was derived from the spatial distribution of NDVI values, through gray-level co-occurrence style texture calculations applied to the NDVI raster surface using a 3×3 moving-window, and then summarized at the park level (Liu et al., 2025). Human Count (HCT) was included as a direct indicator of anthropogenic disturbance as recreational intensity was recognized as capable of altering both bird detection and habitat use. This variable was calculated as the mean number of people recorded per hour during bird surveys at each park. In addition, the centroid coordinates of each park, Longitude (LNG) and Latitude (LAT), were extracted from the polygon geometry and retained to account for broad spatial gradients across the city. To characterize landscape context beyond park boundaries, the percentage of urban land

(U1K) and agricultural-orchard land (A1K) within a 1-km buffer around each park was calculated, considering that the surrounding matrix was understood to strongly influence dispersal, colonization, and the accessibility of complementary habitat resources.

Table 1

Definitions, units, and ecological relevance of the 16 landscape and environmental metrics quantified for the 57 urban parks

Abbre.	Variable	Description	Unit
ARA	Park area	Total area of each park polygon derived from mapped park boundaries	ha
SHI	Shape index	Metric describing deviation of park shape from a simple compact form; higher values indicate more irregular boundaries	unitless
COM	Compactness	Measure of how compact versus elongated or fragmented the park footprint is	unitless
MND	Mean NDVI	Mean Normalized Difference Vegetation Index calculated from Sentinel-2 imagery within each park	unitless
SND	Standard deviation of NDVI	Standard deviation of NDVI values within each park	unitless
P90	90th percentile of NDVI	Upper percentile of NDVI values within the park	unitless
MNR	Mean NDRE	Mean Normalized Difference Red Edge Index derived from red-edge and near-infrared bands	unitless
VFR	Vegetation fraction	Proportion of park area occupied by total vegetated cover	proportion (%)
TFR	Tree fraction	Proportion of park area dominated by tree cover	proportion (%)
GFR	Grass fraction	Proportion of park area dominated by grass cover	proportion (%)
NTX	NDVI texture	Texture metric derived from NDVI spatial variation using a 3 × 3 moving window	unitless
HCT	Human count	Mean number of people recorded per hour during bird surveys in each park	persons h ⁻¹
LNG	Longitude	Longitude of park centroid extracted from polygon geometry	decimal degrees
LAT	Latitude	Latitude of park centroid extracted from polygon geometry	decimal degrees
U1K	Urban land within 1 km	Percentage of urban land cover within a 1-km buffer around each park	proportion (%)
A1K	Agricultural/orchard land within 1 km	Percentage of agricultural and orchard land within a 1-km buffer around each park	proportion (%)

2.4. Statistical Analyses

2.4.1. Principal component analysis

To characterize the environmental and spatial gradients of the urban park network, while mitigating multicollinearity among the landscape and anthropogenic variables, a Principal Component Analysis (PCA) was performed. The analysis was implemented in Python using the scikit-learn and scipy libraries. Prior to ordination, numeric variables were subjected to median imputation for any missing values (via SimpleImputer) and subsequently standardized to z-scores (mean = 0, SD = 1), so that variables with different units could be ensured to contribute equally to the variance structure. The statistical suitability of the dataset for factor analysis was rigorously verified using Bartlett's test of sphericity (Wheelwright et al., 2020), by which it was ensured that the correlation matrix was not identity-based and possessed sufficient common variance. To determine the optimal number of principal components (PCs) for retention, the Kaiser criterion (eigenvalues > 1) was employed. Five orthogonal components were ultimately retained, by which the primary ecological axes of the study area were captured. To ensure interpretability and reproducibility, the component signs were oriented such that the variable with the largest absolute loading on each axis was made positive. These retained PCs were then extracted as site-specific scores, so that they could serve as independent, uncorrelated predictors in the subsequent avian occupancy and community diversity models.

2.4.2. Occupancy modeling

To model the occurrence dynamics of the avian community while accounting for imperfect detection, we implemented single-season occupancy models using maximum likelihood estimation. The presence-absence history across the three replicate counts was modeled as a joint Bernoulli process. This hierarchical framework partitioned the biological state variable, representing true occupancy, from the observational process, representing detection conditional on species presence (Amundson et al., 2014). The probability of occupancy was modeled as a function of the site-specific scores from the five retained principal components using a logistic link function. To maintain model parsimony and avoid overparameterization given the sample size of 57 parks, the detection probability was parameterized as constant across sites and replicates. The parameter vector, consisting of the intercept and slope coefficients for the five principal components in the occupancy sub-model along with the constant detection parameter, was estimated by numerically minimizing the global negative log-likelihood. Optimization was performed using the Broyden-Fletcher-Goldfarb-Shanno quasi-Newton algorithm implemented via the scipy library in Python. Standard errors for the parameter estimates were derived from the diagonal of the asymptotic covariance matrix obtained by inverting the observed Hessian matrix at the maximum likelihood estimate. Wald z-statistics and corresponding p-values were subsequently computed to evaluate the statistical significance of each landscape gradient.

2.5.3. Diversity and abundance modeling

To model the relationship between avian community metrics and the extracted environmental gradients, a systematic regression framework tailored to the mathematical distribution of each response variable was developed. The community metrics evaluated across the urban park network included two count-

based variables (species richness and total bird detection) and three continuous diversity indices (the Shannon-Wiener index, Simpson's index, and Pielou's evenness). All models were parameterized using the five retained principal components as independent environmental predictors. For the count-based response variables, a conditional fitting protocol was applied to control for potential overdispersion. A standard Poisson Generalized Linear Model with a logarithmic link function (Ma et al., 2012) was first fitted. For each Poisson model, the Pearson dispersion ratio was calculated by dividing the Pearson chi-squared statistic by the residual degrees of freedom. If this ratio exceeded a conservative threshold of one point five, indicating that the variance was significantly greater than the mean, the Poisson model was discarded and the data were refitted using a Negative Binomial Generalized Linear Model. By this approach, the aggregated or clumped distribution patterns typical of avian abundance data in urban ecosystems were successfully adjusted for.

For the continuous diversity indices, Ordinary Least Squares regression models (Wu et al., 2013) were constructed. To safeguard against the violation of homoscedasticity (a common issue in ecological data spanning parks of vastly different sizes and configurations) robust standard error estimators were implemented. Specifically, the covariance matrix and associated standard errors were calculated using the HC3 heteroscedasticity-consistent estimator (Baraiya et al., 2025). By this method, reliable confidence intervals and hypothesis tests were yielded even in the presence of non-constant error variance.

To control for inflation of Type I errors arising from testing multiple environmental predictors across several response variables, all raw p-values for the slope coefficients were adjusted using the Benjamini-Hochberg False Discovery Rate procedure (Hao et al., 2023). Furthermore, model diagnostics and validation were rigorously evaluated for each response variable. This included checking the normality of residuals using Shapiro-Wilk tests, visually diagnosing residual behavior using fitted-versus-residual scatterplots and histograms, and comparing observed values directly against model-fitted predictions. All statistical modeling and diagnostic visualizations were performed using the statsmodels, scipy, and seaborn libraries in Python.

3. Results

The bird community surveys yielded a diverse assemblage characterized by a distinct hierarchy of species abundance (Fig. 2). A total of 42 species were identified, with cumulative encounter rates revealing a typical log-normal distribution. The House Sparrow (*Passer domesticus*) was the most abundant species recorded across all replicates (n = 77 total detections), followed by the Barn Swallow (*Hirundo rustica*; n = 63), European Bee-eater (*Merops apiaster*; n = 62), and Laughing Dove (*Streptopelia senegalensis*; n = 58). Hooded Crow (*Corvus cornix*) also showed high site occupancy and frequency (n = 55). Intermediate frequencies were observed for several insectivorous and granivorous taxa, such as the Crested Lark (*Galerida cristata*; n = 49), Little Egret (*Egretta garzetta*; n = 46), and Wood Pigeon (*Columba palumbus*; n = 43). In contrast, specialized or more sensitive taxa exhibited markedly lower detection frequencies. The Rose-ringed Parakeet (*Psittacula krameri*) and Eurasian Sparrowhawk (*Accipiter nisus*)

were the least frequent, with only 7 and 9 total records respectively, indicating limited distribution or lower density within the park centers.

