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Exploring Urban Bird Diversity in a Chinese City Using Citizen Science Data: A Case Study in Shanghai

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Abstract

Urban bird diversity plays an important role in sustaining urban biodiversity and ecosystem health. Previous studies often rely on conventional field surveys to investigate bird diversity and focus on micro-scale urban green spaces such as parks and gardens. The emergence of citizen science data has made it possible to examine urban bird diversity at broader city scales. Using citizen science data, this study investigated urban bird diversity at the city scale in Shanghai, China. Based on approximately 390,000 bird observation records collected from China Bird Report Center (CBRC) in Shanghai in 2024, the study analyzed the spatial patterns of bird species richness, species abundance, and reporting-rate richness. Reporting-rate richness estimates the likelihood that different bird species are reported in a given area, helping to mitigate biases in citizen science data. The results showed that Shanghai recorded a total of 2,436,951 individual bird observations and 345 bird species in 2024. Regarding the spatial patterns of species richness and species abundance, central urban areas of Shanghai had relatively high observation point density while suburban ecological spaces also contained concentrated observation points. Species richness and species abundance were higher near waters and green spaces. The high values of reporting-rate richness were not concentrated in a few specific areas, but instead showed a more continuous and widespread spatial distribution. By integrating conventional biodiversity indicators with a reporting-rate-based metric that accounts for observation biases, this study extends citizen science-based urban bird research from local-scale observations to a continuous city-wide assessment. The findings provide spatial evidence to support the implementation of the Shanghai Biodiversity Conservation Strategy and Action Plan (2024–2035), particularly by informing habitat conservation priorities, ecological network enhancement, and biodiversity monitoring in rapidly urbanizing areas.

Keywords: urban biodiversity; urban bird diversity; citizen science; Chinese cities

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1. Introduction

Urban biodiversity is essential for maintaining urban ecosystem health, enhancing urban resilience, and improving human well-being [1–3]. As cities continue to expand, urbanization has become one of the major drivers of biodiversity loss, primarily through habitat loss, fragmentation, and biotic homogenization [4–6]. Nevertheless, urbanization was also considered as "a problem and a solution" [7] (p. 32), as cities can offer opportunities to address biodiversity loss [8]: a growing body of evidence suggests that cities also harbor their unique biodiversity in terms of vascular plant and animal species, especially where

green and blue spaces are retained or restored [9–11]. Understanding the condition of biodiversity within cities is therefore essential for biodiversity conservation, biodiversity-sensitive urban planning, and the construction of sustainable urban environments.

Among different taxonomic groups, birds are sensitive to environmental changes and are closely associated with human activities, making them important indicator species for characterizing urban biodiversity [12,13]. Birds are relatively easy to observe and identify, and play diverse ecological roles as predators, pollinators, scavengers, etc. [12–15]. Their visibility and cultural familiarity also make them closely connected to public perception of urban nature [16]. Previous studies have shown that urban bird diversity varies along urban–rural gradients [17–19]. Although the precise pattern may be linear or nonlinear depending on the ecological and geographical context, species richness is often reduced under intensive urbanization, while urban-adapted, non-native, and generalist species become increasingly dominant in highly developed areas [17–19]. Dense urban centers also harbor green and blue spaces that help conserve bird diversity [19,20]. Understanding urban bird diversity can provide useful evidence for identifying biodiversity hotspots, ecological corridors and priority areas for conservation and planning interventions.

Previous studies on the investigation of urban bird diversity have mainly relied on conventional field survey methods. These methods provide standardized and reliable data. However, their spatial and temporal coverage may vary depending on available resources, site accessibility, and survey design. Much of the existing research has examined bird diversity within selected urban green spaces at the site-scale, such as parks and gardens, whereas bird diversity across entire urban areas warrants further investigation. One possible reason is the limited availability of spatially comprehensive and standardized bird observations at the city scale. In many cases where such data are not readily available, researchers have often used remotely sensed habitat and environmental variables, such as land cover, vegetation heterogeneity, and topographic complexity, as indirect indicators of potential biodiversity patterns, or have relied on aggregated species-occurrence records [21–23].

In recent years, the development of citizen science has created new opportunities for biodiversity research at macro spatial and temporal scales. Birdwatching platforms allow both professional birders and ordinary citizens to submit georeferenced records of bird observations, producing large datasets that would be difficult to obtain through conventional field surveys alone. These data have been increasingly used in bird diversity research. Sullivan et al. [24] introduced eBird (www.ebird.org) as a large-scale citizen science platform and explains how eBird data are used across avian biodiversity research. Callaghan et al. [25] used eBird data to analyze bird diversity in 112 urban green spaces across 51 cities in eight countries. Methorst [26] used annual bird citizen science data with health data to examine the effects of bird diversity on mental health. In China, studies have applied bird citizen science data for urban bird biodiversity research [27–32], including using the platform of China Bird Report Center (CBRC) (www.birdreport.cn), iNaturalist, and eBird.

Nevertheless, citizen science data also has biases that cannot be neglected. Unlike standardized conventional field surveys, citizen science records are often generated spontaneously without an experimental design, which lacks systematic site layout and standardized survey methods. Thus, the resulting datasets are prone to increased bias and noise [26,28,33,34]. Records tend to cluster in easily accessible locations and popular birding sites. Differences in observer effort, skill, survey duration, and reporting behavior may also influence observed species richness and abundance [26]. If these biases are not considered, areas with more observers or more frequent visits may appear to have higher biodiver-

sity because they are more intensively sampled. Recent methodological studies have increasingly focused on correcting biases in citizen science data. Uneven spatial coverage, sampling effort, and detectability can bias ecological inference, prompting the use of site effects, list length, and detection-related models [33]. Semi-structured surveys and effort-related metadata, such as survey duration, distance traveled, and observer information, further enable the observation process to be modeled explicitly [34,35]. Data filtering and spatial subsampling can also reduce biases arising from clustered and uneven observations, although their effectiveness varies across datasets and analytical objectives [28,36]. More recently, Methorst (2024) developed reporting-rate richness by aggregating effort-adjusted species-specific reporting probabilities, providing an alternative to unadjusted richness and abundance measures [26].

This study used citizen science data to investigate bird diversity in Shanghai at the city scale. Specifically, the study investigated bird diversity using three indicators of species richness, species abundance, and reporting-rate richness to describe the patterns of bird diversity in Shanghai revealed by citizen science data. In addition to the conventional biodiversity indicators of species richness and species abundance, we calculated bird reporting-rate richness, following Methorst's study [26]. Reporting-rate richness describes the probability that a certain number of bird species occurs in a specific area and accounts for potential detection biases in citizen science data [26]. The study evaluates the potential of bias-adjusted citizen science data for macro-scale urban bird diversity research and provides support for biodiversity-friendly urban planning in Shanghai and other rapidly urbanizing megacities.

2. Materials and Methods

2.1. Study Area

The study selected Shanghai, a megacity in China, as the study area (Figure 1), mainly based on its high typicality and the feasibility of data acquisition. First, Shanghai has a high degree of spatial heterogeneity in bird diversity patterns, from densely built-up areas to suburbs and coastal and estuary areas. Second, in terms of the policy, the "Shanghai Biodiversity Conservation Strategy and Action Plan (2024–2035)" clearly proposes the plan to strengthen urban biodiversity conservation and build Shanghai into a model of innovative practices for biodiversity-friendly cities, which provides an important opportunity to expand urban bird diversity research on a larger city scale. Finally, Shanghai provides rich and accessible multi-source big data. Platforms such as CBRC have accumulated a large number of bird observation records in Shanghai, which provides a solid data foundation for this study. The pronounced spatial heterogeneity of Shanghai provides an appropriate context for examining city-scale variation in bird diversity. Dense urban areas contain fragmented but accessible green and blue spaces that may support urban-adapted species, whereas suburban, coastal, and island landscapes provide more diverse habitats, including wetlands and ecological spaces that may support a wider range of bird communities. Therefore, we expected bird diversity indicators to exhibit spatial variation across different landscape contexts.

