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DEVELOPING AND CLASSIFYING URBAN BIOMES AS A BASIS FOR NATURE-BASED SOLUTIONS

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Highlights

1. Laws and regulations often promote the use of species from the local biome for Nature-based Solutions (NbS).

2. They are usually considered the best adapted to regional environmental conditions.

3. We evaluated the extant conditions of the green infrastructure across São Paulo city.

4. 47% of São Paulo has conditions similar to the non-local but adjacent woody savannas.

5. The definition of urban biomes may leverage informed decision-making on urban forests.

Abstract

Urbanization is a major driver of environmental change, which calls for multifunctional and comprehensive actions such as Nature-based Solutions (NbS). They are “inspired and supported by nature… and must benefit biodiversity and support the delivery of a range of ecosystem services”. But what nature should one aim for? We tested the hypothesis that local vegetation may not always be the best source of inspiration, as environmental changes impact both extant conditions and species suitability for restored ecosystems. We analysed the megacity of São Paulo, where laws promote the use of species from the local Atlantic Forest biome. We trained a Linear Discriminant Analysis to classify the Brazilian biomes and predicted the biomes’ correspondence considering city’s vegetation cover and climate. With 80% accuracy, the model predicted correspondence with the Atlantic Forest in 57% of the city, while 43% is better represented by the Cerrado, a dense Tropical Savanna biome. Cerrado species are naturally adapted to higher insolation, temperature and more seasonal precipitation, and they can parallel the ecosystem services from the Atlantic Forest. To help guide NbS implementation, we consider four “urban biomes”: Atlantic Forest, Seasonally Flooded Atlantic Forest, Cerrado, and the Seasonally Flooded Cerrado, and discuss possible examples of NbS.

Keywords: Green Infrastructure, Blue Infrastructure, Urban forests, Machine Learning, NDVI.

Introduction

The world is rapidly urbanizing, with changes in land use and management practices altering natural vegetation cover and environmental quality, which affects cities' functioning, the health of citizens and their well-being (Goldstein, 1990; Seto et al., 2011). Impacts include poor thermal comfort; low air humidity; high air, water, and soil pollution; increased noise pollution; high vulnerability to flooding events and drought; high cityscape oppressiveness; low biodiversity; to name a few (Lehner et al., 2006; Asgarzadeh et al., 2010; Oleson et al., 2015; Elmqvist et al., 2016; Jariwala et al., 2017; Liang et al., 2019). Tackling these environmental issues can be challenging, and many cutting-edge engineering solutions have been proposed in the past. They are often planned and built as monofunctional solutions that frequently lead to other issues including landscape degradation (Brink et al., 2016). These limited solutions may gradually become unsuitable in modern cities as they grow in complexity, and instead multifunctional solutions, policies, and strategies may be required to address current environmental, social and economic problems (Ghafouri and Weber, 2020).

Nature-based Solutions (NBS) - actions "inspired by, supported by, or copied from nature" to tackle environmental, social and economic problems - arose as a multifunctional approach based on natural mechanisms (ECDG, 2015) that have been carefully evolving for thousands to millions of years as a part of Earth's biodiversity evolution (Mace et al., 2012). Biodiversity may provide tools to promote effective green and blue infrastructures and nature-based responses promoting benefits to human populations and helping them to adapt to ongoing environmental changes (van den Bosch and Sang, 2017; Anderson et al., 2019; Wild et al., 2020). However, an outstanding question for the implementation of NbS in different urban contexts is around "What nature should be used as a source of support and inspiration?".

The disputed debate on the use of native and non-native species underlies this question (Schlaepfer 2018). Not only because decisions on the urban green infrastructure of cities are oftentimes culturally and historically oriented (Whitney and Adams 1980), but also because managing urban forests requires pragmatic decisions related to the availability of seedlings in local nurseries (Almas and Conway 2016) and how species perform under the altered urban environment (Locosselli et al 2019). Native species available for urban reforestation may be naturally limited in regions characterized by low biodiversity, and non-native species present a renowned potential to add to the urban ecosystem development (e.g. Zerbe et al 2003, Schlaepfer et al 2020). Nonetheless, the availability of native species and associated environmental conditions exponentially increases across the latitudinal biodiversity gradient peaking at the tropics (Pianka 1966, Willig et al 2003), where native biodiversity may leverage urban ecosystem's function.

The use of native species finds strong support in the scientific literature, local laws and regulations (e.g. Alvey, 2006; Özgüner et al 2007, Ordóñez and Duinker, 2013; Ramage et al., 2013; Zhang and Jim, 2014; Almas and Conway, 2016) and in urban environmental activism worldwide (e.g. Krasny and Tidball 2012, Silva et al., 2019). The main argument holds that native species are better adapted to local environmental conditions, offering improved prospects for their deployment, development and growth to leverage ecosystem services (McPherson et al., 1994; Sydnor and Subburayalu, 2011; Mullaney et al., 2015). The addition of the clause to the European Commission's original definition of NBS that they "*must benefit biodiversity and support the delivery of a range of ecosystem services*" (Wild et al., 2020) may be viewed as underlining this point, if one subscribes to the view that biodiversity and native species are inextricably linked. Nonetheless, environmental change impacts from urbanization are now affecting these prospects and perspectives in most cities.

