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Research Article

Bird richness and Ecosystems Services across an urban to natural gradient in south-eastern Brazil: implications for landscape planning and future scenarios

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Abstract

In natural and altered environments, the Ecosystem Services (ES) provided by the presence of vegetation, especially regulating ES such as climate regulation and air pollutant removal, are essential to improve human health and well-being. In this study, we focused on a tropical-subtropical river basin which covers urban, peri-urban and rural landscape types of a Brazilian municipality located in the ecotone between the Atlantic Forest and the Cerrado (Brazilian savannah). The research aimed to assess the current state of ES and bird richness (as a biodiversity indicator) and their relationships across an urban-rural-natural gradient. We assessed the cooling effect (as microclimate regulation indicator), air pollutant removal (PM10), nature-based recreation opportunities and bird richness and analysed the variations associated with a shift in the prevailing land- cover types along a gradient of urbaniszation. The results indicated a higher bird richness in peri-urban and rural landscapes, as well as greater pollutant removal and cooling effect provided by vegetation. However, recreation opportunities provided mainly by human infrastructure were higher inside the urban zone and in some peri-urban areas. The landscape type significantly influenced the availability and intensity of these four variables ($p < 0.001$). Bird richness, air pollutant removal, and cooling effect were positively correlated ($r > 0.539$; $p \leq 0.048$);, however, a trade-off between them and recreation opportunities ($r = -0.59$, R2 = 0.348, $p < 0.001$) was found. We simulated possible scenarios of reforestation actions in urban areas to predict the ES values when vegetation cover area is increased. According to the results, the urban planning and efforts to improve nNature-based solutions in the studied river basin should consider the observed trade-off to promote sustainable nature-based recreation opportunities in places with higher values of ES (cooling effect, air pollutant removal, and bird richness) and/or to increase the ES values in urban landscape through environmental policies, such as reforestation.

Keywords

Air pollutant removal, cooling effect, nature-based solutions, recreation opportunities, urban planning, trade-off

Introduction

Population growth, intensified urbanisation and constant land-use changes to expand food production coincide with nature degradation and biodiversity loss (McKinney 2002, Yang et al. 2023). Global projections for urban land cover in 2100 suggest a substantial increase of 111% (36–74 million hectares) (Li et al. 2022). This projection is contingent upon factors such as population and economic growth, as highlighted by Seto et al. (2011)and Li et al. (2022) . Under the United Nations' projections of population growth, the global population will reach 8.5 billion in 2030 and is expected to increase further to 9.7 billion in 2050 and 10.4 billion by 2100. Urban expansion, particularly in rapidly growing regions, has emerged as a primary driver of global land-use changes, resulting in habitat conversion and degradation, habitat fragmentation and subsequent biodiversity loss (Xu et al. 2019, Li et al. 2022). Comprehensive assessments reveal that urban expansion can cause approximately 34-95% reduction in local species richness and a 38% decline in total species abundance in heavily urbanised areas compared to naturally unaffected baselines (Newbold et al. 2015, Xu et al. 2019, Li et al. 2022).

On the contrary, nature conservation and restoration generate benefits by supporting healthy and functioning ecosystems that underpin the flow of ecosystem services (ES). In fact, healthy ecosystems provide not only life-supporting services on which human survival depends, but also a wide range of other services that are essential to economic and cultural development (Daily 2002, Cortinovis and Geneletti 2018). Economic and socio-cultural valuations of ES have demonstrated their huge impact on biodiversity, production of food and raw materials and human health and well-being through local to global scales (Costanza et al. 1997, de Groot et al. 2002, Porter et al. 2009, Seidl and Nunes 2019).

In urban and peri-urban areas, ES provided by the presence of vegetation, particularly regulating ES, such as climate regulation and air pollutant removal, are essential for improving human well-being (Bolund and Hunhammar 1999, Sandifer et al. 2015, Zardo et al. 2017, Fusaro et al. 2017). Additionally, vegetation patches (native or exotic) inside and in the proximity of urban areas, along with green infrastructure (parks, green areas, grass areas, brownfields, gardens, vegetations patches) can offer valuable nature-based recreational opportunities. The accessibility of these areas depends on the availability of human-made infrastructure, such as pathways, sidewalks, cycle paths and streets (Zulian et al. 2013, Cortinovis and Geneletti 2018).

With increasing urbanisation and the full impact of human activities, air pollution has increased by the release of particles of combustion processes and has been linked to respiratory diseases (Nowak 2006, CETESB 2017), just as heat islands have formed in urban centres and other areas due to lack of vegetation (Sandifer et al. 2015). Thus, in order to bring a better quality of life to the people who inhabit urban centres, some ES are essential, for example, climate regulation ecosystem services, such as cooling effect (Cortinovis and Geneletti 2018) and the removal of air pollutants, including both inhalable particles (i.e. PM_{10}, $PM_{2.5}$) and gases (e.g. Ozone (O_3)) (Marando et al. 2016, Fusaro et al. 2017). These ecosystem services are provided by vegetation and can be increased by revegetation or enhancement of current vegetation in and around urban areas (Bolund and Hunhammar 1999). To this aim, many nature-based solutions have been studied, planned and implemented around the world, which have been considered a trend not only in improving well-being of people, but also to assist in the conservation of biodiversity (Steven et al. 2011, Kabisch et al. 2016, Raymond et al. 2017, Frantzeskaki 2019).

The local biodiversity provides or facilitates the ES provisioning. Birds are a well-known animal group with a worldwide occurrence in nearly all habitats where they play important ecosystem functions; hence, they are identified as an ideal group to be used as indicators of ES occurrence and availability (Savard et al. 2000, Whelan et al. 2008, Wenny et al. 2011). Pollination and seed dispersal (supporting ES), pest control and carcass removal (regulating ES) and birdwatching activities (educational and cultural ES), are amongst the many examples of birds-related ES (Belaire et al. 2015, Şekercioğlu et al. 2016). Moreover, beyond recreation and cultural services, birdwatching can be used as a tool to promote biodiversity conservation through environmental education programmes for students and/or the local community and to develop socioeconomic opportunities, such as ecotourism (Fieker et al. 2011, Belaire et al. 2015, Whelan et al. 2015, Echeverri et al. 2019). Emphasising the significance of environmental conservation, it is crucial to note that degraded environments lacking vegetation may have adverse effects, leading to the emergence of Cultural Ecosystem Disservices and discouraging birdwatching activities (Echeverri et al. 2019, Teixeira et al. 2019, Brambilla and Ronchi 2020). In this context, conservation initiatives can play a crucial role in alleviating adverse effects and fostering an environment conducive to birdwatching enthusiasts.

