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Urbanization as a driver of change: Differential ecological patterns of native and non-native parrots (Psittaciformes: Psittacidae) in an urban tropical city

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ABSTRACT

Introduction: Parrots and related birds (i.e., Psittacidae, hereafter "parrots") include species that often establish non-native populations in cities. However, little is known about their species-specific ecological patterns to urbanization in tropical cities.

Objectives: To analyze changes in species richness, abundance, and composition across different urbanization levels and to compare abundance trends of most abundant species regarding built-up, grass and tree cover at different spatial scales (i.e., 50, 500, 1 000 m) for parrots in Medellín, Colombia.

Methods: Parrot surveys were conducted from September 2021 to February 2022 (using transects, n = 10) and July 2023 to August 2023 (using point counts n = 220). Parrot abundance patterns were analyzed with Generalized Linear Models (GLMs), selecting the significant variable and best models based on Analysis of Variance (ANOVA) and Quasi-Akaike Information Criterion corrected (QAICc), respectively.

Results: We recorded ten parrot species; six of them were non-native (i.e., outside their natural range of distribution): *Eupsittula pertinax*, *Ara* spp. and *Amazona* spp. The remaining four were native species: *Brotogeris jugularis, Forpus conspicillatus*, *Pionus chalcopterus*, and *Psittacara wagleri. B. jugularis, F. conspicillatus* and *E. pertinax* were the most abundant species, *B. jugularis* increased its abundance in areas with higher urbanization levels and *F. conspicillatus* in areas with lower levels. *E. pertinax* showed higher abundances in areas with medium to high urbanization levels (51-75 %), but it showed relationships with lower statistical power.

Conclusions: Our finding suggest that the parrot assemblage in Medellín is mainly represented by non-native species in richness and composition, but native species are more abundant. Acknowledging these differences in ecological patterns in species can help improve urban wildlife management in tropical cities.

Key words: avian ecology; biodiversity conservation; synurbanization; tropical Andes; urban ecology.

RESUMEN

La urbanización como factor de cambio: patrones ecológicos diferenciales de loros nativos y no nativos (Psittaciformes: Psittacidae) en una ciudad tropical urbana

Introducción: Los loros y aves relacionadas (i.e., Psittacidae, en adelante "loros"), incluyen especies de aves que a menudo establecen poblaciones no nativas en ciudades. Sin embargo, se sabe poco sobre sus respuestas ecológicas a la urbanización en ciudades tropicales.

Objetivos: Analizar los cambios en la riqueza, abundancia y composición de especies de loros en diferentes niveles de urbanización y comparar las tendencias de abundancia en relación con las coberturas construidas, pastos y árboles a diferentes escalas espaciales (i.e., 50, 500 y 1 000 m) en Medellín, Colombia.

Métodos: Los muestreos se realizaron entre septiembre de 2021 y febrero de 2022 (utilizando transectos, n = 10) y de julio hasta agosto de 2023 (utilizando puntos de conteo, n = 220). Los patrones de abundancia de loros se analizaron con Modelos Lineales Generalizados (GLMs), seleccionando las variables significativas y los mejores modelos basados en análisis de varianza (ANOVA) y el criterio de información cuasi-Akaike (QAICc).

Resultados: Registramos diez especies de loros; seis de ellas fueron no nativas (i.e., por fuera de su rango natural de distribución): *Eupsittula pertinax*, *Ara* spp. y *Amazona* spp. Las cuatro restantes fueron especies nativas: *Brotogeris jugularis*, *Forpus conspicillatus*, *Pionus chalcopterus* y *Psittacara wagleri*. *B. jugularis*, *F. conspicillatus* y *E. pertinax* fueron las especies más abundantes. *B. jugularis* aumentó su abundancia en áreas con mayores niveles de urbanización y *F. conspicillatus* la aumentó en áreas con menores niveles. *E. pertinax* mostró mayores abundancias en áreas con urbanización media a alta (51-75 %), pero los modelos tuvieron menor poder estadístico.

Conclusiones: Nuestros hallazgos sugieren que el ensamblaje de loros en Medellín está representado principalmente por especies no nativas en riqueza y composición, pero las especies nativas son más abundantes. Reconocer estas diferencias en las respuestas ecológicas de las especies puede ayudar a mejorar la gestión de la fauna urbana en ciudades tropicales.

