



Urban biodiversity suitability index: decoding the relationships between cities and birds

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Abstract

The expansion of cities has increased the necessity of multidisciplinary strategies to reduce the impacts of urbanization on ecosystems. Here we present the Urban Biodiversity Suitability (UBS) Index, a spatially explicit tool that describes levels of environmental suitability for biodiversity based on several urbanistic and socioeconomic data through a wilderness mapping approach. Using a tropical metropolis as a case study (Belo Horizonte, Brazil), we applied a Multi-Criteria Analysis to produce and join four geospatial layers that we believe describe the main aspects of cities that modulate urban biodiversity distribution: human accessibility, soundscape, built artifacts and volume, and land cover. To assess the accuracy of the UBS Index, we used bird species richness, functional richness (FRic), and Rao's Quadratic Entropy (RaoQ) based on data collected across several urban habitats (from streets to natural vegetation patches). We observed that as the suitability levels described by the UBS Index increases, higher bird species richness, FRic, and RaoQ values are also observed. Thus, quieter, less accessible urban regions, with few built artifacts, and with higher amounts of urban vegetation presented diverse bird communities. Those regions are distributed across the analyzed urban landscape, highlighting its spatial and environmental heterogeneity. The UBS Index is a simple tool that can be replicated in other cities across the globe to inform public policies for biodiversity conservation and environmental restoration in urban landscapes.

Highlights

- We developed a spatially explicit Urban Biodiversity Suitability (UBS) Index.
- The UBS Index is a multidisciplinary approach that joins several geospatial data.
- The UBS Index efficiently described levels of urban bird community diversity.
- The UBS Index can indicate urban areas with different levels of ecological integrity.
- The UBS Index can guide public policies for a more sustainable urban development.

Keywords Functional diversity · Multi-Criteria Analysis · Urban ecology · Urban landscape planning · Urban ornithology · Wilderness mapping

Introduction

In a moment when the human population is mostly urban, which is related to a fast expansion of cities worldwide (Liu et al. 2020), urban ecosystems have become the focus of many studies assessing the impacts of urbanization on biodiversity and human quality of life (McPhearson et al. 2016; Guerry et al. 2021). In this context, concepts from the emerging urban ecology discipline have proved to be valuable for

their multidisciplinary nature. By combining biological, sociopolitical, and economic perspectives to study patterns and trends of biodiversity and ecological processes in cities, it is possible to encourage public policies that reconcile human needs with more sustainable practices in urban planning and management (Bhakti et al. 2021a; Graviola et al. 2021; Gomes et al. 2023). Such an approach is fundamental considering that trends associated with the current climate and biodiversity crises we face correlate with urban areas, e.g., invasive species, habitat loss, and land use/land cover changes (McDonald et al. 2013, 2020).

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A tool that allows the assessment of how human activities modulate environmental conditions and thus, the distribution of biodiversity across landscapes is the wilderness mapping (Carver and Fritz 2016). This spatially explicit tool consists on the merging of geospatial data (such as topography, land cover, and biodiversity records) and human dynamics (such as accessibility, population density, and built structures) to determine regions that could be under less anthropogenic influences – or wilder (SNH 2014; Müller et al. 2015). The wilderness mapping has been applied on large spatial scales to assess levels of conservation of protected areas across countries (Ma and Long 2020) or the human perception of what could be considered as “wild” (Kliskey and Kearsley 1993).

Most recently, studies have been applying the wilderness mapping at the city scale, identifying patterns of urban environmental conditions to determine wilderness levels of urban parks and green spaces, the influences of the urbanization intensity on human quality of life, and to identify priority areas for biodiversity conservation in cities (Hand et al. 2016; Müller et al. 2018; Martin and Hill 2021). By associating characteristics of the urban areas (e.g., land use types) with the composition of species (e.g., native plants and birds) across urban landscapes, it is possible to assess the potential of different urban habitats (such as wooded streets, squares, parks, and cemeteries) to conserve biodiversity and ecological processes in cities (MacGregor-Fors et al. 2022). This identification of environmental suitability levels for biodiversity across urban landscapes can also assist in the definition of regions eligible for rewild initiatives by adopting sustainable and biodiversity friendly management practices, such planting native plant species and maintaining the understory for conserving structurally complex vegetation patches in cities (Matsuba et al. 2016; Kowarik 2018; Hwang et al. 2019). Rewild is a concept that aims to restore ecological functions in green areas through active management, by for example, incorporating the role of key species, such as seed-dispersing birds (Root-Bernstein et al. 2018; Thierry and Rogers 2020). Since wilderness mapping is an interface between ecological and human perspectives, it can be incorporated into urban planning and management (Kowarik 2018), guiding the definition of urbanistic parameters that can increase the permeability and accessibility of urban landscapes for biodiversity (Bhakti et al. 2021a).

Usually, the accuracy assessment of wilderness maps is based on the human perspective of what is wild (Ma and Long 2020). However, it is important to assess the ability of geospatial data-based approaches to infer environmental suitability levels using in situ biological information. Most importantly, the model organisms should be able to indicate the variation of conditions across all habitat types within urban landscapes (from woodless streets to well-preserved

forest patches), promoting a better understanding of the existing ecological relationships (Canedoli et al. 2018). In this context, birds are bioindicators (Morelli et al. 2021) and can be considered the most adequate group of organisms to be applied in the accuracy assessment of wilderness maps, since it is well known that communities' functional, phylogenetical, and taxonomic compositions are modulated by biotic and abiotic singularities of cities (Conole and Kirkpatrick 2011; Curzel et al. 2021). For instance, elevated noise levels are associated with taxonomically and functionally depauperated bird communities in urban parks, small public urban green spaces, and even across the streetscape (Perillo et al. 2017; Silva et al. 2021; Pena et al. 2023). Plant species composition and vegetation structure (e.g., tree height, canopy cover, and standing dead trees) are important attributes that modulate bird species composition in urban vegetation patches (Zhou and Chu 2012; Campos-Silva and Piratelli 2021; Sánchez-Sotomayor et al. 2023). Urbanistic parameters defined across urban zones, such as the maximum height of buildings and the minimum permeable area that needs to be maintained in individual lots, may influence the movement of bird species across urban landscapes (Bhakti et al. 2021a). Considering this vast theoretical framework about the relationships between urban avifauna and urbanization (Aronson et al. 2017; Bernat-Ponce et al. 2020; Sánchez-Sotomayor et al. 2023), birds can be used not only to validate the environmental suitability estimated based on a knowledge driven approach using geospatial data (Müller et al. 2018), but also as additional information to estimate levels of ecological integrity (MacGregor-Fors et al. 2022).