The bird richness can be used as a surrogate of the ecosystem characteristics, such as the quality of habitats and the possible outfits of birds' ecological functions (Whelan et al. 2008). A higher richness leads to broader availability of ecological functions played by birds

(García and Martínez 2012), especially in highly biodiverse environments of the Neotropics (Şekercioğlu 2012). In this scenario, a forest or savannah patch that offers a number of ES which depend on the vegetation structure, can harbour birds that also offer other types of ES (Fieker et al. 2011, Belaire et al. 2015, Whelan et al. 2015, Echeverri et al. 2019).

Amongst the decision-making processes that affect biodiversity and ES provision, urban landscape planning plays an essential role to achieve a high-quality environment (Zulian et al. 2017). A well-planned multifunctional landscape can provide ES and, at the same time, protect biodiversity (Santos-Martín et al. 2019). Depending on the local context, different synergies and trade-offs may emerge (Tomscha and Gergel 2018), which could be explained as a negative or compensating relationship between biodiversity and different ecosystem services, where often to gain in biodiversity conservation or to improve the supply of a specific service, it is necessary to decrease the supply of another service. It requires studies and research efforts to drive the decision-makers towards effective and win-win solutions for each landscape.

In this study, we assessed the current status of three selected ES and bird richness as a surrogate of other ES along waterbodies of a tropical-subtropical river basin which covers urban, peri-urban and rural zones of a Brazilian municipality located in an Atlantic Forest – Cerrado (Brazilian savannah) ecotone, two of the 25 global hotspots for conservation priorities (Myers et al. 2000). We aimed to:

1. assess the current state of ES and bird richness in the Monjolinho River Basin, located in São Carlos, State of São Paulo, south-eastern Brazil;
2. evaluate the relationships between cooling effect, air pollutant removal, nature-based recreation opportunities and bird richness;
3. assess how the main type of land cover can influence the potential degree or availability of ecological services across an urban-rural-natural gradient;
4. assess future scenarios by using nature-based solutions to improve ES and biodiversity; and
5. how it can support urban landscape planning and policies.

Methodology

Study area

The study was conducted in the Monjolinho River Basin, located in the State of São Paulo, south-eastern Brazil (Fig. 1). The regional climate is subtropical humid mesothermal or CWA according to the Köppen classification. The Basin has an area of approximately 275 km² and includes the entire urban zone of São Carlos Municipality. The main river, Monjolinho, has a length of approximately 43.25 km, originates in the east of the city at an elevation of about 900 m and flows in the east-west direction (Espíndola 2000). The administrative area of São Carlos covers 1137.303 km^2 with a population of 221,950 inhabitants, 96% of which is urban (IBGE 2010). The land cover is composed of approximately 60% agricultural areas, where the most common activity is sugarcane cultivation; the remainder is almost equally divided between natural vegetation and urban areas (Ferreira and Cunha-Santinho 2014).

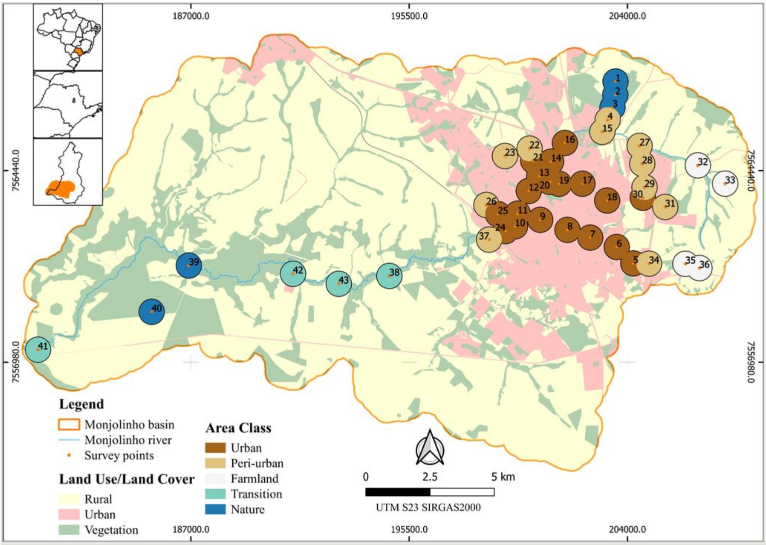

Figure 1.

Characterisation of the study area in the Monjolinho River Basin, central region of the State of São Paulo, south-eastern Brazil.

The population of São Carlos has grown significantly in the last decades (Costa et al. 2013) together with intensive agricultural activities which have been increasingly impacting the local native vegetation and natural resources (Costa et al. 2013, Ferreira and Cunha-Santinho 2014, Neves et al. 2018). The urbanisation has also created a heat island effect which is worsened by air pollution due to the use of fossil fuels. Besides that, the annual dry period (about 6 months), a characteristic of the climatic region, contributes to this effect (Costa et al. 2013, CETESB 2017, Neves et al. 2018).

The original vegetation in the Monjolinho River Basin was characterised by the presence of *Cerradão* (forest), open and dense savannah phytophysiognomies, mesophytic forest (semi-deciduous seasonal forests) and other vegetation types, such as riparian forests and open wetlands (Soares et al. 2003).

In this study, we carried out a comprehensive assessment of biodiversity and ecosystem services, focusing on key indicators: nature-based recreation, cooling effect (microclimate regulation), air pollutant removal (measured using PM_{10}) and bird communities (measured using bird richness).

Biodiversity and Ecosystem Services assessment

We selected 43 sample points in the watershed that are representative of all ecosystems and landscape types, including transition areas. The points have a minimum distance of

200 m from each other and were located along watercourses (Fig. 1). The sampling points were randomly selected, taking into account factors such as minimum distance, accessibility and the effort to encompass all types of riparian environments within the watershed, ensuring a comprehensive assessment of biodiversity. In a subsequent step, we evaluated bird richness (BR), land use and land cover (LULC) and three Ecosystem Services (ES) employing the methodologies described below.

We assessed the land use and land cover and the canopy cover of urban forest inside a buffer of 500 m from each survey point. We used Google images from Open Layers plugin in the Quantum GIS (QGIS) software and data from OpenStreetMap (OSM) and then classified according to the CORINE legend with some adaptation for local features (Suppl. materials 1, 2 - https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html). The land use was classified by using photo-interpretation of remotely-sensed data and field visits for ground-truthing for the year 2018.