Species richness per site varied by more than an order of magnitude, ranging from a minimum of 3 species in isolated or smaller patches to a maximum of 38 species in high-diversity hotspots. These high-richness areas, primarily concentrated in the south-central portion of the study area (Fig. 2), also supported the highest total bird detections (up to 80 individuals per site) and complexity. Shannon-Wiener (H') and Simpson ($1 - D$) diversity indices mirrored this spatial trend. Shannon values ranged from 1.04 to 3.58, while Simpson values reached as high as 0.97 in the most diverse clusters, indicating robust and stable avian communities in these specific urban green spaces. In contrast, several sites exhibited markedly lower diversity indices ($H' < 1.30$).

The 57 surveyed parks exhibit significant spatial and structural heterogeneity in both geometry complexity and vegetation quality (Fig. 3). The wide area spectrum of the park from localized green spaces (1.359 ha) to expansive areas (122.981 ha) in the southwest also showed irregular, non-uniform boundaries with a SHP mean of 1.258 ± 0.232 . Spectral indices, including MNV (0.374 ± 0.183) and MNR (0.362 ± 0.137), revealed substantial localized variation from 0.05 to up to 0.64 which was mirrored by the internal heterogeneity of SND (0.140 ± 0.059) and the canopy-dense signatures captured by P9V (0.541 ± 0.228). These metrics manifest as a distinct spatial hotspot within the central-left to lower-central corridor, where high-density values for VFR (0.735 ± 0.343), TFR (0.417 ± 0.308), and GFR (0.318 ± 0.203) converge. Even fine-scale landscape texture (NTX: 0.062 ± 0.028) aligns with this zone, suggesting that this corridor functions as a high-complexity structural refuge within the broader urban matrix. The usage patterns within this structural configuration are reflected in HCT (32.667 ± 23.190 people/count), which exhibits high inter-park variability (range: 9–147 people/count). These human counts spatially track the vegetation density and complexity identified above, suggesting that parks with superior structural quality often coincide with higher human visitation. Furthermore, while the broader matrix remains predominantly urbanized (mean U1K: 0.665 ± 0.226 ; range: 0.192–0.994), the influence of agricultural fringes (mean A1K: 0.166 ± 0.178) implies that the intersection of these diverse land-use pressures with internal vegetation configuration is the primary driver of the observed ecological and social differentiation. These variables reveal a consistent spatial structure in which park size and form, vegetation condition, visitors, and surrounding land use all vary considerably, with the most notable concentration of favorable vegetation conditions occurring in the central-left portion of the study area.

PCA retained five components based on the scree pattern and parallel analysis, indicating that the 16 variables could be summarized by a relatively compact set of orthogonal gradients. Data suitability was confirmed via Bartlett's test of sphericity ($\chi^2 = 5502$, $df = 120$, $p < 0.001$). Five components were ultimately retained based on the Kaiser criterion (eigenvalues > 1) to capture a more nuanced characterization of the park network. PC1 (eigenvalue = 7.175), explaining 44.055% of the variance, represents the quality and intensity of vegetation cover. It showed strong positive loadings for MNV, P9V, MNR, VGF, TXV, and TRF (Fig. 4). Spatially, this axis was expressed as a clear concentration of high scores in the south-central and eastern parts of the study area, whereas northwestern parks were

consistently positioned at the opposite end of the gradient, indicating that vegetation abundance and canopy structure are the primary drivers of site differentiation. PC2 (eigenvalue = 2.706), explaining 16.616% of the variance, represents park size and human usage, effectively separating larger and more heavily used parks from the rest of the sample. Positive scores for PC2 were concentrated mainly in the south-central portion of the city, while lower scores were more frequent toward the northern and eastern margins.

The remaining components described more localized and context-specific contrasts. PC3 (eigenvalue = 1.708, 10.489% of variance) represents a hybrid axis of tree-based greenery versus grass and urban-ness, displaying a limited and patchy spatial expression across the network. PC4 (eigenvalue = 1.402, 8.610% of variance) provided the clearest signal of the surrounding urban matrix versus agricultural/spatial context, producing a distinct east-west differentiation with positive scores concentrated in central and southeastern parks. Finally, PC5 (eigenvalue = 1.100, 6.755% of variance) represents grass and open/agricultural texture rather than a purely southwestern spatial gradient; it showed a diffuse structural pattern with higher values concentrated in the northern half of the study area. Together, these five retained components demonstrate that park variation is organized along a small number of spatially structured gradients, dominated by vegetation quality and human-use metrics.

Single-season occupancy models revealed distinct, species-specific associations between bird occurrence (ψ) and the five environmental gradients (PC1–PC5) (Fig. 5). Estimated detection probabilities (p) varied across the assemblage, with several species showing high detectability ($P_{\text{Intercept}} > 0.5$; e.g., *Upupa epops*, *P. montanus*, and *Hippolais languida*), while others were more elusive ($P_{\text{Intercept}} < 0$; e.g., *Pica pica* and *Oenanthe isabellina*). The primary vegetation gradient (PC1) was the most frequent predictor of occupancy, particularly for woodland and edge-associated taxa (Fig. 5), with significant positive associations recorded for *Dendrocopos syriacus* ($\beta = 0.885$, $p = 0.049$), *C. cornix* ($\beta = 0.850$, $p = 0.043$), *P. pica* ($\beta = 0.520$, $p = 0.038$), *Oriolus oriolus* ($\beta = 2.150$, $p < 0.001$), *P. domesticus* ($\beta = 1.450$, $p < 0.001$), *P. montanus* ($\beta = 3.037$, $p = 0.031$), *Fringilla coelebs* ($\beta = 1.880$, $p < 0.001$), and *Muscicapa striata* ($\beta = 1.840$, $p < 0.001$).

The park-size and human-usage axis (PC2) emerged as a critical predictor for synanthropic and open-habitat species, with strong positive responses for *P. montanus* ($\beta = 1.850$, $p < 0.001$), *U. epops* ($\beta = 1.420$, $p < 0.001$), *Oenanthe isabellina* ($\beta = 2.250$, $p < 0.001$), *G. cristata* ($\beta = 0.850$, $p = 0.006$), and *M. apiaster* ($\beta = 0.650$, $p = 0.042$). Conversely, *P. domesticus* showed a significant negative relationship with PC2 ($\beta = -1.250$, $p = 0.023$), suggesting a preference for smaller or less human-dense patches despite its high naive occupancy (0.719). Secondary components provided more taxon-specific signals. PC3 (tree-based greenery vs. grass/urban) showed strong positive effects for wetland or edge-associated species such as *Remiz pendulinus* ($\beta = 1.950$, $p < 0.001$), *Motacilla flava* ($\beta = 1.250$, $p < 0.001$), *M. alba* ($\beta = 1.050$, $p = 0.001$), and *E. garzetta* ($\beta = 2.450$, $p < 0.001$), but was negatively associated with *P. krameri* ($\beta = -1.287$, $p = 0.040$). PC4 produced a significant positive association for *Phylloscopus collybita* ($\beta = 0.905$, $p = 0.042$), a negative effect for *Anas platyrhynchos* ($\beta = -0.691$, $p = 0.037$), and a borderline negative response for *Sylvia atricapilla* ($\beta = -1.042$, $p = 0.051$). Finally, PC5 (open/agricultural texture) was generally the weakest

predictor across the community, but significantly constrained the occupancy of *Sylvia atricapilla* ($\beta = -1.544$, $p = 0.035$) and *Turdus philomelos* ($\beta = -1.674$, $p = 0.038$).

