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10 authors, including:

Xiangxu Liu
East China Normal University

Yuhao Zhao
East China Normal University

Di Zeng
East China Normal University

Yangheshan Yang
East China Normal University

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Characterizing bird species for achieving the win-wins of conserving biodiversity and enhancing regulating ecosystem services in urban green spaces

Xiangxu Liu[a], Yuhao Zhao[a], Di Zeng[a], Yangheshan Yang[a], Wande Li[a], Yi Kang[a], Guangpeng Wei[a], Xiao Yuan[b], Shunqi Bo[b], Xingfeng Si[a,*]

[a] Zhejiang Zhoushan Archipelago Observation and Research Station, Shanghai Key Lab for Urban Ecological Processes and Eco-Restoration, Institute of Eco-Chongming, Zhejiang Tiantong Forest Ecosystem National Observation and Research Station, School of Ecological and Environmental Sciences, East China Normal University, Shanghai 200241, China
[b] Shanghai Landscaping & City Appearance Administrative Bureau, Shanghai 200040, China

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ABSTRACT

Urban green spaces provide regulating ecosystem services (RS) to humans and contribute to biodiversity conservation under urbanization pressure. However, trade-offs arise while making development decisions in urban green space planning, as the prioritization of enhancing RS may not always contribute to biodiversity conservation and vice versa. Therefore, achieving a balance between these trade-offs becomes essential in promoting conservation strategies that maximize win-win outcomes for both biodiversity and RS, ultimately leading to sustainable urban development. A practical approach to strike this balance is to prioritize specific species as surrogates for population protection, thereby benefiting co-occurring species and promoting the maintenance of a high RS level. To explore this approach, we conducted monthly bird surveys in green spaces over five years along an urbanization gradient in Shanghai, China. Based on the monthly bird dataset, to begin, we used indicator species analysis to identify bird indicators for the monthly RS (which were calculated from an economic perspective). Following from that, the umbrella index was used to prioritize umbrella species for biodiversity conservation. Finally, surrogate species were selected on the basis of their identification as both RS indicators and umbrella species. Consequently, seven common species were identified as surrogates in Shanghai. The RS indicator species were mainly omnivores and tree-nesting, with most umbrella species belonging to this subset. Furthermore, understanding the population dynamics of surrogate species could provide information on overall biodiversity and RS status, facilitating the optimization of management strategies and policies in cities. Our integrated approach, which combines indicator and umbrella species, provides a tool for establishing connections between ecosystem service maintenance and biodiversity conservation. This approach is useful in promoting planning strategies to conserve biodiversity while ensuring sustainable provision of ecosystem services and can be applied in the sustainable management of human-dominated landscapes.

1. Introduction

Green spaces play a pivotal role in ameliorating the negative ecological impacts of urbanization, thereby promoting human well-being and buffering biodiversity loss in cities (Bertram and Rehdanz, 2015; Lepczyk et al., 2017). In formulating effective preservation and management strategies for urban green spaces, it is essential to understand the linkages between biodiversity and service provision (Harrison et al., 2014; Kabisch, 2015; Schwarz et al., 2017; Methorst et al., 2021). Protecting biodiversity in green spaces may indirectly contribute to the preservation of related ecosystem services, and payments for ecosystem services could promote biodiversity conservation (Watson et al., 2020; Xu et al., 2021). However, recommendations aimed at improving ecosystem services may not always result in an increase in biodiversity, and protecting biodiversity may not necessarily lead to improvements in regulating ecosystem services. For example, a study in Singapore revealed that constructing neighborhood green spaces to reduce temperature did not simultaneously increase bird richness (Jaung et al.,

* Corresponding author.
E-mail address: sixf@des.ecnu.edu.cn (X. Si).

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2020). Moreover, the co-benefits of carbon storage, pollination, and sediment erosion did not increase in green spaces exceeding 10 ha, which represented the minimum threshold required to accommodate most urban bird species (Fernandez-Juricic and Jokimaki, 2001; Grafius et al., 2018). Therefore, effective win-win management strategies can be designed and recommended by balancing biodiversity preservation with ecosystem service provision in urban areas (Xiao et al., 2018; Lin et al., 2022). For instance, the implementation of green infrastructure restoration measures effectively improved biodiversity and mitigated air pollution by strategically considering the interrelationships between biodiversity conservation and the air purification service (Capotorti et al., 2019). Yet, we still have limited knowledge of how to simultaneously protect biodiversity and enhance regulating ecosystem services in urban green spaces. To improve our understanding and inform effective management practices, we aim to propose a nuanced approach that establishes a connection between biodiversity conservation and regulating ecosystem service provision.

A practical approach to enhance biodiversity conservation while considering human well-being is to focus on certain species (hereafter surrogate species) and promote species-generated biodiversity actions (Kirk et al., 2021). Birds, being highly sensitive to environmental changes, are widely used to indicate human disturbance or environmental quality (Chiatante et al., 2021; Morelli et al., 2021). The protection of birds has the potential to enhance regulating ecosystem services and co-occurring species. For example, protecting migratory birds, such as Curlew Sandpiper (*Calidris ferruginea*) and Eastern Curlew (*Numenius madagascariensis*), can enhance ecosystem services (e.g., climate mitigation and tourism) (Xiao et al., 2021). Furthermore, protecting certain bird species, such as the Eurasian stone-curlew (*Burhinus oedicnemus*), an umbrella species in Europe, can benefit other co-existing species (Hawkes et al., 2019). Therefore, birds have the potential to function as surrogates to link ecosystem services and biodiversity in green spaces.