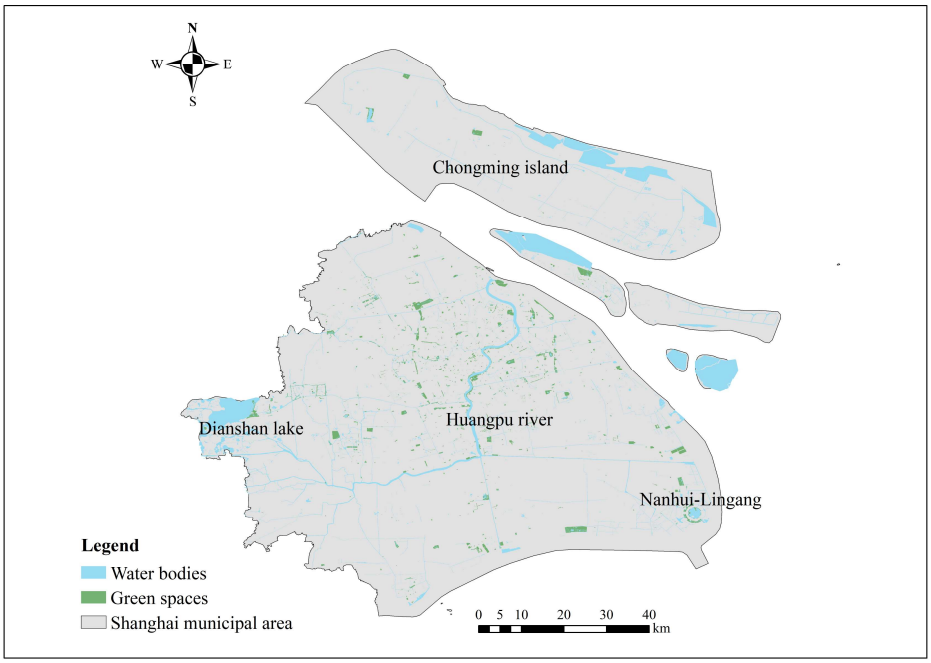


Figure 1. Study area.

2.2. Overall Research Workflow

Figure 2 illustrates the overall workflow used to process and analyze the citizen science bird observation data. First, a 500 m × 500 m fishnet grid covering Shanghai was created in ArcGIS Desktop 10.8.2 to define the spatial units of analysis (Figure 1). The 500 m × 500 m grid resolution was selected to balance spatial representation and data availability. A finer spatial resolution may provide greater spatial detail but could result in many grid cells containing insufficient observation records, given the uneven sampling intensity inherent in citizen science data. Conversely, a coarser resolution may obscure local variations in habitat conditions and urban landscape heterogeneity. The selected resolution provides an appropriate spatial unit for capturing urban-scale variation in bird diversity while maintaining sufficient observations for grid-level biodiversity assessment and reporting-rate modeling.

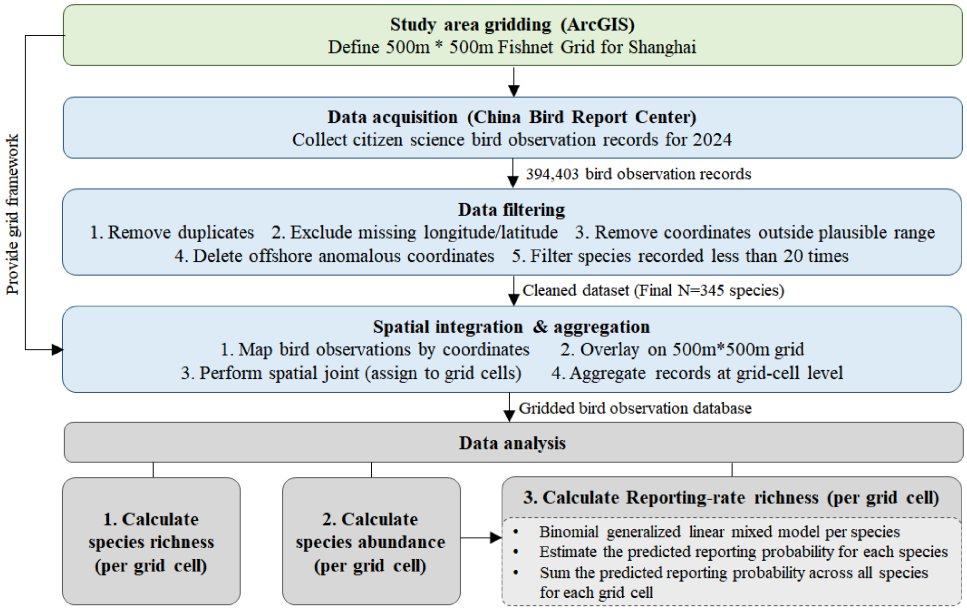


Figure 2. Overall research workflow.

All subsequent bird diversity indicators calculated were spatially matched to the corresponding grid cells. Bird observation records for 2024 were then obtained from CBRC (accessed in July 2025) and subjected to data filtering. The cleaned bird observations were subsequently mapped according to their geographic coordinates and spatially joined to the 500 m × 500 m grid, after which the records were aggregated at the grid-cell level. Three bird-diversity indicators were then calculated for each grid cell: species richness, species abundance, and reporting-rate richness.

2.3. Data Acquisition and Processing

This study first collected citizen science bird observation data in Shanghai throughout 2024 from CBRC (www.birdreport.cn) (accessed in July 2025). CBRC is China's first open, non-governmental organization for bird records, where participants submit bird species observation records through the website. In total, this study obtained 394,403 bird observation records for Shanghai in 2024. The record dataset includes information on report ID, observer, observation start time, observation end time, observation location, number of orders, number of families, number of species, number of records, species ID, species Chinese name, species scientific name, order, family, count, longitude and latitude, and district (for sample of observation records, please see Supplementary Data).

Second, we conducted a data-filtering procedure that included removing duplicate records, excluding records with missing longitude or latitude values, removing coordinates outside plausible geographic ranges, and deleting clearly anomalous coordinates located offshore. Additionally, bird species recorded fewer than 20 times during the sampling period were also excluded to reduce the influence of extremely sparse records and ensure sufficient observations for subsequent analyses [26]. Such filtering is particularly relevant for citizen science data, which can be affected by uneven sampling effort, spatial bias, and reporting errors [36]. This filtering represents a trade-off between improving model stability and potentially excluding rare species. Therefore, the results should be interpreted as representing relatively well-recorded species rather than the complete avian community. After filtering, 345 bird species remained.

The cleaned citizen science data were imported into ArcGIS Desktop 10.8.2, where bird observation records were mapped based on their longitude and latitude coordinates and overlaid onto a 500 m × 500 m grid. A spatial join was then performed to assign each observation record to the grid cell in which it was located. Finally, valid observation records were aggregated at the grid-cell level, providing the basis for calculating species richness, species abundance, and reporting-rate richness, as well as for constructing a gridded bird-observation database covering the entire study area.

Each bird observation record provided by CBRC contains a unique Species ID and standardized taxonomic information, including Chinese name, scientific name, order, and family. The Species ID was used as the unique identifier to link observation records with bird species. Therefore, species identification and taxonomic classification were based on the standardized information provided by CBRC rather than manual classification. Although CBRC records are contributed by both professional and non-professional bird-watchers, potential uncertainties related to observer expertise and species identification cannot be completely excluded. Such uncertainties may represent a common limitation of citizen science datasets.

Three analytical procedures were conducted based on the observation records. First, the overall bird diversity recorded in Shanghai was summarized directly from the observation records. The total number of recorded bird species, total number of individual birds, and the top 20 bird species by recorded occurrences were calculated based on the observation records.