The statistical modeling results demonstrated a hierarchy of performance across the five dependent variables, with richness and diversity indices generally yielding more robust fit statistics than total detection (Table 2 and Fig. 6). For species Richness, the Poisson model provided an excellent fit (AIC = 315.7; Pseudo- $R^2 = 0.824$), successfully capturing the variance with minimal overdispersion (dispersion = 1.23). This performance contrasted with Total detection, which required a negative binomial approach to accommodate its substantially higher overdispersion (dispersion = 3.127). While the negative binomial model for total detection also showed strong predictive power (Pseudo- $R^2 = 0.824$), its significantly higher RMSE (9.951) and MAE (6.969) compared to the richness model (RMSE = 4.179; MAE = 3.126) underscore the greater stochasticity inherent in counting total detections versus tallying distinct species richness.

Among the biodiversity indices, the models for Shannon and Simpson indices outperformed the Pielou index. Both Shannon and Simpson models, fitted via OLS with HC3 robust standard errors, explained the vast majority of variance, with adjusted R^2 values of 0.851 and 0.827, respectively. These models also exhibited exceptional predictive precision, with RMSE values as low as 0.273 for Shannon and 0.038 for Simpson. Furthermore, residual diagnostics validated these models, with Shapiro-Wilk tests indicating non-significant departures from normality ($p = 0.739$). In contrast, the model for Pielou indices, while statistically significant ($p < 0.001$), showed a marked decrease in explanatory power (adjusted $R^2 = 0.419$) and significant residual non-normality (Shapiro-Wilk $p = 0.023$). This suggests that while environmental variables (PCs) effectively structure the overall bird community composition and species richness, the evenness component of the community structure is more complex or influenced by processes not fully captured by the current predictors. The residual distributions across all models remained well-centered, though the range of residuals was notably wider in the total detection and richness models, reflecting the larger scale and higher variance of those metrics compared to the normalized indices.

Table 2

Statistical summary of the five occupancy and diversity models. Models were fitted using Poisson regression for Richness, negative binomial regression for Total detection, and OLS with HC3 robust standard errors for the Shannon, Simpson, and Pielou diversity indices

Response	Richness	Total detection	Shannon	Simpson	Pielou
Model type	Poisson	Neg. Binomial	OLS_HC3	OLS_HC3	OLS_HC3
AIC	315.7	477.6	25.8	-199.2	-342.6
BIC	-146.8	-200.7	38	-187	-330.4
Loglik	-151.8	-232.8	-6.9	105.6	177.3
Over dispersion poisson check	1.23	3.127	-	-	-
R ² (Adj)	-	-	0.851 (0.837)	0.827 (0.810)	0.419 (0.363)
Pseudo R ² (mcfadden)	0.824 (0.478)	0.824 (0.052)	-	-	-
Model p-value	-	-	0.000	0.000	0.000
Residual shapiro p	-	-	0.739	0.625	0.023
RMSE	4.179	9.951	0.273	0.038	0.011
MAE	3.126	6.969	0.216	0.029	0.008
Min	-7.806	-27.230	-0.663	-0.109	-0.034
Q1	-2.470	-4.599	-0.190	-0.022	-0.005
Residuals Median	-0.740	-1.614	-0.020	-0.003	0.002
Q3	2.443	2.951	0.172	0.027	0.006
Max	14.454	27.787	0.625	0.084	0.029

Comparative regression results showed a clear hierarchy in the strength and breadth of the environmental effects across the five response variables. Among the five models, Richness was the most broadly structured response, followed by Shannon, then Simpson, while Pielou and especially Total detection were more limited in the number of meaningful predictors retained (Table 3). PC1 emerged as the only universal driver across all responses, consistently positive and statistically robust, which identifies it as the dominant ecological axis in the system. PC2 contributed positively only to Richness and Shannon, indicating that its influence was real but conditional and not shared by abundance, Simpson, or Pielou. PC3 consistently exerted negative pressure on the more composition-sensitive responses, especially Richness and Shannon, and to a weaker extent Simpson. PC4 and PC5 were

significant only for Richness, showing that these components mainly influenced species counts rather than overall abundance or evenness

Among all responses, Richness was the most responsive to the principal components. It increased significantly with PC1 (Coef = 0.183, $p < 0.001$, $p_{FDR} < 0.001$) and PC2 (Coef = 0.060, $p = 0.002$, $p_{FDR} = 0.006$), but declined with PC3 (Coef = -0.065, $p = 0.037$), PC4 (Coef = -0.059, $p = 0.045$), and PC5 (Coef = -0.091, $p = 0.013$). After FDR correction, all five components remained significant for Richness, confirming that this response captured the widest and most balanced sensitivity to the environmental gradients. In comparative terms, Richness was the only response that reacted positively to two components while simultaneously showing consistent negative effects for the remaining three, which indicates a broad and structured dependence on the full PC space rather than a narrow dependence on a single axis. Total detection showed a much more restricted pattern. Its intercept was high (Coef = 3.098, $p < 0.001$), but among the predictors only PC1 was significant (Coef = 0.224, $p < 0.001$, $p_{FDR} = 0.001$). PC2 through PC5 were all non-significant, with p-values ranging from 0.404 to 0.725 and FDR-adjusted p-values uniformly at 0.725. Relative to Richness, this model is notably simpler: total detection was driven almost entirely by the first principal component, while the remaining gradients contributed little explanatory information. This contrast suggests that overall detection intensity increased mainly where the main vegetation-quality gradient was favorable, but it was not strongly structured by the secondary spatial or urban-matrix axes.

The Shannon index occupied an intermediate position between Richness and Total detection. It responded positively to PC1 (Coef = 0.192, $p < 0.001$, $p_{FDR} < 0.001$) and PC2 (Coef = 0.075, $p = 0.032$), and negatively to PC3 (Coef = -0.062, $p = 0.019$, $p_{FDR} = 0.048$). PC4 and PC5 were not significant at the conventional level, although PC5 approached significance ($p = 0.053$). In comparative terms, Shannon was less comprehensive than Richness but more responsive than Total detection, because it retained three meaningful directions of influence rather than one. This pattern implies that Shannon diversity was shaped by both the primary vegetation gradient and, to a lesser extent, by park structure and surrounding spatial context. Compared with Richness, however, its response was more selective, indicating that diversity in the Shannon sense is less sensitive to the full suite of gradients than simply counting species. Simpson diversity showed a narrower and more concentrated response. Only PC1 was clearly significant (Coef = 0.028, $p < 0.001$, $p_{FDR} < 0.001$), while PC3 was negative and nominally significant (Coef = -0.009, $p = 0.039$) but lost support after FDR correction ($p_{FDR} = 0.098$). PC2, PC4, and PC5 were not significant. Compared with Shannon, the Simpson model was therefore more conservative, retaining only the strongest signal and largely discarding the secondary gradients. This difference indicates that the Simpson index was dominated by the main ecological axis and was less affected by the broader urban-structural contrasts that still influenced Shannon and Richness. Pielou was the least responsive of the diversity indices, although it still retained a significant relationship with PC1 (Coef = 0.003, $p = 0.002$, $p_{FDR} = 0.008$). The remaining PCs were not significant, with all p-values above 0.32. Relative to Shannon and Simpson, Pielou showed the weakest explanatory structure, suggesting that evenness was only marginally associated with the measured environmental gradients. In other words, the predictors

explained changes in richness and diversity composition much better than they explained how evenly individuals were distributed among species.