Here, we recommend that the selection criteria for surrogate bird species in urban green spaces should mutually benefit human well-being and biodiversity conservation. Following this, integrating indicator and umbrella species would be useful for linking ecosystem services and biodiversity conservation. Specifically, indicator species are selected through Indicator Species Analysis first, which explores the relationships between bird species abundance and ecosystem services (Birkhofer et al., 2018). Second, umbrella species can be identified based on the umbrella index, a measure of biodiversity conservation priorities that represents co-occurring species (Costa and Zalmon, 2021). Combined, we propose that bird species serving as both indicator species and umbrella species can function as surrogate species, allowing the effective management of regulating ecosystem services through their conservation.

Additionally, cities contain various green spaces characterized by heterogeneous features, including size, quality, and quantity, reflecting the economic gradient and diverse management policies (Aronson et al., 2017; Lepczyk et al., 2017). Ecosystem service provision and biodiversity conservation in these green spaces depend on their specific types. For example, parks, public gardens, and woodlands showed better pollutant removal capabilities compared to motorways, tree-lined streets, and private gardens (Graca et al., 2018). Moreover, urban forests supported greater bird diversity and abundance than urban parks (de Groot et al., 2021). Furthermore, forests exhibited the potential for co-benefits between bird conservation and regulating ecosystem services (i.e., carbon sequestration), while other green space types received relatively less emphasis in this regard (Sabatini et al., 2019). Thus, it is crucial to understand the relationship between bird populations and regulating ecosystem services in diverse green space types. This could inform effective and suitable urban planning policies that guide management tailored to specific biodiversity requirements within each green space type.

We explored the potential of birds as a surrogate index, capable of reflecting high levels of biodiversity and regulating ecosystem services (RS), at 12 urban green space sites representing three distinct types (i.e., forest parks, urban parks, and green belts) located in Shanghai, China. We hypothesized surrogate bird species with variations expected between forest parks, urban parks, and green belts. We first calculated the economic value of regulating ecosystem services, a critical perspective to raise awareness of the importance of ecosystems (de Groot et al., 2012). Subsequently, we investigated the potential correlation between bird species populations and monthly RS. Next, we used the umbrella index to identify umbrella bird species within each green space type. Lastly, we selected surrogate bird species based on their attributes as high-RS indicators and umbrella species and conducted further analyzes to assess their consistency across the three distinct urban green space types.

2. Materials and methods

2.1. Study area

This study was carried out in Shanghai (120°52′–122°12′E, 30°40′–31°53′N), located in the Yangtze River Delta, eastern China. Shanghai has significantly emphasized green planning to become an ecological and low-carbon city. Over the years, urban green spaces in Shanghai have experienced remarkable and rapid growth, increasing from 125,741.32 ha in 2014 to 157,785.08 ha in 2019 (Shanghai Statistical Yearbook, 2015, 2020). With this increase in green space areas, the value of ecosystem services has also been significantly enhanced. For example, the value of forest ecosystem services (including forest recreation, air quality regulation, climate regulation, regulation of water flows, biodiversity protection, forest nutrient accumulation, soil fertility maintenance, and forest protection) increased from 1905 million USD in 2015 to 2203 million USD in 2019, as reported by the Shanghai Forestry Bureau. By 2019, there were 494 bird species in Shanghai, accounting for approximately 33.51 % (494/1474) of the total species of birds observed in China (bird checklist from the Wild Bird Society of Shanghai).

We focus on studying three green space types, categorized by their specific characteristics and typical use: forest parks, urban parks, and green belts (Czembrowski and Kronenberg, 2016). Forest parks are established in urban areas with a predominant tree-covered landscape and limited recreational facilities, primarily aimed at preserving biodiversity and ecosystem services (Zhao et al., 2022). Urban parks provide many recreational opportunities and require high maintenance efforts to preserve diverse and well-manicured vegetation (Xiao et al., 2017). Here, we define green belts as forested areas surrounding roads that serve to mitigate wind, noise, and particulate matter (Pathak et al., 2011). These urban green spaces are critical in regulating ecosystem services, such as air quality regulation, waste treatment, and climate regulation (Veerkamp et al., 2021). In this study, we selected 12 green space sites located on the mainland of Shanghai, including four forest parks, four urban parks, and four green belts (Fig. 1, Table S1). The four sites in each green space type were selected along an urbanization gradient.

2.2. Bird survey

In each green space study site, we surveyed bird species and abundance using line transect methods every month from March 2014 to February 2019, a total of 60 months. A transect was established along the road within each green space site to encompass the entire green space (Fig. 1). During each survey, at least two trained bird watchers walked along the transect at a constant speed (ca. 1.5 km/h) and recorded all individual birds seen or heard in the front and on both sides. All field surveys were conducted by the same surveyors. Birds flying from behind to the front of the surveyor were not recorded to prevent duplication. Surveys were conducted within an hour after sunrise to