Second, the spatial distribution of bird diversity indicators was analyzed using a 500 m × 500 m grid framework. The longitude and latitude coordinates contained in each bird observation record were first used to generate spatial point features in ArcGIS. Each point represented a species-level bird observation record and retained its associated attributes, including species identification information and the number of individuals recorded. Meanwhile, a 500 m × 500 m fishnet grid covering the entire Shanghai study area was generated in ArcGIS Desktop 10.8.2 to define the spatial units for subsequent analysis. A spatial join was then conducted between the bird observation point layer and the fishnet grid layer, allowing each observation record to be assigned to the grid cell in which it was spatially located. After spatial assignment, all observation records were aggregated according to grid cells. Within each grid cell, species-level records were summarized to calculate three bird diversity indicators: species richness, species abundance, and reporting-rate richness.

Third, the grid-level bird diversity dataset generated from ArcGIS was exported for statistical analysis. The descriptive statistics, including minimum value, maximum value, mean, median, and standard deviation of species richness, species abundance, and reporting-rate richness, were calculated using SPSS Statistics 27.

2.4. Data Analysis

For each grid cell, three bird diversity indicators were calculated: species richness, species abundance, and reporting-rate richness (Table 1). All data were visualized and analyzed in ArcGIS Desktop 10.8.2 to identify the spatial distribution patterns of these three indicators.

Reporting-rate richness is a bird diversity indicator derived from citizen science data that adjusts for measured components of the observation and reporting process. It represents the probability of observing or reporting multiple bird species within a given area and can be interpreted as an encounter-oriented measure of bird diversity [26]. Because citizen science data are typically collected without a systematic sampling design, reporting probabilities may vary with observer effort, reporting behavior, and spatial differences in reporting opportunities. Following Methorst (2024) [26], report length and observation duration were included as report-level effort-related covariates, while grid-cell population size was included as a grid-level contextual covariate to account for spatial variation in reporting probability associated with differences in human population and potential reporting opportunities. Population size was not treated as a focal ecological predictor of bird occurrence, although it may also be correlated with urban environmental conditions.

Report length, observation duration, and grid-cell population size enter the species-specific binomial GLMM as fixed-effect covariates, with their coefficients estimated separately for each species. Their effects therefore modify the predicted reporting probability on the logit scale, with positive coefficients increasing and negative coefficients decreasing the predicted probability. When generating standardized reporting rates, report length and observation duration were fixed at their mean values, thereby placing predictions under a common level of measured report-level effort.

Correlations among species richness, species abundance, and reporting-rate richness were evaluated using Spearman rank correlations because species richness and abundance exhibited strongly right-skewed distributions. To assess the potential influence of uneven observation intensity, Spearman correlations were also calculated between each diversity indicator and the number of bird observation reports.

Table 1. Bird diversity metrics and descriptions.

Bird Diversity Indicator	Definition	Formula and Interpretation
Species richness	The total number of different species reported within a specific area	$S_r = K_r$ K_r is the number of distinct bird species reported in grid cell r
Species abundance	The total number of bird individuals reported within a specific area	$A_r = \sum_{i=1}^{K} N_{i,r}$ $N_{i,\,r}$ is the number of individuals of species i reported in grid cell r; and K is the total number of bird species considered
Reporting-rate richness	A bird diversity indicator derived from citizen science data that adjusts for measured components of potential detection and reporting bias by incorporating species-specific reporting probabilities. Higher reporting-rate richness values indicate a greater likelihood of observing or reporting multiple bird species within an area than lower values	Step 1. Fit the species-specific reporting model: For each bird species i, the response variable was defined at the observation-report level, with $Y_{ijr} = 1$ if species i was recorded in observation report j located within grid cell r, and $Y_{ijr} = 0$ otherwise. The binary response was assumed to follow a Bernoulli distribution, $Y_{ijr} \sim \text{Bernoulli}(p_{ijr})$ where p_{ijr} represents the probability that species i was reported in observation report j within grid cell r. For each species, a binomial generalized linear mixed model (GLMM) with a logit link was fitted as: $\text{logit}\,(p_{ijr}) = \beta_{0i} + \beta_{1i}L_j + \beta_{2i}T_j + \beta_{3i}D_r + \mu_{ir}$ $u_{ir} \sim N\left(0, \sigma^2_{u,i}\right)$ where L_j is report length (the number of species recorded in observation report j); T_j is observation duration; D_r is the population size of grid cell r, included as a grid-level contextual covariate to account for population-related spatial variation in reporting probability and potential reporting opportunities; β_{0i} is the intercept; β_{1i}, β_{2i}, and β_{3i} are the corresponding fixed-effect coefficients; and u_{ir} is the grid-cell-level random intercept for species i, assumed to follow a normal distribution. Step 2: Estimate the standardized species-specific reporting rate: $L_j = \overline{L},\ T_j = \overline{T}$ $RR_{i,r} = \hat{p}_{ir}^{std} = \text{logit}^{-1}(\hat{\beta}_{0i} + \hat{\beta}_{1i}L_j + \hat{\beta}_{2i}T_j + \hat{\beta}_{3i}D_r + \hat{\mu}_{ir})$ where $\overline{L}$ and $\overline{T}$ are the mean report length and mean observation duration, respectively. Step 3: Aggregate and standardize species-specific reporting rates: $RRrich_r = \frac{\sum_{i=1}^{K} RR_{i,r}}{K}$ where $RRrich_r$ is the reporting-rate richness of grid cell r, and K is the total number of bird species included in the reporting-rate models. The reporting-rate richness ranges from 0 to 1, with higher values indicate a greater likelihood of observing or reporting multiple bird species.

The selection of effort-related covariates follows Horns et al. (2018) [34] and Methorst (2024) [26]. They were also available in the CBRC. Other informative variables, such as observer identity and checklist type, were not available in the dataset and therefore could not be included in the model. S_r A_r $RR_{i,r}$ and $RRrich_r$ denote species richness, species abundance, the standardized reporting rate of species i in grid cell r, and the reporting-rate richness of grid cell r, respectively. All other mathematical symbols are defined in the "Formula and interpretation" column.

Global spatial autocorrelation was evaluated using Global Moran's I. A row-standardized eight-nearest-neighbor spatial weights matrix was constructed from grid-cell centroid coordinates, and statistical significance was assessed using 999 permutations. Recorded abundance was transformed as log(x + 1) because of its highly skewed distribution. Analyses using four- and twelve-nearest-neighbor weights were conducted as sensitivity tests. As an exploratory assessment of the urban gradient, we calculated the great-circle distance from the centroid of each grid cell to People's Square (121.4737° E, 31.2304° N), used here as the operational city center of Shanghai. Spearman correlations were calculated between distance and the three bird indicators. This analysis was treated as a center–periphery check because distance does not fully represent local built-up intensity.

To assess the reliability of the species-level reporting-rate models, we first examined model convergence diagnostics and retained models that met the predefined convergence criteria. For models that converged successfully, predictive performance was further evaluated using five-fold cross-validation. Model discrimination was assessed using the area under the receiver operating characteristic curve (ROC-AUC), while predictive accuracy was evaluated using the Brier score. We additionally calculated the Brier skill score relative to a training-prevalence baseline and assessed probability calibration using the calibration slope. These diagnostics were summarized across species to evaluate both overall model performance and between-species variation in predictive reliability.

3. Results

3.1. Bird Observation

A total of 393,701 valid bird observation records were obtained in Shanghai in 2024 after data cleaning and filtering, comprising 2,436,951 individual birds and 345 bird species. Based on the citizen science data, the 20 bird species with the highest number of observation records in Shanghai were identified (Figure 3). Among them, *Spilopelia chinensis*, *Pycnonotus sinensis*, and *Turdus mandarinus* had the highest numbers of observation records. These species have broad ecological niches and wide distributions, indicating their strong adaptability to urban environments.

In addition, several waterbird species had relatively high numbers of observation records, including *Egretta garzetta*, *Tachybaptus ruficollis*, *nycticorax*, and *Ardea cinerea*. Among the top 20 species, several winter visitors were also recorded, such as *Ardea cinerea*, *Phoenicurus auroreus*, *Spodiopsar cineraceus*, and *Motacilla alba*.