Table 3

Coefficients, standard errors, test statistics, p-values, 95% confidence intervals, exponentiated coefficients, and FDR-adjusted p-values for Richness, Total detection, Shannon, Simpson, and Pielou regressed against PC1–PC5

Response	term	Coef	SE	Stat	P value	CI low	CI high	Exp. Coef	p_FDR
Richness	const	2.514	0.040	62.095	0.000	2.435	2.593		
	PC1	0.183	0.020	9.177	0.000	0.144	0.222	1.201	0.000
	PC2	0.060	0.020	3.033	0.002	0.021	0.100	1.062	0.006
	PC3	-0.065	0.031	-2.084	0.037	-0.127	-0.004	0.937	0.045
	PC4	-0.059	0.029	-2.004	0.045	-0.116	-0.001	0.943	0.045
	PC5	-0.091	0.037	-2.483	0.013	-0.162	-0.019	0.913	0.022
Total det	const	3.098	0.138	22.422	0.000	2.827	3.368		
	PC1	0.224	0.061	3.699	0.000	0.105	0.343	1.251	0.001
	PC2	0.075	0.090	0.834	0.404	-0.101	0.252	1.078	0.725
	PC3	-0.064	0.120	-0.532	0.595	-0.300	0.172	0.938	0.725
	PC4	-0.041	0.117	-0.351	0.725	-0.270	0.188	0.960	0.725
	PC5	-0.075	0.135	-0.551	0.581	-0.340	0.191	0.928	0.725
Shannon	const	2.396	0.039	60.680	0.000	2.319	2.473		
	PC1	0.192	0.017	11.181	0.000	0.158	0.225	1.211	0.000
	PC2	0.075	0.035	2.144	0.032	0.006	0.144	1.078	0.053
	PC3	-0.062	0.027	-2.342	0.019	-0.114	-0.010	0.940	0.048
	PC4	-0.054	0.036	-1.488	0.137	-0.124	0.017	0.948	0.137
	PC5	-0.092	0.048	-1.937	0.053	-0.185	0.001	0.912	0.066
Simpson	const	0.879	0.005	168.240	0.000	0.868	0.889		
	PC1	0.028	0.003	8.688	0.000	0.022	0.034	1.028	0.000
	PC2	0.002	0.005	0.417	0.677	-0.007	0.011	1.002	0.802
	PC3	-0.009	0.005	-2.062	0.039	-0.018	0.000	0.991	0.098
	PC4	-0.005	0.005	-0.945	0.345	-0.014	0.005	0.996	0.575
	PC5	0.002	0.007	0.251	0.802	-0.012	0.015	1.002	0.802
Pielou	const	0.970	0.002	637.278	0.000	0.967	0.973		

Response	term	Coef	SE	Stat	P value	CI low	CI high	Exp. Coef	p_FDR
	PC1	0.003	0.001	3.140	0.002	0.001	0.004	1.003	0.008
	PC2	0.001	0.001	0.863	0.388	-0.001	0.003	1.001	0.485
	PC3	-0.001	0.002	-0.656	0.512	-0.005	0.002	0.999	0.512
	PC4	0.001	0.001	0.990	0.322	-0.001	0.003	1.001	0.485
	PC5	-0.001	0.001	-0.865	0.387	-0.004	0.002	0.999	0.485

4. Discussion

The avian community structure within the studied urban park network exhibited a pronounced hierarchy of species abundance, reflecting the strong environmental filtering typical of arid metropolitan environments. The overall findings demonstrate that urban green spaces in this region support a highly skewed assemblage where a few adaptable, synanthropic species dominate the landscape. For instance, the sheer dominance of species such as the House Sparrow with 77 total detections sharply contrasts with the rarity of specialized predators like the Eurasian Sparrowhawk, which was recorded only 9 times. This pattern of dominance aligns closely with observations from Guangzhou, China, where Xiong et al. (2022) documented that the top 20 most abundant bird species accounted for 87.5% of the total individuals recorded across 18 urban parks, underscoring the pervasive nature of this skewed abundance structure in urban systems globally. Furthermore, the extreme spatial variability in species richness, ranging from a mere 3 to 38 in highly complex parks, underscores the heterogeneous quality of urban green infrastructure. This spatial heterogeneity is consistent with the findings of Chaiyarat et al. (2019) in Bangkok, who reported that Phutthamonthon, the largest urban park (400 ha), contained the greatest number of species (39 species), while smaller parks supported progressively fewer species, with the smallest parks harboring as few as 10–15 species. It can be concluded from these distribution patterns that the urban matrix in Isfahan also acts as a stringent ecological sieve. Rather than providing a uniform refuge, the city's green spaces create isolated pockets of viability for diverse bird communities, whereas the majority of smaller or less structurally complex parks can only sustain highly generalized taxa capable of exploiting human-dominated resources.

Vegetation quality and structural intensity emerged as the most critical determining factors for both species-specific occupancy and overall community diversity. In this study, canopy cover, vegetation health, and internal structural complexity served as the primary ecological axes for urban birds, heavily outweighing spatial or patch-shape metrics. This is explicitly supported by the fact that PC1 captured over 44% of the environmental variance and was the sole universal driver across all community response variables. Specifically, the occupancy of woodland and edge-dependent species responded powerfully to this gradient, with taxa like *P. montanus* ($\beta = 3.037$, $p < 0.05$) and *O. oriolus* ($\beta = 2.150$, $p < 0.01$) showing high sensitivity to canopy volume. The primacy of vegetation structure as a driver of bird diversity is strongly corroborated by Kotsiotis et al. (2025), who demonstrated that the mean and standard

deviations of vegetation indices (like NDVI) were the most important proxies positively related to taxonomic and functional diversity at all spatial scales examined in the urban core of Kavala, Greece. Similarly, Leveau and Isla (2021) established that taxonomic and functional diversity in Mar del Plata, Argentina, increased with increasing NDVI values, with their predictive models explaining 64–81% of the taxonomic and functional diversity variation, further confirming that vegetation quality serves as a reliable indicator of avian community structure across different biogeographic contexts. Consequently, it is evident that total green area alone is insufficient for sustaining avian biodiversity. Instead, the vertical and horizontal complexity of the vegetation, alongside its physiological vigor, provides the essential foraging and nesting microhabitats required by non-synanthropic species. The strong concentration of these high-quality vegetation traits in specific geographic corridors suggests that maintaining contiguous, high-vigor vegetation networks is the most effective mechanism for buffering sensitive species against urban environmental stress. This conclusion is reinforced by the work of Shih (2018), who found that while greenspace size, water area, and habitat heterogeneity were positively associated with bird richness and diversity in Taipei City, greenspace structure metrics such as shape, distance to nearest greenspaces, and proximity to source patches showed little relationship with diversity, indicating that vegetation quality and habitat complexity within parks are more influential than mere spatial configuration.