In addition to habitats' fragmentation and degradation during urbanization (Seto et al., 2011), climate has significantly changed in the cities largely affecting the potential use of some species in urban forests (Esperon-Rodriguez et al 2019). Heat islands are an emblematic issue in the cities worldwide (Manoli et al 2019). The replacement of green cover with grey infrastructure causes significant reduction in the turbulent convection, evaporative cooling, and albedo while enhancing heat retention and emissions (Oke 1982, Arnfield 2003). Such changes in the energy balance in the cities further affect the convective activities that shift precipitation regimes across cities (Marengo et al., 2020). Thus, both changes in vegetation and climate lead to altered extant local conditions found within cities.

Because substantial variations in vegetation and climate conditions define biomes (Conradi et al., 2020), cities are now considered as a new unique world biome (Pincetl, 2015). But classifying an entire city as the unique urban biome (Pincetl, 2015) is limiting and does not aid NbS decision-making or action because cities are heterogeneous. Such heterogeneity of urban environments has long been studied and debated (e.g. Grimm et al., 2000) and classification systems have been proposed to aid integrated urban planning and governance in relation to ecosystem restoration. For instance, biotopes have been long used to characterize the heterogeneity of urban vegetation for green infrastructure plans and implementations, attesting the importance of the clear understanding of vegetation structure across the city (e.g. Sukkop and Weiler, 1988; Stewart et al., 2009; Yilmaz et al., 2010). But this approach fails to account for the broad variability in climate conditions within the city (Steenberg et al., 2015) and new classification systems are needed that account for intra-urban variation of both vegetation structure and climatic conditions. If carefully analysed, vegetation and climate conditions may vary within cities perimeter in a similar magnitude to that observed among natural biomes.

While local native species may still fully grow and provide optimum ecosystem services in many urban settings, unfavourable conditions to the development, growth and longevity of local native species may jeopardize their potential role as a solution for local environmental problems (Kendal et al., 2018; Burley et al., 2019; Gesualdo et al., 2019; Locosselli et al., 2020; Marengo et al., 2020; Hanley et al., 2021). We propose that the urban environment should not be considered as single biome (Pincetl, 2015), rather, the variability of the urban conditions may be evaluated in terms of regional biomes, to define corresponding "urban biomes" and associated habitat types as a source of support and inspiration for the implementation of urban NbS. Towards that goal, we analysed the current climate and vegetation cover of the megacity of São Paulo as a case study to test the following hypotheses: I) there is a significant variation in vegetation cover, precipitation, and temperature in the city; II) the variation of vegetation and climate is similar to that observed among natural surrounding biomes; III) the current distribution of vegetation cover and climate values give support to the use of natural elements from biomes other than the one found before urbanization. Here we refer to plant species including herbs, shrubs, and trees, their associations, and how they related to the physical environment, as "elements of nature" that can be used in NbS.

Material and Methods

The city of São Paulo

The city of São Paulo is one of the largest megacities in the world (United Nations, 2018), with more than 11.25 million people and a demographic density of 7398.26 people per square kilometre (IBGE, 2010). This population faces an urban territory with highly unequal environmental conditions ranging from districts with no street trees or green spaces to large protected urban forest patches (Silva et al., 2019). Overall, 75% of the residences are on roads that hold street trees whose density increases towards the city centre (Silva et al., 2019). In addition, the city of São Paulo has large private green areas such as education centres, sports centres, cemeteries, to name but a few, plus 107 parks under the responsibility of the municipality, and some larger State parks, including one of the largest urban rainforests in the world (Negreiros et al., 1974).

The city of São Paulo is located within a Tropical/Subtropical Moist Broadleaf Forest biome, according to Olson's classification (Figure 1, Olson et al., 2001), or Atlantic Forest according to the official Brazilian biome classification (IBGE, 2004). This vegetation is associated with the subtropical humid / temperate summer climate, according to Köppen's classification (Alvares et al., 2014), with a strong influence from the Southern Atlantic Ocean. The Atlantic Forest domain is considered a "hotspot" of biodiversity (Myers et al., 2000), with more than 3,000 tree species (Zappi et al., 2015), of which 577 may still be found in the city of São Paulo (Biodiversity Inventory of the City of São Paulo, 2016). These native species belong to the "Serra do Mar Coastal Forest" ecoregion (Olson et al., 2001) that used to represent most of the vegetation before the urbanization (Figure S1). This ecoregion borders the "Alto do Paraná Atlantic Rainforests" that are the semi-deciduous forest formations of the plateau, and the "Cerrado" that corresponds to the Tropical/Subtropical Grasslands, Savannas, and Shrublands biome (Olson et al., 2001), another world "hotspot" of biodiversity (Myers et al., 2000). Studies from the early 20th century reported patches of Cerrado in the city, mostly grasslands and shrublands, immersed in the matrix of the Atlantic Forest. The genesis of these grasslands, however, is still debated and may be less natural, but related to past anthropogenic fires that changed soils' compositions (Usteri, 1911; Joly, 1950; Garcia and Pirani, 2003).

Because the city lies in the domain of the Atlantic Forest, municipal laws and strategic plans regarding street trees, green spaces, and protected areas promote (to some extent) the restoration of ecosystems based on the structure and composition of this specific biome. For instance, the municipal laws 15.428/2011 and 16.050/2014 promote urban reforestation with native species that contribute to a better environmental quality and chosen based on scientific and technical studies (see Silva et al., 2019 for further details). Activists working in the city largely agree with the current municipal regulation, by promoting urban reforestation mainly using species from the previously found forest biome, based on the argument that such species are the best adapted to the local conditions (Silva et al., 2019).