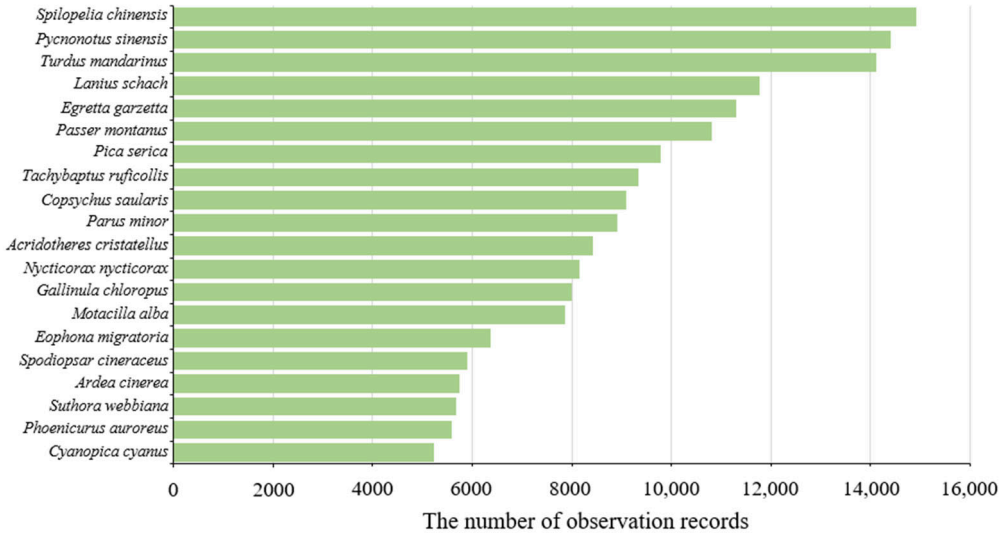


Figure 3. The top 20 bird species by recorded occurrences in citizen science data.

3.2. Species Richness, Species Abundance, and Reporting Rate Richness

Table 2 presents the descriptive data of the species richness, species abundance, and reporting rate-richness calculated from the citizen science data. Across the grid cells, bird species richness ranged from 1 to 321 species. The distribution was strongly right-skewed (Figure 4a), with a median of 16 species per grid cell and an interquartile range of 7–33 species. The mean species richness was 28.08 species per grid cell (SD = 38.23), which was higher than the median because of a small number of grid cells with very high recorded species richness. Overall, 58.8% of the grid cells contained no more than 20 recorded species, and 80.7% contained no more than 40 species, whereas only 6.8% contained more than 80 species.

Table 2. Descriptives of the species richness, species abundance, and reporting rate-richness from the citizen science data.

	Mean	Standard Deviation	Median	1st Quartile	3rd Quartile	Minimum	Maximum
Species richness	28.08	38.23	16	7	33	1	321
Species abundance	1830.92	14,552.06	55	12	291	1	309,583
Reporting rate richness	0.401	0.086	0.394	0.357	0.443	0.009	0.831

A total of 2,436,951 individual bird observations were recorded. Recorded bird abundance varied substantially among grid cells, ranging from 1 to 309,583 observations. The distribution was right-skewed (Figure 4b), with a median of 55 observations per grid cell and an interquartile range of 12–291. In Figure 4b, the horizontal axis is shown on a logarithmic scale because recorded abundance was strongly right-skewed. The mean abundance was 1830.92 observations per grid cell (SD = 14,552.06), substantially exceeding the median due to a small number of grid cells with exceptionally high values. Approximately 48.4% of the grid cells contained no more than 50 recorded individual observations, whereas only 4.5% contained more than 5000. The highest-ranked 1% of grid cells accounted for approximately 63.8% of all individual bird observations, indicating a highly concentrated distribution of citizen science records across the study area.

Reporting-rate richness varied across the grid cells, ranging from 0.009 to 0.831. The distribution was unimodal and slightly right-skewed (Figure 4c), with a mean of 0.401 (SD = 0.086) and a median of 0.394 (IQR = 0.357–0.443). Most grid cells exhibited intermediate values: 45.7% of the cells had reporting-rate richness values between 0.3 and 0.4, while a further 34.7% had values between 0.4 and 0.5. Overall, 80.4% of the grid cells fell within the range of 0.3–0.5, whereas values below 0.2 or above 0.7 were uncommon. Compared with observed species richness and recorded bird abundance, reporting-rate richness exhibited a less skewed distribution and was more concentrated around intermediate values. This more balanced distribution suggests that the reporting-rate-based metric may reduce, although not necessarily eliminate, the influence of highly uneven observation intensity.

Of 345 primary full-data species models, 337 met the convergence criteria. Among the accepted primary models, complete five-fold predictions were available for 318 species. Across these species, median ROC-AUC was 0.814 (IQR 0.761–0.859), median Brier score was 0.018 (IQR 0.008–0.038), and median Brier skill was 0.018 (IQR −0.124–0.094); 183 species improved on the training-prevalence baseline. Median calibration slope was 1.255 (IQR 0.941–1.890).

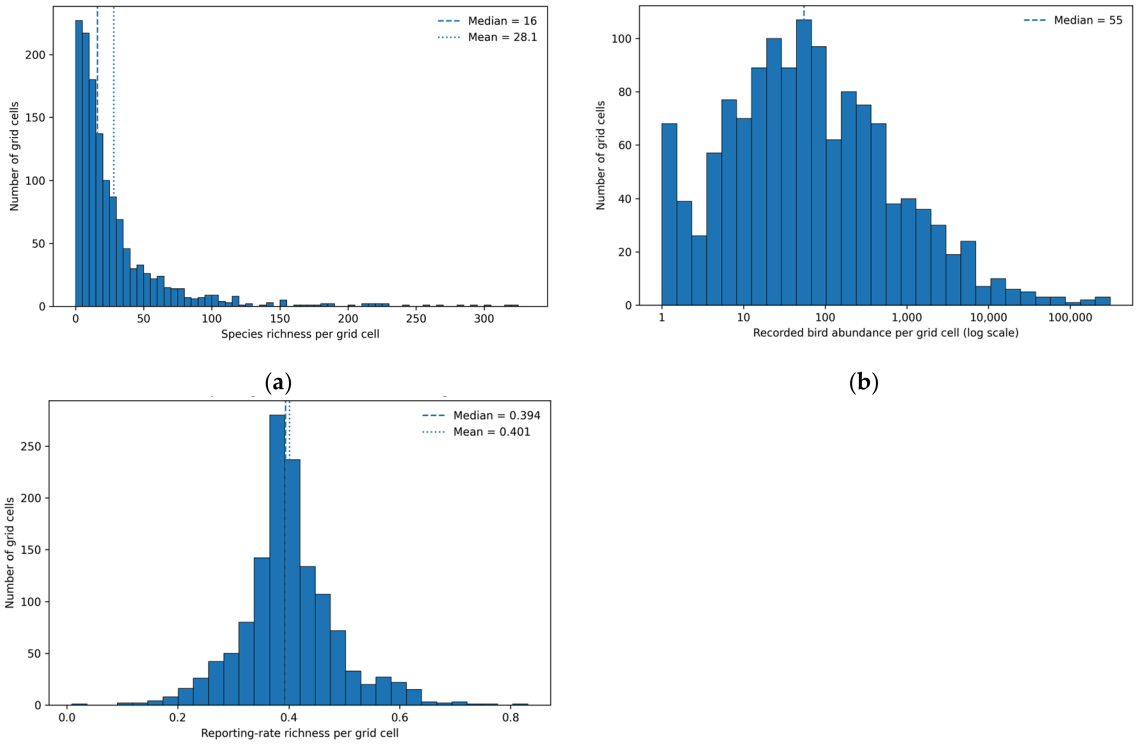


Figure 4. Histograms of the data of species richness, species abundance, and reporting rate richness: (**a**) Distribution of species richness across grid cells; (**b**) Distribution of species abundance across grid cells (log scale); (**c**) Distribution of reporting-rate richness across grid cells.

The three bird diversity indicators were significantly and positively correlated (Table 3). Species richness and species abundance showed a strong Spearman correlation (ϱ = 0.901, $p < 0.001$), whereas reporting-rate richness showed moderate correlations with species richness (ϱ = 0.467, $p < 0.001$) and recorded abundance (ϱ = 0.394, $p < 0.001$). Thus, reporting-rate richness retained information shared with the two conventional indicators while representing a distinct dimension of the citizen science observations.