Bird survey

For the bird community assessment, we employed the traditional "point count" method, described by Matter et al. (2010). Two visits were made in each season (summer, autumn, winter, spring) between 2016 and 2017, totalling eight visits at each point lasting 10 minutes each. Those visits were not conducted on consecutive days to ensure a diverse representation of bird species over time.

Spatial independence was rigorously maintained by adhering to a minimum distance of 200 m between each sampling point. Species identification and counting were conducted within a 50 m radius area centred around the watercourse at each of the 43 sampling points, following the methodology outlined by Matter et al. (2010). More information about the field methods can be found in Lessi et al. (2020).

Nature-based recreation

Nature-based recreation was calculated by applying an adjusted version of the ESTIMAP-Recreation model, considering the Recreation Opportunity Spectrum (ROS) as a final indicator (Zulian et al. 2013, Cortinovis and Geneletti 2018). The second process to calculate the ROS assesses the availability of infrastructures and facilities to access (e.g. cycle paths, bus stops, streets) and to use (e.g. playgrounds, sport fields, pathways) the areas, thus providing an assessment of the opportunities offered to the citizens.

We considered the ROS to reflect the current recreation opportunities and scored all elements into a 0-1 scale. For facilities to access the areas, we considered how much they contribute to accessibility and for how many people, for example, bikeways received higher scores because everyone can use them for reaching a destination and even for recreation; residential streets are well ranked because people can walk, ride a bike or drive a car; and highways received low scores because only autos can use them. For facilities to use the areas, we scored them based on how much opportunity of recreation each facility offers.

The final score (0-1) is the mean score of all criteria applied to each evaluated infrastructure.

After mapping and scoring the facilities, we converted the information to raster and generated the buffer of effect, which we considered equal to 500 m for all elements. Then, we combined all the facilities to produce the final map of the Recreation Opportunity Spectrum (ROS).

Microclimate regulation

We estimated the cooling effect from vegetation by applying the model for urban green infrastructures using the Continental climate parameters (Koppen: Cfa) for the cooling capacity developed by Zardo et al. (2017). The model considers the soil cover, the shading produced by the canopy cover, the size of each patch of green infrastructure (parks, green areas, grass areas, brownfields, gardens, vegetations patches) and characteristics of the climate region, including the evapotranspiration rate and the cooling effect of the surroundings. The cooling effect is classified in cooling capacity classes (A-E), with the same range of expected temperature difference (Geneletti 2016).

Following the methodology developed by Zardo et al. (2017), first, we classified the land use and land cover into soil-cover classes (sealed, bare soil, heterogeneous, grass, water, see Suppl. material 1), then we calculated the percentage of canopy cover (five classes of percentage) and the size (< 2 ha and > 2 ha) of each patch (Zardo et al. 2017), which will reflect the more or less cooling capacity. We used the climate parameters of the Continental climate (Koppen: Cfa) (min cooling 1.0°C; max cooling 4.8°C) because it was the closest climate for which the model parameters were provided.

The model calculates a score (0 to 100) to classify the cooling capacity of each area. The scores can be classified into five classes (Class A: 100-81; B: 80-61; C: 60-41; D: 40-21; E: 20-0; see more details on Geneletti (2016)) and each class can be linked to a maximum expected temperature difference (for the Continental climate: Class A: 4.8°C; B: 3.8°C; C: 2.9°C; D: 1.9°C; E: up to 1°C) between the analysed area and a reference area with the lowest cooling capacity (i.e. a sealed surface with no trees; see more details in Zardo et al. (2017)).

To map the cooling effect produced in the surroundings, decay functions with buffers around the areas were used. These buffers of effects depend on the Cooling capacity class (A-E) and the size (< 2 ha and > 2 ha) in a decay function of effect: areas smaller than 2 ha provide a cooling effect of 25 m and areas greater than 2 ha a buffer of 50 m, with the buffer being classified in the subsequent cooling capacity class. The shading effect of urban trees is classified into Class A, with a 5 m of cooling effect buffer on the surroundings. Finally, we converted the final map in a raster image with temperature data of cooling effect.

Air pollutant removal

Air pollutant removal estimation was based on PM_{10} (particulate matter) deposition through model adopted by Fusaro et al. (2017), based on the formula: Q = F*L*T (Q - PM_{10} removed on 1 m^2 (μg/m²); F -deposit velocity (m/s) multiplied by PM_{10} concentrations (μm^{-3}); T – Vegetative period of ecosystem vegetation (number of days in one year); and L - Leaf Area Index (LAI)). To obtain the final model, we used the formula in the QGIS raster calculator and cut the final raster image with a 500 m buffer of the 43 study points.

The concentration data of PM_{10} (28 μg/m³) (CETESB 2017) in the atmosphere was estimated from the approximation mean value of the average annual concentration amongst the cities of Araraquara, Bauru, Jaú and Ribeirão Preto, all around São Carlos region, which exhibit population, environmental and climate characteristics similar to the study area. The deposition velocity was set to a median value of 0.0064 m/s (Lovett 1994, Fusaro et al. 2017). For vegetation, since no forest has deciduous characteristics in the region (Soares et al. 2003), we considered it as "always green" and, thus, presented leaves 365 days of the year.

For the Leaf Area Index (LAI), we used Sentinel-2 images (T22KHA, N205, date 12/09/2017) as Level-1C product, i.e. geometrically-corrected top-of-atmosphere reflectance, downloaded from the United States Geological Survey (USGS) Earth Explorer website (http://earthexplorer.usgs.gov). We applied the atmospheric correction to the S2 image using Sen2cor module version 6.0.2 and, after this procedure, we applied the 10 metres resembling process to the corrected image (Sentinel-2A MSI image). Then we applied the automatic Biophysical Processor for LAI (Leaf Area Index) within the Sentinel-2 Toolbox (S2TBX), Sentinel Application Platform (SNAP) version 6.0.0 (Korhonen et al. 2017, Vinué et al. 2018) from ESA (European Spatial Agency). In the end, we resampled the image with LAI index with 10 m resolution to 1 m resolution and then calculated the PM_{10} removal.

Synergies and trade-off assessment

For each model, we generated a final raster image, from which we extracted the mean values of ES, using the zonal statistics of QGIS algorithms on the processing toolbox, for each 500 m buffer of the 43 surveyed points. Based on the results, we assigned a score to each sample area. First, we calculated the mean value of each ES in the 500-m buffer around each sample point and bird richness and then normalised the results between 0-1, where 1 was the highest value amongst the sample areas. After that, we classified the results into three classes, dividing the range 0-1 into three equal parts (low – 0-0.33, medium – 0.33-0.66, high – 0.66-1.00) to facilitate the visualisation and comparison amongst the results.

