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INFLUENCE OF LAND SURFACE TEMPERATURE AND VEGETATION COVER ON BIRD COMMUNITIES IN THE URBAN LANDSCAPE OF YOGYAKARTA

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Abstract
Urbanisation alters ecological processes and reshapes biodiversity patterns, with significant implications for bird communities. This study examined avian community structure across an urban gradient in Daerah Istimewa Yogyakarta, Indonesia, by integrating field surveys with remotely sensed environmental variables. Bird species richness and composition were assessed at 300 observation points stratified by urbanisation class. Environmental predictors, including vegetation cover and land surface temperature, were derived from Landsat 8 imagery. A Generalized Linear Mixed Model (GLMM) was used to identify key environmental drivers, accounting for spatial clustering within 2×2 km grids. Model selection via backward stepwise elimination revealed that bird species richness was positively associated with vegetation cover and negatively influenced by surface temperature. These results highlight the ecological importance of vegetation in urban landscapes and the adverse impacts of urban heat on biodiversity. Enhancing green infrastructure and maintaining vegetation cover are essential strategies to support avian diversity in rapidly urbanising regions.

Keywords: Bird community structure, Generalized Linear Mixed Model, urban biodiversity

Introduction

The shrinking of natural areas (e.g., forests and wetlands) is increasingly positioning cities as providing opportunities for biodiversity conservation (Angel *et al*. 2011, Aronson *et al*. 2017). This trend encourages various stakeholders to adapt urban environments, creating suitable habitats that support the coexistence of diverse species with humans (Smith *et al*. 2018). Birds, due to their high mobility, are commonly observed among urban wildlife (Pennington & Blair 2012, Isaksson 2018). For instance, species able to withstand high-stress conditions but facing global decline, such as the Java sparrow (Mardiastuti *et al*. 2020), offer promising potential for wildlife conservation within urbanized ecosystems. Petersen *et al*. (2022) demonstrated that changes in land cover due to urbanisation do not alter bird species composition but rather shift the prevalence of certain functional groups based on habitat conditions. Additionally, a study conducted by Jernakoff *et al.* (2023) in tropical regions demonstrated that functional diversity in birds is influenced by the complexity of existing vegetation structure. The loss of vegetation structural complexity, or in other words, the decline in habitat quality, can lead to changes in bird species composition (Clergeau *et al.* 1998, Evans *et al.* 2009). For example, suboptimal habitat quality in urban areas displaces specialist bird species that rely on the presence of certain vegetation to support their survival (Fernández-Juricic 2004). These findings underscore the role of habitat quality in shaping bird communities; however, this does not diminish conservation concerns, as human-induced disturbances within urban areas still influence the survival of bird communities (Chace & Walsh 2006). Additional research by Pauw and Low (2012) highlights that urbanisation can affect specific functional groups, leading to the loss of species with critical ecological roles. These findings should be addressed with site-specific ecological evidence.

The expansion of built-up areas resulting from urbanisation frequently leads to a decline in environmental quality (Congedo & Macchi 2015). This demand for development leaves limited space for ecological regulators within urban areas (Gu *et al*. 2016, Teimouri *et al*. 2023). Urban areas typically have a lower proportion of vegetation cover compared to other land cover types. However, vegetation plays a crucial role as an ecological regulator in urban settings, offering a range of ecosystem services. One of its key functions is climate regulation (Ferrini *et al.* 2020, Rózová *et al.* 2020, Sandoval *et al.* 2024).

In an ecological context, vegetation within an urbanized ecosystem is essential for supporting bird communities. Beyond meeting basic wildlife needs, vegetation provides foraging resources and acts as a buffer against high temperatures. Urban landscapes often generate higher temperatures than surrounding areas (urban heat island effect/UHI) due to the prevalence of built-up areas relative to vegetation cover (Weng 2011, Vujovic *et al*. 2021). However, previous research has shown that incorporating vegetation into urban landscapes can significantly mitigate UHI effects (Susca *et al*. 2011, Rushayati *et al*. 2018, Zhao *et al*. 2020). This mitigation not only improves thermal comfort for humans and wildlife but also reduces energy demand for cooling (Akbari *et al.* 2001, Solecki *et al.* 2005, Cai *et al.* 2023).

Birds are among the species highly sensitive to temperature (Jimenez & Williams 2014, Andreasson *et al*. 2020, Pattinson *et al*. 2020). Elevated environmental temperatures restrict the activity range of birds due to thermoregulatory limitations (du Plessis *et al*. 2012, Freeman *et al*. 2020). Under high-temperature conditions, birds often display heat-dissipation behaviours, such as panting and seeking shade (du Plessis *et al*. 2012, Silva *et al*. 2015). However, these behaviours carry negative consequences, reducing feeding efficiency and potentially leading to the loss of body mass due to increased metabolic rates (Pis 2010, du Plessis *et al*. 2012). In tropical regions, high temperatures can have even more pronounced impacts; for example, in Costa Rica, increased mortality was observed among the rufous-and-white wren (*Thryophilus rufalbus*) during the dry season (Woodworth *et al*. 2018). High temperatures in tropical areas can also drive bird species to shift their distribution to cooler regions (Forero-Medina *et al*. 2011). Conversely, some studies have found that tropical bird species exhibit greater adaptability to elevated temperatures (Weathers 1997, Wiersma *et al*. 2007, Londoño *et al*. 2015, Noakes *et al*. 2016). Despite these physiological adaptations to temperature variation, tropical birds still have upper thermal tolerances that can be exceeded by increased urban temperatures, rendering them vulnerable to temperature increases, which can compromise their fitness and survival (Monge *et al*. 2023). Londoño *et al*. (2015) highlighted, through their findings on the efficient metabolism of tropical birds in relation to environmental temperature, the necessity for further ecological investigation into the relationship between temperature and avian species survival. Woodworth *et al*. (2018) also observed that while some species can adapt to high-temperature conditions, others remain highly susceptible.