Vegetation data

Since vegetation structure (such as leaf structure and deciduousness) is a key factor to characterize biomes (Woodward et al., 2004), the vegetation found in the Brazilian biomes and across the city of São Paulo was characterized using the Normalized Difference Vegetation Index (NDVI) products from MODIS, with 250 meters spatial resolution (MYD13Q1v006 product, United States Geological Service, Earth Explorer platform). Although NDVI is a measure of greenness (Tucker 1979), it is largely dependent on leaf status and biomass, and thus can be used as an indirect measure of vegetation structure related to crown closure and leaf area index (Ren et al 2017), and thus it has been long used for monitoring vegetation across different environments, cities included (e.g. Gallo et al 1993, Yuan F, Bauer ME 2006 Bilgili et al 2013, Wong et al 2019 Aabeyir et al 2022). MODIS images have been used before for the evaluation of the cities' heterogeneities with great success (e.g. Engel-Cox et al., 2004; Tomlinson et al., 2010; Ferreira and Duarte, 2019; Mishara et al., 2019), and this spatial resolution represents about 4 blocks in the city which is sufficiently fine-grained for the large-scale biome approach used in this study. The use of the same MODIS products to characterize the natural Biomes of Brazil and the "urban biomes" of São Paulo greatly reduced any bias related to mixing imaging periods and potentially different satellite sources, atmospheric corrections for different areas of the country and the city, and further data corrections and analyses.

We obtained NDVI images for all of Brazil to characterize vegetation during wet and dry seasons from 2013 to 2019. We then calculated the mean NDVI value for the entire period to characterize the vegetation structure, the maximum NDVI, and the mean ratio of the NDVI (max NDVI / min NDVI) to characterize vegetation seasonality (Figures S2 and S3). For the city of São Paulo, we only used the images from 2013 and 2017, because other years were strongly influenced by clouds during the wet season (Figure S3). Finally, we compared the distribution of the values of NDVI variables from São Paulo and the Brazilian biomes using density plots.

Climate data

To characterize the climate, we used spatially interpolated bioclimatic variables at 30" spatial resolution from WorldClim V2 (Fick and Hijmans, 2017), which are based on local records of temperature and precipitation. We selected bioclimatic variables over regular climate variables for having more biological and ecological meaning. The spatial coherence of the interpolated data was calibrated using local observations of precipitation and temperature obtained from 28 climate stations from the Emergency Management Centre of São Paulo (CGE-SP, Figure 1). Ten-minute frequency measurements were obtained from automatic stations covering the period between 2013 to 2019. We calculated the monthly values of temperature and precipitation to then estimate the 19 bioclimatic variables for each climate station using the 'Dismo' package in R (Booth et al., 2014). The distribution of the values of precipitation and temperature variables were then compared for the São Paulo and Brazil-wide biomes, using density plots.

Characterization of the Brazilian biomes

We trained a classification algorithm based on the values of the bioclimatic and NDVI variables from protected areas with distinct levels of disturbance in Brazil. This step allowed us to characterize the natural vegetation of each biome other than the surrounding matrix of vegetation cover mostly related to different crops like soybean, sugarcane, cotton, and pastures that cover most of the former natural areas. We calculated the centroid for the polygon of 550 protected areas (Figure S4), including 303 protected areas in the Atlantic Forest (Tropical Moist Broadleaf Forest biome), 130 in the Cerrado (Tropical Grasslands and Savannas biome, considering both Cerrado and Pantanal as Savanna biomes, Olson et al., 2001), 79 in the Amazon Forest (Tropical Moist Broadleaf Forest biome) and 79 in the Caatinga (Tropical Desert and Xeric Shrublands biome), using QGIS software. We used the coordinates of the centroids of the protected areas to obtain the values of bioclimate variables and NDVI variables.

We then used these variables to train a Linear Discriminant Analysis (LDA, Venables and Ripley, 2002) that is a learning method (Araújo et al 2021) to classify the Brazilian biomes. We used the following three steps for the variables' selection. Firstly, we selected the least collinear variables based on a Hierarchical Clustering Analysis that group the variables according to their linear association (Figure S5, Chavent et al., 2017). In this step, we selected variables that represent annual and seasonal values of NDVI, temperature, and precipitation. Secondly, we validated the spatial variation of the chosen interpolated bioclimatic data using the data from the 28 climate stations in São Paulo (Figure 1, two climate stations were removed for presenting unusual behaviour for temperature, Figure S6). Thirdly, we looked for the combination of vegetation and climate variables that resulted in the highest model accuracy. We then calculated the Kappa coefficient for that model using the package 'e1071' (Meyer et al., 2019) in R. For the Linear Discriminant Analysis, we standardized the data using z-scores and then used 80% of the data of the protected area to calibrate the discriminant model and the remaining 20% to validate it in R.

Characterization of the urban biomes of São Paulo

Once we established appropriate variables to classify the Brazilian biomes, the same variables were sampled across the city of São Paulo. A grid with 30,426 points across the city was built, excluding areas covered by two large water reservoirs, with an approximate spatial resolution of 250 m, to match the spatial resolution of the climate and NDVI data. For each point, NDVI and climatic values were obtained. We then used the dataset obtained with the grid of points to predict each corresponding urban biome in the city using the previously trained Linear Discriminant model. We used the same standardization parameters used in the model training to predict the corresponding "urban biomes". A raster file was built in QGIS (V.3.12) with the spatial distribution of the corresponding "urban biomes" of São Paulo. We further validated the application of the trained linear discriminant model in the city by testing the accuracy in the biome classification of São Paulo's Atlantic Rainforest remnants (GEOSAMPA).