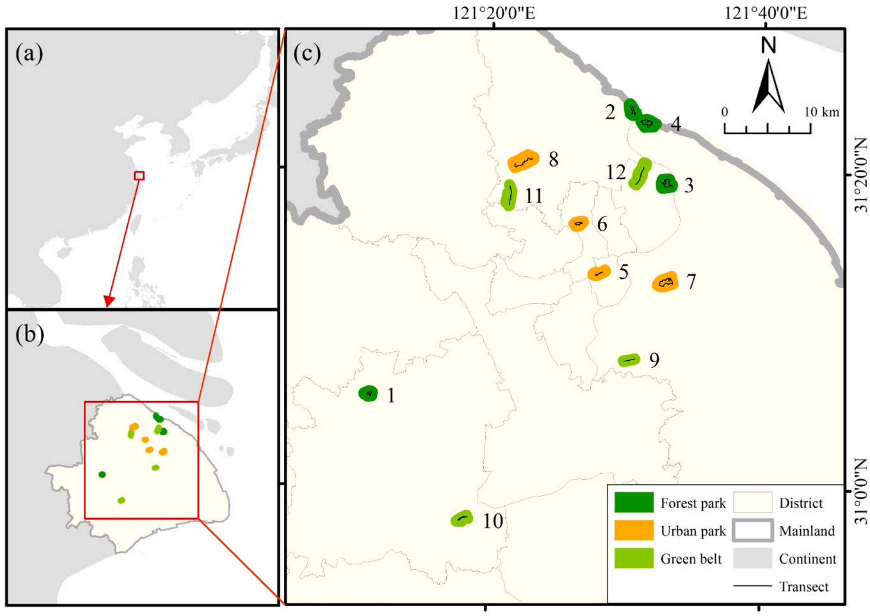

Fig. 1. Green space sites where bird surveys were conducted monthly from March 2014 to February 2019 are located along an urbanization gradient in the mainland of Shanghai, China. (a) The location of Shanghai city. (b) Study area in the mainland of Shanghai. (c) Study sites and corresponding bird survey transects in each green space type. The attributes and land use maps of the 12 green space study sites are presented individually in Table S1 and Fig. S1.

11:00 a.m. on sunny days.

2.3. Calculating regulating ecosystem services

We used the equivalent factor method proposed by Xie et al. (2017) to calculate the monthly economic value of regulating ecosystem services with respect to air quality, climate, water flow, and waste treatment for each site from March 2014 to February 2019. Before performing the calculations, we conducted field surveys combined with Google aerial photographs captured in 2018 to map each green space site into woodland, shrub, grass, water, building, and road (Fig. S1). We consider woodlands, shrubs, grass, and water as functional units that provide the regulating ecosystem services mentioned above and simultaneously serve as crucial bird habitats (Arnberger and Eder, 2012; Xie et al., 2017). To determine the value of regulating ecosystem services (RSV) in each functional unit, we first calculated the economic value per unit area of each particular regulating ecosystem service, subsequently multiplying it by the corresponding area. We summed the values obtained from the four functional units to determine the total monthly value of regulating ecosystem services within each green space site. The formulas are as follows:

$$RSV_{gj} = \sum_{1}^{i} A_{gi} \times V_{gij} \tag{1}$$

$$V_{gij} = \sum_{1}^{n} UV_{in} \times F_{gnj} \tag{2}$$

where RSV_{gj} is the total economic value of regulating ecosystem services in site g in month j, A_{gi} is the area of functional unit i ($i = 4$ in this study) in site g; V_{gij} is the unit value of regulating ecosystem services for functional unit i in site g in month j; UV_{in} is the unit area value of a certain kind of regulating ecosystem service n ($n = 4$ in this research) of functional unit i, which is the product of the standard equivalence factor (known as the economic value benchmark) and the equivalent coefficient; F_{gnj} is the dynamic regulation factor for regulating ecosystem service n in month j (the factor that strongly correlates with the specific regulating ecosystem service) in site g. We used NPP and precipitation as regulation factors to calculate monthly RSV. More detailed methods and parameter values are shown in the Supplemental materials.

2.4. Statistical analyses

2.4.1. Indicator species of regulating ecosystem services

We used Indicator Species Analysis (ISA) to investigate the monthly indicator bird species associated with regulating ecosystem services in each green space type. ISA was originally applied in exploring environmental changes and has been consistently adopted in ecosystem services studies in recent decades (Dufrene and Legendre, 1997; De Caceres and Legendre, 2009; Birkhofer et al., 2018). Indicator species were identified by the calculation of their indicator value using abundance data, with the indicator value being determined by specificity (A) and sensitivity (B). Specificity refers to the probability of a site being categorized within the target site group upon the detection of an individual of the species, with this index reaching its peak when the species is exclusively observed in the target site group. Sensitivity is the probability of the species being found in a site belonging to the target site group, and it reaches its maximum when the species frequently occur in the target group sites (De Caceres and Legendre, 2009). The indicator value (IndVal) of one species in each green space type is calculated as follows:

$$IndVal_{gi} = A_{gi}B_{gi} \tag{3}$$

$$A_{gi} = Nindividuals_{gi} / Nindividuals_{allg} \tag{4}$$

$$B_{gi} = Nsites_{gi} / Nsites_{gall} \tag{5}$$

where $Nindividuals_{gi}$ is the average abundance of species i in sites belonging to the target group g, and $Nindividuals_{allg}$ is the sum of the mean abundances of species i over all groups. $Nsites_{gi}$ is the number of sites in the target group g where species i is present, and $Nsites_{gall}$ denotes the total count of sites in that particular target group. Species with IndVal greater than 0.5 and p-values below 0.05 were considered potential indicators for target groups (Chiatante et al., 2021; Morelli et al., 2021).