The interplay between park size and human usage introduces a highly complex, species-specific dynamic that reshapes avian occupancy beyond simple habitat availability. The findings reveal that while larger parks with higher human visitation attract a specific subset of open-habitat and synanthropic birds, they simultaneously deter other widespread urban exploiters. This dichotomy is best illustrated by the contrasting responses to the second principal component where the occupancy of *U. epops* increased significantly ($\beta = 1.420$, $p < 0.01$) alongside park size and human presence, whereas the highly ubiquitous *P. domesticus* exhibited a significant negative association ($\beta = -1.250$, $p < 0.05$). This nuanced relationship between human activity and avian occupancy patterns is consistent with the findings of Korňan (2023), who examined bird assemblage stability in three small parks in Zvolen, Slovakia, and found that the Sørensen (incidence) index-based clustering almost perfectly divided year samples into three groups corresponding to the park sites, while the Horn (dominance) index only into two, suggesting that different species respond to park characteristics (including human disturbance gradients) in fundamentally distinct ways. Additionally, Huang et al. (2022) observed that in Fuzhou, China, the park shape index positively affected the α -diversity of birds and the abundance of resident birds, while woodland proportion and waterbody shape index positively influenced the richness and α -diversity of resident birds, indicating that both park morphology and habitat composition mediate species-specific responses to urban green spaces. Accordingly, human presence in urban parks does not act merely as a uniform disturbance factor that suppresses bird activity. Instead, it functions as a niche-partitioning mechanism. Certain adaptable species actively exploit the resources and open foraging grounds associated with intense human recreational use in larger parks, while other species, even those typically considered urban adapters, seek smaller, less densely populated refuge patches to minimize continuous anthropogenic interference. This interpretation is further supported by the work of Alghanimi and

Asgarian (2026) in an arid basin, who demonstrated that urban bird abundance increased with urban area and building coverage and declined with building isolation, revealing that fine-scale built morphology, including human infrastructure density, structures the occupancy of urban-adapted species, while non-urban groups are constrained at broader landscape scales by the configuration of the surrounding matrix.

The mathematical structuring of the avian community reveals that environmental gradients exert a much stronger regulatory control over the number of species present than over the sheer volume or evenness of individuals. The overall findings from the systematic regression framework highlight a distinct hierarchy in ecological predictability. Species richness was highly sensitive to a broad array of landscape variables, whereas total abundance and community evenness were subjected to higher stochasticity. This is supported by the stark contrast in model performance, where the Richness model successfully integrated all five environmental components with minimal overdispersion (dispersion = 1.23), while Total detection was severely overdispersed (dispersion = 3.127) and driven almost exclusively by PC1 ($\beta = 0.224$, $p < 0.01$). The greater predictability of species richness relative to abundance is consistent with the findings of Kontsiotis et al. (2025), who showed that mean NDVI was negatively related to abundance at the 500 m spatial scale, suggesting that abundance patterns are influenced by scale-dependent and often conflicting environmental factors, contributing to their higher stochasticity. Furthermore, Alghanimi and Asgarian (2026) demonstrated that agricultural principal components reduced the probability of absence for non-urban bird groups by 29–42%, indicating strong responses to landscape structure for species presence, reinforcing the notion that occupancy and abundance are governed by different ecological processes. From these statistical behaviors, it can be concluded that landscape configuration and vegetation quality strictly dictate the ecological carrying capacity for diverse species occurrences, essentially setting the boundary for how many different niches are available. However, once a species establishes residency, the localized population density and the relative dominance of one species over another are likely governed by highly localized factors, such as sudden resource pulses, territorial flocking behaviors, or micro-climatic variations, rather than the broader structural gradients of the park. This hierarchical regulation of community structure is further supported by Xiong et al. (2022), who demonstrated that while habitat heterogeneity and vegetation quality predict species richness, the fine-scale distribution of individuals is subject to additional local contingencies that operate independently of these broader gradients. The practical implications of these findings for urban planning are substantial, as they suggest that conservation strategies should prioritize the maintenance of structurally complex, high-quality vegetation networks to maximize species richness, while acknowledging that managing population densities and community evenness may require more localized interventions that address the specific ecological needs of individual species.

5. Conclusion

This study aimed to investigate the environmental drivers structuring avian communities within an urban park network in an arid metropolitan region, with particular emphasis on vegetation quality, park morphology, and human usage patterns. The main findings demonstrate that urban green spaces

support a highly skewed community dominated by synanthropic generalists, while specialized species are confined to a few high-quality habitat patches. Vegetation structural complexity and physiological vigor emerged as the predominant determinants of species richness and occupancy, outweighing park size and patch-shape metrics, whereas total abundance and community evenness exhibited greater stochasticity and weaker environmental predictability. Human presence in larger parks produced species-specific responses, functioning as a niche-partitioning mechanism rather than a uniform disturbance. These results underscore that conserving avian biodiversity in arid cities requires prioritizing contiguous, structurally complex vegetation networks, with park enlargement and habitat heterogeneity enhancement as complementary strategies. However, the study is limited by its cross-sectional design and the absence of temporal replication across seasons and years, which precludes assessment of community dynamics and turnover. Additionally, the focus on a single urban region restricts the generalizability of the findings to other climatic and biogeographic contexts. Future research should incorporate multi-season and multi-year monitoring to capture phenological shifts and long-term stability, while also integrating functional trait-based approaches to elucidate the mechanisms underlying species-specific responses to urbanization. Comparative studies across cities with varying aridity and urbanization intensities would further clarify the generality of the observed environmental filtering processes and inform adaptive management strategies for urban biodiversity conservation.

Declarations

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Author Contribution

Maryam Razazzadeh: Methodology, Software, Writing. Ali Lotfi: Conceptualization, Methodology, Writing—original draft preparation, Writing—review & editing, Supervision.

Ali Asgarian: Conceptualization, Methodology, Software, Formal analysis, Writing—original draft preparation.

Sima Fakheran: Analysis, Writing – review and editing.

Data Availability

The datasets generated and analyzed during the current study, including bird observation records from 57 urban parks and corresponding environmental variables derived from Sentinel-2 imagery, are not

publicly available due to the ongoing nature of the research project but can be obtained from the corresponding author upon reasonable request.