The decline of bird species in a particular location can have adverse effects on the ecosystem. Birds function as environmental bioindicators and perform key ecosystem roles, such as pollination, especially important in fragmented vegetation within areas subject to stochastic disturbances, like urban environments (Gregory *et al*. 2003, Szlavecz *et al*. 2011, Mekonen 2017, Estevo *et al*. 2017, Xu *et al*. 2018, Fraixedas *et al*. 2020). Moreover, the characteristics of urban landscapes, which are dominated by built-up areas with minimal vegetation cover, can influence bird community assemblages due to the scarcity of high-quality habitats (Manhães & Loures-Ribeiro 2005, Leveau 2021, Wang *et al.* 2023, Suarez-Castro *et al.* 2024). This issue is not only associated with habitat availability but also with changes in macroclimatic conditions, particularly the increase in surface temperatures, which are higher compared to vegetated areas (Buyadi *et al.* 2014, Lima Alves and Lopes 2017, Gherri 2023, Yaşlı *et al.* 2023). Such conditions can undoubtedly restrict the presence of certain species that are sensitive to high temperatures, leading urban bird communities to be predominantly composed of generalist species that can adapt to more extreme environmental pressures.

Daerah Istimewa Yogyakarta (DIY) is a region in Indonesia experiencing significant climatic and spatial environmental changes. Climatically, 60% of DIY has become drier (Wredaningrum & Sudibyakto 2014), with air temperatures rising over the past three decades (Wuragil 2021). A study by Wacano *et al*. (2021) demonstrated that urban areas in DIY are particularly vulnerable to climate change. In terms of landscape configuration, spatial transformations are marked by the conversion of agricultural land to non-agricultural uses (e.g., housing, settlement, and built-up area) on the periphery of DIY's urban areas, driven by population shifts from urban centres to suburban areas (Selang *et al*. 2018, Rozano & Yan 2018). In urban areas, agricultural land is considered a valuable habitat due to the surrounding environment being predominantly built-up. This land conversion has led to a reduction in green open spaces within DIY's urban areas (Widiyastuti *et al*. 2020), despite the critical ecological role green spaces play in supporting wildlife communities (Prihandi & Nurvianto 2022, Hadi *et al.* 2024, Oropeza-Sánchez *et al.* 2025).

Previous research has investigated the dynamics of bird communities within DIY's urban landscapes. Prihandi & Nurvianto (2022) found that vegetation within green open spaces enhances bird diversity in DIY. Other studies corroborate these findings, with evidence showing that vegetation, particularly understory cover, supports greater species abundance and richness compared to areas with sparse vegetation (Utama & Nurvianto 2022). Additionally, research by Pudyatmoko *et al*. (2009) indicated that DIY's urban landscape offers better opportunities for bird conservation compared to forested areas and agroforestry. Suripto *et al*. (2020) also demonstrated that vegetation on various university campuses in DIY not only contributes to campus aesthetics but also supports bird communities. However, previous research has not incorporated temperature as a climatic variable, which can influence the success of bird conservation efforts in hot urban tropical regions like DIY. Consequently, this study aims to explain bird community responses to environmental factors in DIY's urban landscape, now subject to climatic (land surface temperature/LST) and spatial pressures through the lack of vegetation in areas with dominant anthropogenic factors. To address these aims, non-parametric statistical analysis will be used. The study thus poses the following research questions: (1) What is the structure of bird communities within DIY's urban landscape? (2) Does bird diversity respond to LST and vegetation cover in DIY's urban landscape?

Materials and methods

Study region. This study was conducted in the urban areas of DIY and its surroundings in July 2023. DIY, a province in Indonesia, is located in the central region of Java Island. Geographically, DIY lies between 7º33'-8º12' South Latitude and 110º00'-110º50' East Longitude. Administratively, DIY comprises five regencies: Sleman, Kulon Progo, Bantul, Gunung Kidul, and Kota Yogyakarta. According to data obtained from BMKG (2025), the daily temperature in DIY in 2023 ranged from 18.2 to 35.6 °C. The annual precipitation in DIY in 2023 ranged from 1 to 671 mm (BPSPDIY 2024). Given its status as the provincial capital and the most densely populated area in DIY, the research primarily focused on Kota Yogyakarta and its surrounding areas (BPSPDIY 2022).

Site Characterization. The placement of observation points was designed based on land classification using Supervised Classification. The results of this classification were used to define urban classes, as proposed by Marzluff *et al*. (2001), specifically according to the percentage of built-up areas: non-urbanized area (rural) (5-20% built up), suburban (30-50%), and urban (>50%). Land classification was conducted using the Semi-Automatic Classification Plugin in Quantum GIS (QGIS) software (QGIS 2009, Congedo 2021, UNOOSA 2025).

Landsat 8 OLI/TIRS imagery with 30m pixels was used to perform supervised classification. The overall accuracy of the classification results was 0.76, with ESA WorldCover as the reference raster (Zanaga *et al.* 2021). Accuracy assessment was conducted in R Studio using a confusion matrix approach (Günlü *et al.* 2009, Sari *et al.* 2021). The ESA WorldCover dataset was reclassified to match the land cover classes used in this study, and stratified random sampling was applied to generate 100 validation points across all classified land cover types (Olofsson *et al.* 2014). Classification values were extracted from both the supervised classification output and the reference dataset at the sampled locations. A confusion matrix was then constructed to evaluate classification performance, and accuracy metrics were calculated.