To assess synergies and trade-offs between all the ES and biodiversity indicators, we ran the correlation bivariate model using the Reduced Major Axis (RMA) algorithm with log transformation to data aiming to avoid errors related to different measures used to calculate each indicator (Hammer et al. 2001). To investigate the variation across the urban-rural-natural gradient, we classified and grouped points according to five major landscape types defined by the land-cover proportion and dominance of the following landscape units: native vegetation and superficial water, crops and pastures and urbanised areas. Thus, we categorised the areas surrounding the sampling points in five landscape types:

1. urban (URB);
2. peri-urban (PERI), i.e. the transition between urban areas and non-urban areas;
3. farmland (FARM);
4. transition (TRAN), defined as the transitional landscapes between farmland and native vegetation; and
5. nature (NAT), comprising native vegetation and superficial water (streams, river, lakes) (Suppl. material 1).

We tested the influence of these five landscape types on the mean values of ES performing the analysis of variance (ANOVA) and the post-hoc Tukey's Q test to identify significant differences between pairs of landscape types, using PAST Program (Hammer et al. 2001), v.4.03 released in 2020. For ES datasets with at least one out of five matrix types showing non-normal distribution confirmed with the Shapiro-Wilk normality test, we proceeded with a log transformation. We considered the significance level alpha = 0.05 to accept an alternative hypothesis of each test.

Generation of future scenarios

We identified available public areas which could be targeted by a reforestation programme (Fig. 2) to simulate the future scenarios with an improvement in the canopy cover of public green areas. As available areas, we used the difference between areas covered by trees and not covered on the selected public green areas. Inside the areas available for future reforestation, we simulated possible scenarios considering the use of 25%, 50%, 75% and 100% for the improvement of canopy cover. Then we recalculated the cooling effect and air pollutant removal models for each of these four percentages of possible scenarios. To run the air pollutant removal, we adopted a LAI index of 0.9 m^2/m^2 on the newly-planted areas (this value was selected through a good and tangible value, based on the values of existing canopies in good conditions).

To better address the urban management and facilitate the decision-making, we assessed the results of the future scenarios for each urban watershed area (Fig. 2). The micro-basins were delimited in QGIS using GRASS 7 (r.watershed model) in the processing toolbox with a 30 m resolution Digital Elevation Model (DEM) (images 21S48 and 22S48) elaborated from SRTM data from USGS, available in the geomorphological database of the Brazilian National Institute for Space Research (INPE) (http://www.webmapit.com.br/inpe/topodata/).

With the increase of forested areas, we assumed that this scenario could influence the bird richness and the available services offered by these animals. Thus, we tried to predict the consequences of a management focused on reforestation by identifying the relationship between the vegetation cover area and the number of bird species. We used the polynomial regression analysis, based on a least-squares criterion and singular value decomposition, to select the best-fit model using the Akaike Information Criterion – AIC value. For the selected model, we tested the significance of the fit using the F test and obtained the coefficient of determination (R^2), i.e. the proportion of the variance explained by the model (Hammer 2020). This procedure was implemented in PAST Program (Hammer et al. 2001) using data collected in the selected micro-basins inside the urban zone, which represent the current land use and added data collected in the peri-urban zone, representing a scenario with more vegetation and ecological corridors, but with a similar species pool of the bird community composed by those that can inhabit completely urbanised habitats.

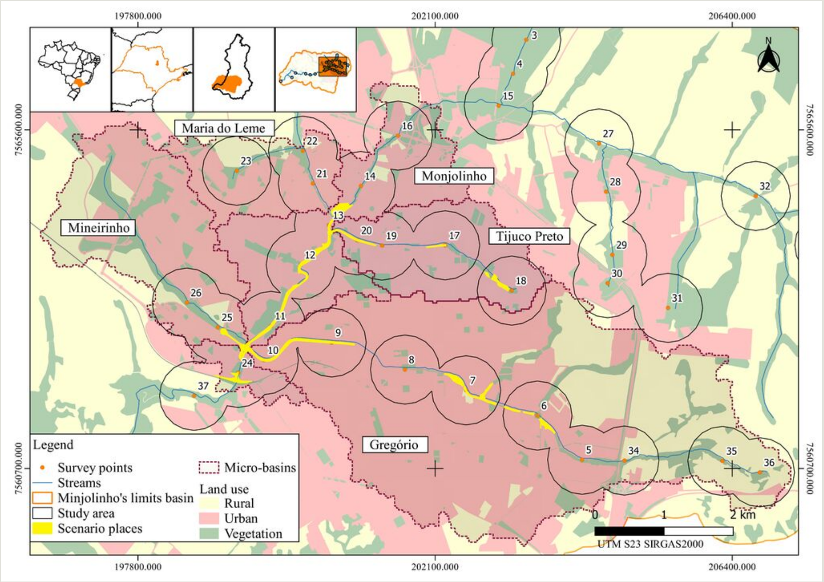

Figure 2.

Division of micro-basins of the Monjolinho River (main basin) in the urban area, with indication of the buffers where the future possible scenarios of reforestation were estimated and the planting sites (yellow) identified for the scenarios.

Results

Mapping of ES supply

The indicators of Ecosystem Services (ES) assessed along watercourses in the Monjolinho Basin were categorised into three intensity classes (low, medium, high) for each sampling point, based on the normalised values (detailed data in Suppl. material 2). These data were plotted on the maps showing the spatial patterns of ES provisioning intensity for pollutant removal and cooling effect, the availability of recreation opportunities for people and the bird richness (number of bird species sampled *in situ*) occurring in each sampling point (Fig. 3).