In this study, we present the Urban Biodiversity Suitability (UBS) Index. Although based on the same fundamentals as traditional wilderness mapping approaches (SNH 2014; Müller et al. 2018), we propose the replacement of the terms “wilderness levels” by “biodiversity suitability levels”, since in the city scale the use of “wild” may not be the most appropriate due to the intense human influences on environmental conditions (McDonald et al. 2009, 2020). Despite other environmental suitability indices based on abiotic and biotic aspects of cities have already been proposed to describe levels of ecological integrity (e.g., land surface temperature, built cover, and the richness of native plant and bird species, MacGregor-Fors et al. 2022), the UBS Index is based on a diverse set of geospatial data that describes urban landscape features that influence patterns of biodiversity distribution in cities (Alberti 2005; Luck 2007; Amaya-Espinel et al. 2019). We developed the UBS index based on four landscape attributes: human accessibility, soundscape, built artifacts and volumetry, and land cover. To assess its accuracy, we related the levels of suitability indicated by the UBS Index and bird data (species richness, functional richness (FRic), and Rao's Quadratic Entropy (RaoQ) collected

across different habitats of the city, from streets to native vegetation patches. We expected that more biodiverse suitable urban areas described by the UBS index would be related to more diverse bird communities, described by higher functional and taxonomic diversities.

Methods

Study area

The tropical city of Belo Horizonte (43° 56' 34" S, 19° 55' 37" W), located in southeastern Brazil, was selected as a case study to build the UBS Index and test its ability to describe levels of functional and taxonomic diversities of urban bird communities (Fig. 1). The city has an area of 331,354 km² with an estimated human population of 2,530,701 people (IBGE 2021), and is located in the transition zone between two biodiversity hotspots, Cerrado and Atlantic Forest (Myers et al. 2000). Belo Horizonte can be considered an interesting model for the application of an urban biodiversity suitability map because it is a completely urbanized municipality, without a rural zone, forming a heterogeneous mosaic of vegetated and non-vegetated areas. Across its territory there are more than 90 conservation units (from municipal and state parks to private protected areas) (Fig. 1), besides several peri-urban native vegetation patches without a properly defined land use (Belo Horizonte 2019).

Geospatial data for the Urban Biodiversity Suitability (UBS) Index map

To build the UBS Index map based on a knowledge driven approach, we merged four main layers that describe several landscape attributes that may modulate the environmental suitability for birds across urban landscapes using the ArcMap v.10.x software (Fig. 2): (1) human accessibility (described by streetscape attributes, human population density, and land use types), (2) soundscape (described by traffic noise, urban canyons, and commercial density), (3) built artifacts and volumetry (described by building volume, street lighting, and NDVI), and (4) land cover (describing water, mining, and woody and herbaceous vegetation). We used bird data collected across several urban contexts to assess the ability of our knowledge driven approach to estimate environmental suitability for urban birds. All these layers were selected to produce the most complete representation of environmental conditions across the urban landscape as possible, and were already used in previous studies (Müller et al. 2018; SNH 2014). We produced layers (1), (2), and (3) by merging other geospatial data (hereafter intermediate

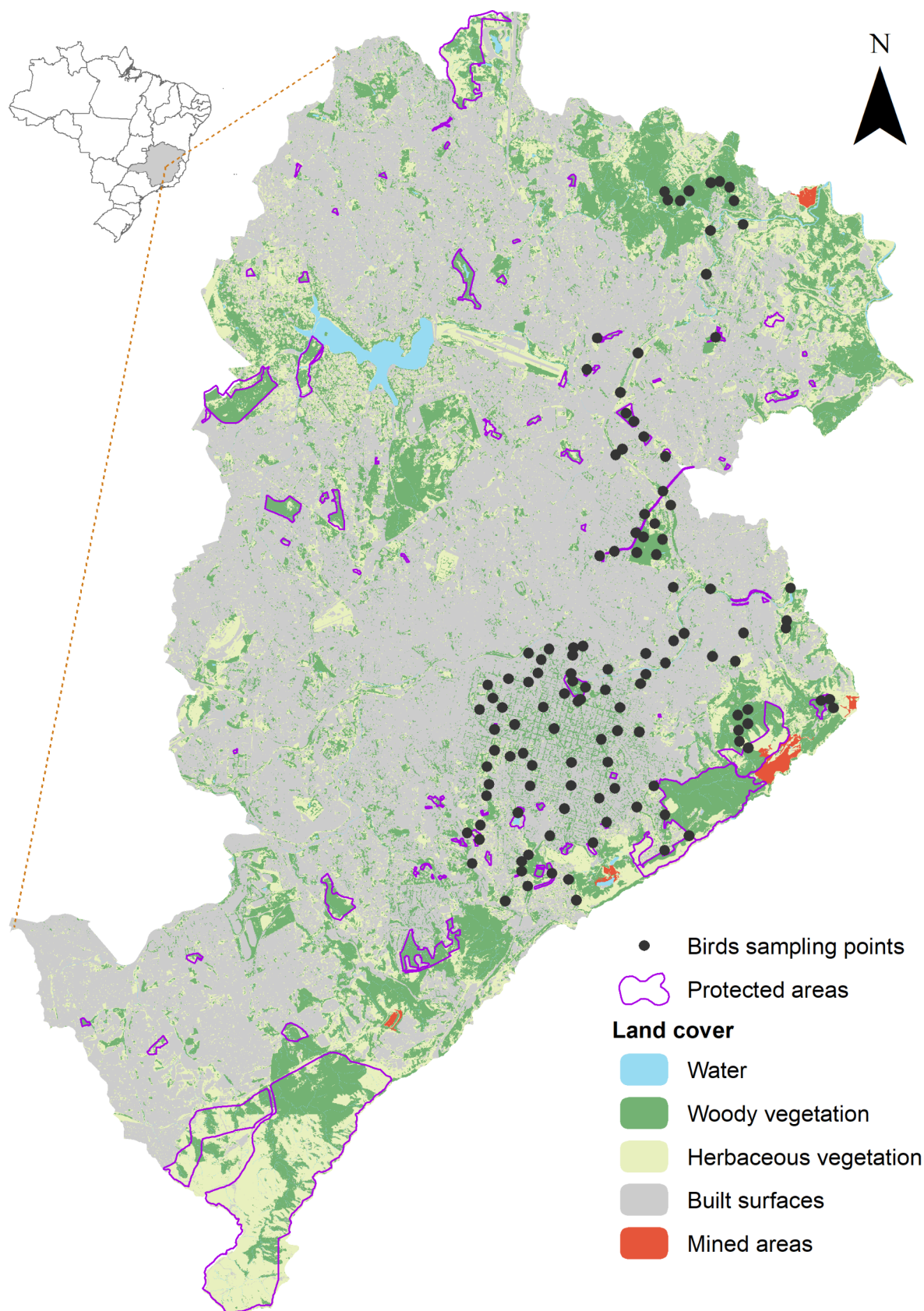
layers) through a Multi-Criteria Analysis (MCA). In the MCA approach, the reality is decomposed into main variables (i.e., layers) that are transformed into matrices (i.e., sets of pixels), in which the attributes are transformed into numerical values according to, in our case study, how they facilitate or hinder the ability of birds to exploit the different regions of the landscape. We standardized all geospatial data into raster files with 5 m of spatial resolution, under UTM projection DATUM WGS 84, 23 S Zone and pixel values ranging from 1 to 10, being 10 higher urban birds' vulnerability (or lower suitability). Then, to produce each layer, we applied a map algebra process by summing the intermediate layers and calculating the average value of each pixel of the resulting matrix, maintaining the variation of each layer into values between 1 and 10. The MCA approaches adopted to build layers (1), (2), and (3), as well as the methods adopted to produce the land cover map (layer 4) are described in the following sections. The development process and the origin of each layer will be detailed in the following sections.