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Figures

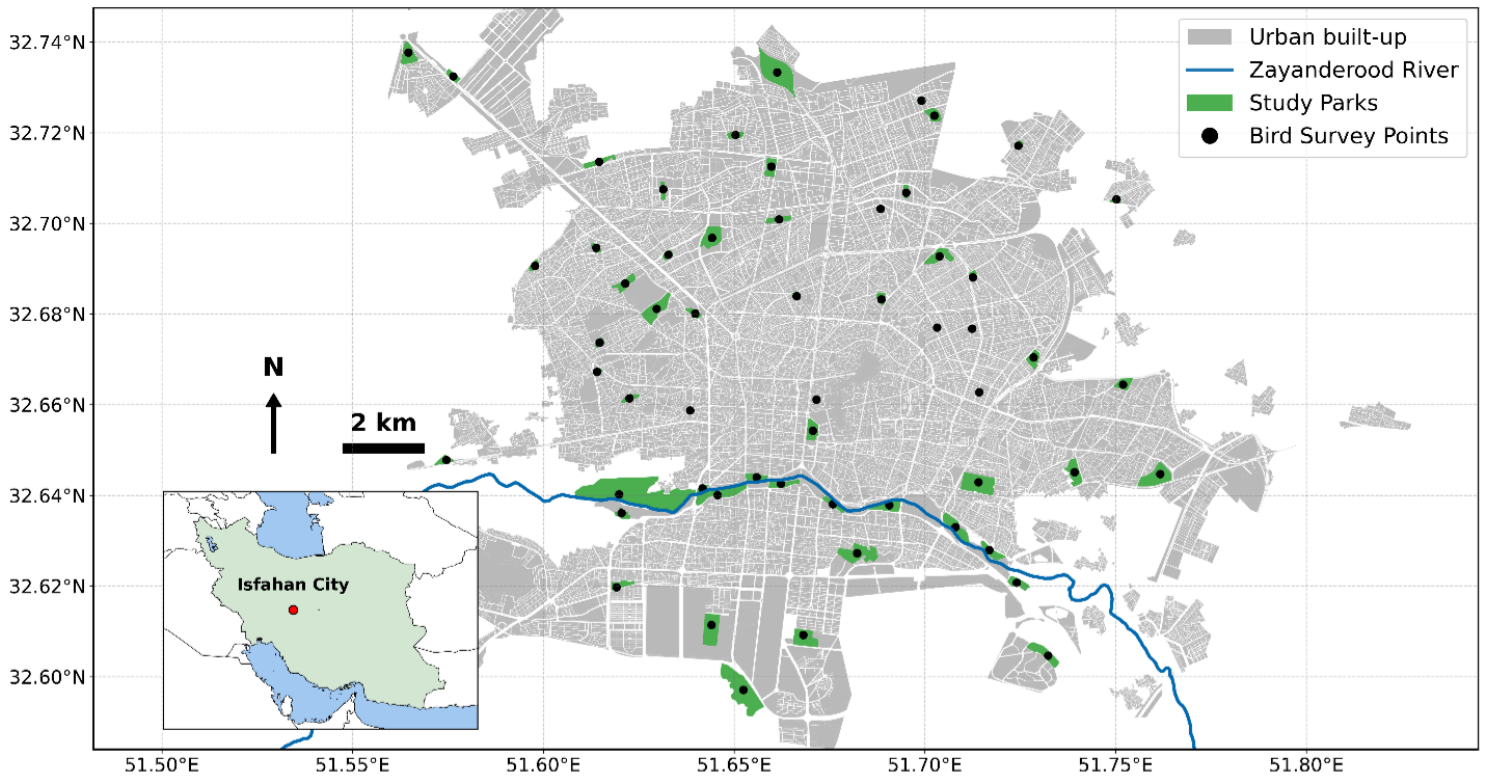


Figure 1

Geographic location of the study area in Isfahan, Central Iran, showing the spatial distribution of the 57 selected urban parks and the locations of the bird survey points (point-count stations) used for avian sampling

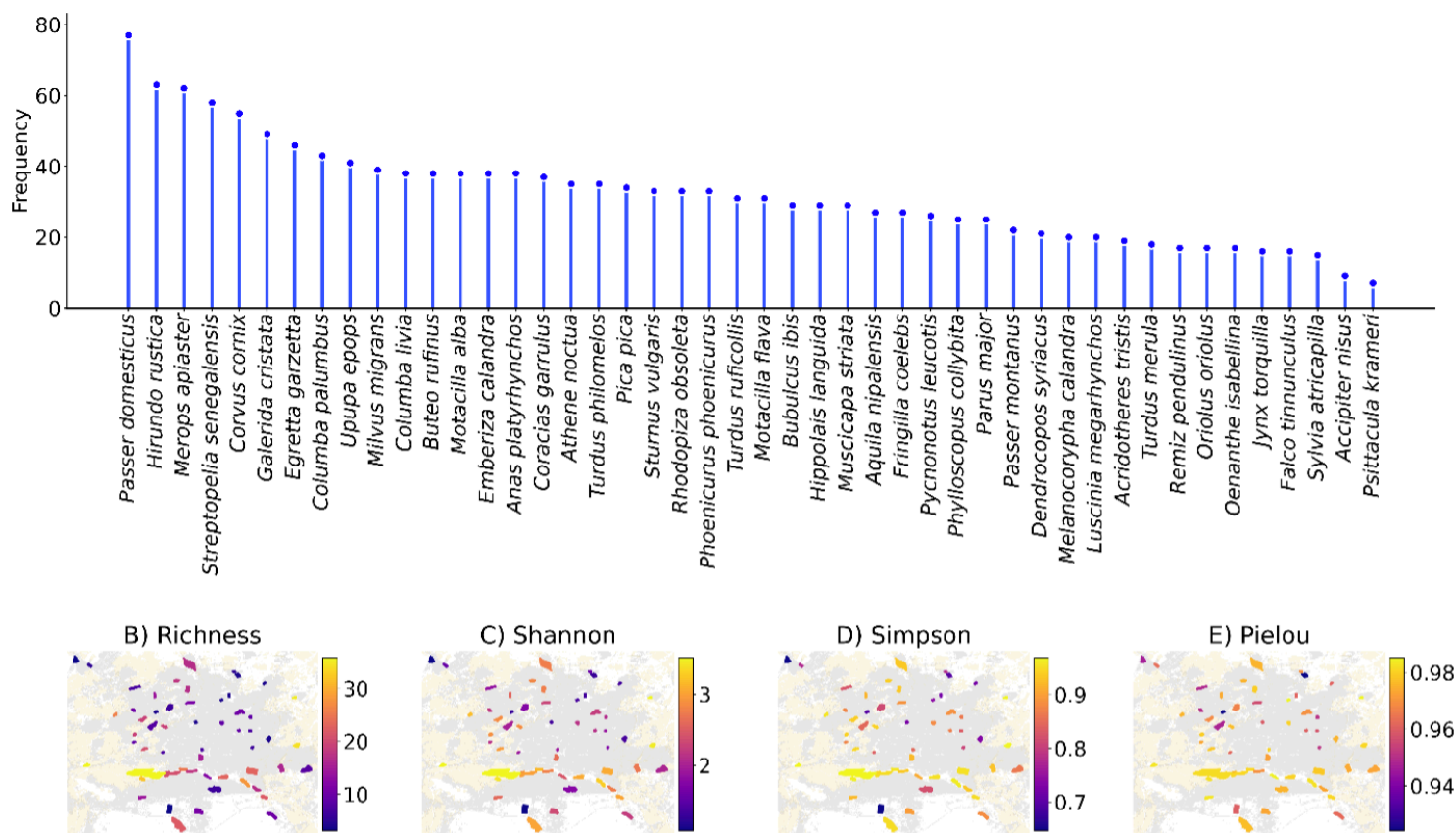


Figure 2

Bird community structure and spatial diversity patterns including the total abundance of recorded bird species ranked from highest to lowest frequency and the spatial distribution of species richness, Shannon diversity, Simpson diversity, and Pielou's evenness across sampling parks