In our study, the target groups in each green space type were represented by the value of regulating ecosystem services (RSV), which was used to group green space sites into monthly low and high RSV groups. We used k-mean cluster analysis, an unsupervised pattern recognition method that allowed site grouping based on data similarities by setting a predetermined number of clusters (in this analysis, two) (Hill et al., 2013; Chiatante et al., 2021). Here, we calculated monthly RSV indicator species for study sites in each green space type, considering the possibility of sites with high RSV in one month subsequently experiencing a decline to a low RSV status in another. Additionally, monthly data could mitigate the uncertainty introduced by seasonal fluctuations in RSV and bird species abundance. ISA was performed using the package *indicspecies* in R (version 1.7.9).

2.4.2. Umbrella index

We adopted the methodology of Fleishman et al. (2000) to identify umbrella species based on their co-occurrence, rarity, and sensitivity to human disturbance in each green space type. To start with, we calculated the mean percentage of co-occurring species (PCS) of each species as follows:

$$PCS = \sum_{i=1}^{n} [(S_i - 1)/(S_{\max} - 1)]/N_j \tag{6}$$

where n is the number of sites where bird species j occurs during the study period, S_i is the count of bird species in site i, S_{max} is the total count of bird species in all sites of a green space type, and N_j is the number of sites where species j occurs in a certain green space type. The PCS values range from 0 to 1.

After that, we calculated the medium rarity (R) of each bird species j followed by

$$R = 1 - |0.5 - Q_j| \tag{7}$$

where Q_j equals $N_{present}$ divided by N_{total}, $N_{present}$ is the number of sites where species j is present, and N_{total} is the number of all sites in a green space type. The R values range from 0.5 to 1.

Furthermore, we used the disturbance-sensitivity index (DSI) to calculate the sensitivity of bird species to human disturbance based on life histories that are thought to be influenced by human activities (Fleishman et al., 2000). DSI is measured as follows:

$$DSI = \sum_{i=1}^{n} X_i / X_{\max} \tag{8}$$

where X_i is the sensitivity value for each trait i and n is the total number of life-history traits. X_{max} is the maximum sum for one species in the bird database. Thus, the DSI values range from 0 to 1. The disturbance sensitivity index (DSI) for birds in Shanghai was based on three life history traits: fecundity, nest form, and habitat specificity. These traits are of significant importance as they can influence the probability of bird species experiencing population declines in response to human activities in urban areas (Baudains and Lloyd, 2007; de Matos Sousa et al., 2021; Kurucz et al., 2021). For each of the three parameters (Table 1), we assigned an integer value ranging from 1 (low sensitivity) to 4 (high sensitivity) for each species.

Finally, the umbrella index (UI) for each species is calculated by summing the mean percentage of co-occurring species (PCS), the medium rarity (R), and the disturbance-sensitivity index (DSI). The identification of umbrella species within each green space group was based on their UI values, whereby species with UI values greater than the mean UI plus one standard deviation were acknowledged as umbrella species. All analyzes were performed in R software (version 4.0.3, https://www.R-project.org).

Bird species identified as both indicators of high RSV and umbrella species were recognized as surrogates.

Table 1
Life history criteria used to assess bird sensitivity in Shanghai, China, with a scoring system ranging from 1 (least sensitive) to 4 (most sensitive). These criteria have been adapted from Fleishman et al. (2000).

Parameter	Sensitivity score			
	1	2	3	4
Reproductive effort (eggs/year)	[10,12]	[6,10)	[3,6)	(0,3)
Nest form	cavity	shrub	tree	ground
Habitat specificity	[10,16]	[6,10)	[3,6)	(0,3)

3. Results

3.1. Bird community composition and regulating ecosystem services in green spaces

During the 60-month sampling period, a total of 140 bird species were observed, including 41 resident species and 99 migratory species (Table S2). Resident birds showed higher species richness and abundance per hectare compared to migratory birds in each green space type (Fig. 2). We exclusively focused on resident forest birds due to their prolonged presence in a given region (Morelli et al., 2021), enabling them to detect changes in green spaces promptly. Consequently, the 41 resident species were subjected to the following analyzes (Table S3). The richness of resident birds per hectare was higher in green belts (mean = 0.28) compared to urban parks (mean = 0.16) and lowest in forest parks (mean = 0.15) (Table S1). The highest abundance of resident birds per hectare was observed in green belts (mean = 3.00), followed by urban parks (mean = 2.84) and forest parks (mean = 2.42) (Table S1). Light-vented Bulbul (*Pycnonotus sinensis*, $n = 699$), Spotted Dove (*Streptopelia chinensis*, $n = 678$), Chinese Blackbird (*Turdus mandarinus*, $n = 661$), Cinereous Tit (*Parus cinereus*, $n = 609$) and Long-tailed Shrike (*Lanius schach*, $n = 567$) were the five most frequently observed bird species during our five-year study period in twelve green space sites per month (n_{total} = 12 green space sites × 12 months × 5 years) (Table S2).

The value of regulating ecosystem services (RSV) per hectare in the three green space types exhibited instability from March 2014 to February 2019 (Fig. 3). Notably, the mean RSV per hectare was relatively high in green belts at 5360.17 USD ha^{-1}, compared to 4643.21 USD ha^{-1} in forest parks and 5282.20 USD ha^{-1} in urban parks. Additionally, the variation in RSV per hectare was relatively higher in urban parks (standard deviation [SD] = 1832.98 USD ha^{-1}) compared to forest parks (SD = 1606.34 USD ha^{-1}) and green belts (SD = 1004.44 USD ha^{-1}). The lowest RSV typically occurred during summer or autumn in all three green space types (Fig. 3).