Palabras clave: ecología aviar; conservación; sinurbanización; Andes tropicales; ecología urbana.

INTRODUCTION

Urban growth is one of the most prominent challenges to biodiversity conservation (Piano et al., 2020). The transformation of landscapes into urban environments is mainly characterized by the replacement of pre-existing vegetation with highly human-related land cover (Radomska & Horobtsov, 2019). Although urbanization represents environmental constraints for most species of the regional pools (Belmaker & Jetz, 2013; Evans et al., 2018; Hansen et al., 2023), some are able to persist and even increase their populations in such environments (Isaksson, 2018). Particularly in birds, assemblages often include highly abundant non-native species or widely distributed native species (Marcolin et al., 2023; Sol et al., 2011). These birds that maintain or expand their populations in cities usually exhibit high environmental tolerance (Neate-Clegg et al., 2023; Wang & Liu, 2021), by taking advantage of the reduction of ecological pressures (e.g., predation, interspecific competition) (Evans et al., 2021; Martin-Albarracin et al., 2015) or the proliferation of emerging resources (e.g., artificial nesting sites and human-related supplementary food) (Lazarina et al., 2020). In addition, some urban bird assemblages include species that are illegally trafficked (Chan et al., 2021; Restrepo-Rodas & Pulgarín-Restrepo, 2021) and then released into areas outside of their natural distribution (i.e., non-native species) (Carpio et al., 2020).

Parrots and related birds (i.e., Psittacidae, hereafter "parrots") exemplify a heavily trafficked bird lineage with up to 16 % of species having established non-native populations worldwide, including cities (Menchetti & Mori, 2014; Dickinson et al., 2023). Several parrot species are considered generalist or opportunist on either feeding or nesting behavior, including the use of exotic trees (Ragusa-Netto, 2025) and human-related resources for feeding or nesting (Borray-Escalante et al., 2020; Santiago et al., 2023), frequently outcompeting

native species (Louarn et al., 2016; Strubbe et al., 2010; Mori & Menchetti, 2021). However, most of the current knowledge on the establishment of parrots in cities derives from temperate regions (Blackburn & Duncan, 2001; Minor et al., 2012). In tropical regions it remains unclear whether urbanization represents opportunities or limitations for native and non-native species, beyond non-systematic observations (Fragata et al., 2022; Lara-Vásquez et al., 2007; Londoño-Betancourth, 2011; Jezuíno et al., 2021). In Neotropical countries such as Colombia, some parrots are among the most trafficked species (Restrepo-Rodas & Pulgarín-Restrepo, 2021) with frequent reports of incidental or voluntary releases of non-native species into cities (Flórez, 2008). This can drive changes in local parrot assemblages in cities such as Medellín (Colombia), where up to 71 % of parrot species are considered non-native (Flórez, 2008), which provides an opportunity to test contrasting urban ecological patterns within the same bird lineage.

Considering that parrots have a high proportion of threatened species worldwide (Daut et al., 2016), but they also have the potential to become invasive species (Menchetti & Mori, 2014; Uehling et al., 2019), the understudied presence of these birds in tropical cities implies a knowledge gap in both ecology and conservation. Thus, we aimed (i) to analyze changes in species richness, abundance, and composition of the parrot assemblage in Medellín (Colombia) across different urbanization levels, explicitly considering the distinction between native and non-native species, and (ii) to compare the abundance trends regarding the percentage of built-up, grass and tree cover for the most abundant species. Based on previous knowledge, we hypothesized that (i) widely distributed native and non-native species would be more related to higher urbanization levels, and (ii) narrowly distributed native species would show the opposite pattern. Therefore, we predicted that overall parrot species richness and abundance would increase with urbanization level, mainly due to non-native and widely distributed native species increasing their abundances towards sites with higher percentage of built-up cover. In contrast, narrowly distributed native species would increase their abundances towards sites with lower urbanization levels, including sites with either higher grass or tree cover.