The results of the land classification were further used to stratify urbanization classes based on the percentage of built-up areas following Marzluff *et al.* (2001). A 2×2 km grid was randomly placed, and each grid cell was categorized according to the proportion of built-up area within it. This approach ensured that urbanization classes were assigned systematically while maintaining consistency with the classification criteria. The 2×2 km grid size was selected because the settlement classification by Marzluff *et al.* (2001) is most effective for areas of at least 1 km².

Environmental factors characterising the study site were generated using a macro approach (Morin 2011). Landsat 8 OLI/TIRS imagery served as the primary data source for identifying environmental characteristics. The Landsat 8 imagery, acquired in July-August 2023, was selected for its temporal alignment with the field survey, ensuring consistency between remote sensing data and ground observations of bird communities. These factors included the Normalized Difference Vegetation Index (NDVI), Normalized Difference Built-up Index (NDBI), Normalized Difference Water Index (NDWI), and Land Surface Temperature (LST). Processing of Landsat 8 OLI/TIRS imagery to derive these environmental characteristics was conducted using the Google Earth Engine (GEE) cloud platform (Gorelick *et al*. 2017) and QGIS software.

Bird survey. The bird community survey was conducted throughout July 2023, during both morning (05:30–10:00 a.m.) and afternoon (03:00–5:30 p.m.) periods. Each of the 2 × 2 km grids was subsequently divided into sub-grids of 400 × 400 meters, which represent an effective spatial scale for landbird surveys (Knutson *et al.* 2016). The survey method followed the approach recommended by Bibby *et al*. (1992), employing a 50 m radius circular plot at each observation point, with a 10-minute observation period. A total of 300 observation points (Fig. 1) were utilised, with 100 points assigned to each urban class.

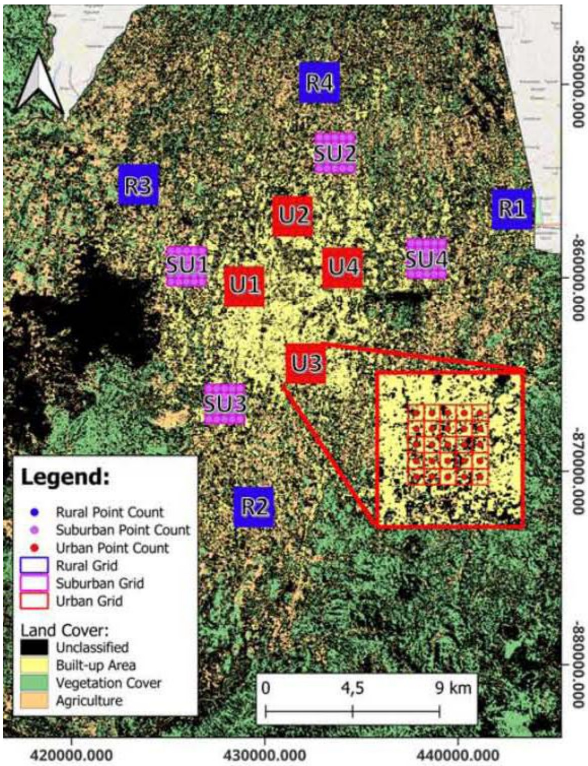

Figure 1. The study site in Yogyakarta, Central Java. Observation points were distributed across twelve 2 × 2 km grids classified into three urbanization levels: Rural (R), Suburban (SU), and Urban (U), as shown in the map. Grids were selected using a combination of stratified and systematic random sampling. Within each grid, observation points were spaced 400 meters apart, resulting in a total of 300-point counts equally divided among the three urbanization classes. The map displays the grid locations, point count distributions, and land cover types used to support classification and analysis.

Data analysis. The analysis of bird community structure commenced with describing species diversity within each urban class using the Shannon-Wiener Index, chosen for its relatively low standard error (Magurran 2004, Gaur *et al*. 2020, Novriyanti *et al*. 2021, Saka *et al*. 2022, Xu *et al*. 2022, Hadinoto *et al*. 2023, Mahata & Sharma 2023). The Shannon-Wiener Index was also selected for its effectiveness in measuring species diversity in biological communities with a few dominant species, as is typical in urban ecosystems (Szlavecz *et al*. 2011, Yeom & Kim 2011, Isaksson 2018). In addition to diversity, species dominance and abundance distribution within each urban class were illustrated using a Whittaker Rank-Abundance Plot (Magurran 2004, Ulrich *et al*. 2010). Bird abundance data were log10-transformed to aid interpretation (Magurran 2004, Ortega-Álvarez & MacGregor-Fors 2009). Further to community structure, a descriptive analysis of the mean body size of bird species within each urban class was conducted to identify any class-specific patterns. Bird species body size references were derived from literature on Indonesian bird species (MacKinnon *et al*. 2010, Eaton *et al*. 2016, Taufiqurrahman *et al*. 2022). The R Studio packages used for this analysis included Stats (R Core Team 2024) and ggplot2 (Wickham 2016).