3.2. Indicator bird species of the high level of regulating ecosystem services

We found 13 bird species in forest parks, 14 in urban parks, and 16 in green belts that were significantly correlated with the corresponding RSV (Table S4). These birds were commonly observed in Shanghai, with occupancy frequencies ranging from 12.78 % to 97.08 % in our study region (Table S3). *T. mandarinus* was a significant indicator species in forest parks and green belts, ranking among the top ten frequently recorded species (Table S4). White Wagtail (*Motacilla alba*) and Yellow-billed Grosbeak (*Eophona migratoria*) were typical important indicators in urban parks. The indicator species exhibited a high level of specificity (A) with values exceeding 0.70, while their sensitivity (B) was relatively lower, averaging 0.49 (Table S4).

3.3. Umbrella species for bird conservation

Nine species were identified as potential umbrella species for bird conservation in urban green spaces (Table 2). *M. alba* and Oriental Turtle Dove (*Streptopelia orientalis*) were regarded as umbrella species in three green space types, followed by Vinous-throated Parrotbill (*Sinosuthora webbianus*) and *E. migratoria* in two of the types. Five species were identified as representative umbrella species, namely Hwamei

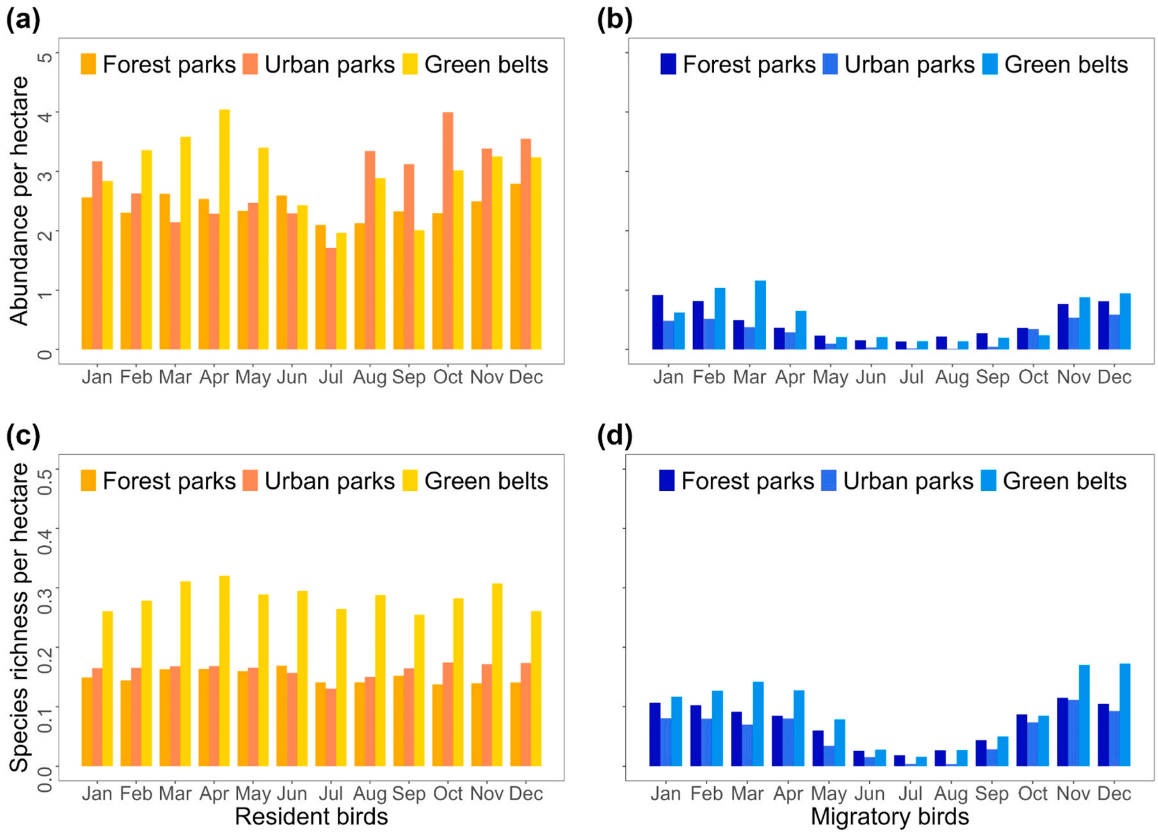

Fig. 2. Illustration of monthly mean bird species abundance (a–b) and richness (c–d) per hectare within each green space type in Shanghai, China. The number and individuals of resident bird species were higher than those of migratory birds in the same sites. Each bar represents the mean abundance or richness per hectare within each green space type for a month over five years.