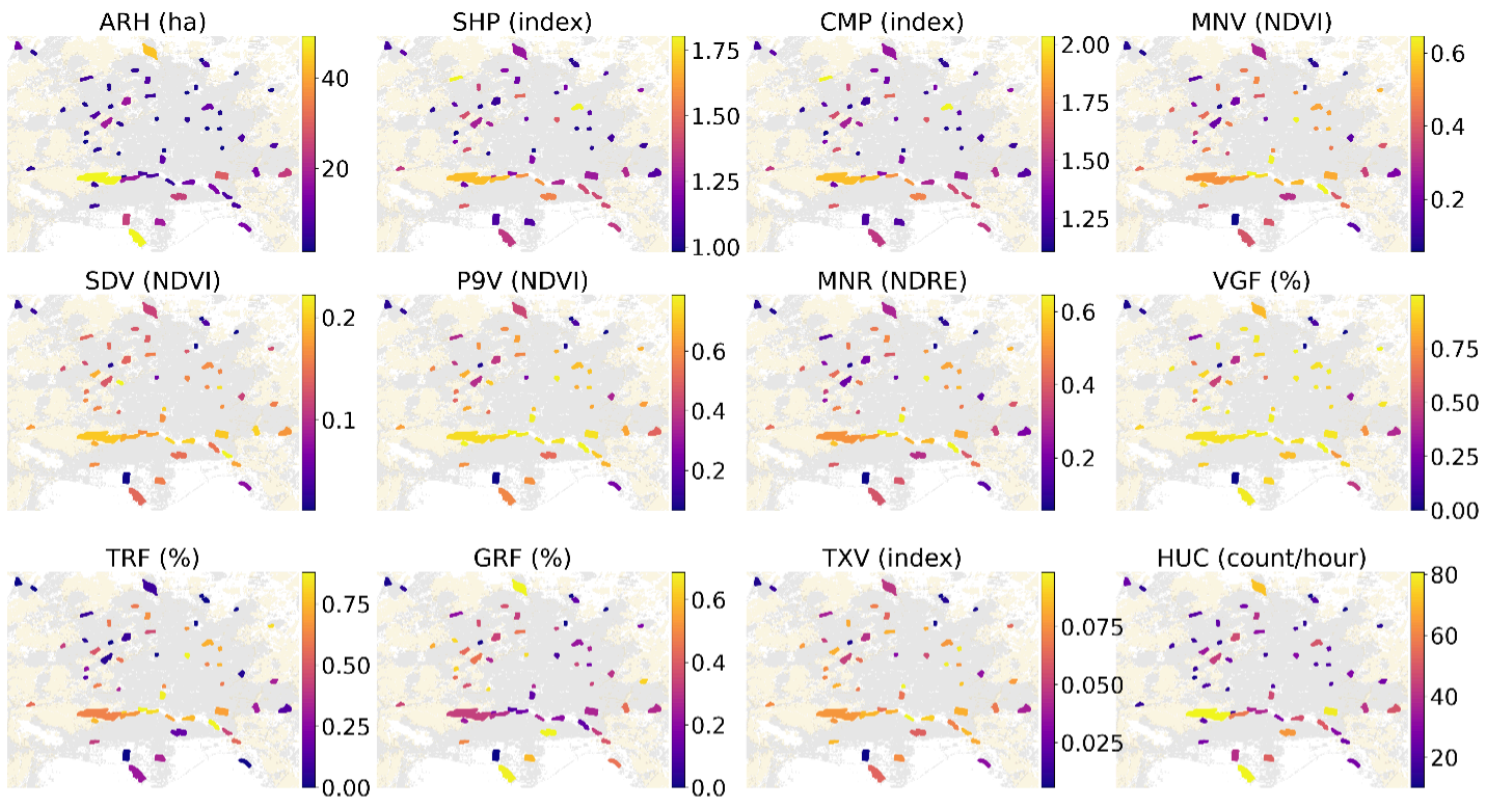


Figure 3

Spatial distribution of park morphology, vegetation structure, surrounding land use, and bird activity across the 57 sampled parks

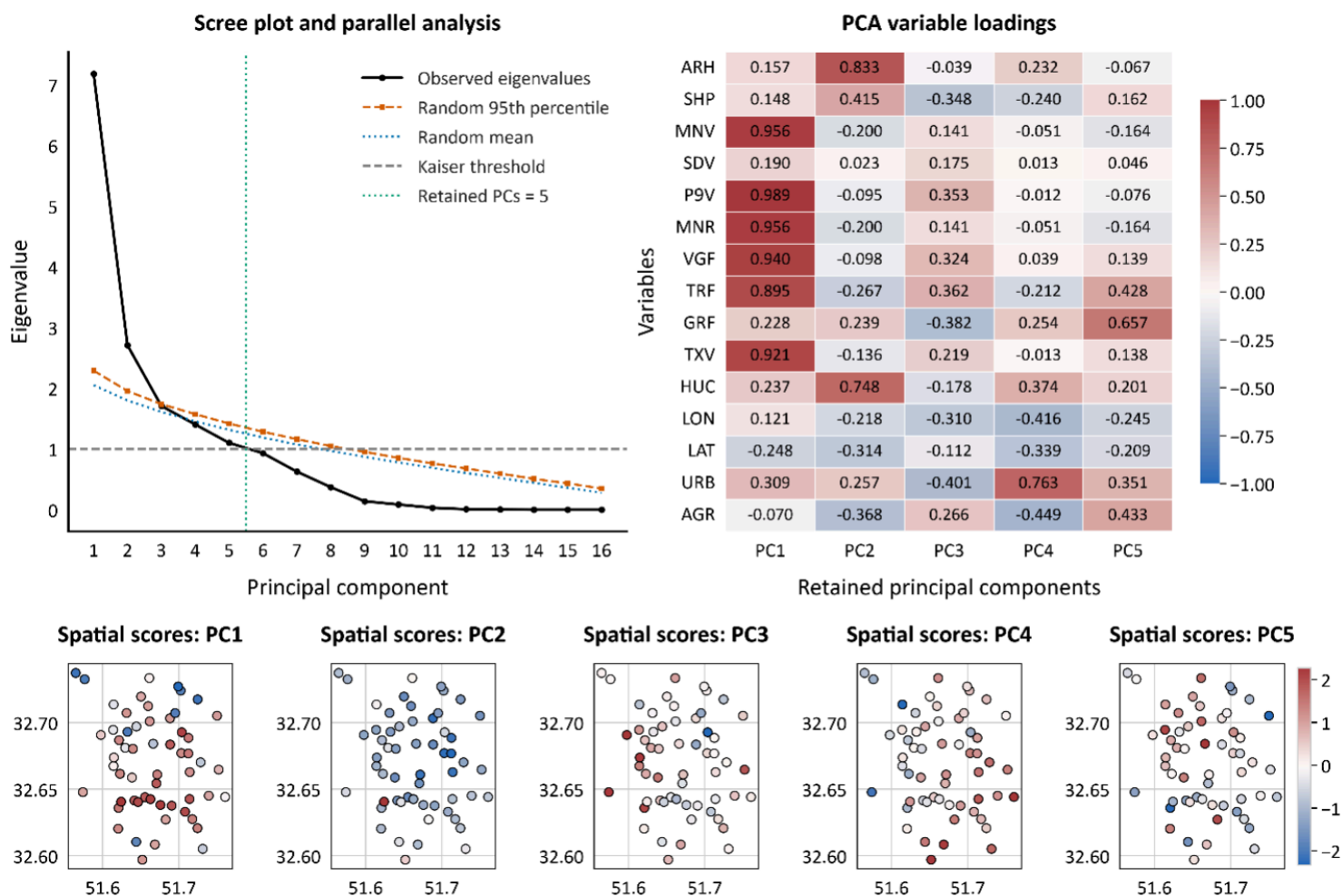


Figure 4

Principal component analysis (PCA) of urban park structural and environmental metrics including Scree plot and parallel analysis, heatmap of variable loadings (correlations) for PC1–PC5, and spatial distribution of PC scores across the 57 sampled parks