Layer 1: human accessibility

The first intermediate layer used to produce the spatially explicit representation of Human accessibility of Belo Horizonte's landscape describes streetscape accessibility and capillarity, originally as a line feature map (obtained from the Company of Informatics and Information of the Municipality of Belo Horizonte - PRODABEL). It is based on the density and the carrying capacity (i.e., traffic volume) of different types of streets (e.g., roads, highways, alleys). We applied the kernel density estimator weighted by the streets' typology (or attribute) to produce a raster surface describing the density of streets and the traffic volume across the landscape of Belo Horizonte (Supplementary I Fig. S-1). Values closer or equal to 10 represent regions with high density of roads and highways with the largest carrying capacity (Supplementary I Fig. S-1). Those regions would present highly stressful conditions for biodiversity (Pena et al. 2017b).

The second intermediate human accessibility layer was the human population density, originally obtained as polygons describing census sectors and their respective population density estimated during the last Brazilian population census in 2010 (IBGE 2012). Values closer or equal to 10 represent highly densely occupied regions across Belo Horizonte (Supplementary I Fig. S-2). Human population density can have important influences on bird species richness (Luck 2007) and on the proportion of vegetation – especially native vegetation – that comprise urban landscapes (Liu and Slik 2022).

The third intermediate human accessibility layer describes the land use type attributed to each individual lot across Belo Horizonte landscape originally as a vector map



Coordinate System: WGS 1984 UTM 23S

Fig. 1 Land cover map of the urban landscape of Belo Horizonte (Minas Gerais, Brazil), the municipality used as a model for the application of the Urban Biodiversity Suitability (UBS) Index. Purple polygons highlight the protected areas spread across the landscape. The black dots highlight the 120 survey sites where the bird data used to test the accuracy of the UBS Index was collected

(<http://bhmap.pbh.gov.br/>). Each individual lot (or polygon) was classified as commercial, residential (low, medium and high density), industrial, mixed uses, green spaces, among others (Supplementary I Fig. S-3 and Supplementary II Table S-1). We reclassified polygons to values between 1 and 10 (Supplementary II Table S-1), being 10 attributed to land use types that we believe can lead to higher disturbances to the urban biodiversity, such as areas that produce high levels of noise and air pollution and/or are related to a high flow of people across the landscape (airports, industrial zones) (Alberti 2005; Hodgson et al. 2007; Reis et al. 2012; Pena et al. 2023). Finally, we summed and calculated the average between those three intermediate layers to obtain the description of the degree of human accessibility across Belo Horizonte landscape (Supplementary I Fig. S-4).

Layer 2: Soundscap

First, we obtained a line feature map representing the city streetscape in which the lines' attributes describe the traffic volume (i.e., number of vehicles per track of road) of each street (PRODABEL – 2018). We applied the kernel density estimator weighted by the traffic volume to produce a raster surface that describes both the density of streets and the noise pollution that would be produced due the number of vehicles in circulation, being 10 attributed to those with a high degree of noise (Supplementary I Fig. S-5). Noise exposure is considered a limiting factor for urban bird communities, modifying physiology communication, reproductive success, and leading to a reduction on communities' functional and taxonomic diversities (Ortega 2012; Pena et al. 2017b; Curzel et al. 2021; Redondo et al. 2021; Bernat-Ponce et al. 2021).

We also included a description of the urban morphology, the urban canyons, as the second intermediate soundscape layer. Using a vector map composed of polygons containing as attributes the estimated buildings' height obtained through LiDAR flights in 2007 (Pinto 2015), we measured the frontal distances between the facades of the buildings. We then identified the urban regions where buildings with heights equal to or greater than five floors are positioned facing each other (i.e.: urban canyons), which indicates high potential for sound reverberation (Nakamura and Oke 1988). Values were normalized between 1 and 10, being the highest values related to regions with higher potential for the formation of urban canyons (Supplementary I Fig. S-6).

The third soundscape intermediate layer was a description of the distribution of commerce and services across the landscape. From the land use map describing the attributes of individual lots, we extracted only polygons classified as commercial, services, industrial or similar uses. We then applied the kernel density estimator weighted by the number of activities conducted within each individual lot. In the resulted intermediate layer values closer to 10 indicate regions with high concentration of commerce and service activities (Supplementary I Fig. S-7). Those regions would be related to higher noise pollution due to the concentration of people and especially, vehicles in circulation. Finally, we summed and calculated the average between those three intermediate layers, obtaining a raster surface describing the soundscape of Belo Horizonte (Supplementary I Fig. S-8).

Layer 3: built artifacts and volumetry

The first intermediate layer is the building volumetric density, for which we applied the kernel density estimator on the vector map describing the estimated buildings' height weighted by the height value. We normalized the produced raster surface to values between 1 and 10, being 10 representing regions with higher concentrations of tall buildings (Supplementary I Fig. S-9). Buildings may represent barriers for birds to access and move through urban landscapes due to the risks of window collisions (van Doren et al. 2021). Furthermore, the increase in building density was already observed to be negatively related to the richness of bird groups, such as insectivorous species (Amaya-Espinel et al. 2019).

The second intermediate built artifacts layer was based on a point feature map describing the Belo Horizonte public lighting poles obtained from PRODABEL (from: <https://prefeitura.pbh.gov.br/prodabel>). We made a 45-degree cone in relation to the height of the poles (15 m) representing the radius under influence of light around each point. As a result, we obtained a raster surface describing urban regions with different lighting levels. Values closer or equal to 10 indicate the brighter regions across Belo Horizonte landscape (Supplementary I Fig. S-10). Cities considered as having high environmental quality for birds are related to those with lower light pollution (Morelli et al. 2021).

The third intermediate built artifacts layer was a Normalized Difference Vegetation Index (NDVI) surface which we produced from a Sentinel 2 A satellite image obtained in August 2020 (from: <https://scihub.copernicus.eu/>). The data and image were selected due to the absence of clouds. Originally the NDVI surface is composed of values ranging from -1 to 1, being values closer or equal to -1 representing areas with absence of vegetation (e.g., bare soil, water, impermeable surfaces). Values closer or equal to 1 are related to