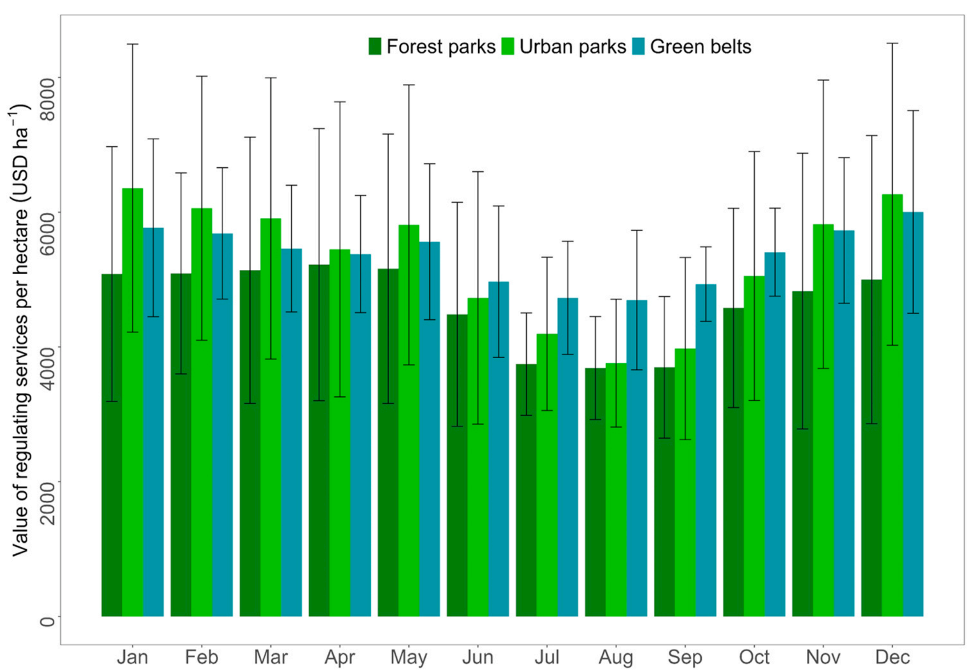

Fig. 3. Illustration of the monthly economic value of regulating ecosystem services per hectare in forest parks, urban parks, and green belts in Shanghai, China. Average values are presented as bars for each green space type in each month over five years, with error bars indicating the corresponding standard deviations.

(*Garrulax canorus*) and Common Kingfisher (*Alcedo atthis*) for forest parks, Crested Goshawk (*Accipiter trivirgatus*) and Besra (*Accipiter virgatus*) for urban parks, and Crested Myna (*Acridotheres cristatellus*) for green belts. The mean percentage of co-occurring species (PSC) among most umbrella species did not exceed 0.60 in the three green space types (Table 2). The median rarity (R) of these umbrella species often

Table 2
Umbrella bird species within forest parks, urban parks, and green belts in Shanghai, China. The mean percentage of co-occurring species (PCS), median-rarity (R), disturbance-sensitivity index (DSI), and umbrella index (UI) were calculated according to Fleishman et al. (2001). Bird species identified as indicators of the high value of regulating ecosystem services are highlighted in bold, while common species present across all three green space types are marked with asterisks. Nomenclature follows Zheng (2017).

Type	Species	PCS	RAR	DSI	UI
Forest parks	***Motacilla alba****	0.43	0.78	1.00	2.21
	Eophona migratoria	0.45	0.91	0.73	2.09
	Garrulax canorus	0.39	0.88	0.82	2.09
	Alcedo atthis	0.45	0.87	0.73	2.05
	Streptopelia orientalis	0.39	0.83	1.00	2.22
	Sinosuthora webbianus	0.39	0.86	0.82	2.07
Urban parks	***Motacilla alba****	0.38	0.87	1.00	2.25
	Accipiter trivirgatus	0.52	0.51	1.00	2.03
	Streptopelia orientalis	0.53	0.61	1.00	2.14
	Accipiter virgatus	0.60	0.50	0.91	2.01
Green belts	***Acridotheres cristatellus***	0.41	0.97	0.73	2.11
	Motacilla alba*	0.40	0.97	1.00	2.37
	Eophona migratoria	0.40	0.98	0.73	2.11
	Streptopelia orientalis	0.41	0.71	1.00	2.12
	Sinosuthora webbianus	0.37	0.89	0.82	2.08

exceeded 0.70, except for three species observed in urban parks (Table 2). All identified umbrella species were sensitive to human disturbances, with a disturbance sensitivity index (DSI) greater than 0.70 (Table 2).

3.4. Surrogate bird species

Surrogate species, identified as indicators of the high value of regulating ecosystem services while simultaneously serving as umbrella species, were predominantly from the order Passeriformes. Specifically, in forest parks, urban parks, and green belts, 5, 2, and 4 species were identified as surrogates, respectively (Fig. 4). *M. alba* was identified as the surrogate species in three green space types but did not consistently serve as the surrogate species throughout each month. *E. migratoria* was the predominant surrogate species in forest parks and green belts, while *S. orientalis* was the surrogate in both forest parks and urban parks. *G. canorus* and *A. atthis* were characteristic surrogate species in forest parks, while *A. cristatellus* and *S. webbiana* were specialized surrogates in green belts.

4. Discussion

Our approach identified surrogate bird species by simultaneously considering indicator and umbrella species, thus establishing linkages between sustainable ecosystem management and bird conservation in urban green spaces. These key species that we identified were based on continuous monthly bird data in an effort to decrease bias introduced by seasonal fluctuations in bird communities and the environment (Fraixedas et al., 2020), in contrast to previous studies primarily based on yearly observations (Hawkes et al., 2019; Chiatante et al., 2021; Morelli et al., 2021). Taking advantage of bird species as a tool to assess the status of ecosystem services and overall biodiversity may present an opportunity for urban planners to enhance their decision-making processes.