MATERIALS AND METHODS

Study area and land cover classification: The study area includes Medellín and six adjacent municipalities in Colombian Andes (hereafter Medellín, 6°15' N & 75°34' W, 1 500 to 3 000 m.a.s.l.) (Ramírez-Cardona & Jiménez-Mejía, 2023) (Fig. 1). This urban continuum is mostly covered by built-up areas, which occupy approximately 80 % of the landscape (Paniagua-Villada et al., 2024). Land cover types were described based on supervised classification methods (Mohd-Hasmadi et al., 2009), following Paniagua-Villada et al. (2024) from 10 × 10 m-resolution satellite images (Sentinel-2). We define three types of land cover: built-up, representing areas dominated by buildings, roads and other infrastructure; grass, areas dominated by herbaceous and shrubby vegetation; and trees, areas dominated by woody vegetation. The percentage of each land cover type was defined at buffers of 50, 500, and 1 000 m from each point centroid or transect established for parrot surveys, to account for potential scale-dependent variability, including local and landscape scales (Harms et al., 2017).

Parrot surveys: Two independent parrot sampling methods were carried out to account for potential differences on spatial patterns exhibited by often highly mobile parrot species. Following Bibby et al. (1992), we established transects and point counts, both with a fixed observation distance of 50 m (Fig. 1). Transects were located across the city at sites with different urbanization levels (ranging from 2 to 84 %, each transect categorized according to the total percentage of built-up cover at the 50 m observation distance, n = 10). These 1 km long transects were visited four times by the same observer (JAG-C) during 20 min, from September 2021 to February 2022. Point counts were

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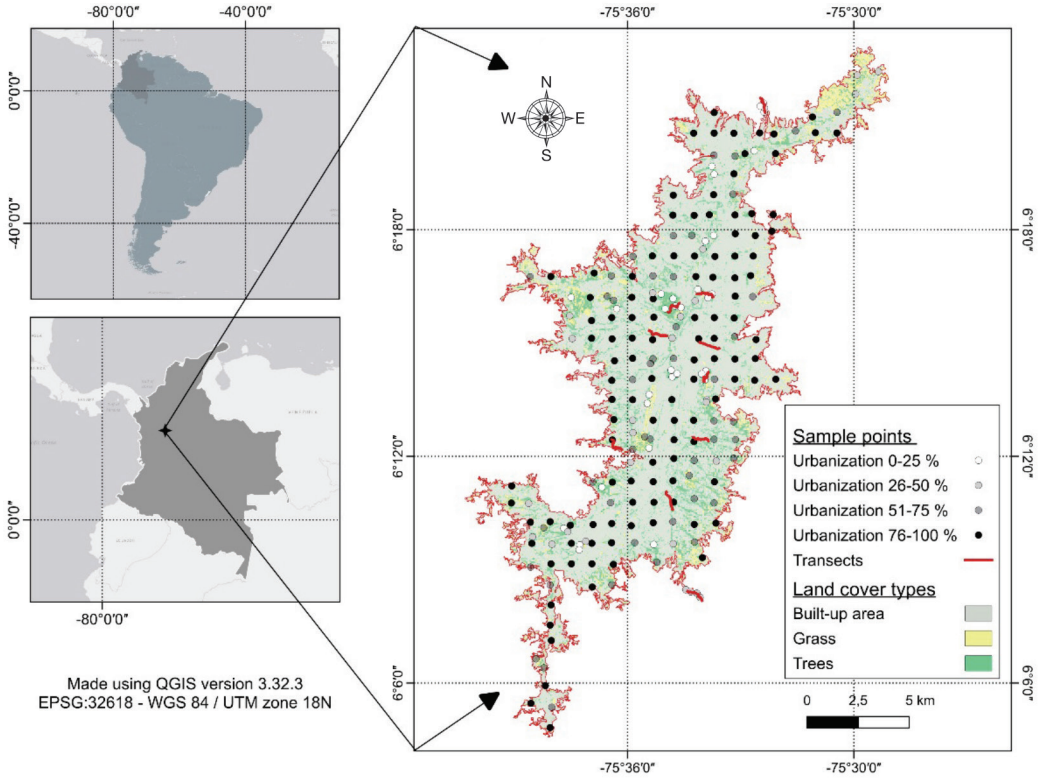

Fig. 1. Study area: Point counts and transects established for parrot species surveys across urban areas of Medellín and adjacent municipalities in Colombian Northern Andes. The map includes three different land cover types (i.e., built-up, grass, and tree cover), with point counts coded by gray intensities to show their corresponding urbanization level.