Layers

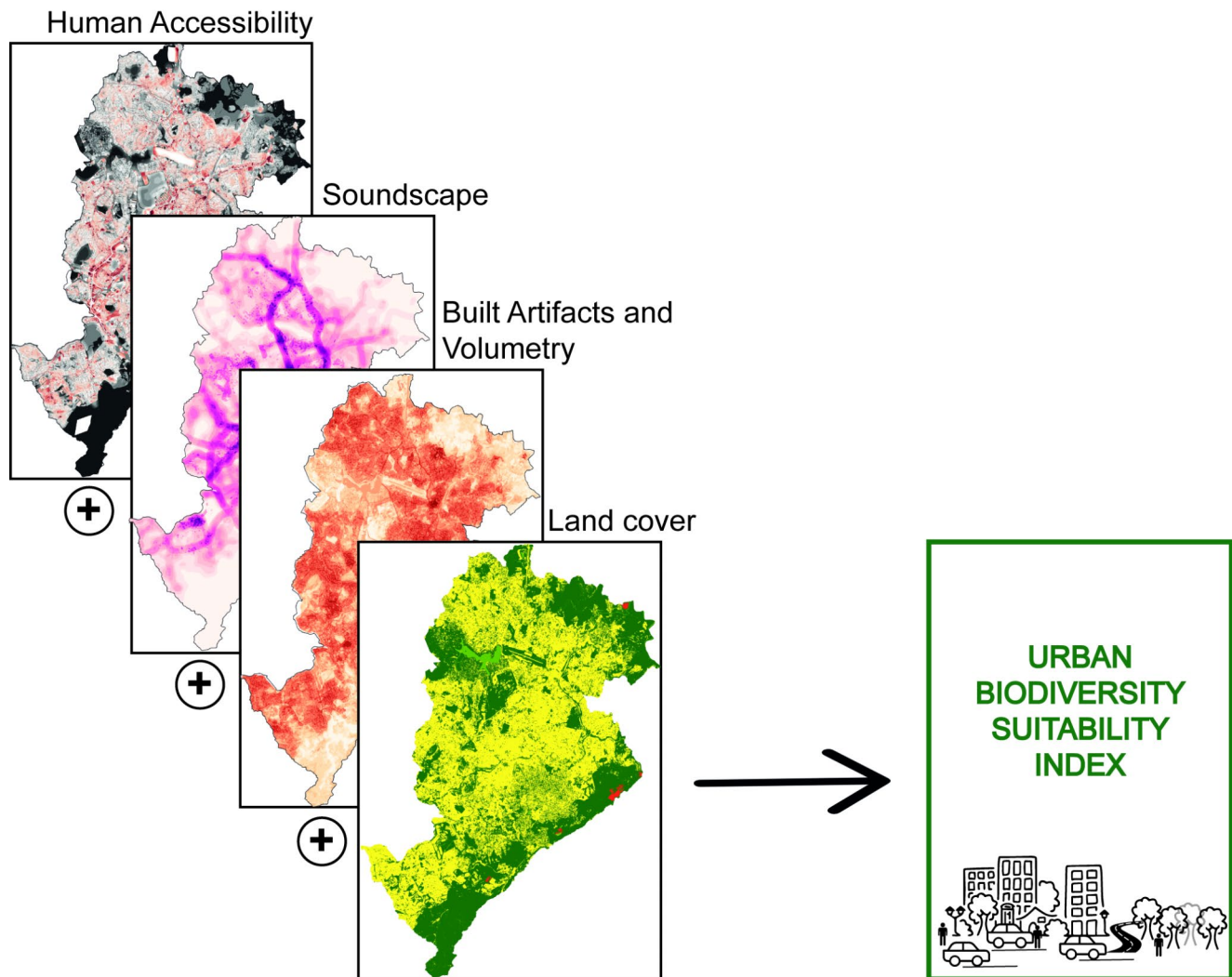


Fig. 2 Representation of the Multi-Criteria Analysis approach adopted to merge the four main layers – human accessibility, soundscape, built artifacts and volumetry, and land cover – for the formulation of the Urban Biodiversity Suitability (UBS) Index

vegetation patches with high photosynthetic activity (e.g., dense woody vegetation cover). We normalized the NDVI layer to values between 1 and 10, being 10 the urban regions with absence of vegetation, i.e., pixels originally with values closer or equal to -1 (Supplementary I Fig. S-11). The NDVI was recently applied to estimate bird species richness across urban landscapes, being values closer to 1 indicating the most diverse communities (Leveau et al. 2020). We summed and calculated the average between those three intermediate layers to obtain the description of the density and volumetry of built artifacts, as well as the quality of the urban vegetation, across Belo Horizonte landscape (Supplementary I Fig. S-12).

Layer 4: land cover map

The final layer used to produce the UBS Index was the land cover map developed for Belo Horizonte landscape (Supplementary I Fig. S-13). We obtained Planet Scope satellite imagery from September 2020 with 3 m resolution (Planet Team, 2017). Through a supervised classification using the Maximum Likelihood Algorithm of ArcGIS 10.X software, we identified three classes: woody vegetation, herbaceous vegetation and built surfaces (Kappa=0.86). We added the hydrography and the mined areas by merging the classified raster map with layers originally obtained in vector format (<http://bhmap.pbh.gov.br/>). Then, we reclassified the raster surface into four classes between 1 and 10, being 1 woody + herbaceous cover, 3 for water, 6 for built surfaces,