We also investigated the role of green cover across the whole city in the classification of the urban biomes. We first focused on the green spaces (GEOSAMPA) of the city larger than 62,500 m^2, which is equivalent to the spatial resolution of the urban biome analysis. These spaces include public parks, sports centres, education centres, cemeteries, large extension private lands, restored landfills. We then focus on characterizing four summarized green cover types (GEOSAMPA) – including grass and shrubs, low tree density, medium tree density, and forest patches. We also characterized the composition of the green cover outside the largest green areas but across the urban fabric using the same grid of points used for the urban biome classification to understand how green cover types influenced the classification of the urban Cerrado and Mata Atlântica. Principal component analyses were used to evaluate the composition of green cover of the different urban biomes at both spatial scales.

In addition, to gain further insights into aquatic and wetland ecosystem types, flood extents were mapped, corresponding with each urban biome. A raster file was generated using flooding datasets from GEOSAMPA to infer the locations of the seasonally flooded sites in the city, and thereby to infer terrestrial c.f. aquatic and riparian ecosystems. Main flood areas were checked using city flood events datasets (Fundação Centro Tecnológico de Hidráulica - FCTH - Poli-USP).

Results

A wide variety of vegetation structure and climate conditions were observed in the city of São Paulo (Figure 2, S6). Vegetation structure varied considerably in the city, from highly vegetated areas in the south and north, represented by mean NDVI values higher than 0.7, to areas almost entirely lacking vegetation cover, represented by mean NDVI values lower than 0.25. Climate also varies consistently across the city. Current annual mean temperature varies between 16.46˚C and 21.69˚C across the city, while the mean temperature of the warmest quarter varies between 19.28 and 24.64˚C. Precipitation presented a two-fold variation both in terms of total annual precipitation volume (1366 to 2724 mm / year), precipitation of the driest month (53 to 112 mm / month), and three-fold variation during the coldest quarter (118 to 368 mm / month). These interpolated values showed consistent spatial variability with the calculated values based on the data from the local climate stations. Correlation between interpolated and observed annual values are statistically significant for temperature ($r = 0.75$, $p < 0.05$, Figure S7), as well as for the selected precipitation variables ($r = 0.41$ to 0.80, $p < 0.05$, Figure S7).

The spatial variability of the vegetation structure and climate conditions across the city of São Paulo (Figure 2) paralleled that of the Brazilian biomes (Figure 3). Overall, the vegetation density as measured by the NDVI across the city of São Paulo ranges from that observed in the dense Atlantic Forest and Amazon, to that observed in the Cerrado and Caatinga, to the complete absence of vegetation. On the other hand, the distribution of temperature and precipitation within the city of São Paulo falls mainly within the climate envelope of the Atlantic Rain Forest and the Cerrado.

Because of these similarities in the vegetation structure and climate conditions between the city of São Paulo and some of the Brazilian biomes, we trained a Linear Discriminant

Analysis to classify the four main Official Brazilian biomes in terms of natural coverage. According to the criteria of variables selection for this model described in section 2.4 (Figure 4) the most accurate model incorporated the following variables: mean NDVI; the ratio of summer NDVI: winter NDVI; annual mean temperature (Bioclim 1); mean temperature of the warmest quarter (Bioclim 10); annual precipitation (Bioclim 12); precipitation of the driest month (Bioclim 14); and precipitation of the coldest quarter (Bioclim 19). This model showed 80% accuracy (95% confidence interval) in predicting official Brazilian biomes according to the mentioned variables, with a Kappa coefficient of 0.66. The misclassified biomes coincided with protected areas in the transition between different biomes, especially between Cerrado and Atlantic Forest (Table S2). The mean temperature of the warmest quarter, annual precipitation, and annual mean temperature are the main variables in the first linear discriminant (LD1) that comprises 62% of the data variability (Table 1). Mean temperature of the warmest quarter, annual precipitation, and mean NDVI are the main variables in the second linear discriminant (LD2) that comprises 30% of the data variability. Annual precipitation, precipitation of the driest month, and annual temperature are the main variables in the third linear discriminant (LD3) that comprises 8% of the data variability. In a second round of the model validation, this model accurately classified 99.92% of the area of São Paulo's Atlantic Rainforest remnants (Figure S8).

According to this Linear Discriminant Model, 57% of the city has vegetation structure and climate conditions that correspond to the Atlantic Forest biome according to the classification model (Figure 5). It is continuously distributed in the north and south, with a fragmented distribution in the west and at the extreme east. The other 43% of the city has vegetation structure and climate conditions that were classified as Cerrado. These conditions are mainly found in the central and eastern areas of São Paulo, whilst the Cerrado biome type is highly fragmented in the west.

Out of São Paulo's 165 green spaces with more than 62,500 m^2, 48 were classified as Cerrado and 117 were classified as Mata Atlântica regardless of the land use (Figure 5A, B and C). According to the PCA, the main difference between the classification of the green spaces classified is the higher proportion of forest cover in those classified as Mata Atlantica, with almost any influence from other vegetation cover types (Figure 5E). This pattern is still consistent when vegetation cover is evaluated outside the largest green spaces where the presence of even small forest patches across the urban fabric results in the Mata Atlântica category (Figure 5F). Overall, green cover is consistently lower in the areas classified as Cerrado, and 9.36% of the city of São Paulo has less than 5% of green cover (Figure 6).