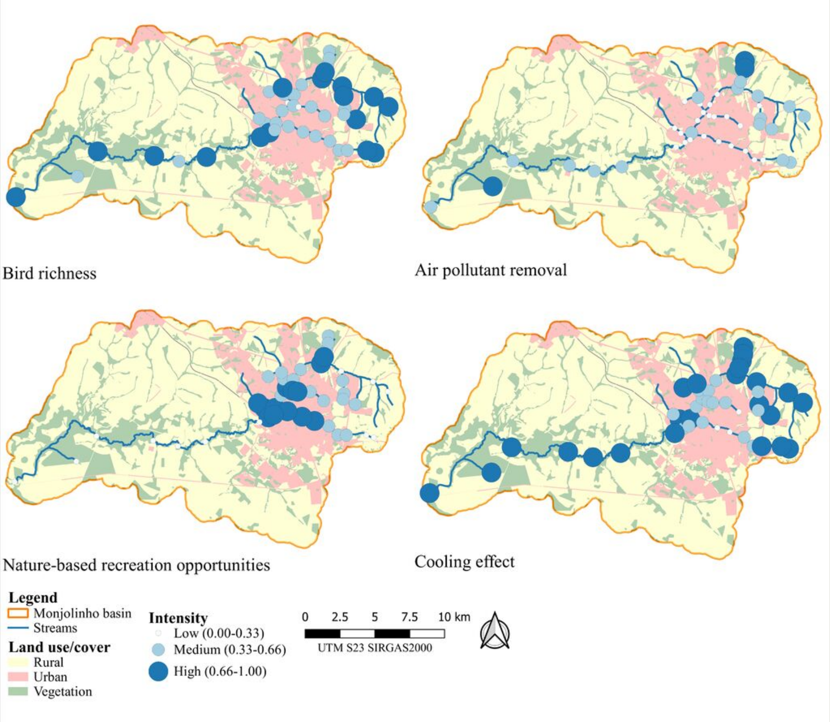

Figure 3.

Supply of Ecosystem Services in sampling points along waterbodies of Monjolinho Basin, south-eastern Brazil.

The different zones of land use at landscape scale influenced the mean values of ES provided by nature: pollutant removal (F = 23.64, $p < 0.0001$), cooling effect (F = 25.11, $p < 0.001$) and bird richness (F = 11.29, $p < 0.001$) as a surrogate for services offered by animals; and the nature-based recreation opportunities for people (F = 20.19, $p < 0.001$). The variation of ES values of each zone is detailed in Fig. 4. The post-hoc test indicated that the points completely immersed in the urban matrix were significantly different from other landscape zones, considering paired comparisons for each of four ES ($p < 0.05$, see Suppl. material 3).

While the urban landscapes showed the lowest means of pollutant removal, cooling effect and bird richness, those areas have the highest means of recreation opportunities (Fig. 4). Additionally, we found significant differences between points located in landscapes with a higher proportion of native vegetation and the points in peri-urban areas, regarding cooling effect and recreation ($p < 0.01$). Additionally, areas with native vegetation are significantly different from all other zones in terms of pollutant removal ($p < 0.012$).

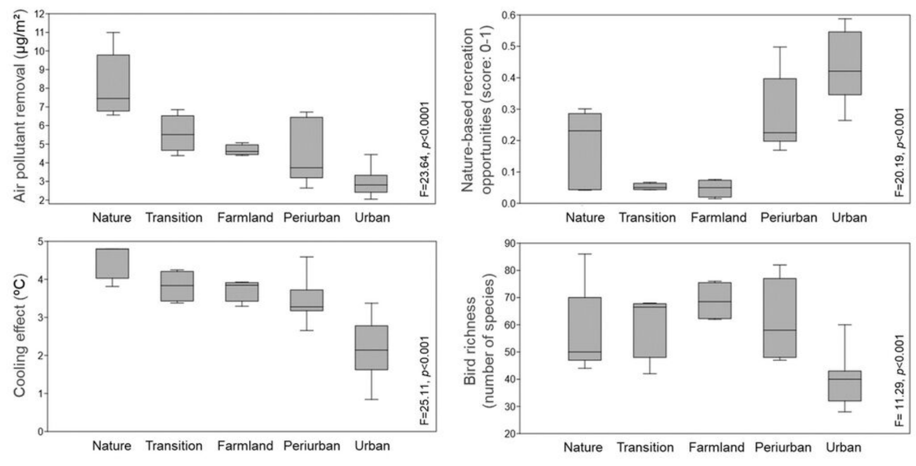

Figure 4.

Variation in Ecological Services values across different landscape zones along waterbodies in the main basin of Monjolinho River, south-eastern Brazil and respective ANOVA results.

Relationships between ecosystem services and biodiversity

The assessment of relationships between each ES (Fig. 5) indicated a significant positive correlation between PM_{10} removal and cooling effect ($r = 0.827$, $R^2 = 0.684$, $p < 0.001$). Towards the same direction, the bird richness-ES correlations pointed to a positive and significant relationship with PM_{10} removal ($r = 0.539$, $R^2 = 0.29$, $p < 0.001$) and cooling effect ($r = 0.649$, $R^2 = 0.42$, $p < 0.001$). Beside these positive relationships, we found trade-offs with the recreation opportunities, that exhibited a significant negative correlation with cooling effect ($r = -0.578$, $R^2 = 0.335$, $p = 0.048$), with PM_{10} removal ($r = -0.419$, $R^2 = 0.176$, $p = 0.005$) and with bird richness ($r = -0.59$, $R^2 = 0.348$, $p < 0.001$).

Assessing future scenarios

Four possible scenarios were simulated to understand how the increase in forest cover area could enhance the two ES which are primarily determined by the presence of vegetation, the cooling effect and pollutant removal, as shown in Table 1. The available sites to allocate restoration efforts correspond to only 1.46% of the total area. However, in the best scenario with the restoration actions applied in 100% of the available area, the pollutant removal indicator can be increased from 2.61% up to 7.73% and cooling effect from 1.35% up to 3.34%, according to the sections (micro-basins) of the main river basin which varied in available areas to be restored. There is one micro-basin without available area to increase these two ES, but it showed the highest current values. In another case, the available area of one micro-basin is so small (0.973 ha) that no changes in the cooling effect indicator were observed in the four possible future scenarios (Table 1).

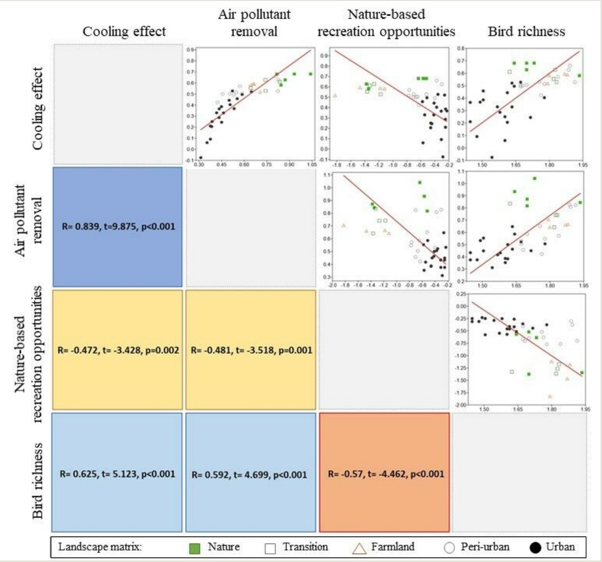

Figure 5.