Table 3. Correlations between the three bird diversity indicators and correlations with the number of bird observation reports (note: *** indicates statistical significance at $p < 0.001$).

Correlations	Spearman ϱ	Correlations	Spearman ϱ
Species richness–species abundance	0.901 ***	Number of bird observation reports–species richness	0.761 ***
Species richness–reporting rate richness	0.467 ***	Number of bird observation reports–species abundance	0.800 ***
Species abundance–reporting rate richness	0.394 ***	Number of bird observation reports–reporting rate richness	0.134 ***

Observation intensity was strongly associated with the two raw indicators. The number of bird observation reports per grid cell was strongly correlated with species richness (ϱ = 0.761, $p < 0.001$) and recorded abundance (ϱ = 0.800, $p < 0.001$), but its correlation

with reporting-rate richness was substantially weaker ($\varrho = 0.134$, $p < 0.001$) (Table 3). This pattern is consistent with reporting-rate richness being less sensitive to uneven observation intensity, although it does not demonstrate that all sources of observation bias were eliminated.

Moreover, a direct grid-cell-level comparison showed a moderate positive association between species richness and reporting-rate richness (Spearman's $\varrho = 0.761$, $p < 0.001$, Figure 5). Despite this overall positive relationship, considerable dispersion was evident across grid cells, indicating that reporting-rate richness was not simply a rescaled representation of species richness. Grid cells with similar observed species richness could have different reporting-rate richness values, reflecting differences introduced by the model-based estimation of species-specific reporting probabilities.

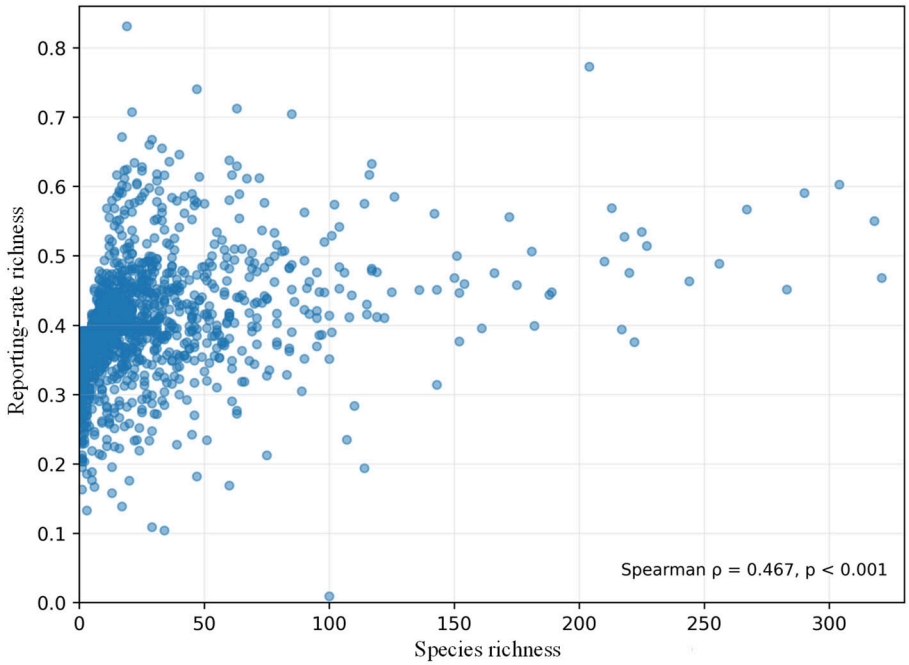
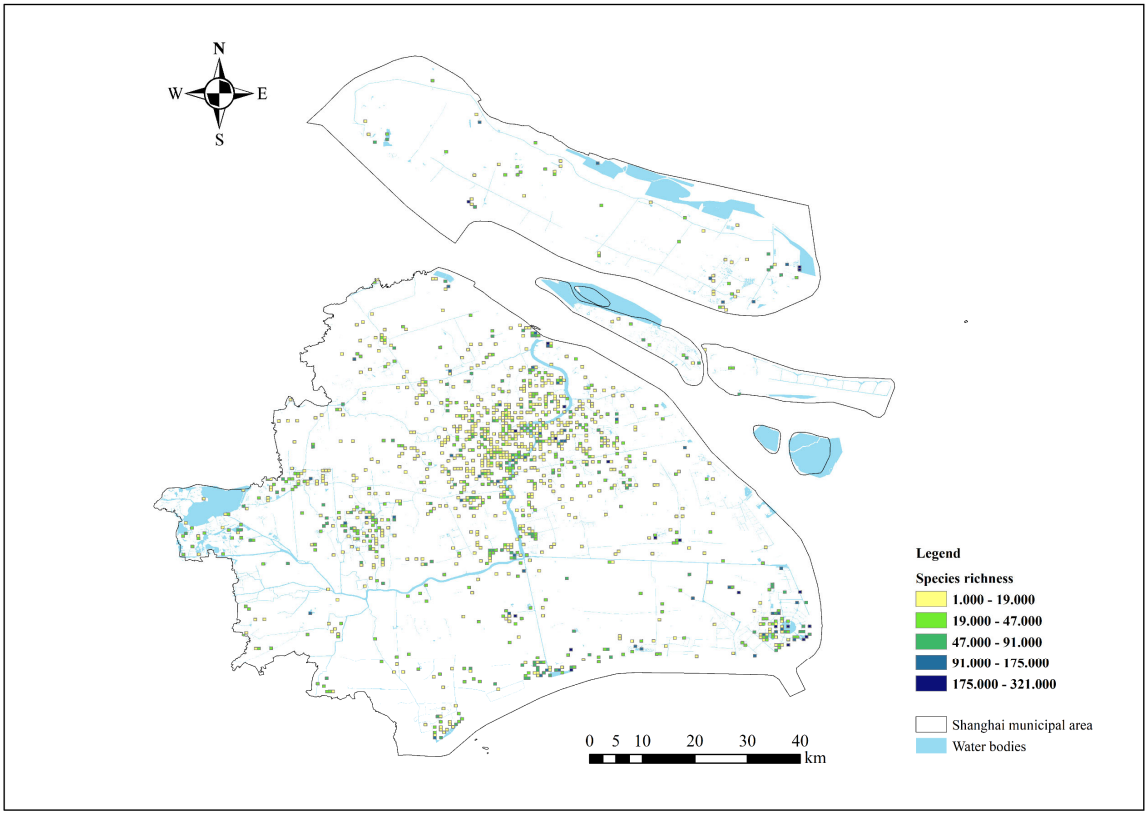
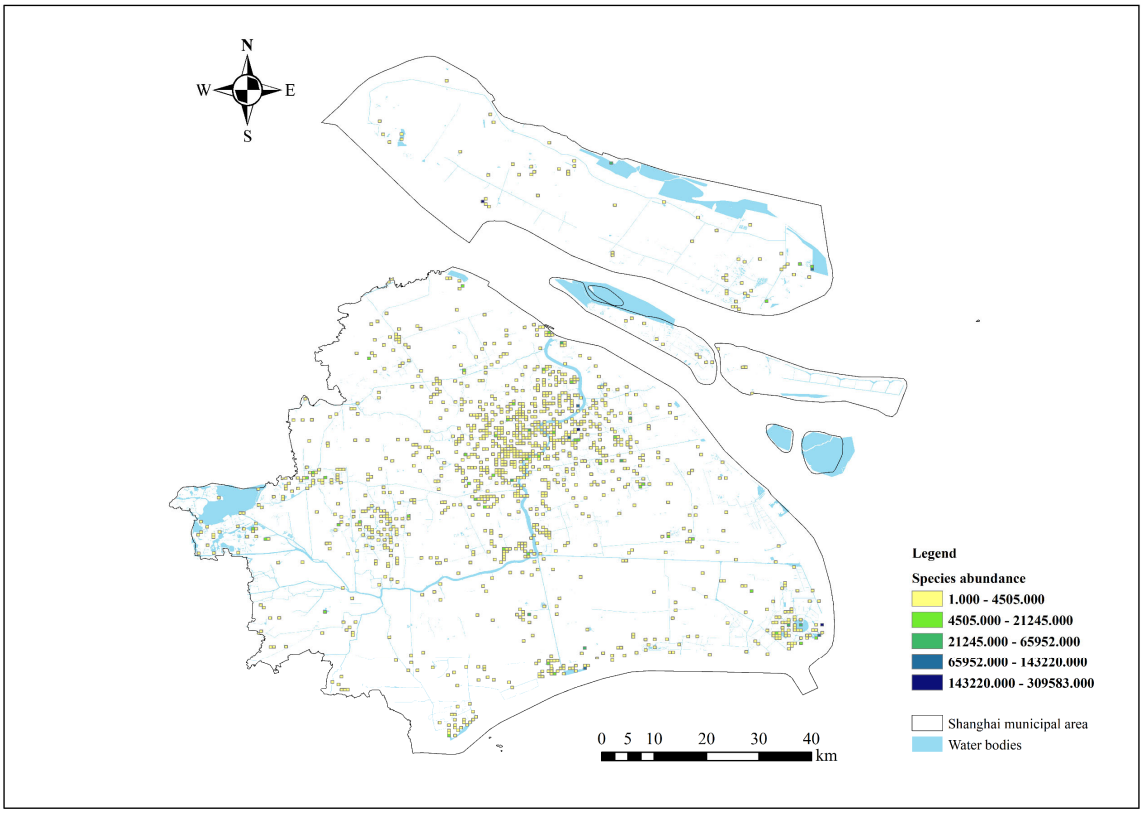