In addition, about 5% of the city is under the influence of seasonal floods (Figure S9). These aquatic and riparian habitats were thus classified as Seasonally Flooded Atlantic Forest (1%) and Seasonally Flooded Cerrado (4%), thus resulting in a total of four urban biomes in the city of São Paulo (Figure 6).

Discussion

Nature-based Solutions are planned to tackle environmental, social, and economic challenges through actions supported by nature (van den Bosch and Sang, 2017). But what nature should be used as a source of support and inspiration? Municipal laws, regulations, and activists of São Paulo prioritize the use of tree species from the local Atlantic Forest (Silva et al., 2019). The main argument is built around the long adaptation of this vegetation to the local environmental conditions (Silva et al., 2019). However, the local conditions that used to support this vegetation may no longer be found across the entire city, because land-use change resulted in a significant increase in mean temperature (Silva et al., 2019), and changes in convective activities and precipitation patterns (Marengo et al., 2020).

To evaluate if such environmental changes have the potential to affect the source of inspiration of NbS, we trained a Linear Discriminant model to classify the Brazilian Biomes. The final model showed an 80% accuracy, equivalent to other classification models for the Brazilian biomes (Miranda et al., 2018), and a moderate to substantial Kappa coefficient (McHugh, 2012). The biomes' discrimination depends mostly on the local climate conditions and to a certain extent on the vegetation cover as assessed using NDVI, which is an expected result given the importance of climate and vegetation in this broad classification system (Conradi et al., 2020). When validated at the city level, the discriminant model yielded an accuracy of 99.92% in the classification of the Atlantic Rainforest remnants pointing to its reliable use in the city despite potential reflectance noise from atmospheric pollution and deposition of particulate matter on the surface of leaves. Despite the evidence of model robustness, a careful evaluation must be taken in areas with extremely low vegetation cover where the model may fail to properly find a meaningful correspondence with the natural biomes based on greenness derived from NDVI values (dashed areas of Figure 6). Significant uncertainties where also found in the transitions between Atlantic Forest and Cerrado, so that it may not be as accurate in the limits of these two biomes either in the natural or urban environments.

According to this model, 57% of the city may be classified as Atlantic Rainforest. It corresponds to the actual large patches of Atlantic Forest in northern and southern São Paulo and adjacent districts, and the so-called green districts characterized by a dense vegetation cover. The model results also point to 43% of the city with a better correspondence to the Cerrado, a Tropical Grassland, Savanna, and Shrublands biome (Olson et al., 2001) that is characterized by the combination of grasses, shrubs, and relatively dense tree cover (Coutinho, 1978). The predicted Cerrado areas in the city correspond to large green spaces with lower proportion of forest cover, and densely urbanized but still sparsely vegetated parts of São Paulo. Interestingly, they include former areas of anthropogenic savannas long described by Usteri (1911) at the early 20th century at the city centre, where most of the early urbanization took place. Thus, we propose the classification of the city of São Paulo in two main "urban biomes" according to its current environmental conditions, the Urban Atlantic Forest and the Urban Cerrado, or the Urban Moist Broadleaf Forest and Urban Savanna for international use, respectively.

We then characterized the urban biomes according to the occurrence of floods given their significant geographical extension in the city and overall severity of impacts (Gu et al., 2015; Haddad and Teixeira, 2015). Seasonally flooded areas require interventions based on elements from nature that are adapted to a humid phase (Scharenbroch et al., 2016; Yuan et al., 2017) a fact that led us to define the seasonally flooded urban biomes. The urban seasonally flooded Atlantic Forest would require elements from the swamp forests locally known as “Florestas Paludosas”, which are characterized by various plant species adapted to seasonal flood (Figure 7, Teixeira and Assis, 2005, 2009; Reis et al., 2009). Whereas the seasonally flooded Cerrado requires elements from the wet grasslands locally known as “Campos Húmidos” (Figure 6, Ruggiero et al., 2006; Tannus et al., 2006; Rossato et al., 2008), or riparian forests for larger watercourses. These are likely the best sources for suitable species to the specific conditions found in rain gardens, detention / retention basins, wetlands, and bioswales, to name few devices related to Green and Blue Infrastructure. These sustainable drainage systems are needed in at about 5% of the entire city of São Paulo to make room for water storage and regeneration, and in the rest of the watersheds for control and treatment of the runoff.

Two questions remain to be answered. Does the Cerrado truly holds more resilient species? Can it equal or surpass the ecosystem services provided by the species from the Atlantic Forest? Based on studies currently limited to natural areas, trees from the Cerrado are naturally adapted to high temperatures and seasonally restricting precipitation conditions (Cabral et al., 2015, Loram-Lourenço, 2020), similar to that found in parts of São Paulo. Because the dry season length is expected to increase by two or three months in the upcoming decades (Gesualdo, 2019), Cerrado’ species may also be considered future proof in terms of environmental changes increasing the resilience of the green infrastructure. Their deep root systems (Coutinho, 1978, 2016; Oliveira et al., 2005) may also represent an adaptation advantage useful to cope with the lowering of water tables resulting from climate extremes, construction work, extensive soil impermeabilization, excessive water pumping, and reduction in the vegetation cover (e.g. Hirata and Conicelli, 2012; Mohanavelu et al., 2020; Yadav et al., 2020; Nath, 2021). Their adaptation to the high metal concentrations in the soil (Coutinho, 1978, 2016) likely make them also adapted to the diffuse urban metal pollution (Moreira et al., 2018) that severely restricts tree growth and development (Locosselli et al., 2019). Thus, these species have advantages in terms of growth that may increase the prospects for long-term of ecosystem services delivery urban environment.