located based on a 1 × 1 km² grid across the city (179 points counts), relocating points to the closest accessible site when necessary (i.e., to avoid unavailable sites). We established 41 additional point counts within green spaces larger than 10 ha, locating them at minimum 200 m from previously established point counts, but averaging 735 m between them (= mean nearest-neighbor distance across 220 points counts) to avoid potential bird recounting (Bibby et al., 1992). All point counts were assigned to urbanization levels based on the percentage of built-up cover at the 50 m observation distance, using ranges each 25 %: 0-25 %, 26-50 %, 51-75 %, and 76-100 % of built-up cover. Point counts (n = 220 overall) were visited twice by the same observer (JAG-C) during 5 min, from July 2023 to August 2023. Parrot observations based on both transects and point counts methods were conducted between 05:30 and 10:30 hours, always under favorable weather conditions (i.e., without heavy rain or winds). Visual and auditory detections were recorded, but only visual records were included in abundance analyses (auditory records were used solely to confirm species presence/absence). Similarly, flying birds were only considered for the species composition (not for analysis on species richness and abundance).

Data analysis: Parrot species were classified as native or non-native. Native species were defined as parrots whose historical distribution encompassed the study area (Medellín and adjacent municipalities), according to records dating back at least 100 years. We

assessed parrot species richness, abundance, and composition across the urbanization gradient independently for transects and point counts. Transects were considered independent sampling units, each with a specific percentage of urbanization (SMT 1). On the other hand, because most points counts fell into highly urbanized areas (75-100 %), for data analysis, we randomly selected 20 points counts per urbanization level (0-25 %, 26-50 %, 51-75 % and 76-100 % of built-up cover) to reduce bias toward urbanized sites. In addition, the parrot abundance in each urbanization level was standardized to facilitate comparisons and avoid potential bias regarding sampling effort differences. This was done by dividing the total number of individuals of each species by the number of sampled points counts per urbanization level, reflecting the relative abundance per unit of sampled area. In both, transects and point counts, the abundance of each parrot species corresponded to the maximum number of individuals counted in a single repetition (i.e., the maximum accumulated count in the two repetitions per point count, conducted in the same day, or the maximum accumulated count in the four repetitions per transect, conducted in different days).

To assess statistical differences in parrot species richness, abundance, and composition across urbanization levels, we used point counts data. We estimated the cumulative species richness based on rarefaction methods with 1 000 bootstrap replications (Gotelli & Colwell, 2001), using the iNEXT R package (Hsieh et al., 2016). Statistical significance for pairwise differences between urbanization levels was determined by examining the non-overlapping 84 % confidence intervals (CI, see MacGregor-Fors & Payton, 2013) (SMF 2) Regarding overall parrot abundance, we used violin plots and the General Linear Hypothesis Tests to assess statistical significance across urbanization levels ($p < 0.05$), based on contingency tables from a General Lineal Model (GLM, quasi-Poisson distribution of error). We tested differences in parrot assemblage composition using a Permutational Multivariate Analysis of Variance (PERMANOVA, adonis2), with built-up area at multiple spatial scales as explanatory variables (SMT 2, SMT 3).

Finally, to assess the relationships between the most abundant parrot species and the built-up cover percentages across spatial scales (i.e., 50, 500 and 1 000 m), we followed a multi-model inferential approach (Burnham & Anderson, 2002). This information-theoretic procedure allowed us to select the most relevant variables based on how well they explain the data, considering a set of competing models (Grueber et al., 2011). First, we conducted an exploratory correlation analysis (correlation matrices) to identify potential autocorrelation issues across land cover types (built-up, grass and tree cover) and scales (50, 500 and 1000 m) using the stats package (R Core Team, 2023) and the Performance Analytics R package (Peterson & Carl, 2020). After excluding variables with significant Pearson's correlation coefficients with $r2 > 0.5$ and $p < 0.05$ (Zuur et al., 2010), keeping the variables showing the highest variance, we generated GLM with a quasi-Poisson error of distribution, because data showed overdispersion with Poisson distribution (Brooks et al., 2017; McCullagh & Nelder, 1989). We based model selection on the quasi-Akaike Information Criterion corrected for small sample sizes (QAICc) to compare and select the best models ($\Delta QAICc \leq 2$), using the deviance instead of "$2 \log(L(\hat{\theta}))/c$" as an approximation (Burnham & Anderson, 2002; Bolker, 2008). We calculated Variance Inflation Factors (VIF) for all predictor variables in the best models and excluded those models with variables showing $VIF \leq 5.0$. Only species with presence in at least two sampling sites and with abundances ≥ 5 individuals were modeled, to exclude accidental records or individuals from recent releases.