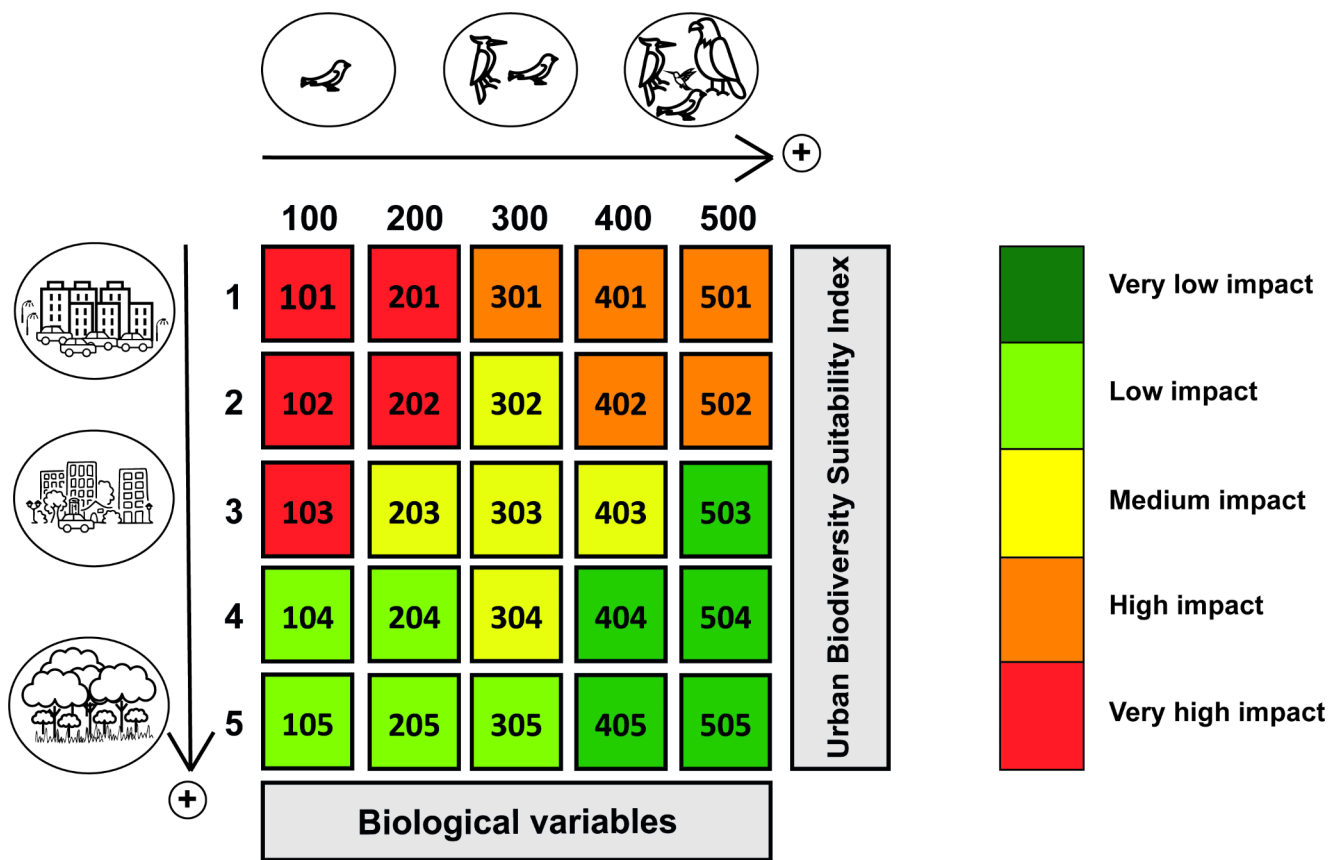


Fig. 3 Representation of the combinatorial analysis matrix used to assess the relationships between the suitability levels described by the Urban Biodiversity Suitability (UBS) Index and the taxonomic and

functional diversity levels observed across 120 bird survey sites in Belo Horizonte (Minas Gerais, Brazil)

and 10 for mined areas. We merged the woody and herbaceous covers since the built artifacts layer already describes the vegetation volume. Finally, we resampled the resolution of the raster surface to 5 m (Supplementary I Fig. S-13). Land cover data can be used to estimate the presence and the ability of bird species to move across urban landscapes (Fillooy et al. 2019; Bhakti et al. 2021a; Graviola et al. 2021).

Building the UBS Index map

To produce the UBS Index map, we also applied the MCA approach by summing and calculating the average between the four layers (human accessibility, soundscape, built artifacts and volumetry, and land cover) (Fig. 2). We then obtained a raster surface that varies between 1 and 10, being 10 regions of the urban landscape more vulnerable (or least suitable) to the bird community. We are aware that some selected intermediate spatial layers could be correlated with each other. However, this is not an issue since we are assessing the relationship between the resulting UBS map and bird diversity metrics, not the influences of each intermediate layer separately. Furthermore, correlated layers would

highlight urban regions that could have a higher influence (positive or negative) on the bird community. For example, a joint effect of the amount (land cover, layer 4) and quality (built artifacts and volumetry, layer 3) of the urban vegetation on bird species richness.

To facilitate the interpretation of the resulting UBS index map, we reclassified the raster surface to its inverse values. Thus, instead of vulnerability, the final map describes suitability levels being values closer to 1 indicating low suitability (or high vulnerability) and values closer to 10 indicating urban regions with high suitability for the bird community (or with low vulnerability). This final map is the spatial explicit representation of the UBS Index (Figs. 2 and 4).

UBS Index validation and statistical analysis

We obtained bird data from 120 survey sites distributed across the Belo Horizonte landscape. The data from 60 sites was obtained from Pena et al. (2017b), who conducted bird surveys across the streetscape of the southern region of Belo Horizonte between September 2014 and February 2015. The other 60 sites were surveyed between October

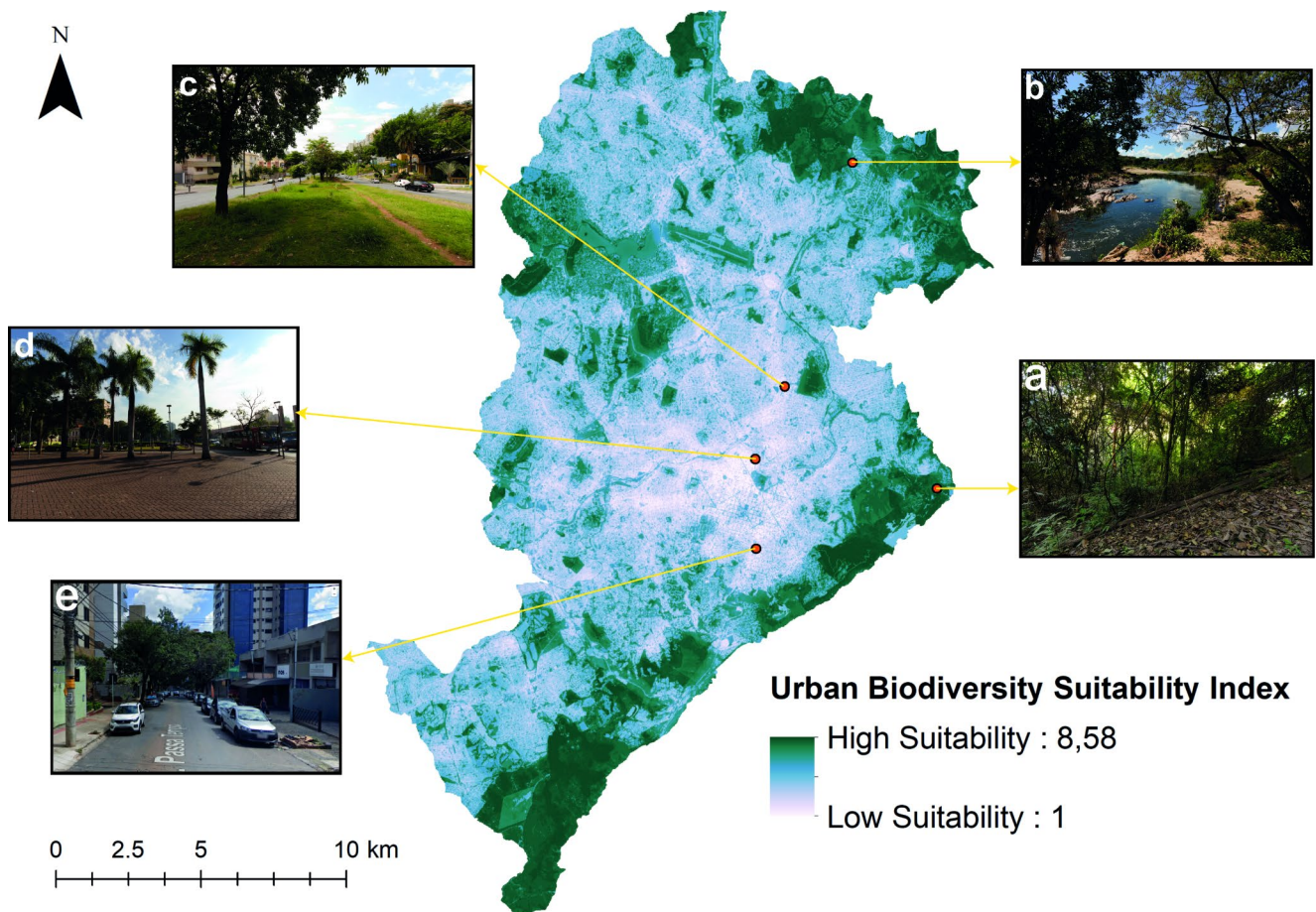


Fig. 4 The Urban Biodiversity Suitability (UBS) Index formulated for the landscape of Belo Horizonte (Minas Gerais, Brazil). Images “a” to “e” are examples of areas that presented different suitability levels according to the UBS Index, being a = 8.58, b = 6.55, c = 5.16, d = 4.2, and e = 3.85