In terms of ecosystem services quality, again based on the current literature limited to the natural environment, Atlantic Forest species have a greater potential to control temperature since taller and densely arranged trees may provide better thermal comfort (Abreu-Harbich et al., 2015) but only if the natural structure and conditions of the Atlantic Forest can be replicated along the urban infrastructure. For the most compact urban areas, the often-shorter Cerrado species will still promote thermal comfort through shading (Bowler et al., 2010; Abreu-Harbich et al., 2015) and evaporative cooling (Bowler et al., 2010, Moss et al., 2019) sustained by their deep root systems (Coutinho, 1978, 2016; Oliveira et al., 2005). Likewise, the carbon sink potential of the Atlantic Forest can be higher than in the Cerrado if the vegetation structure, longevity and recruitment of trees are replicated in the city (David et al., 2017). Otherwise, Cerrado trees often present higher growth rate at early stages of life (Locosselli et al., 2017) favouring the establishment of young trees especially in open spaces, and higher investment of carbon in below ground organs (Castro and Kauffman, 1998; Ribeiro et al., 2011) and overall wood density (Chave et al., 2009). The thick and rough barks of the Cerrado trees (Loram-Lourenço, 2020) may represent an additional advantage in terms of adsorption of particulate air pollution (Moreira et al., 2018) and rainfall interception (Oliveira et al., 2015; Tonello et al., 2021), that is on par or even higher to that observed in the mature Atlantic Forest (Junior et al., 2019). Although restricted to natural areas, these observations could inform their potential roles in the deployment of ecosystem services in urban areas.

The implementation of Cerrado inspired NbS would further benefit from the often-neglected ecosystem services provided by grasses and shrubs (Deletic et al 2006, Ryan et al 2016). Consideration of other vegetation assemblages (and supporting substrates) is required if cities are to make use of all the tools in the toolkit of NbS to become more resilient to climate change, and to address other urgent challenges such as wellbeing, pollution, biodiversity, and inclusion. When integrated into NbS, grasslands and shrublands can provide improvements in thermal comfort (vaz Monteiro et al., 2016), rainfall-runoff response (Davis et al., 2021) and air quality (Escobedo et al., 2008), water pollution remediation (e.g. Urbonas et al., 1989; Clary et al., 2017), and biodiversity support (Sala and Maestre, 2014).

Both the natural Atlantic Forest and the Cerrado have a long and dynamic history of contraction and expansion, and they often co-exist as mosaics in the ecotones nowadays. Such dynamics are naturally controlled by changes in the climate conditions and by major disturbance forces like fire (Silva and Bates, 2002). The natural co-existence of these two biomes in the ecotones evidence a potential balanced co-existence in the cities, where their dynamics will likely be controlled by changes in the climate condition from climate change, urbanization, and implementation of NbS, and by major disturbance forces such as the anthropogenic activities undertaken in the cities. The urban ecosystem restoration could benefit from such natural and dynamic processes in which the Cerrado could act as a transient urban biome in the way of restoring the urban forests through soil horizon development and species succession followed by the densification of the vegetation whenever this planting scheme is possible. The urban Cerrado could also act as a permanent urban biome in appropriate areas of the city where dense vegetation cover is not possible, likely without compromising the ecosystem services delivery including biodiversity support.

The diversity of challenges faced by cities in becoming more resilient can therefore be considered as being addressed by a range of different interventions drawing on the diverse, valuable properties of natural processes, such as infiltration, evapotranspiration, pollination, and so on. Our findings present an important piece of the jigsaw puzzle, by providing a more nuanced and fine-grained appreciation of extant environmental conditions and appropriate ecologies from which to draw inspiration for the retrofitting of green elements back into the urban fabric. If NbS are to be successful in how they are ‘locally adapted, resource-efficient and systemic’ (EC, 2021), cities urgently need to know which types and combinations of vegetation may thrive when planted. They also need better spatial data on the supporting environmental conditions that will enable that flourishing of vegetation, so that these locally ‘attuned’ NbS may effectively deliver their intended ecosystem services.

Conclusions

We show that the use of elements of nature inspired by the local biome to improve the quality of the urban environment, as supported by laws and regulations, may not always be the best practice in the entire city. Because of changes in vegetation structure and climate conditions, 47% of the city of São Paulo has conditions that may better support elements inspired in the Cerrado, a Tropical Grassland, Savanna, and Shrubland biome, instead of the Atlantic Forest, a Tropical Moist Broadleaf Forest biome originally found there. This shift towards low vegetation coverage, high temperature, and changes in precipitation regime are expected outcomes of urbanization in many cities of the world, and thus, the use of elements from adjacent biomes may bring resilience to the urban green infrastructure, while also acting as transition steps. These transitions among urban biomes may occur as local conditions change with the implementation of NbS, and the results point to the effectiveness of increasing the vegetation density wherever possible. The implementation of NbS inspired by different natural biomes such as proposed here may leverage the biodiversity in cities and its benefits to the population.

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Data availability

The data used in the present study, R codes, and the final raster file of the Urban Biomes of the city of São Paulo are available at Figshare.