RESULTS

We recorded eight species of parrots combining both point counts and transects: five in point counts and all in transects. In addition, two species were reported exclusively flying over urban sites with percentage of built-up

cover < 25 %: *Pionus chalcopterus* and *Psittacara wagleri* (Table 1). Considering all records, including overflying individuals, most recorded species were non-native (six species), including *Eupsittula pertinax*, *Ara macao*, *Ara severus*, *Amazona amazonica*, *Amazona autumnalis* and *Amazona ochrocephala.* Only four species were considered native to Medellín: *Brotogeris jugularis*, *Forpus conspicillatus*, *P. chalcopterus*, and *P. wagleri* (Table 1).

Based on point count data, parrot species richness increased significantly and non-linearly with urbanization, peaking at 51-75 % of built-up cover. Parrot species richness was intermediate at 26-50 % and 76-100 %, and lowest at 0-25 % (Fig. 2, SMF 1). Although parrot abundance also peaked at the 51-75 % urbanization level, differences across the gradient were not significant (Fig. 2, SMF 2). Transect data showed similar patterns: the transect with 51 % urbanization level exhibited the highest species richness and abundance, followed by the two most urbanized transects (84 and 61 %, respectively). Regarding species composition, PERMANOVA analyses indicated that overall community composition was significantly related to built-up cover, specifically at the 1 000 m scale ($F = 5.028$, $p = 0.014$, SMT 2), although the percentage of variance explained was low ($R^2 = 0.078$, SMT 2).

Two of the three most abundant species were native—the parakeets *B. jugularis* and *F. conspicillatus*—whereas *E. pertinax* was considered non-native. On the other hand, the least abundant species were non-native (excluding the two species recorded exclusively overflying), including those parrots of the genera *Amazona* and *Ara.* However, in some cases, transects and point counts reveal contrasting patterns, particularly for rare species. For instance, *Ara* spp. were recorded only at the 51-75 % urbanization level in point counts, but in transects they occurred at sites both below and above 50 % (Fig. 2).

The three most abundant species exhibited contrasting abundance trends across urbanization levels. *B. jugularis* (native species) exhibited higher abundances at medium to high urbanization levels (Fig. 2). However, according to point count data, the abundance of *B. jugularis* was unrelated to all land cover types across all buffer distances (Table 2), while, according to transects data, this parrot species significantly decreased its abundance in sites with higher percentages of tree cover, especially at the 1 000 m scale (Table 2). *F. conspicillatus* (native species), exhibited higher abundance at lower urbanization levels (≤ 35 %, Fig 2). In this case, point counts data also showed no significant variables, while transects

Table 1
Recorded parrot species across urban areas of Medellín in Colombian Northern Andes.

Scientific name	Common name	Species status	Altitudinal range (m.a.s.l.)	Body mass (g)
Amazona amazonica	Orange-winged Amazon	Non-native	0-600	370
Amazona autumnalis	Red-lored Amazon	Non-native	0-1 550	416
Amazona ochrocephala	Yellow-crowned Amazon	Non-native	0-500	476.9
Ara macao	Scarlet Macaw	Non-native	0-500	1 015
Ara severus	Chestnut-fronted Macaw	Non-native	0-600	343
Brotogeris jugularis	Orange-chinned Parakeet	Native	0-1 400	63.2
Eupsittula pertinax	Brown-throated Parakeet	Non-native	0-1 200	89
Forpus conspicillatus	Spectacled Parrotlet	Native	100-1 800	26.4
Pionus chalcopterus**	Bronze-winged Parrot**	Native	1 400-2 400	210
Psittacara wagleri**	Scarlet-fronted Parakeet**	Native	1 000-2 500	194

We specified species' common name, as well as their status regarding origin (native or non-native), altitudinal range, and body mass (based on Wilman et al., 2014). ** Species recorded exclusively overflying.