Bird community structure was further analysed through clustering and comparison of bird species differences across urban classes. Bird species clustering or distribution was assessed using Bray-Curtis Similarity in PAST software (Hammer *et al*. 2001, Ortega-Álvarez & MacGregor-Fors 2009, Kaban *et al*. 2018, Leveau *et al*. 2018, Titoko *et al*. 2019). Comparison of bird species across urban classes was conducted using the Kruskal-Wallis test, with pairwise Wilcoxon tests as post hoc analyses (Tassicker *et al*. 2006, Abilhoa & Amorin 2017, Dröge *et al*. 2021). These analyses were performed in RStudio using the Stats package (R Core Team 2024).

To address potential non-independence among observations within the same 2 × 2 km grid, a Generalized Linear Mixed Model (GLMM) with a Poisson distribution was fitted, incorporating grid code as a random effect, as the response variable—bird species richness—represents count data (Zuur *et al.* 2010, St-Pierre *et al.* 2018). Environmental predictors, including NDVI, LST, NDWI, and NDBI, were selected based on their well-established role in explaining wildlife distribution and diversity (Nieto *et al.* 2015, Marasinghe *et al.* 2015, Ikhumhen *et al.* 2020, Azeem *et al.* 2021, Teng *et al.* 2021, Rahman *et al.* 2022, Kontsiotis *et al.* 2023, Zhai *et al.* 2024), particularly in relation to climatic and spatial variation. All continuous predictors were standardised (mean = 0, SD = 1) prior to modelling to enhance convergence and comparability of effect sizes. A backward stepwise elimination approach was applied to derive the minimal adequate model by removing non-significant predictors (Crawley 2013). While the final model was constructed using standardised values, predicted values were back-transformed to the original scale to facilitate interpretation in visualisations, which were produced using *ggplot2* (Wickham 2016), *ggridges* (Wilke 2022), *hrbrthemes* (Rudis 2020), *ggpubr* (Kassambara 2023), and *viridis* (Garnier *et al.* 2021).

Results

Community structure. A total of 45 bird species were recorded during the survey. These were wild perching birds, not domesticated pets from the local community. According to the International Union for Conservation of Nature (IUCN), most recorded species were of relatively low conservation concern (Sup. Table 1). Additionally, the species recorded were primarily synanthropic (Mardiastuti *et al*. 2020). Synanthropic species are those that have adapted to anthropogenic conditions, while synurbic species are associated with urbanised environments (Luniak 2004, Francis & Chadwick 2012). The three species with the highest densities, from most to least abundant, were the Javan Munia (*Lonchura leucogastroides*), Eurasian Tree Sparrow (*Passer montanus*), and Sooty-headed Bulbul (*Pycnonotus aurigaster*). Feeding guilds were determined by reviewing previous studies (MacKinnon *et al*. 2010, Azman *et al*. 2011, Rumblat *et al*. 2016, Mardiastuti *et al*. 2018, 2020, Muhammad *et al*. 2018, Shafie *et al*. 2023).

Based on Shannon-Wiener Index calculations, bird communities in rural areas showed higher diversity compared to those in suburban and urban areas (Sup. Table 2). This indicates that greater levels of urbanisation are associated with lower bird diversity. Additionally, species richness and bird abundance also varied across the different urban classes. The feeding guild classification of bird species at the study site included insectivorous, omnivorous, granivorous, carnivorous, and nectarivorous species (Fig. 2). Insectivorous species were dominant in each urban class (Fig. 3). The number of species in each feeding guild remained relatively stable across urban classes, except for omnivorous species, which increased in urban areas. The graph indicates that certain species were dominant in each class. The Javan Munia was the most frequently recorded bird species across all urban classes. The Sooty-headed Bulbul (in rural and suburban areas) and the Eurasian Tree Sparrow (in urban areas) were also among the dominant species.

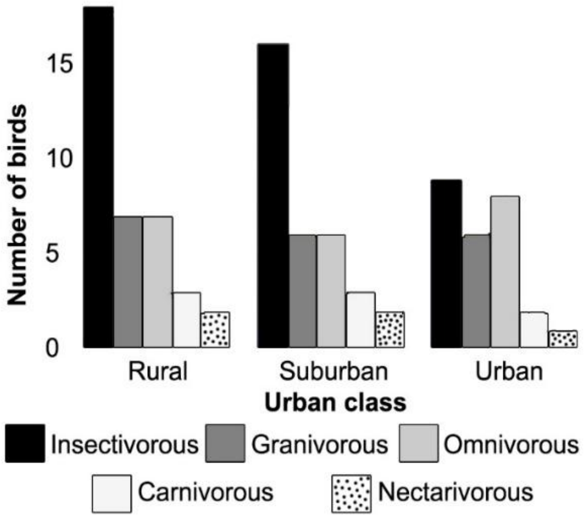

Figure 2. Composition of feeding guilds in bird communities across each urban class. Insectivorous species were the dominant feeding guild in each urban class, with the highest number found in rural areas.

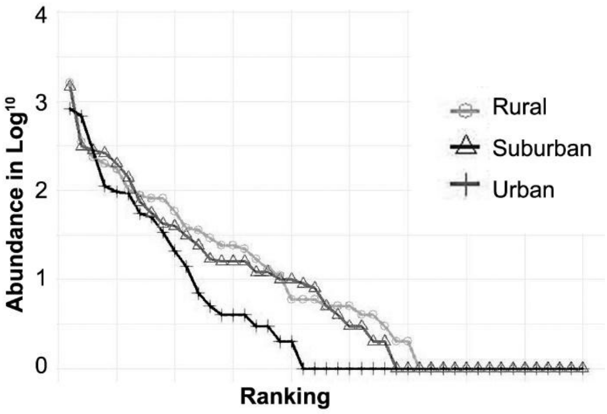

Figure 3. Bird abundance distribution in each urban class. This graph indicates that certain bird species were dominant in each urban class. The rural area shows a gradual decline, indicating greater species richness and evenness, while the urban area has a sharp drop-off, meaning a few bird species dominate while others have low abundance.