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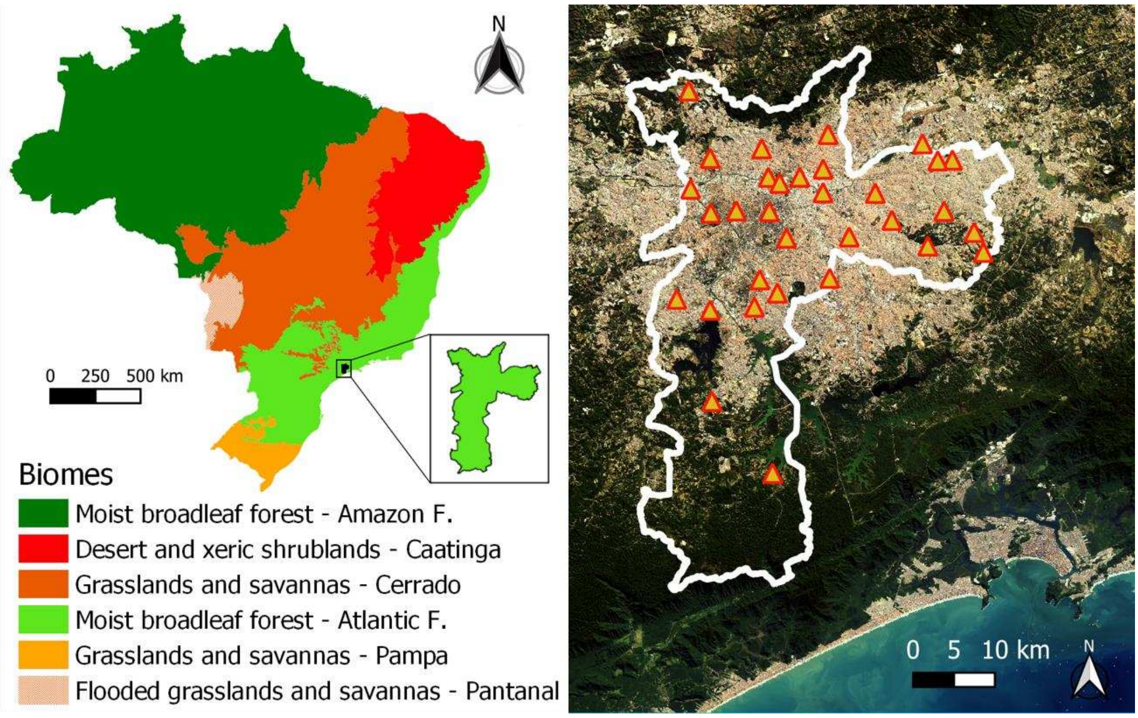

Figure 1: The left panel shows the Official Brazilian Biomes and the location of the city of São Paulo in the Atlantic Forest biomes, a Tropical Moist Broadleaf Forest according to the international biome's classification (Olson et al., 2001). The right panel shows a detail of the city of São Paulo (white outline) on a panchromatic satellite imagery (Landsat 8) with the 28 climate stations of the Emergency Management Centre of the City of São Paulo used in the validation of the spatially interpolated climate variables.

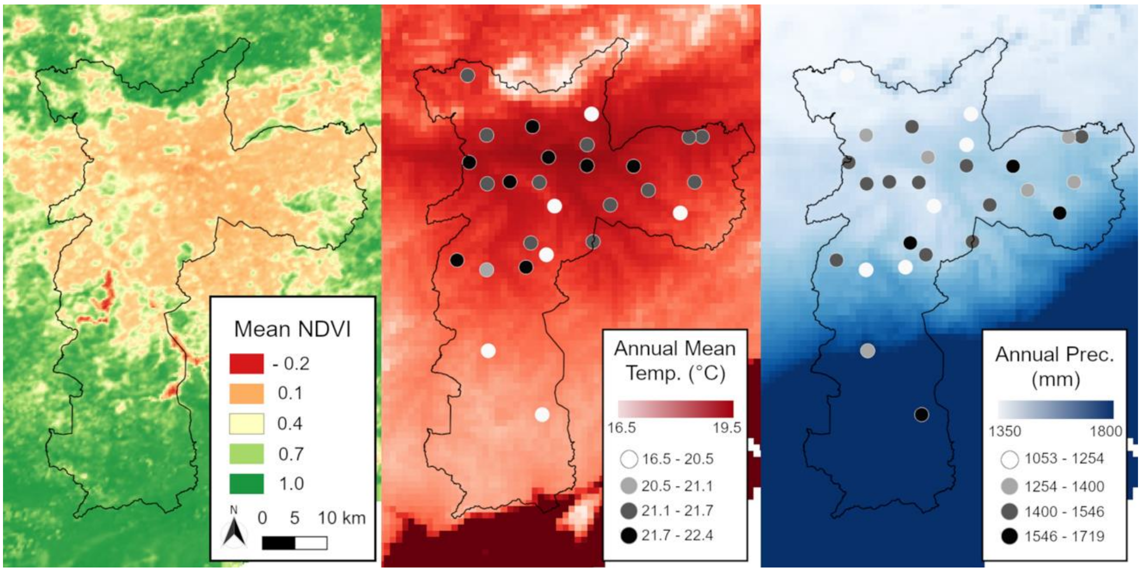

Figure 2: Spatial distribution of variables related to the vegetation structure and climate in the city of São Paulo (black outline). Vegetation structure is represented by the mean NDVI ratio, while the seasonality of the vegetation structure is represented by the ratio of the NDVI values between the summer (wet season) and the winter (dry season). Climate spatial variability is represented here by the annual mean temperature and the total annual precipitation values. For the seasonal NDVI, precipitation and temperature, refer to Figure S6). The circles represent the climate stations from the Centre of

Emergency Management of São Paulo (CGE). Shades of grey indicate the values of the respective climate variables in each of the stations (refer to Figure S7 for the linear association between the interpolated data and the data from the CGE stations).