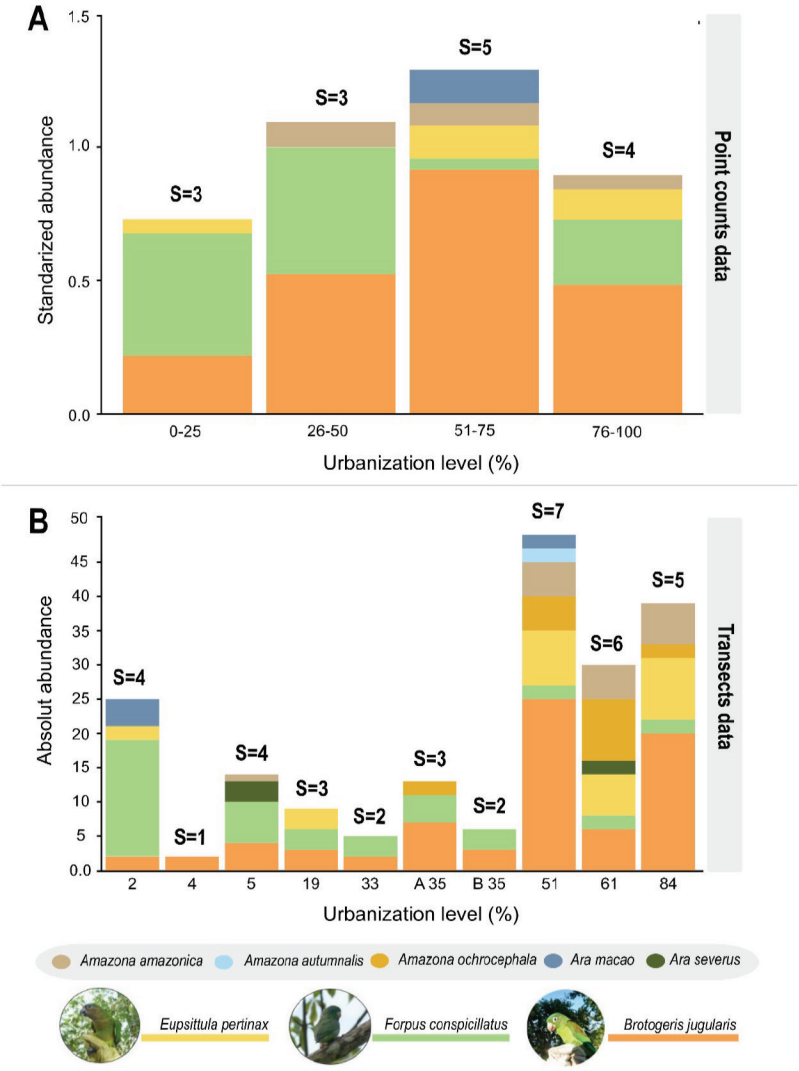

Fig. 2. A. Standardized point-based abundance. **B.** Transect-based abundance of parrot species across urbanization levels in Medellín in Colombian Northern Andes. In graph B, each bar for transect represents a different sample location with its respective urbanization level. The parrot species richness found in each urbanization level is indicated by an "S" above the corresponding bar. The data A (35 % urbanization) corresponds to a protected park within the city, while B (35 % urbanization) represents a site at the edge of an urban stream.

data showed significantly higher abundances in sites with higher grass cover at the 50 m scale ($p < 0.05$) (Table 2). *E. pertinax* (non-native) exhibited higher abundances at medium to high urbanization levels, with slightly lower numbers at intermediate urbanization levels (Fig. 2). Similarly, no significant variables were found in models based on point counts, while transect data suggest that the abundance of this species increased in sites with higher percentage of built-up cover at the 50 m scale (Table 2).

DISCUSSION

In light of the presence of highly generalist and heavily trafficked parrot species in

Table 2

Best-supported GLM models for abundances of *Brotogeris jugularis*, *Forpus conspicillatus*, and *Eupsittula pertinax* across Medellín in Colombian Northern Andes, based on transects data (point counts yielded no models with variables showing $p < 0.05$ and were therefore not presented).