The bird communities in rural and suburban areas showed similar patterns, while the abundance distribution in urban bird communities was different compared to rural and suburban areas (Fig. 3). Steeper slopes (rapid drop in relative abundance) suggest low evenness, meaning a few bird species have much higher abundance than others. Flatter slopes (slower decline) indicate higher evenness, where abundance is more evenly distributed across urban classes. The rural areas have a more extended and gradual decline, which suggests higher species richness and greater evenness. Urban has a sharp drop-off, which means fewer dominant plots hold most of the species, with others having very low abundance. This aligns with the Bray-Curtis Similarity analysis, which found that bird communities in suburban and rural areas were more alike based on bird species composition (Fig. 4). Although visually, bird communities in suburban and urban areas appeared similar, the Kruskal-Wallis comparison and Post hoc Pairwise Wilcoxon tests showed significant differences in bird communities' species richness across all urban classes, as indicated by the differences in bird species richness recorded at the study site (Fig. 5).

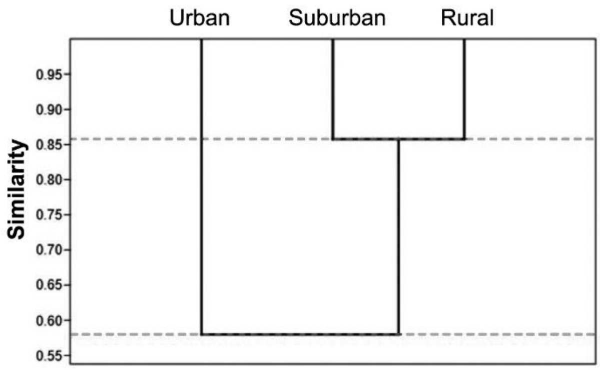

Figure 4. Bray-Curtis Similarity dendrogram of each urban class at the study site. The bird communities in suburban and rural areas tended to be similar (>85%, upper dashed line) compared to the bird communities in urban areas (<60%, lower dashed line).

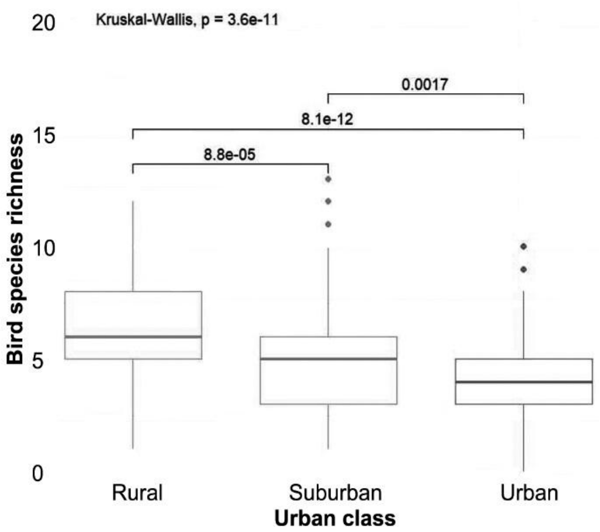

Figure 5. Comparison of bird species richness across each urban class. The differences in bird species richness in each urban class were significant.