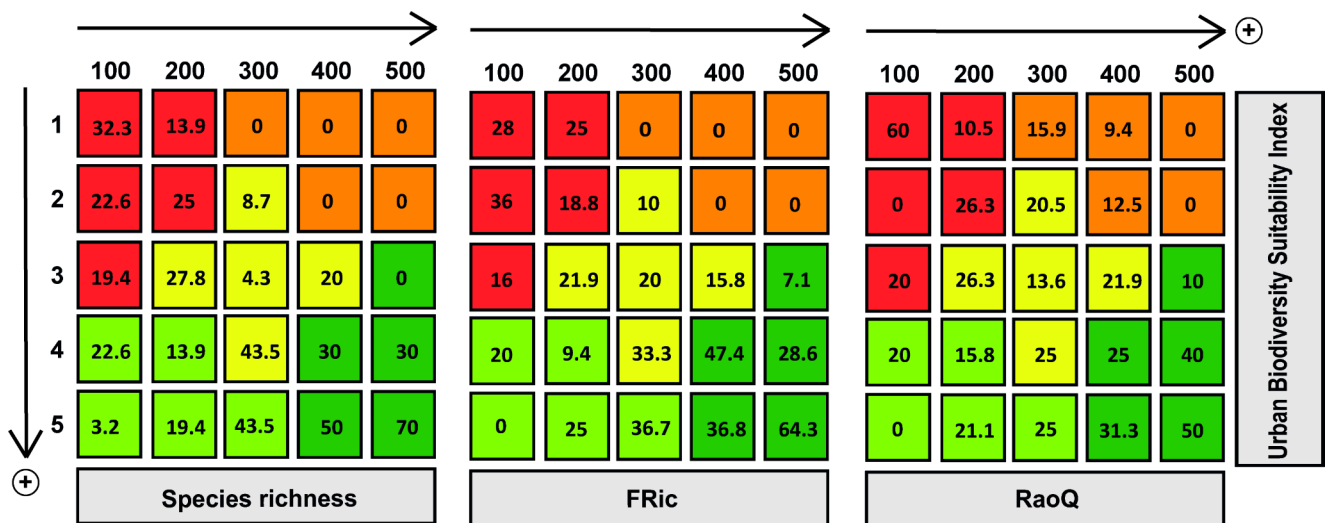


Fig. 5 Result general linear regression models of the biological data in relation to the values of the Urban Biodiversity Suitability (UBS) index. Taxonomic richness (SR) Pseudo- $R^2 = 0.42$, $P < 0.001$; Func-

tional richness (FRic) Pseudo- $R^2 = 0.38$, $P < 0.001$; and Rao's quadratic entropy (RaoQ) Pseudo- $R^2 = 0.10$, $P < 0.001$

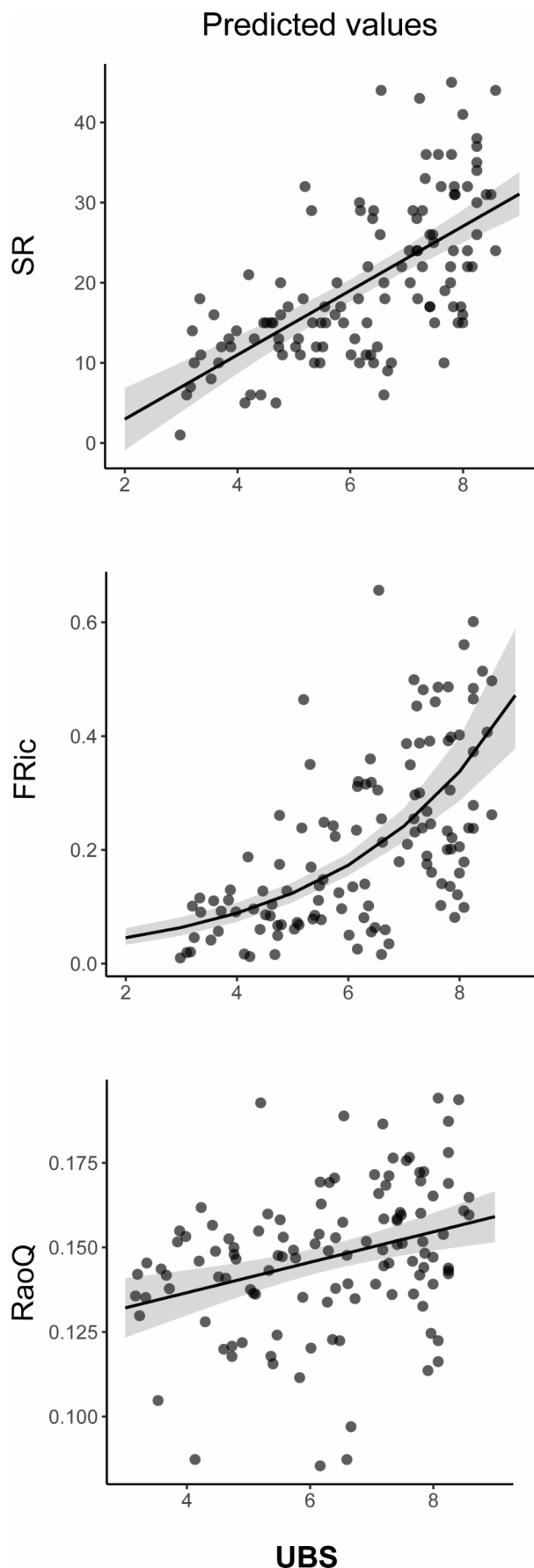


Fig. 6 Results of the combinatorial analysis matrices to assess the relationships between levels of bird species richness, functional richness and Rao's Quadratic Entropy, and the levels of the Urban Biodiversity Suitability (UBS) Index. Values inside squares represent the proportion of each bird diversity level (100–500, being 500 sites with high functional or taxonomic diversity) that were classified according to each UBS Index level (1–5, being 5 sites with high suitability)

2020 and March 2021 adopting similar methods as in Pena et al. (2017b), but bird data was collected in a variety of green spaces distributed across the urban landscape of Belo Horizonte (natural vegetation patches, cemeteries, leisure spaces, linear parks, among others) (Fig. 1). In both surveys, point counts were performed during birds' breeding season in southeastern Brazil. The fieldwork started 30 min after sunrise and extended during the first three hours of daylight on days with favorable weather (sunny and non-windy days). Each site was visited three times and each visit lasted 20 min. The duration of each visit was defined by Pena et al. (2017b) in a pilot study, through which they observed that after 10 min visits (standard approach applied in bird studies) new species were still being included, especially in regions where green cover is high. We recorded all bird individuals observed perching, nesting, foraging or singing in a 50 m radius around the observer. By using both bird survey data, we are able to describe the taxonomic and functional diversities of communities inhabiting urban habitats that comprise a gradient of urbanization intensity, from peri-urban conservation units to brownfields, streets, and train tracks. Thus, we used a database that describes the bird community across a variety of urban contexts, which would be adequate to assess the accuracy of the UBS Index map.