Linear models indicating the correlation between Ecosystem Services. The diagonal above shows the surveyed points representing the five landscape matrices plotted in linear correlation models. The diagonal below shows the correlation results. Dark and light blue colours: positive correlations. Red and orange colours: negative correlation.

Table 1.

Possible scenarios for implementation of active reforestation as a nature-based solution to enhance two Ecosystem Services (ES) directly promoted by vegetation type and its cover area: cooling effect (Cool.) and air pollutant removal (PM_{10}). The scenarios consist in recalculating the ES indicators of each waterbody (sections) that compose the main basin in urbanised landscapes, considering four percentages of the available area (expressed in ha = hectares) that could be used for reforestation.

Urban sections of the basin	Area (ha)	Current ES values		Available area for reforestation (ha)	Possible future scenarios: reforestation percentages of the available areas							
					25%		50%		75%		100%	
		Cool. (ºC)	PM10 (µg/m²)		Cool. (ºC)	PM_{10} (µg/m²)	Cool. (ºC)	PM_{10} (µg/m²)	Cool. (ºC)	PM_{10} (µg/m²)	Cool. (ºC)	PM_{10} (µg/m²)
Mainstream:												
Monjolinho river	343.483	1.747	3.391	10.543	1.775	3.456	1.797	3.522	1.805	3.588	1.805	3.653
Tributaries:												
Tijuco Preto stream	213.224	1.057	2.550	2.239	1.058	2.575	1.061	2.599	1.071	2.623	1.071	2.648
Gregório stream	605.391	0.815	2.883	7.256	0.818	2.910	0.830	2.937	0.834	2.964	0.834	2.992

Urban sections of the basin	Area (ha)	Current ES values		Available area for reforestation (ha)	Possible future scenarios: reforestation percentages of the available areas							
					25%		50%		75%		100%	
		Cool. (ºC)	PM10 (μg/m²)		Cool. (ºC)	PM_{10} (μg/m²)	Cool. (ºC)	PM_{10} (μg/m²)	Cool. (ºC)	PM_{10} (μg/m²)	Cool. (ºC)	PM_{10} (μg/m²)
Mineirinho stream	107.889	0.704	3.382	0.973	N/C	3.404	N/C	3.426	N/C	3.448	N/C	3.470
Sta Maria do Leme stream	169.625	2.132	3.415	0	No changes (N/C)							
Total:	1439.612			21.011								

Bird species richness, which represents a set of ES being offered in urban areas, can be increased with the addition of forested areas, based on the model that considers data collected in points of urban and peri-urban zones (Fig. 5). Sampled points immersed in the urban matrix are the focus for implementation of nature-based solutions and showed the lowest mean number of bird species (Fig. 3). Since the peri-urban zone is the only type of landscape directly connected to urban zones, we included data from peri-urban points in the model as the most plausible optimum state of bird richness that some of the urban environments could reach if they have similar features to the peri urban areas, i.e. larger vegetated area. The regression model that best fits the data (AIC = 4.3) is a linear or one order polynomial regression, which indicates a significant positive influence of vegetation cover area on the richness of bird species (Fig. 6). About 39.2% of data on bird richness in urban and peri-urban landscape matrices can be explained by forested areas ($R^2 = 0.392$; $F = 18.045$; $p < 0.001$).

Discussion

Assessing the distribution and intensity of ecosystem services and biodiversity

Through the ecosystem services (ES) assessment, it was possible to identify clear patterns of intensity spatially distributed according to land cover and land use, mainly derived from a gradient from natural to urbanised areas. While air pollutant removal, cooling effect and bird richness were strongly associated with vegetation cover (well-structured vegetation, for example, forests), the nature-based recreation opportunities, which also depend on human infrastructure, presented the highest values in urbanised areas, indicating a trade-off amongst the availability of these ES.

The assessment data map (Fig. 3) favours the comprehension about the differences amongst points and areas in terms of the distribution of bird richness and the intensity of ES provision in a land-use gradient composed by urban, peri-urban, farmland, transition and natural landscape matrices. Each point encompasses the current land use at a medium scale (500 m buffer), that was used to calculate ES values. Hence, it can be asserted that the sense of well-being an individual may experience varies across the river basin due to the distinct combinations of ES provided in different locations, thereby promoting diverse benefits (Rendón et al. 2019).

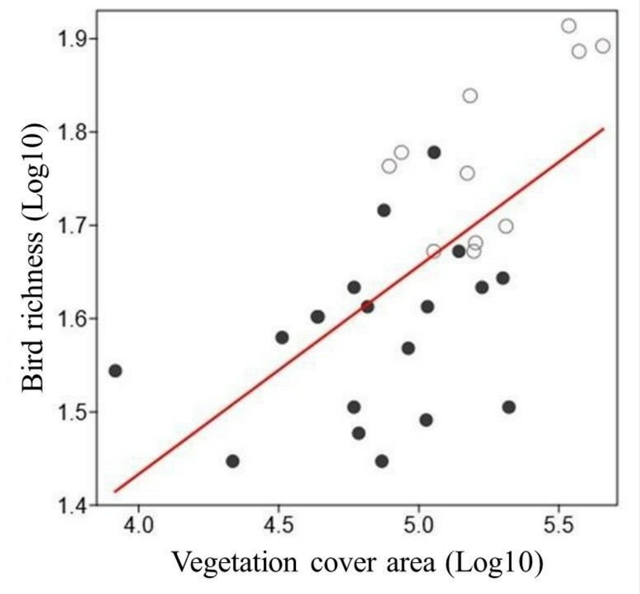

Figure 6.

Linear regression model fitted to data of bird richness and vegetation cover area, considering restored forests and similar vegetation types in n = 30 surveyed points located in urban (filled circles) and peri-urban (empty circles) zones. This model can be represented by the equation 0.223x+0.542 (log-transformed data).

Looking at the current state of the ecosystem services, for the cooling effect, it is possible to see a positive scenario considering that over half of the sampled areas have a high level of cooling, as shown in Fig. 3. On the other hand, there was a clear drop in this effect in the urban area, the place with the highest demand for this service by citizens, since it has a higher human population density of the municipality (IBGE 2010, Costa et al. 2013) and its physical characteristics, including low vegetation cover, enhance the possibility of heat island phenomena (Sandifer et al. 2015). There are some vegetation patches in assessed urban areas, but only small fragments or green areas with low canopy cover (e.g. anthropogenic fields, parks, gardens).