Figure 5. Scatterplot on the grid-cell-level comparison between species richness and reporting rate richness.

The three indicators showed distinct but partly overlapping spatial patterns across Shanghai (Figure 6). Recorded species richness was most densely represented in the central urban area, particularly along both sides of the Huangpu River, while additional concentrations occurred in western Qingpu near Dianshan Lake, the southern coastal districts, and the Nanhui–Lingang area in southeastern Shanghai. The highest richness values were relatively localized, with a prominent cluster in the southeastern coastal zone. On Chongming Island, observation cells were more dispersed and were frequently associated with water bodies, wetlands, and green spaces. Recorded bird abundance displayed an even more concentrated pattern. Most grid cells had low abundance, whereas exceptionally high values occurred mainly around the Nanhui–Lingang coastal area, with several smaller hotspots in the central city and other suburban ecological sites. In contrast, reporting-rate richness was distributed more continuously across the central urban area, western Shanghai, Chongming Island, and the southeastern coast. Moderate reporting-rate richness values were widespread, while higher values appeared as scattered rather than highly concentrated clusters.

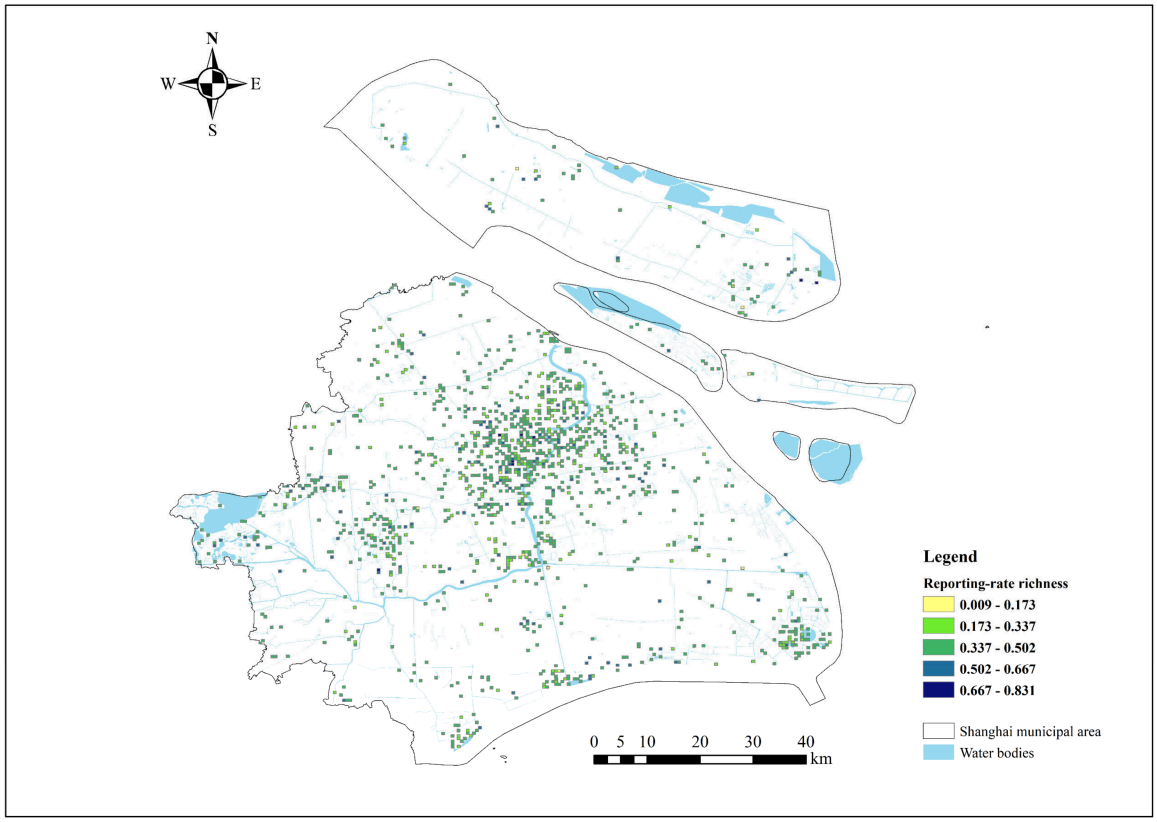


(**a**)



(**b**)

Figure 6. *Cont.*



(**c**)

Figure 6. Spatial distribution of species richness, species abundance, and reporting-rate richness in Shanghai from the CBRC platform: (**a**) Spatial distribution of species richness; (**b**) Spatial distribution of species abundance; (**c**) Spatial distribution of reporting-rate richness.

Overall, species richness and abundance were spatially concentrated in areas with dense observation activity and prominent green or blue habitats, whereas reporting-rate richness produced a less clustered pattern. This contrast suggests that the raw richness and abundance measures may be more strongly affected by uneven observation intensity, while reporting-rate richness may provide a more spatially balanced representation of the likelihood of recording different bird species across Shanghai. Global Moran's I indicated significant but relatively weak positive spatial autocorrelation for species richness (I = 0.123, permutation p = 0.001), log-transformed recorded abundance (I = 0.075, permutation p = 0.001), and reporting-rate richness (I = 0.061, permutation p = 0.001). Sensitivity analyses using four and twelve nearest neighbors produced positive and statistically significant Moran's I values for all three indicators. Species richness consistently exhibited the strongest spatial autocorrelation, whereas the relative difference between recorded abundance and reporting-rate richness varied with the spatial weights definition.

Across the grid cells, distance from the city center was positively associated with recorded species richness (Spearman's ϱ = 0.266) and recorded bird abundance (ϱ = 0.181), but it was only weakly associated with reporting-rate richness (ϱ = 0.048). The number of reports was also only weakly related to distance (ϱ = 0.047).

4. Discussion

4.1. City-Scale Bird Diversity Revealed by Citizen Science Data

Using nearly 390,000 observation records, this study found observations of 345 bird species and 2,436,951 individual birds across Shanghai in 2024. The data provided a city-scale view spanning dense urban districts, suburban landscapes, islands, estuarine

wetlands, and coastal habitats. This broad coverage is consistent with previous applications of eBird and other citizen science platforms, which have supported bird diversity analyses across multiple urban green spaces, cities, and regions [24–32]. The present study further demonstrates the potential of the CBRC for urban bird diversity research at a scale that might be difficult to achieve through conventional surveys alone.