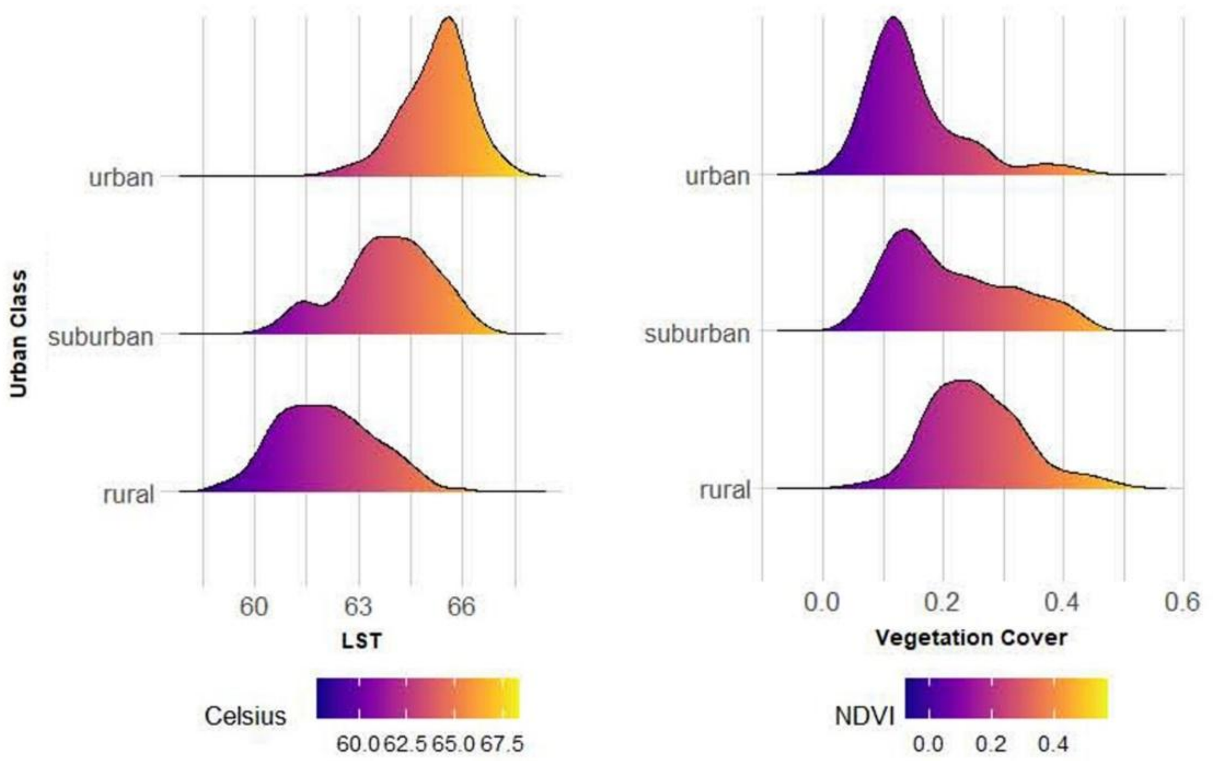

Figure 6. Visualization of surface temperature (LST) and vegetation cover (NDVI) conditions in each urban class at the study site.

Bird community response to environmental factors. As the level of urbanisation increases, vegetation cover declines while land surface temperature increases. This indicates that high-temperature areas are likely to coincide with regions with minimal vegetation (Fig. 6).

The GLMM model with Poisson error distribution showed that LST and NDVI had a significant impact on bird communities at the study site (Sup. Table 3). LST exhibited a negative association (-0.11836 ± 0.0334, $p \leq 0.001$), while vegetation cover showed a positive association (0.14129 ± 0.03278, $p \leq 0.001$) with bird species richness in each urban class at the study site. The overdispersion test yielded a chi-squared value of 231.76 with 296 degrees of freedom (overdispersion ratio = 0.78, p = 0.9977), indicating no evidence of overdispersion in the model and supporting the appropriateness of the Poisson distribution for modelling species richness (Fig. 7).

The mean body size of bird species decreases as urbanisation intensity increases at the study site. Urban areas are inhabited by bird species with relatively smaller body sizes compared to other classes. The average body size of bird species in each urban class is 16.1 ± 1.85 cm in rural areas, 14.1 ± 1.78 cm in suburban areas, and 10.8 ± 1.67 cm in urban areas (Fig. 8).

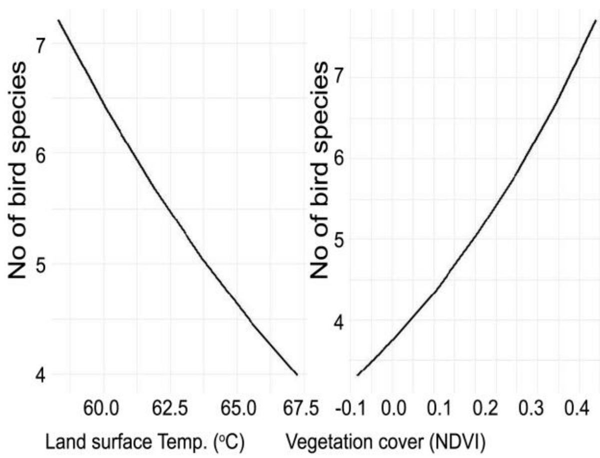

Figure 7. Bird species richness response model to a) land surface temperature (LST) and b) vegetation cover (NDVI).

Discussion

The findings of this study provide evidence that bird communities in DIY urban landscapes are associated with climatic conditions and land use. The bird species recorded were predominantly classified as Urban Exploiters and Urban Adapters, or, in other terms, synurbic species (Mardiastuti *et al*. 2018, 2020). Furthermore, bird species composition across urban classes displayed relatively similar patterns due to the dominance of a few species over others.

Bird community structure can be described by three main components: composition, diversity, and abundance (Clergeau *et al*. 1998). In each urban class, bird community composition was dominated by generalist species, as shown in Sup. Table 1 and Fig. 3, where species such as Javan Munia, Eurasian Tree Sparrow, and Sooty-headed Bulbul were dominant (Fardila & Sjarmidi 2012, Aditya *et al*. 2020). Additionally, omnivorous species predominated in urban areas. This pattern aligns with previous studies on urban bird communities, where urban landscapes are generally dominated by a few synanthropic, omnivorous species (Marzluff 2001, Concepción *et al*. 2015, Abilhoa & Amorin 2017, Isaksson 2018, Mardiastuti *et al*. 2020). The abundance distribution graph (Fig. 3) visually illustrates that urban areas display a relatively steeper slope compared to the other classes (McIntyre 2014). In line with disturbance ecology, greater ecosystem disturbance is associated with more uneven species distributions, resulting in a steeper abundance distribution graph (Battisti *et al*. 2016). Previous studies also suggest that increasing urbanisation levels often correlate with declines in ecosystem quality due to changes in ecosystem and habitat structure (Wan *et al*. 2015, Adams *et al*. 2016, Wang *et al*. 2020, Ouyang *et al*. 2021). Consequently, as urbanization alters landscapes, it impacts the types and availability of habitats for bird species, leading to changes in community composition, diversity, and abundance (Blair & Johnson 2008, Szlavecz *et al*. 2011, Silva *et al*. 2016, Larson *et al*. 2020).