The analysis of the PM_{10} removal throughout the Monjolinho Basin indicated better removal where there is more vegetation cover. The air pollutant removal has a direct relationship with the leaf area of plants, which depends on vegetation type and its conservation state (Manes et al. 2016, Fusaro et al. 2017). These results pointed to a bad current situation, in which the places where the greatest amounts of pollutants are produced are precisely those where there is the greatest demand and the lowest availability of the pollutant removal services promoted by vegetation.

The current state of the nature-based recreation model indicated more opportunities in urban areas, despite these areas presenting the lowest levels of cooling effect and air pollutant removal and comparatively low bird richness. This scenario highlights important issues with the green infrastructure in the urban areas. Considering that the locales intended for recreation are the places where there is a concentration of people using them, the low levels of regulation ES is an indicator of the need to improve green infrastructure (i.e. tree cover) in those areas in order to increase and restore ES levels (Elmqvist et al. 2015, Fusaro et al. 2017, Cortinovis et al. 2018). The assessment of nature-based recreation opportunities shows better opportunities in the most urbanised areas, followed by the peri-urban zone, with a lack of opportunities in areas beyond city limits towards rural and natural areas (Fig. 3).

Even with the landscape types influencing the bird richness and ecosystem services levels, it is possible to notice in the maps one region on the north, where we found medium and high levels of bird richness and the other ES. That area can be considered a biodiversity and ES hotspot in the studied watershed. It is an important area with a large continuous vegetation fragment, belonging to the Federal University of São Carlos and to a neighbouring Zoopark (Parque Ecológico de São Carlos). The natural fragment has some trails that are used by people for exercise and by University students to do their research. The Zoopark attracts local people and visitors of other municipalities for recreation and education about wildlife. At the same time, the presence of conserved vegetation not only regulates the climate and reduces the air pollutants at the local level, but also can play a role as an important peri-urban barrier for the air pollutants (Fusaro et al. 2017). That vegetation also harbours at least two water springs of the Monjolinho River, the main river of the Basin, which is one of the main water sources for local agriculture and human consumption. It is a good example of a multifunctional landscape offering many ecosystem services for people's demands (Zasada 2011, Santos-Martín et al. 2019).

The current state of bird richness and ecosystem services shown in Fig. 3 indicated an apparent synergy amongst the bird richness, cooling effect and air pollutant removal, but there is a trade-off with nature-based recreation opportunities. These trends were confirmed by the correlation statistics (Fig. 4). This synergy between cooling effect and air pollutant removal was expected due the relationship of both models with canopy cover and the consequent synergy with bird richness once this vegetation contributed with more habitats for birds (MacGregor-Fors and Schondube 2011, Fusaro et al. 2017, Zardo et al. 2017). However, the trade-offs between nature-based recreation and other ES were unexpected, once the recreation opportunities considered here are according to the nature-based spectrum, so a better green infrastructure (i.e. the presence of vegetation, tree and canopy cover, environmentally-friendly playground) was expected in these places destined for recreation (Wen et al. 2018). This trade-off scenario could be reversible with nature improvement in the urban areas and/or recreation improvement in natural areas, which could be reached by planning a multifunctional landscape supported by Nature-based solutions (Cortinovis et al. 2018, Escobedo et al. 2019). Those solutions must consider offering more ecosystem services promoted by vegetation according to the population demand and create or enhance bird habitats throughout the Monjolinho Basin.

Influence of landscape zone on ES indicators, synergies and trade-offs

The variations of ES indicators throughout the Basin were driven by the landscape matrix, i.e. the predominant land use inside the assessed areas. The mean values of ES in urbanised areas significantly differed from all other landscape matrices, indicating that anthropogenic environments are the most distinct and can cause intense impact on services offered by nature.

The influence of the urban-rural-nature gradient on bird richness and ecosystem services was clearly shown by this assessment (Figs 3, 4). It is possible to notice two main patterns. The first was that the gradient flows in a positive direction from landscapes more impacted to less impacted or from urban (worst scenario) to nature (better scenarios with more suitable habitats) for bird species richness and the availability of regulation services (cooling effect and PM_{10} removal). Additionally, in the second, the gradient drives the results in the opposite direction, being positive from less impacted to more impacted landscapes or from (worse) nature to urban (better) for recreation services, even though considering the nature-based recreation opportunities.

The lower of bird richness in urban areas may further increase the negative picture for ES in these areas, as birds also have their ecological roles that can be converted to ES and greater bird species richness levels may provide a greater richness of ecological functions and a consequent supply of ES (Şekercioḡlu 2006, Lessi et al. 2020). Furthermore, many Neotropical birds in the assessed community are seed dispersers, i.e. they contribute to forest maintenance, as well as the enhancement of current vegetation and the recovery of degraded areas (Wijedasa et al. 2020), which could lead to an enhancement of other ES, including air pollutant removal and cooling effect.

The different responses to the gradient and the different correlations show that the difference on the land use of point surroundings have a major impact on biodiversity and the supply of ES. Thus, the ES and bird richness assessed in this study follow the gradient of the landscape, decreasing from natural to urban (except recreation services), as found in other surveys (Haase et al. 2012, Hou et al. 2015), while population density and demand for ecosystem services increase in the same gradient. The trade-off relationship between recreational opportunities and climate-regulated ES in this type of gradient was also evidenced by Haase et al. (2012), as well as the trade-off relationship between recreation and biodiversity in different landscapes (Turkelboom et al. 2018). In this way, the loss of ES in the natural-rural-urban gradient and, at the same time, the increase in the demand for ES due to the increase in the population with the increase of urban landscape in this gradient are clear. The substitution of areas with vegetation for anthropogenic uses and the lack of policies that encourage the preservation or restoration of areas with native vegetation in urban areas, such as the surrounding streams, are identified as the main causes of this lack of ES supply. On the other hand, once the distribution of ES and biodiversity are diagnosed, we may assess how different areas could interconnect in a compensatory system for ES supply and biodiversity aiming to benefit areas with less ES offerings and more human demand.

It is known that urban areas do not support the same biodiversity as natural landscapes, but with the improvement of green areas and the creation of heterogeneous landscapes using native vegetation and wetlands, it is possible to increase the support capacity of the environment, increasing biodiversity rates and ES supply. On the other hand, the large areas of native vegetation close to urban zone (peri-urban and rural landscapes) can play a role as local hotspots for both biodiversity and ES, a situation that can be used for planning nature-based solutions, since those hotspots can serve as source areas to support improvements in the most degraded environments. Likewise, the cooling effect and air pollutant removal services within the urban zones are important for climate regulation and air quality in the landscape scale (Larondelle and Haase 2013, Fusaro et al. 2017, Cortinovis and Geneletti 2018).