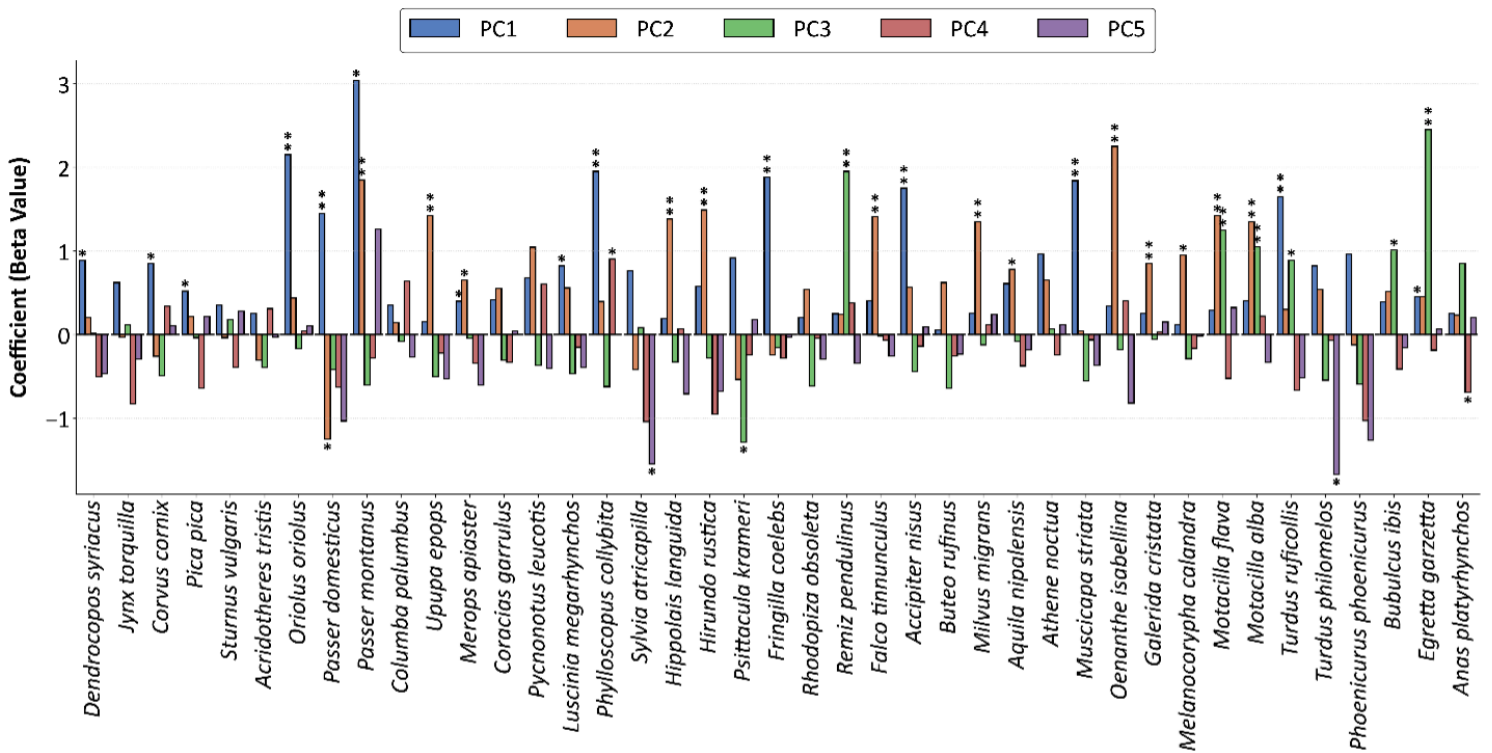


Figure 5

Occupancy-model regression coefficients (β) for bird species in relation to the five retained principal components (PC1–PC5). Bars show species-specific occupancy effects for each component. ** and * denote statistically significant coefficients at 0.05 and 0.01, respectively.

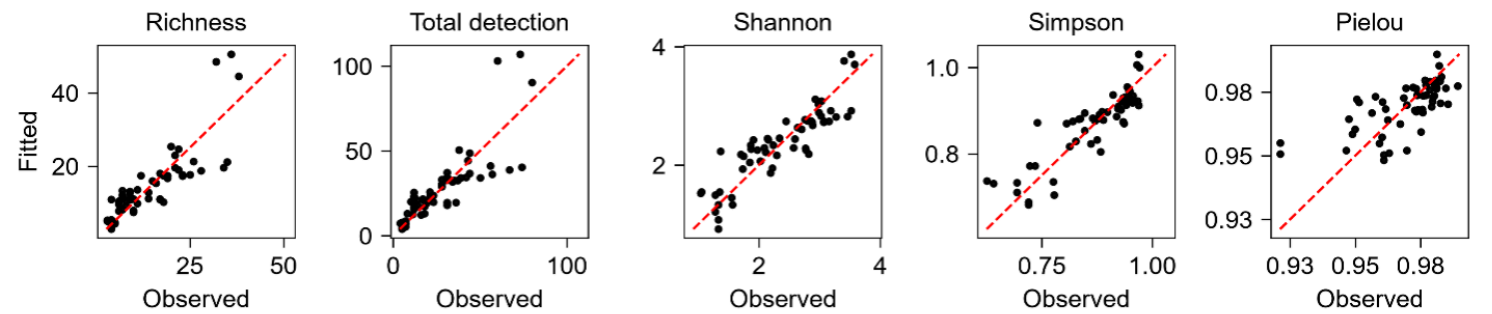


Figure 6

Observed versus fitted values for the five response models representing the goodness-of-fit across response types

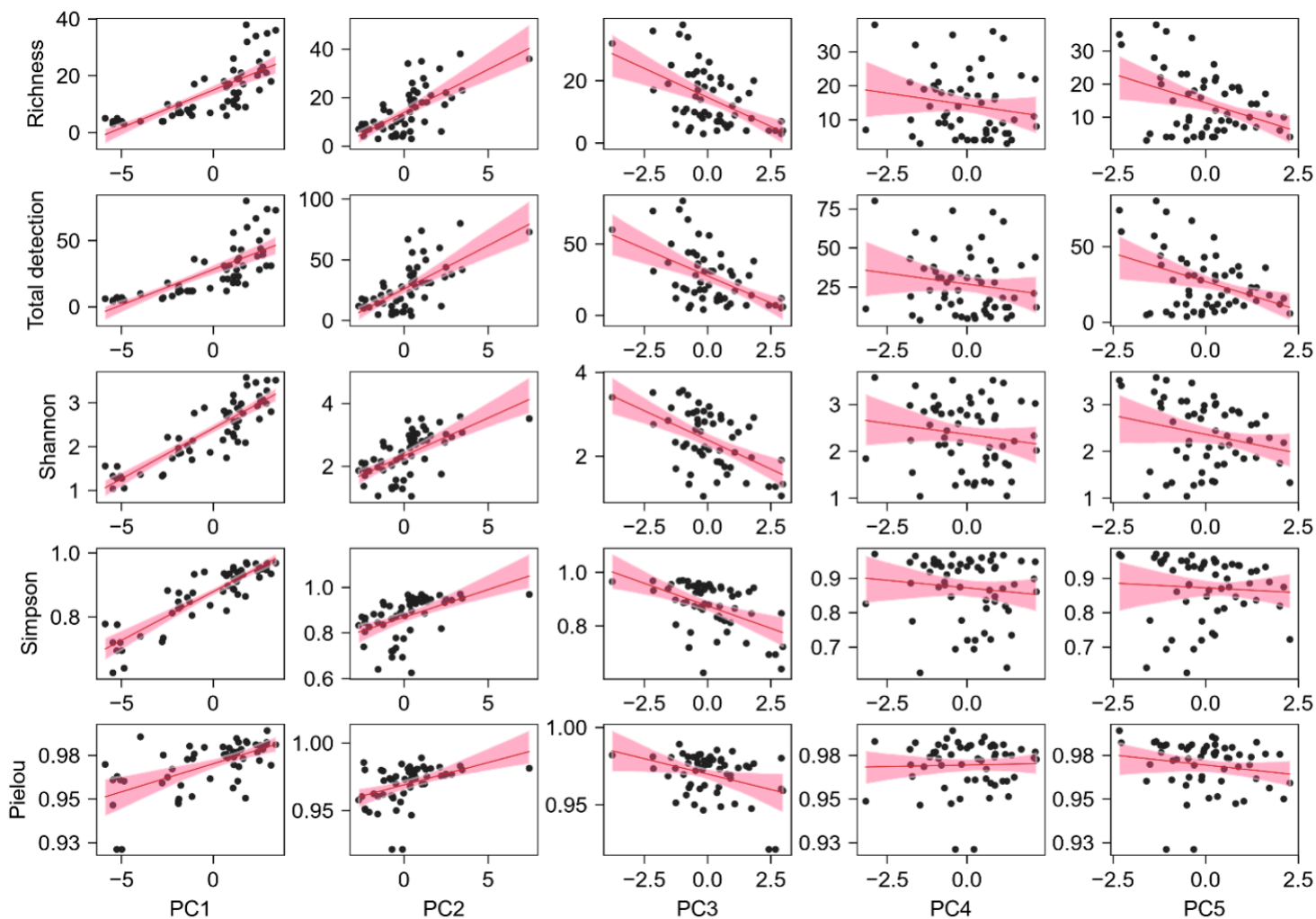


Figure 7

Scatterplots of each response variable against PC1–PC5 showing the strength and direction of the relationships across all five community metrics