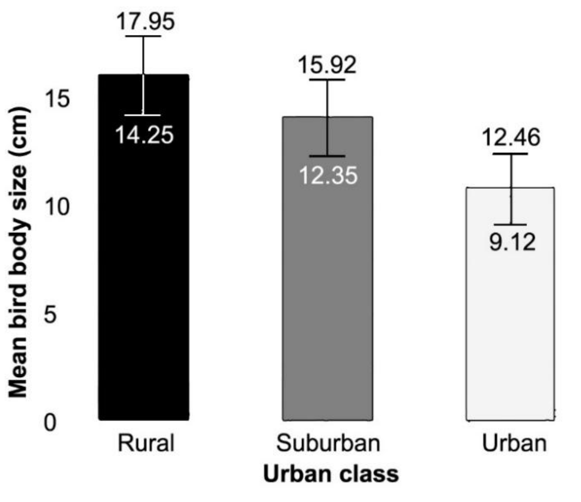

Figure 8. Mean bird body size in each urban class.

In terms of functional groups, insectivorous birds were present across all urban classes (Fig. 2). However, insectivorous species richness declined with increasing urbanisation. A similar pattern was observed by Pabico *et al*. (2021), where insectivorous species numbers decreased under heightened habitat pressure. This trend may reflect the impact of anthropogenic pressures, which reduce insect density through habitat alterations driven by settlements and built-up areas within urban landscapes (Reichard *et al*. 2001).

All functional groups recorded in this study showed a decline in species richness with increasing urbanisation, except for omnivorous species. Omnivorous species richness increased with increased urbanisation. Species such as the Yellow-vented Bulbul often thrive in disturbed and relatively open habitats (Pabico *et al*. 2021). This finding aligns with previous studies, which indicate that omnivorous species frequently persist in high-pressure environments, such as urbanised areas (Chace & Walsh 2006, Ducatez *et al*. 2015, Coogan *et al*. 2018, Gorosito & Cueto 2020, Pena *et al*. 2023). The presence of omnivorous species in urban areas is related to a relatively broader diet range compared to other species (Jokimäki & Suhonen 1998, Karjee *et al.* 2022). These species often exploit urban areas by consuming human food scraps or waste (Clergeau *et al.* 1998).

Urban areas typically exhibit low bird diversity but high abundance (Clergeau *et al*. 1998, MacGregor-Fors & Schondube 2012, Leveau 2019, Kurucz *et al*. 2021). High bird abundance in urban environments may be attributed to synanthropic species that exploit anthropogenic resources, such as alternative food sources and artificial nesting sites (Isaksson 2018). Bird communities in urban areas often have extensive breeding distributions, high dispersal capabilities, and innovative behaviours in resource utilisation within anthropogenic landscapes (Møller 2009). However, observations from this study showed that bird communities in urban areas exhibited lower abundance compared to other areas. This decline in abundance from rural to urban settings is likely due to the reduction in resources (Villegas & Garitano-Zavala 2010, Evans *et al*. 2018), resulting in comparatively lower abundance than in less disturbed areas (Francis 2015, Battisti *et al*. 2016, Srivastava 2020).

Anthropogenic pressure is not the sole threat to bird communities in urban landscapes; climatic pressures also limit opportunities for birds to access available resources (Isaksson 2018, Guillaumet & Russell 2022). Much like urbanisation, increasing temperatures contribute to a decline in avian species specialisation by altering habitat suitability and resource availability (Studds and Marra 2007, Tryjanowski *et al.* 2013, Sumasgutner *et al.* 2023). As thermal stress intensifies, species with narrow ecological niches face greater challenges in maintaining viable populations, leading to shifts in community composition (Şekercioğlu *et al.* 2012, van der Hoek *et al.* 2022). In contrast, generalist species with broader thermal tolerance and behavioural plasticity are more likely to persist, resulting in a homogenisation of bird assemblages and a loss of biodiversity at both local and regional scales (Davey *et al*. 2012).

Increasing temperatures combined with the dominance of built-up areas in urban landscapes contribute to the UHI phenomenon (Gu & Li 2018) and it exerts a profound influence on bird community dynamics by modifying species composition, breeding success, foraging behaviour, and survival strategies (Cai *et al.* 2023, Sumasgutner *et al.* 2023, Chen *et al.* 2023). While heat-tolerant generalist species demonstrate resilience and proliferate in urban environments, many specialists and thermally sensitive taxa experience population declines (Jiguet *et al.* 2006, Pipoly *et al.* 2022). This study supports this by demonstrating that urban areas have higher temperatures and lower bird species diversity compared to other areas (Sup. Table 2).

In temperate regions, bird communities in urban areas may benefit from warmer temperatures, which assist in temperature regulation. However, the opposite effect occurs in tropical regions (Wilby & Perry 2006, Isaksson 2018). The results of this study indicate that bird species richness is negatively associated with LST (Figure 7). This could be because bird species in the study area tend to avoid habitats with relatively high temperatures (Cai *et al.* 2023). Veech & Crist (2007) demonstrated that temperature significantly influences community structure, in terms of species richness, across landscapes. Furthermore, high temperatures may impair birds' adaptive abilities, potentially posing a threat to their survival (du Plessis *et al*. 2012, Xie *et al*. 2017). The findings of this study support temperature as a strong predictor of bird diversity in urban areas.