4.1. Regulating ecosystem services in urban green spaces

We followed the equivalent factor method (Xie et al., 2017) to characterize the monthly value of regulating ecosystem services (RSV) and to capture their fluctuations and discrepancies among the three green space types. A site characterized by high levels of forest, shrub, grass, and water cover in the month with high net primary productivity (NPP) and precipitation indicated a high RSV. The relatively high RSV observed in urban parks underscores the need for policymakers to consider regulating ecosystem services beyond their cultural significance when making decisions in urban planning (Stepniewska, 2021). Green belts, typically used for managing urban land expansion and providing ecological protection within cities (Tang et al., 2007), exhibited minimal fluctuations in RSV, possibly due to their limited exposure to human interference as they are located far from buildings in our study sites. Although forest parks with more woodland coverage have the potential to enhance regulating ecosystem services, their RSV per hectare may not necessarily be the highest due to complex variations in determining factors such as NPP (influenced by NDVI and microclimate), potentially arising from conflicts between biodiversity

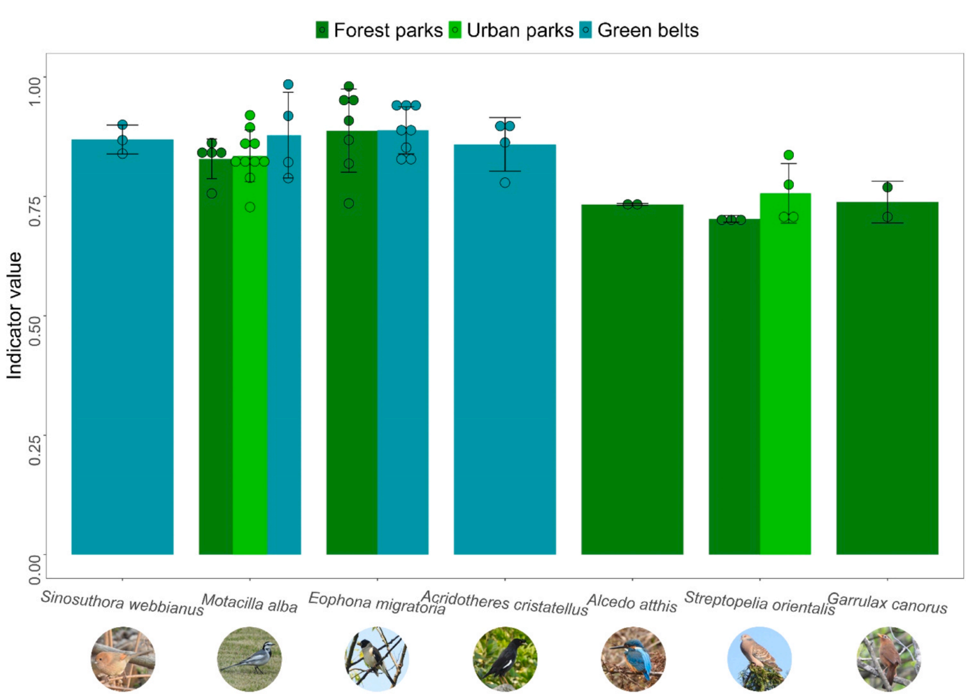

Fig. 4. Illustration of surrogate bird species identified in forest parks, urban parks, and green belts in Shanghai, China. The y-axis displays the indicator value of birds that is highly correlated with the high level of regulating ecosystem services. The count of circles corresponds to the frequency at which each species serves as a monthly indicator. Each bar represents the mean value, with error bars indicating standard deviations. The x-axis shows umbrella species (bird photo credit: Guangpeng Wei & Wande Li) according to Table 2, arranged in descending order from left to right based on their occupancy in the study sites. Nomenclature follows Zheng (2017).

conservation and recreational activities (Zhao et al., 2022).

4.2. Surrogate species in urban green spaces

We have provided evidence that bird species can serve as potential ecological indicators for RSV, based on their population variations within urban areas. These birds were common species in Shanghai, although their species identities varied between three green space types. Forest parks and green belts are mainly covered by woodlands dominated by tall and large trees with a high potential to provide regulating ecosystem services. As such, birds that prefer forest habitats, such as *T. mandarinus* (a tree-associated species; Wang et al., 2015), may serve as reliable indicators of high RSV in these green spaces. Urban parks with large trees, grass, and a relatively high impervious surface provide suitable habitats for many open-land species. Therefore, *M. alba* and *E. migratoria*, due to their versatile habitat preferences, including even human settlements (Zhao, 2001), could be indicators in these highly disturbed areas. All selected indicator species were easily detected during the survey period, indicating their potential to signal variations in RSV reliably.

The selection of bird species as indicators was further influenced by their functional traits and dietary preferences (Trindade-Filho et al., 2012). Most of the selected species were omnivores, allowing them to adapt to human-dominated environments and exhibit high resilience in response to environmental changes (Hodgson et al., 2007; Jokimaki et al., 2016). These tolerant species had a high probability of being indicators due to their wide distribution compared to other co-existing species (Martin and Bonier, 2018). Certain indicator species in urban parks, such as *M. alba* and *E. migratoria*, exhibited relatively short incubation periods and high fecundity, which may facilitate their rapid adaptation to changing disturbances. The most dependable indicator species for high RSV in forest parks and green belts were those exhibiting a preference for habitats abundant in tree cover, such as *S. orientalis* and *C. cyanus*. These species also demonstrated to be reliable indicators with average specificity (A) approaching 0.80 and sensitivity (B) approaching 0.50, thereby suggesting that the absence of these species at a given green space site indicates a low probability of the site belonging to the high RSV group.