We calculated for each bird survey site the species richness (SR) and two Functional Diversity indices, Functional Richness (FRic) and Rao's Quadratic Entropy (RaoQ). We obtained information on bird functional traits – body mass (g), clutch size (number of eggs per clutch), diet, nesting and foraging substrates – from published literature (del Hoyo et al. 2010; Wilman et al. 2014). We used the FD package (Laliberté et al. 2014) in the R programming environment (R Core Team 2021) to calculate the functional diversity indices. FRic is a representation of the amount of niche space occupied by the species at each site (Schleuter et al. 2010). RaoQ incorporates species relative abundances to estimate the pairwise functional differences between species (Botta-Dukát 2005), and can be considered as a measure of functional evenness, since the higher the value of RaoQ, the greater the dissimilarity between functional groups. We extracted the UBS Index values from each of the 120 bird survey sites.

In order to validate the ability of the UBS Index map to describe levels of bird diversity across the urban landscape, we modeled the relationships between the UBS index at each survey site, as a predictor, and the diversity indexes

as response variables using generalized linear models. For SR and RaoQ we used the gaussian distribution and for the FRic index, we used the Gamma distribution with a log link function. The assumptions were checked through simulation-based residual diagnostics (Hartig 2022). We used the Cox and Snell pseudo-R squared as a measure of goodness of fit. These models were performed using the DescTools package (Signorell 2023) in the R programming environment (R Core Team 2021).

To facilitate the interpretation of the results and the relationships between the UBS Index and the bird diversity indexes, we also built three combinatorial analysis matrices. To do this, we applied Jenk's Natural Breaks to reclassify the UBS Index values into five suitability classes ranging between 1 and 5, being 5 high suitability for the bird community. We also used Jenk's Natural Breaks to reclassify the SR, FRic, and RaoQ values into five classes between 100 and 500 (being 500 the highest values observed for each diversity index). The three combinatorial analysis matrices represent all possible spatial combinations between the five UBS Index classes in one axis and the five levels of each bird diversity indexes (SR, FRic, and RaoQ) in the other axis, separately (Fig. 3). Using this approach, it is possible to identify and interpret the meaning of all existing arrangements (Xavier-da-Silva 2001; Moura 2003). For example, when the maximum UBS Index value (i.e., 5) coincides with the maximum diversity index value (i.e., 500), the final arrangement (i.e., 505) indicates high bird diversity inhabiting an area with high biodiversity suitability (Fig. 3). This visual approach can be useful to inform decisions and can assist in the interpretation of the modeling approach we adopted to validate the UBS Index map.

Results

The final UBS Index map describes urban biodiversity suitability levels across the Belo Horizonte landscape (Fig. 4). Suitability values ranged from 1 (low suitability, such as woodless streets and highways) to 8.58 (high suitability, such as peri-urban protected and non-protected areas) (Fig. 4).

Across Belo Horizonte streetscape, Pena et al. (2017b) registered a total of 73 bird species, distributed in 26 families and 12 orders. During the 2020–2021 survey period, we registered a total of 148 species, distributed in 49 families and 19 orders. This difference is related to the higher bird species richness usually observed in green spaces in comparison with streets, especially in natural vegetation patches. Thus, in total 153 bird species were recorded inhabiting a variety of urban habitats across the Belo Horizonte landscape.

The number of species recorded in each survey site considering both databases varied between 1 and 45. The indices scores ranged between 0.002 and 0.065 for FRic and 0 to 0.194 for RaoQ. The ability of the UBS Index to describe the bird diversity distribution across the urban landscape was confirmed by the general linear regression models for SR (Pseudo- $R^2 = 0.42$, $P < 0.001$), FRic (Pseudo- $R^2 = 0.38$, $P < 0.001$), and RaoQ (Pseudo- $R^2 = 0.10$, $P < 0.001$) (Figs. 5 and 6). All the raw data used to assess the accuracy of the UBS Index is available at Supplementary II Table S-2.

When assessing the combinatorial analysis matrices, it is also possible to visualize that most sites with high bird diversity levels (SR, FRic, and RaoQ) also presented high UBS Index values (Fig. 5). The same is true for sites with low bird diversity, which were mostly related with low UBS Index values (Fig. 5).

Discussion

The UBS Index was able to efficiently describe levels of environmental suitability for birds across the urban landscape of Belo Horizonte. Our multidisciplinary knowledge driven approach allowed us to produce a holistic view of the relationships between several urban environmental characteristics and how they modulate the levels of suitability for biodiversity. Cities comprise high dynamic and heterogeneous ecosystems, shaped by environmental, sociopolitical, and economic influences, which we believe we could represent by the geospatial data we included during the development of the UBS Index. By assessing the accuracy of our suitability map using a bird database, we described the potential of regions across the urban landscape to support different biodiversity levels. Whereas high suitability regions inhabited by high bird diversity in Belo Horizonte can be considered as important for conservation, some urban areas, especially vegetation patches that present medium-to-low biodiversity suitability levels, may be eligible for restoration or rewild initiatives.

Based on our previous knowledge and the urban ecology literature, we selected layers (i.e., landscape and environmental variables) that influence the ecosystem dynamics that occur within cities. This process allowed us to have an overview of the relationships between the human and the ecological dimensions across the landscape. The human accessibility, soundscape, and built artifacts and volumetry layers describe important influences that may reduce the environmental suitability for biodiversity (in this case, birds) such as the land use types, streets and population densities, noise exposure, buildings' height, and the street lighting (Heggie-Gracie et al. 2020). The NDVI, together with the land cover layer, describe the amount, volume, and the

quality of the vegetation across the landscape, which modulate the diversity and composition of urban bird communities (Leveau et al. 2018). Although several studies have already shown that the amount and configuration of vegetation patches can describe the diversity of organisms across urban landscapes (Hayes et al. 2020; La Sorte et al. 2020), it is important to recognize the potential of unconventional habitats (such as cemeteries, wooded streets, small green spaces, and yards) to support biodiversity in cities (Morelli et al. 2018a, b; Soanes et al. 2019). By including those four dimensions (human accessibility, soundscape, built artifacts and volumetry, and land cover), formed by combinations of several geospatial data, the UBS Index highlighted the high heterogeneity of the urban ecosystem and areas with high biodiversity suitability can be found across the landscape. Even in the most central part of urban landscapes, it is possible to find regions with low traffic noise and volume, smaller buildings, lower street and human densities, and other aspects that led to higher UBS Index values.