Model/Variable	Association	QAIC	Δ QAICc	W	Residual d.f.	χ^2	p-value
***B. jugularis* models**							
Abundance = Tree cover at 1000 m		27.74	0.00	1.00	8.00	53.05	< 0.001
Tree cover at 1000 m*	-				8.00	53.05	< 0.001
***F. conspicillatus* models**							
Abundance = Grass cover at 50 m		18.06	0.00	0.55			
Grass cover at 50 m*	+				8.00	24.12	< 0.001
Abundance = Tree cover at 50 m + Grass cover at 50 m		19.83	1.77	0.23			
Tree cover at 50 m	+				8.00	0.14	0.702
Grass cover at 50 m*	+				7.00	26.49	< 0.001
Abundance = Grass cover at 50 m+ Built-up cover at 50 m		19.83	1.77	0.23			
Grass cover at 50 m*	+				8.00	24.12	< 0.001
Built-up cover at 50 m	-				7.00	2.52	0.109
***E. pertinax* models**							
Abundance = Built-up cover at 50 m		29.05	0.00	1.00			
Built-up cover at 50 m*	+				8.00	17.21	0.007

Best models include the Chi-square value (χ^2) for each term, residual degrees of freedom, and associated p-values to assess the significance of land cover types at 50, 500, and 1 000 m buffer distances (variables highlighted with an asterisk (*) are considered significant: $p < 0.05$). QAICc was used to compare models, with ΔQAICc indicating the difference from the best model and W representing the relative likelihood of each model.

urbanized landscapes (Menchetti & Mori, 2014; Neate-Clegg et al., 2023), our study suggests that the parrot assemblage of Medellín is primarily composed of non-native species (60 % in our records), consistent with Flórez (2008), who reported 71 % (12 of 17 species) in the same city, based on historical records. The high proportion of non-native species in the city is likely due to multiple releases from wildlife trade (Restrepo-Rodas & Pulgarín-Restrepo, 2021), and the establishment of some individuals that exploit human-related resources across urban environments (Salinas-Melgoza et al., 2013; Peck et al., 2014; Wang & Liu, 2021), including supplementary food (Pena et al., 2016; Álvarez-Castillo et al., 2022) and nesting sites (Romero-Vidal et al., 2023). This species assemblage drives higher species richness in areas with medium to high urbanization levels, due to the mainly positive associations between non-native parrots and human-related activities (Menchetti & Mori, 2014). Nevertheless, some native species associated with open areas in their natural environments, including forests openings and edges (Forshaw & Knight, 2010), remain among the most abundant within the city. These findings are consistent with other tropical cities such as Manaus (Brazil), where most parrot species are considered non-native, while most abundant species are highly generalist regardless their origin (Fragata et al., 2022). Thus, beyond the environmental filtering of less generalist native species from the regional pool, human facilitation (i.e., human-related dispersal and establishment) appears to be a major driver of parrot diversity in cities (see Aronson et al., 2016).

However, our findings suggest that, despite the high proportion of non-native species, the most abundant parrot species in Medellín include both native and non-native species primarily associated with open areas. *B. jugularis*

(native) is considered highly abundant in agricultural and urbanized landscapes, avoiding evergreen forest (Del Hoyo et al., 2020), while *E. pertinax* (non-native) occurs in arid scrub and agricultural areas with scattered palms and other trees (Del Hoyo et al., 2020). Similarly, *F. conspicillatus* (native)—although less tolerant to landscape transformation—is also considered abundant in agricultural and urbanized landscapes with scattered trees (Del Hoyo et al., 2020). In addition, these three species correspond to medium- to small-sized parrots, which are also common in other Andean cities (especially the two natives, *B. jugularis* and *F. conspicillatus*) (Cediel & Lozano, 2021). This pattern suggests that urban environmental filtering may be linked to body size or mass, consistent with studies reporting that smaller species are generally more successful in urban environments (Neate-Clegg et al., 2023).