The analyses of the landscape gradient helped to understand how to plan a compensation system, based on policies for the preservation of natural areas and the enrichment of urban areas using green infrastructure. The identification of synergies, trade-offs and the land-use types that contribute to the ES provision allows policy-makers to better understand the hidden consequences of preferring one ES to another (Haase et al. 2012). In addition, the results indicated a necessity to develop conservation planning (Chan et al. 2011), especially in areas subject to intensive human activities (Wu et al. 2013). Planning a multifunctional landscape can be the solution for implementing actions and creating infrastructures to contribute to ES supply and biodiversity conservation (Peña et al. 2018).

Using nature-based solution for ES improvement to support urban planning

The results made it evident that simple public policies, such as tree planting as a nature-based solution to urban problems, can achieve good results in short and medium-term periods (Fig. 5 and Table 1). However, this conclusion was only possible after mapping the environment and proceeding with an assessment of current ES, which allows us to understand the interactions amongst landscape elements and ecosystem services.

The selected ES indicators for modelling the future scenarios, i.e. air pollutant removal and cooling effects, depend on green areas, mainly the vegetation type and structure, which are also precursors of bird assemblage structure and the services they can offer. In this context, the most valuable nature-based solution to enhance these three ES in areas with low values of indicators and to provide contact with nature during recreation activities inside the city, is the restoration of non-vegetated areas. If public sites without arboreal vegetation that are abandoned and many are extremely degraded, were used to create green areas with well-structured vegetation in urbanised landscapes (urban and peri-urban zones), our results showed that the three ES provided exclusively by nature could be significatively enhanced (Table 1) and consequently people's well-being (Sandifer et al. 2015, Rendón et al. 2019).

Nature-based recreation opportunities are not determined by forested areas as the other ES are. Instead, urban green infrastructures can be used to increase the opportunities, but only if there is planning focused on recreation, generally associated with infrastructure which allows such activity (Cortinovis et al. 2018). In this sense, it is not viable to try to estimate this ES indicator in scenarios with land restoration efforts. However, it is possible to state that the enlargement of vegetation cover area can serve for both, to promote a higher quality of recreation at sites already being used for this purpose (e.g. outdoor exercises, birdwatching) (Whelan et al. 2008, Rendón et al. 2019, Teixeira et al. 2019) or to create potential new areas for future use after a well-designed plan, focused on providing opportunities for the population (Sandifer et al. 2015, Cortinovis et al. 2018, Frantzeskaki 2019).

There are already several techniques for planning, decision-making and project execution, i.e. nature-based solutions, to improve the urban and agricultural scenarios of ecosystem services (Kabisch et al. 2016, Burkhard and Maes 2017, Zulian et al. 2017) and bring to these areas a greater supply of ES and a better quality of life for people as well. Nature-based recreations can even be one of the planning guidelines for bringing more biodiversity to the cities and achieving higher ES rates in those centres that are the places with the highest ES demand because of the higher concentration of people (Cortinovis and Geneletti 2018).

The synergy found between cooling effect and air pollutant removal services (Fig. 5) allows an evident improvement of these services in the future scenarios evaluated. Despite this, we see that the improvement is not achieved in the same proportion for all services (Fig. 5) mainly for recreation opportunities that depend on other actions and gain in biodiversity that depends on several factors (Belaire et al. 2015, Elmqvist et al. 2015, Frantzeskaki 2019).

The synergy present between ecosystem services allows a win-win relationship in a future scenario on well-planned landscapes, as discussed above. Additionally, it is important to consider a scenario based on native vegetation with high diversity to support biodiversity (Freitas et al. 2020, Berthon et al. 2021). Contrarily, it could cause a loss of synergy and create a trade-off relationship between services and biodiversity (Haase et al. 2012), as occurs in monoculture sites (Barros 2017, Berthon et al. 2021).

The assessment, based on micro-basins, may facilitate the decision-makers to access results of each section of the main basin, to rank the priorities to better address policies at small scales (due to a common lack of investment) and to meet local demands in each area. A focused design which considers the results of an ES assessment can play an important role as a facilitator instrument for natural resources management (Campanelli 2012, Tundisi and Scheuenstuhl 2012). As an example, this study shows Tijuco Preto and Gregório micro-basins with low and medium levels of ES as shown in the maps in Fig. 2 and indicate a lack of vegetation in the middle of their urbanised area (Table 1 and Suppl. material 1) even after the improvement in the future scenarios. Therefore, the assessment indicates that these regions should be prioritised in planning of public urbanisation policies. We found that only one of the possible tasks that ES mapping and assessment can perform to support urban planning and how we can activate that using a nature-based solution. From that, we can perform a range of elements, including the preferences, perspectives and demands from stakeholders and then apply other possibilities and multi-criteria analysis for even more accurate planning (Adem Esmail and Geneletti 2018, Geneletti et al. 2020).

In the end, some limitations on the ES assessment and analysis must be acknowledged. Part of the methodology was adapted to deal with the study area characteristics to run all models. There is a lack of studies on the same topic that could enhance and/or support the model development. The adaptation and mapping of land use, soil and canopy cover classification and the lack of an official map in high resolution could generate inaccurate data and assessments. Additionally, the mapping of the recreation opportunities was made in the laboratory by OpenStreetMap (OMS) infrastructure and confirmed *in loco*, but it would require the active involvement of local stakeholders able to score the elements, based on local knowledge and experience.

Conclusions

The presence of synergies between regulatory ecosystem services and the richness of bird species shows that it is possible to plan the urban environment to enhance the people's well-being and also for biodiversity conservation. Hence, biodiversity should be considered in urban planning, but in a more profound way than just the presence of vegetation. In this sense, this study integrated the avifauna structure as a biodiversity indicator for future scenarios' modelling and landscape assessment.

The future scenarios' assessment showed that nature-based solutions, such as improving the urban forest in green public areas, can be a simple way to achieve the desired results for a quality urban ecosystem for people and suitable in terms of biodiversity.

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Conflicts of interest

The authors have declared that no competing interests exist.
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Supplementary materials

Suppl. material 1: Supplementary material 1 doi

Authors: Lessi, B.F.; Geneletti, D.; Cortinovis, C.; Dias, M.M.; Reis, M.G.
Data type: Land-use and Land-cover classification
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