Most identified umbrella species, often more sensitive to human disturbances than the co-existing species (Fleishman et al., 2000; Costa and Zalmon, 2021), indicated high RSV (Table 2, Fig. 4). In addition, distinct green space types serve various ecological functions. For instance, urban parks are important for providing recreational opportunities to residents and may prioritize biodiversity conservation less, whereas forest parks are designed to regulate microclimates and protect biodiversity (Ayala-Azcarraga et al., 2019; Li et al., 2022). Therefore, selecting specific umbrella bird species tailored to each green space type is an optimal strategy for effectively managing biodiversity protection. Interestingly, although they are carnivorous and prefer arboreal nest sites, *A. trivirgatus* and *A. virgatus* did not function as umbrella species in forest parks and green belts as might have been anticipated due to their potential higher occurrence there (Zhao, 2001). However, these species served as umbrella species in urban parks, which can be attributed to the increased availability of alternative habitats surrounding urban parks and the effective implementation of conservation measures within urban areas (Evans et al., 2011; Wang et al., 2022). Our findings demonstrated the presence of multiple umbrella species within each green space type, thereby providing evidence that a diverse range of umbrella species can address the requirements of co-occurring organisms (Costa and Zalmon, 2021).

Multiple surrogate species, primarily comprising omnivores that prefer arboreal nesting and are abundant in Shanghai, make their protection a dependable approach for promoting the conservation of co-occurring species in practical conservation efforts. Furthermore, the selected surrogate species effectively reflect the quality and characteristics of green space types: In particular, in forest parks, acknowledged for their considerable biodiversity due to complex vegetation cover and diverse landscapes (de Groot et al., 2021), surrogate species are the most in the three green space types (Fig. 4) and tend to have distinct dietary preferences and habitat requirements. In contrast, surrogate species in urban parks, recognized as highly disturbed areas, are relatively fewer and tend to favor open-land habitats.

4.3. Conservation implications

The primary objective of green space management is to protect biodiversity and preserve ecosystem services (Aronson et al., 2017; Liu and Russo, 2021). However, the main challenge in achieving the goal is to develop effective strategies that simultaneously conserve biodiversity and maintain ecosystem services. In this context, the identification of surrogate species represents a relatively straightforward and practical approach to informing design recommendations (Kirk et al., 2021). The conservation of multiple surrogate species guarantees the fundamental habitat requirement of most co-occurring bird species. Simultaneously, the presence of multiple surrogate species provides suitable indicators for assessing ecosystem services in dynamic urban environments. For example, a decrease in the population of surrogate bird species or a reduced frequency of detecting such species might suggest a severe disturbance to the capacity of the ecosystem to provide high-level ecosystem services. Moreover, monitoring surrogate species populations can serve as an effective tool to evaluate the effectiveness of measures aimed at biodiversity conservation and ecosystem service maintenance in urban green spaces.

Our proposed approach can be easily implemented through indicator species analysis and the umbrella index, and its applicability can be extended to other regions using bird surveys and online geodata datasets. Furthermore, the identified surrogate species are common species, making them applicable in citizen science programs for data collection. Additionally, this approach has the potential to accelerate the understanding of preserving biodiversity and ecosystem services in both short-term and long-term initiatives.

4.4. Limitations

We conducted an investigation of monthly indicator species in 12 green space sites, with four sites representing each green space type. Our study demonstrated a significant correlation between species abundance and the value of regulating ecosystem services over five years. Despite our efforts to mitigate the impacts of seasonal changes by conducting 60 repeated bird surveys, it is possible that the limited number of sampling sites for each green space type may have led to an underestimation of the complete range of bird species. Furthermore, we have not validated the effectiveness of selected bird species as surrogates in other green space sites within Shanghai, potentially limiting the generalizability of these findings to urban planning. Therefore, it is recommended that future studies should incorporate longer time series of bird data and expand sampling sites to identify surrogate species, thus enhancing the comprehensive understanding of the interconnections between sustainable ecosystem management and bird conservation. Future research should also validate the feasibility and suitability of identified bird species, particularly in monitoring programs designed for biodiversity conservation and enhancing ecosystem services in human-dominated landscapes.

5. Conclusions

We present a framework that integrates indicator species combined with umbrella species to understand the interaction between ecosystem service maintenance and biodiversity conservation. We successfully validate the efficacy of birds as surrogates for strengthening biodiversity conservation and capturing variations of ecosystem services based on bird abundance in green spaces. Furthermore, the lack of consistency in bird surrogates in three green space types emphasizes the importance of selecting multiple bird species as biological indicators. Using multiple surrogate species can enhance the reliability of indicators to capture the status of biodiversity and ecosystem services, effectively mitigating unexpected variations in abundance that may arise when relying on a single species. Therefore, our approach provides a reliable tool for developing effective species-based planning strategies by identifying multiple surrogates that establish links between biodiversity and service provision.

CRediT authorship contribution statement

Xiangxu Liu: Conceptualization, Investigation, Methodology, Software, Writing – original draft. **Yuhao Zhao:** Writing – original draft, Validation. **Di Zeng:** Methodology, Writing – original draft, Validation. **Yangheshan Yang:** Writing – original draft, Validation. **Wande Li:** Validation. **Yi Kang:** Investigation. **Guangpeng Wei:** Investigation. **Xiao Yuan:** Investigation. **Shunqi Bo:** Investigation. **Xingfeng Si**: Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ufug.2023.128064.

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