As anthropogenic disturbance intensity increases, bird communities experience a shift towards smaller-bodied species due to thermal regulation advantages, dietary flexibility, higher reproductive success, increased adaptability to fragmented habitats, and reduced vulnerability to predation and human pressures (Marzluff 2001, Liker *et al.* 2008, Isaksson 2018, Evans *et al.* 2022). In line with this trend, this study found that smaller-bodied birds were more commonly observed in highly urbanised areas, whereas larger-bodied species were more prevalent in rural regions (Fig. 8). These findings are consistent with previous studies indicating that regions with higher temperatures tend to be inhabited by bird species with smaller body sizes (Liker *et al*. 2008, Gardner *et al*. 2011, Weeks *et al*. 2022). This pattern was initially documented by Bergmann (1847), who noted that species in warmer climates generally have smaller body sizes compared to those in colder areas. Bergmann's theory was later supported by Olson *et al*. (2009), who demonstrated that temperature is a major factor driving global differences in bird body sizes. This pattern of declining mean body size is a key indicator of how ecosystems are changing in response to human activities, with long-term implications for biodiversity conservation and ecosystem functioning (Gardner *et al.* 2014).

Adaptation to temperature conditions is related to the ability of smaller birds to dissipate body heat more effectively in high-temperature environments due to their higher surface area-to-volume ratio (Gardner *et al*. 2011). Conversely, larger birds tend to face greater difficulties in responding to high temperatures, rendering them more vulnerable to elevated environmental temperatures (Porter & Kearney 2009, Pattinson *et al*. 2020). While the findings of this study are somewhat broad due to limited investigation of body size within community-level contexts (Weeks *et al*. 2022, Bosco *et al*. 2023), the observed patterns suggest that the urbanisation gradient from rural to urban areas influences not only species distribution but also the community structure of birds based on body size.

In addition to climatic factors, this study demonstrates that spatial factors within the urban landscape, particularly vegetation cover, are associated with bird species richness (Figure 7). Previous research has also identified vegetation cover as a fundamental factor affecting the dynamics of bird communities in urban landscapes (Villegas & Garitano-Zavala 2010, Naithani & Bhatt 2012, Schütz & Schulze 2015, Rodrigues *et al*. 2018, Mardiastuti *et al*. 2020, Novriyanti *et al*. 2021, Prihandi & Nurvianto 2022, Wong *et al*. 2023). Bird species diversity in an area is not necessarily driven by the diversity of plant species, but rather by the structure of the vegetation, including the extent of vegetation cover (Tworek 2007). Vegetation can provide essential resources for birds, such as food, as well as offering shelter from predators and human disturbances (Murgui 2007, Wood & Esaian 2020, Morelli *et al*. 2021). Moreover, vegetation cover can enhance connectivity for wildlife within urban environments (Morelli *et al*. 2021). Landscape connectivity for wildlife is a crucial component in promoting conservation efforts within areas modified by human activities (Douglas & Sadler 2011).

The vegetation condition and surface temperature at the study site exhibited contrasting spatial patterns, both at the landscape scale and in their influence on bird community responses. Despite the relatively low ecological and biophysical quality of urban environments, this study highlights the continued importance of natural elements, particularly vegetation, in supporting wildlife assemblages. Furthermore, the decline in vegetation cover driven by urban expansion has likely contributed to elevated surface temperatures at the study location (Husna *et al.* 2018, Dewantoro *et al.* 2021, Arif and Toersilowati 2024). Previous research has established that urban vegetation plays a critical role in mitigating surface temperature (Gherri 2023, Yaşlı *et al*. 2023). Assuming a similar relationship exists within the study area, the findings presented here may reflect analogous vegetation-mediated cooling effects, although this study did not explicitly examine the correlation between vegetation cover and LST.

Elevated temperatures in urban areas, combined with habitat pressures that leave only small habitat fragments, contribute to reducing habitat availability for certain species, especially specialist species such as woodpecker (Sup. Table 1; Fröhlich *et al.* 2022, Neate-Clegg *et al.* 2023). This finding aligns with the results of this study, which observed lower bird species richness and dominance of generalist species in urban areas with limited natural habitats. However, further research involving multi-year data is necessary to better understand the effects of environmental changes, particularly spatial and climatic factors, on bird communities. Nevertheless, the findings of this study suggest that the absence of vegetation and elevated temperatures offer valuable insights into bird community responses to environmental pressures in urban landscapes, as noted in previous studies (Gilbert 1989, Cueto & de Casenave 1999, H-Acevedo & Currie 2003, du Plessis *et al*. 2012, Schwarz *et al*. 2014, Shivanna 2022).

This study provides insights into the relationship between vegetation cover, land surface temperature (LST), and bird species richness within an urbanising landscape. The findings indicate a positive association between bird species richness and vegetation cover, as represented by NDVI, reinforcing the ecological importance of urban green spaces in sustaining avian diversity. Conversely, increasing LST corresponds with lower species richness, suggesting that rising temperatures and UHI effects may impose physiological and habitat constraints on bird communities. Despite the ecological degradation associated with urbanisation, the persistence of natural elements, particularly vegetation, continues to play a crucial role in maintaining biodiversity. The reduction in vegetation cover due to urban expansion has likely contributed to elevated surface temperatures, further exacerbating habitat constraints for thermally sensitive species. These findings highlight the need for conservation-oriented urban planning that prioritises green infrastructure to mitigate the adverse effects of urbanisation on bird communities. Integrating vegetation into urban landscapes can enhance habitat availability, support species persistence, and counteract temperature increases linked to habitat loss. Future research incorporating long-term monitoring, finer-scale habitat assessments, and species-specific thermal tolerances would provide a deeper understanding of how urban environmental changes shape avian biodiversity patterns.

Author contributions

IFN and SN contributed equally; KK improved the discussion on urban forest ecology.

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Research permits

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