Although the city may provide resources for these three abundant medium- to small-sized parrot species, their contrasting patterns to urbanization suggest differences in ecological requirements, environmental tolerance, and spatial-scale patterns. For instance, *B. jugularis* was more abundant in sites with lower tree cover at the 1 000 m scale, while *E. pertinax* was more abundant in sites with higher built-up cover at the 50 m scale. Interestingly, tree and built-up cover were negatively correlated, suggesting that both species increased in abundance toward higher urbanization levels but with stronger ecological relationships at different spatial scales. These contrasting scale patterns may reflect differences in habitat use or other traits such as feeding behavior. *B. jugularis* feeds mainly on fruits and seeds from relatively large and scattered trees, including widely distributed species such as *Ficus*, *Ceiba*, *Bombax*, and *Muntingia* spp. (Del Hoyo et al., 2020). In contrast, the feeding behavior of *E. pertinax*—a highly trafficked non-native species in Medellín—is likely linked to human activities, particularly supplementary food (Cassey et al., 2004; Menchetti & Mori, 2014). This may also apply to other non-native less abundant species such as *Amazona* and *Ara* spp., which are primarily found in residential areas and frequently visit feeders (pers. obs.). Although there is no published evidence of successful reproduction in our study area, their populations seem to rely on continuous releases. Thus, like *E. pertinax*, these species appear to be aggregated at specific locations within the city, coinciding with medium to high urbanization levels.

For *F. conspicillatus*, the other highly abundant native species, we observed a stronger ecological relationship at the 50 m scale, similar to *E. pertinax*, but with a positive association with grass cover and no significant relationship with tree or built-up cover. This suggests that, regardless of urbanization level, *F. conspicillatus* aggregates in urban sites characterized by grass dominance, which are clustered in specific areas of Medellín (Paniagua-Villada et al., 2024). Such patterns may be also linked to its diet—mainly grass seeds collected from the ground, along with berries, fruits, buds, and possibly blossoms (Del Hoyo et al., 2020)—resources that are abundant but aggregated in open areas, including bushes and second-growth vegetation. Overall, our results indicate that species-specific ecological patterns depend both on resource associations and on the spatial scales at which species respond, including local and landscape scales.

At the community level, our results suggest that the variation of parrot species composition is mainly reflected by the percentage of built-up cover at the broader scale (i.e., 1 000 m). This pattern is consistent with previous studies suggesting that bird communities often respond more strongly to environmental characteristics measured at broad spatial scales (i.e., ≥ 1 km), highlighting the role of landscape context in structuring urban bird assemblages (Bellocq et al., 2017). Nevertheless, the relatively low explanatory power of this relationship in Medellín's parrot assemblage calls for caution when interpreting ecological associations, particularly in assemblages strongly driven by human-related factors (e.g., wildlife trade, supplementary feeding). In addition, at both the species and community levels, although ecological patterns appear relatively consistent

between point counts and transects, transects may provide more accurate insights. Despite point counts allow higher sampling size and thus provide stronger statistical information on parrot assemblages across environmental gradients, transects increase the likelihood of detecting more parrot species and identify clearer species-habitat associations, even with lower sampling efforts. Therefore, given that most species of parrots are highly mobile and gregarious, transects may generally be more effective than point counts for capturing ecological patterns (Sutherland et al., 2024). However, some differences between point counts and transects may also stem from sampling conducted in different years and seasons. Indeed, other studies have reported seasonal variation in urban parrot assemblages, linked to temporal changes in resource availability that are often influenced by the breeding season (Ibáñez-Álamo et al., 2017; Santiago et al., 2023).

The breeding biology of Medellín's parrot assemblage, including the timing of the breeding season, remains largely unknown. Moreover, local populations of rare and low-abundance species may persist mainly due to ongoing human-mediated releases into the city (Dickinson et al., 2023) and their reliance on permanently available anthropogenic resources (Santiago et al., 2023). Therefore, despite the high representation of non-native species, most of them may lack stable or increasing local populations.

Therefore, the role of wildlife trade and human-related resources in tropical cities must be further studied, as wildlife trade can be of the primary contributors to the establishment of non-native parrot populations (Su et al., 2021; Dickinson et al., 2023). These human-related factors should be studied along with environmental filtering, which possibly acts non-randomly on parrot assemblages across urbanized landscapes. In conclusion, understanding species-specific ecological patterns and the influence of human-related factors is crucial for developing strategies that enable cities to conserve biodiversity both within the city and its surroundings. By comprehensively studying how different species respond to urbanization and how human activities influence bird assemblages, targeted and more effective conservation efforts can be designed, addressing specific needs and limitations for distinctive species and contexts. This approach would not only help in preserving existing wildlife but also contribute to creating better practices in wildlife management and people-biodiversity interactions.

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See supplementary material
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