Comparison with previous field-based surveys in Shanghai further helps contextualize the present findings. Importantly, the species composition showed substantial consistency for commonly occurring urban birds. All 32 species recorded by the conventional line-transect survey in Shanghai's Chunshen Park [37] were also represented in the present CBRC dataset. Moreover, *Pycnonotus sinensis*, *Spilopelia chinensis*, *Turdus mandarinus*, and *Cyanopica cyanus*, identified as dominant species in the Chunshen Park survey [37], were all among the 20 most frequently recorded species in our dataset, with *Spilopelia chinensis*, *Pycnonotus sinensis*, and *Turdus mandarinus* ranking first, second, and third, respectively. This consistency suggests that citizen science data capture important common components of Shanghai's urban bird community.

A quantitative comparison with a previous field-based survey in Shanghai further contextualizes the present results. Wang et al. [38] conducted line-transect and point-count surveys in Shanghai's Binjiang Forest Park and recorded 64 bird species in total. Their published appendix provides a complete list of 46 terrestrial bird species. After harmonizing minor differences in species nomenclature, 45 of these 46 species were also represented in our retained CBRC dataset, corresponding to a field-survey species coverage of 97.8%. The Jaccard and Sørensen similarity indices between the 46-species field-survey list and our city-wide 345-species dataset were 0.130 and 0.230, respectively. These relatively low whole-set similarity values largely reflect the substantial difference in spatial extent and habitat coverage between a single urban park and the entire municipality, rather than poor agreement in locally recorded species. The high field-survey coverage indicates that the citizen science dataset captured most terrestrial species documented through conventional surveys.

The species with the largest numbers of records included *Spilopelia chinensis*, *Pycnonotus sinensis*, *Turdus mandarinus*, and several other widespread species commonly encountered in human-modified environments. Their prominence is broadly consistent with urban ecological filtering, through which adaptable and generalist species are more likely to persist in developed landscapes, whereas habitat specialists often decline with increasing urbanization [17–19]. These rankings, however, should not be interpreted as direct estimates of population size. Conspicuous, widespread, and easily identified species, as well as species occurring at popular birding sites, are more likely to be reported. The rankings therefore reflect both the bird community and the citizen science observation process.

Several water-associated birds, including *Egretta garzetta*, *Tachybaptus ruficollis*, *nycticorax*, and *Ardea cinerea*, were also frequently recorded. This is ecologically plausible given Shanghai's extensive river network, ponds, lakes, estuarine areas, and coastal wetlands. Previous studies have shown that urban water bodies can support higher bird diversity by increasing habitat availability and providing important resources and refuge for different bird groups [20,39]. Research in Delhi further found that pond and shoreline heterogeneity supported substantial bird richness at the landscape scale [40]. The Shanghai results therefore reinforce the importance of considering blue spaces together with terrestrial vegetation in urban bird diversity conservation.

4.2. Spatial Patterns of Recorded Species Richness and Abundance

Recorded species richness and recorded bird abundance were strongly uneven across the grid cells. Species richness was highly right-skewed, and species abundance was even

more concentrated: the highest-ranked 1% of grid cells accounted for 63.8% of all individual observations. Spatially, both indicators were densely represented in central Shanghai, particularly along both sides of the Huangpu River, while additional concentrations appeared near Dianshan Lake, in southern coastal districts, and around Nanhui–Lingang.

The central-city concentration may appear inconsistent with studies reporting declining bird richness toward highly urbanized areas. However, urban–rural relationships are not universally monotonic. Blair (1996) found that bird species richness peaked at intermediate levels of urban development [17], while subsequent studies have shown that large and heterogeneous urban green spaces, retained woodland patches, and reduced habitat isolation can help sustain bird diversity under increasing urbanization [19,25]. A global study across 137 cities likewise showed that urban bird diversity is shaped by both local habitat characteristics and broader city-level environmental conditions, rather than urbanization alone [41]. Thus, parks, riparian corridors, and water bodies embedded within central Shanghai may contribute to the observed pattern.

Nevertheless, observation effort is an important alternative explanation. Central districts contain accessible parks, waterfronts, transport connections, and large residential populations, all of which may increase citizen science participation. High species richness in a grid cell may therefore reflect genuine habitat diversity, greater sampling effort resulting from repeated visits, or a combination of both. The extremely skewed abundance distribution is particularly indicative of repeated observations at a limited number of locations. This accords with methodological research showing that volunteer records are influenced by accessibility, participant preferences, survey duration, observer expertise, and popular birding hotspots [35,36]. Species richness and abundance maps should consequently be interpreted as joint products of ecological variation and observation intensity. The suburban and coastal concentrations provide clearer ecological signals. Nanhui–Lingang contained prominent cluster of very high recorded abundance and several high-richness cells. Nanhui–Lingang forms part of an important coastal wetland landscape for migratory birds, although reclamation and hydrological modification have altered its ecological conditions [42,43]. On Chongming Island, records were more dispersed and often associated with wetlands and waterways. Mudflats, tidal creeks, and wetland vegetation at Nanhui–Lingang and Chongming Island have been identified as important habitats for migratory waterbirds [44,45], and restoration measures can increase waterbird richness and abundance [46]. These findings support the importance of the Nanhui–Lingang and Chongming Island coastal systems within Shanghai's wider bird habitat network. However, the high annual richness and abundance observed in these coastal and estuarine areas may also be interpreted in light of seasonal bird movements. Because Nanhui–Lingang and Chongming Island serve as important habitats for migratory waterbirds [42–45], temporary concentrations during migration periods may increase the number of species and individuals recorded within particular grid cells. Therefore, some of the high annual values in these areas may reflect seasonal peaks rather than consistently high bird diversity throughout the year.

4.3. Interpretation and Value of Reporting-Rate Richness

Reporting-rate richness showed a somewhat different pattern from the two raw indicators. Its values were concentrated around an intermediate range, with relatively limited skewness, and its spatial distribution was broader across central Shanghai, western suburbs, Chongming Island, and the southeastern coast. Higher values occurred as scattered cells rather than a few dominant hotspots. This contrast is consistent with reporting-rate approaches, which estimate the probability that individual species will be reported while accounting for measured characteristics of the observation process. Methorst (2024) used

reporting-rate richness derived from citizen science data as a spatial measure of the likelihood of encountering a diverse bird community [26]. Methodological guidance likewise recommends filtering records and incorporating survey effort, checklist characteristics, observer effects, and spatial sampling structure when estimating distributions or encounter rates [28,33–36].

The less concentrated reporting-rate pattern suggests that some of the extreme hotspots in raw richness and abundance may be associated with uneven observation intensity. In the reporting-rate models, report length and observation duration were used to account for measured report-level effort, while population size was included as a grid-level contextual covariate associated with spatial differences in reporting opportunities. When generating standardized reporting probabilities, report length and observation duration were fixed at their mean values, whereas population size was retained at its observed grid-cell value. The resulting reporting-rate richness therefore standardizes measured report-level observation effort while remaining conditional on the local population context. Areas with moderate probabilities of reporting multiple species thus became visible across a larger portion of Shanghai. This shifts attention from locations with the greatest volumes of records toward locations where diverse birds may be encountered more consistently, which is useful for city-scale planning and research concerning people's opportunities to encounter biodiversity.

However, the more balanced distribution does not demonstrate that bias was fully removed or that bird diversity is homogeneous. Residual bias may remain when observer identity, expertise, survey protocol, weather, and habitat accessibility are unavailable or represented indirectly. Population size may also be correlated with urban environmental conditions and should therefore not be interpreted as a pure measure of sampling effort. Model shrinkage and the aggregation of probabilities can also pull estimates toward intermediate values. Reporting-rate richness should therefore be regarded as an observation process adjusted and encounter oriented indicator rather than an unbiased estimate of true species richness. It is most informative when interpreted alongside raw richness, recorded abundance, and observation density. The three indicators of species richness, species abundance, and reporting-rate richness answer distinct questions, namely how many species were recorded, how many individual observations accumulated, and how likely a diverse set of species was to be reported.