We observed a significant relationship between bird taxonomic and functional diversities and the UBS Index levels, as we expected. It has already been shown that the amount and quality of the urban vegetation has positive influences on the diversity of bird communities inhabiting urban and peri-urban vegetation patches (Anderson et al. 2016; Sánchez-Sotomayor et al. 2023). Thus, the largest areas with the highest UBS Index levels were concentrated in the peri-urban region, where the largest native vegetation patches are located. In addition to the amount of vegetation, the land use types can influence the level of conservation, and the quality and structural complexity of the urban vegetation (Sol et al. 2020). Residential areas, comprising houses with yards, with reduced traffic volume and noise and nearby natural habitat patches, may be inhabited by a high diversity of species (Belaire et al. 2014; Canedoli et al. 2018; Bhakti et al. 2021b; Pena et al. 2023). In fact, the vegetation in some of these areas presented medium-to-high biodiversity suitability across the Belo Horizonte landscape. Therefore, the UBS Index was able to identify different suitability levels of the urban vegetation, considering a series of disturbances already described in the literature that may affect habitat quality, such as noise and light pollutions (Alberti 2005; Morelli et al. 2021). It is important to mention, however, that the highest suitability level identified by the UBS Index (8.58) indicates that all of Belo Horizonte landscape presents a level of human disturbance, even the core of the protected areas. Therefore, this large metropolis probably does not harbor a completely wild or pristine habitat patch, which is probably the reality of every metropolis across the globe.

Besides the identification of the best and most suitable areas for biodiversity, the UBS Index can also assist in the identification of areas that could be restored or have the

management type or conservation level modified. Regions with intermediate suitability levels may be eligible for the application of rewild or restoration projects, while the lowest UBS Index levels (closer to 1) highlight areas that are already occupied by the human population for a variety of purposes (e.g., housing, industries, commerce). Nevertheless, urban areas dominated by low suitability levels may receive special attention for the creation of new and multifunctional vegetation patches. This process should consider human well-being, allowing a higher contact with nature and increasing awareness about the importance of conserving biodiversity even within urban landscapes (Locke et al. 2019). The support of the human population can assist the application of rewild initiatives for increasing biodiversity, reducing management intensity, and changing plant species composition in green spaces (Zefferman et al. 2018; Kowarik 2018). The UBS Index can be tested by researchers in cities in different countries or regions to assess the efficiency of our mapping approach in identifying different suitability biodiversity levels in urban landscapes. The accuracy of the UBS Index could also be tested for other animal groups, allowing us to assess if the same geospatial layers can describe suitability levels for other organisms or adjustments need to be made.

Although the wilderness mapping technique has its main applicability on large spatial scales (SNH 2014), it has been demonstrated to be adequate to estimate habitat suitability levels for biodiversity at the city scale. Another application of the UBS Index is in the assessment of landscape connectivity, by identifying greenways connecting areas with high environmental suitability across the landscape. They can be multifunctional and lower cost alternatives to the traditional ecological corridors, connecting not only the biodiversity but also people through cycling paths or wooded streets (Ignatieva et al. 2011; Keith et al. 2018). In Belo Horizonte, the train tracks and several wooded avenues were highlighted as intermediate suitability levels for biodiversity. Wooded streets provide refuges and resources for several bird species (Pena et al. 2017b; Wood and Esaian 2020) and train tracks can act as habitat areas due to the lower traffic volume than the streetscape (Erickson 2004; Bhakti and Rodrigues 2020). The creation of greenways can also follow the margins of the rivers, helping the preservation of riparian forests (Parris et al. 2018).

The UBS Index can be used by urban planners and managers that aim to include biodiversity in their agenda. It is possible to identify regions of the city that lack areas with high environmental suitability for biodiversity, determining priority areas for the adoption of sustainable management and planning strategies, such as the creation of parks and green areas. Regions with high suitability can provide numerous ecosystem services for the human population

(e.g., thermal comfort, increased soil permeability, absorption of pollutants) due to the large amount of vegetation, less vehicles circulation and concentration of less impacting land uses (e.g., low density residential buildings). Finally, it is possible to include the UBS Index in participatory decisions, considering the views and needs of all sectors of society (civil society, academia, economic sectors, politicians) about how to plan and manage the landscape during the formulation or revision processes of cities' master plans (Pena et al. 2017a). To inform decisions, both the final map and the combinatorial analysis matrices can be used to illustrate the potentialities and limitations regarding urban biodiversity conservation across the landscape.

Belo Horizonte has the advantage of the availability of several high-quality geospatial data that allow the production of high-quality maps. Thus, the UBS Index map approach can be easily replicated for cities where a collection of geospatial data is available. It is important to highlight that our MCA approach is not a simple process of overlapping layers, but it was based on an interdisciplinary knowledge driven approach that allowed for the interpretation of how different geospatial layers, and their interactions, would influence biodiversity. Either way, the UBS Index approach can be replicated for other cities by including similar or different layers that describe environmental, socioeconomic or biological aspects of landscapes and also be adapted to assess the suitability levels for other animal groups. For example, in the case of arboreal mammals, the light cable network could improve landscape connectivity for more generalist species (Duarte et al. 2012). For pollinators, more information on green space management or the distribution of flowering plant species, could assist in the identification of suitability levels for different organisms (e.g., bees, butterflies), allowing inferences about the realization of ecological processes across urban landscapes. Our approach also allows for analysis regarding the influences of socioeconomic aspects on the distribution of urban biodiversity by crossing the suitability map with information on, for example, family income. Thus, considering the high potential of the UBS Index as a management tool, we hope that our approach, not only stimulates city planners and managers to invest in the acquisition of geospatial data, but also on their application to assess how the complex environmental conditions of urban ecosystems modulate local biodiversity.

Conclusions

We demonstrated that it is possible to apply a knowledge driven approach to produce a spatial explicit urban biodiversity suitability index based on several geospatial data.

The UBS Index efficiently described the functional and taxonomic diversities of the bird community inhabiting a variety of habitats across the urban landscape. Furthermore, the UBS Index highlighted the high environmental heterogeneity across urban landscapes; throughout the whole city it is possible to find regions highly suitable for biodiversity. However, we did not observe a pristine natural habitat patch in Belo Horizonte, reinforcing our decision of not using wilderness levels when describing environmental conditions within urban landscapes. The approach described in our study can be considered a management tool, helping decision makers to identify priority areas for conservation and restoration, as well as urban regions that lack areas with high environmental quality for biodiversity and for the human population.

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Authors' contributions T.B. wrote the main manuscript; prepared Figs. 1, 2, 3, 4, 5 and 6 and the graphical abstract; conducted fieldwork and developed the methodology. J.C.P. developed the methodology and supervision. A.C.M.M. developed the methodology; prepared Figs. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 and 13 in the Supplementary Material and performed the statistical analysis using GIS software. D.P. performed the statistical analysis and prepared the graphs in Fig. 5. L.S. performed the statistical analysis using GIS software. M.R. developed the methodology and supervision. All authors made substantial contributions to the intellectual content, interpretation of the literature review, and editing/review of the manuscript.

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