Although the reporting-rate models showed generally good discriminatory ability, model performance was not uniform across species. In particular, the variation in Brier skill scores and calibration slopes indicates that some species were predicted more reliably than others, and successful model convergence did not necessarily imply strong out-of-sample predictive performance. Reporting-rate richness should therefore be interpreted as a model-based estimate rather than as an error-free measure of local bird diversity. Because the index aggregates predicted reporting probabilities across species, uncertainty in individual species models may propagate into the resulting grid-level richness estimates. Consequently, the spatial patterns identified using reporting-rate richness are most appropriately interpreted in terms of broad relative differences among areas rather than precise absolute values. Future studies could further quantify this uncertainty by propagating species-level prediction errors or confidence intervals into the aggregated reporting-rate richness estimates.

4.4. Implications for Biodiversity-Sensitive Urban Planning

The results provide spatial evidence relevant to the objectives of the Shanghai Biodiversity Conservation Strategy and Action Plan (2024–2035) (SBCSAP), which aims to strengthen biodiversity conservation, improve ecological spatial networks, and promote biodiversity-friendly urban development. The results indicate that bird conservation is

relevant to both peripheral ecological areas and the densely built urban core. Along the Huangpu River and within central Shanghai, protecting mature vegetation, improving riparian habitat, and strengthening connections among parks and green spaces can help sustain bird habitat where residents frequently encounter urban nature. These measures are consistent with Action 9 on habitat optimization in central Shanghai outlined in SBCSAP. Existing projects in Shanghai provide practical examples of how such interventions can be implemented in densely built environments. For example, a series of Habitat Garden projects in Shanghai's densely built environments transformed small community green spaces into biodiversity-friendly habitats in residential areas. Evidence from Beijing and Singapore demonstrated the value of water bodies, vegetation, and habitat complexity for urban birds [20,39]. Such interventions may also contribute to a broader shift toward health-supportive and biophilic urban environments, in which everyday contact with natural elements is increasingly recognized as an important component of therapeutic and salutogenic urban landscapes [47].

At the metropolitan scale, the high values around Dianshan Lake, Nanhui–Lingang, Chongming Island, and the southern coastal districts emphasize the need to conserve large wetland and open space systems as connected landscapes rather than isolated patches. The completed ecological restoration of Chongming Dongtan provides a relevant example. The Spartina alterniflora control and bird habitat optimization project combined invasive-species control, hydrological regulation, native vegetation restoration, and habitat-island construction to restore approximately 24.2 km^2 of coastal wetland habitat. Subsequent monitoring showed substantial increases in bird populations within and around the restoration area, illustrating how large-scale habitat restoration can directly support migratory waterbirds. Major ecological spaces should also be connected with smaller urban and suburban habitat nodes to facilitate movement among feeding, resting, and breeding areas, consistent with Action 5 on ecological networks outlined in SBCSAP.

Meanwhile, the relatively dispersed reporting-rate richness pattern suggests opportunities to strengthen smaller habitat nodes and ecological stepping stones, including community parks, ponds, canals, and roadside vegetation. Bird-friendly planning should therefore combine the protection of major biodiversity hotspots with improvements to ordinary urban landscapes. In these everyday green spaces, biodiversity-sensitive maintenance should also be considered alongside habitat creation [48]. Such an approach may broaden opportunities for residents to encounter diverse birds rather than concentrating these opportunities within a limited number of well-known parks and wetlands.

The results also demonstrate how citizen science data can contribute to biodiversity monitoring and assessment in Shanghai. Areas with few records or low raw species richness should not automatically be classified as low diversity areas, because some may simply be under-surveyed. Targeted field surveys and citizen science activities in poorly covered peripheral districts would help distinguish genuine ecological gaps from data gaps. The simultaneous mapping of observation intensity, recorded richness, and model-adjusted reporting-rate richness could provide a more transparent basis for prioritizing conservation and monitoring resources. These approaches may support the development of more comprehensive biodiversity monitoring systems by integrating public participation and spatially explicit biodiversity information, consistent with Action 20 on biodiversity monitoring networks outlined in SBCSAP.

4.5. Limitations and Future Research

Several limitations should be acknowledged. First, the analysis covered only 2024. Shanghai's coastal and estuarine wetlands support seasonal movements of birds, and annual aggregation may obscure differences among breeding, migration, and wintering

periods. A grid cell with very high annual richness or abundance may reflect a short period of intensive migration rather than consistently high year-round diversity. Future analyses should therefore examine seasonal variation and incorporate multiple years of CBRC data to assess the temporal stability of the identified patterns and distinguish persistent biodiversity concentrations from seasonally driven peaks associated with breeding, migration, and wintering periods.

Second, excluding species recorded fewer than 20 times improved the robustness of the broad spatial analysis but may have underrepresented rare, recently arrived, or highly localized species. Such species can be of particular conservation concern because restricted distributions and small population sizes are associated with elevated extinction risk [49]. Rather than being excluded from all analyses, low-frequency records could be evaluated separately through expert verification, photographs, and sound recordings.

Third, the reporting-rate model adjusted for selected effort variables, but some components of detection and reporting behavior remained unmeasured. Although record length and observation duration captured aspects of observation effort, other factors affecting detection probability, such as observer identity, expertise, checklist type, and survey protocol, were unavailable in CBRC. Future studies incorporating these variables may further improve reporting-rate estimation. Because checklist length can reflect both observer effort and underlying ecological richness, sensitivity analyses could also test whether its inclusion removes part of the ecological signal that the model is intended to estimate. Finally, the spatial patterns identified in this study should be interpreted at the 500 m analytical resolution. Spatial aggregation can influence the apparent intensity, continuity, and boundaries of high value areas, and a coarser grid might be expected to smooth local variation, reduce local extremes, and merge adjacent high value cells into broader spatial clusters. Therefore, some fine-scale spatial heterogeneity detected at the 500 m resolution may become less visible at larger spatial units, whereas broader regional patterns may remain relatively stable. The identified high value areas should therefore not be interpreted as scale-invariant spatial boundaries. Future multi-resolution analyses comparing alternative grid sizes would be valuable for assessing the extent to which the observed spatial patterns are robust across spatial scales and for distinguishing fine-scale local variation from broader city-level spatial structure. Integrating land cover, water-body characteristics, vegetation structure, accessibility, and human density would further enable future studies to move from describing spatial patterns of bird diversity to identifying the ecological and social mechanisms that generate them.

5. Conclusions

This study examined the spatial patterns of urban bird diversity across Shanghai using citizen science data and three complementary indicators: species richness, species abundance, and reporting-rate richness. The results revealed clear spatial heterogeneity in observed bird diversity. Species richness and abundance were generally higher in areas associated with water bodies and green spaces, while observation records were concentrated both in densely populated central urban areas and in suburban ecological spaces. In contrast, reporting-rate richness exhibited a more continuous and spatially widespread pattern rather than being concentrated in a limited number of locations, suggesting that accounting for variation in reporting processes can provide a different perspective on the spatial distribution of urban bird diversity. The analytical framework developed in this study could be applied to other Chinese cities or megacities where georeferenced citizen science bird records are available. The general workflow can provide a comparable basis for city-scale bird diversity assessment. However, several components should be adapted to local conditions, including the spatial resolution of the analytical grid, the availability

and structure of citizen science records, the selection of effort-related covariates, and local ecological and planning contexts.

The findings of our study highlight the importance of distinguishing observed patterns of bird diversity from patterns that may be influenced by uneven sampling effort in citizen science data. By incorporating reporting-rate richness alongside conventional indicators of species richness and abundance, this study demonstrates how citizen science data can be used to characterize urban bird diversity at the city scale while reducing the influence of potential observation biases. More broadly, the study extends urban bird diversity research beyond individual parks and other small-scale green spaces and provides a city-wide perspective on the spatial distribution of bird diversity. The findings can inform bird-friendly urban planning by emphasizing the importance of conserving and enhancing interconnected green and blue spaces and by demonstrating the value of citizen science data for large-scale urban biodiversity research.

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