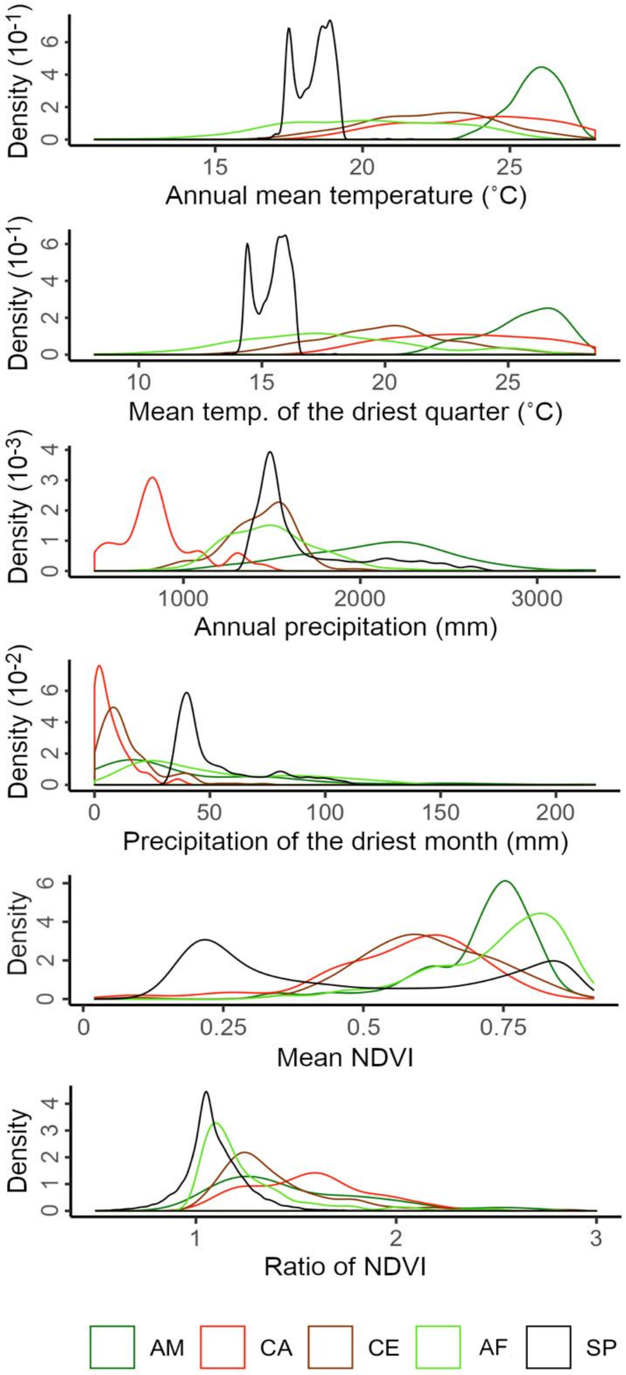

Figure 3: Density plots showing the distribution of the vegetation and climate variables used the Linear Discriminant Analysis. Distribution of the values are show for the main Official Brazilian Biomes (AM: Amazon Forest – Tropical Moist Broadleaf Forest, CA: Caatinga - Tropical Deserts and Xeric Shrublands, CE: Cerrado – Tropical Grassland and Savanna, and MA: Atlantic Forest – Tropical Moist Broadleaf Forest) and the city of São Paulo.

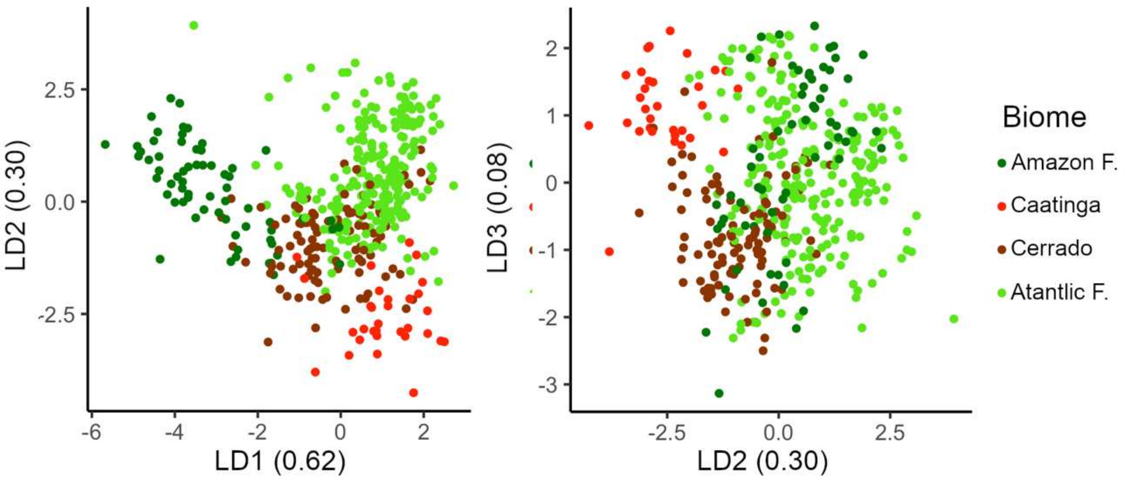

Figure 4: Scatterplot of the Linear Discriminant Analysis used to classify the main Brazilian biomes. Proportion of the explained variability is given for each Linear Discriminant axes (LD). This discriminant model has an accuracy of 80%.

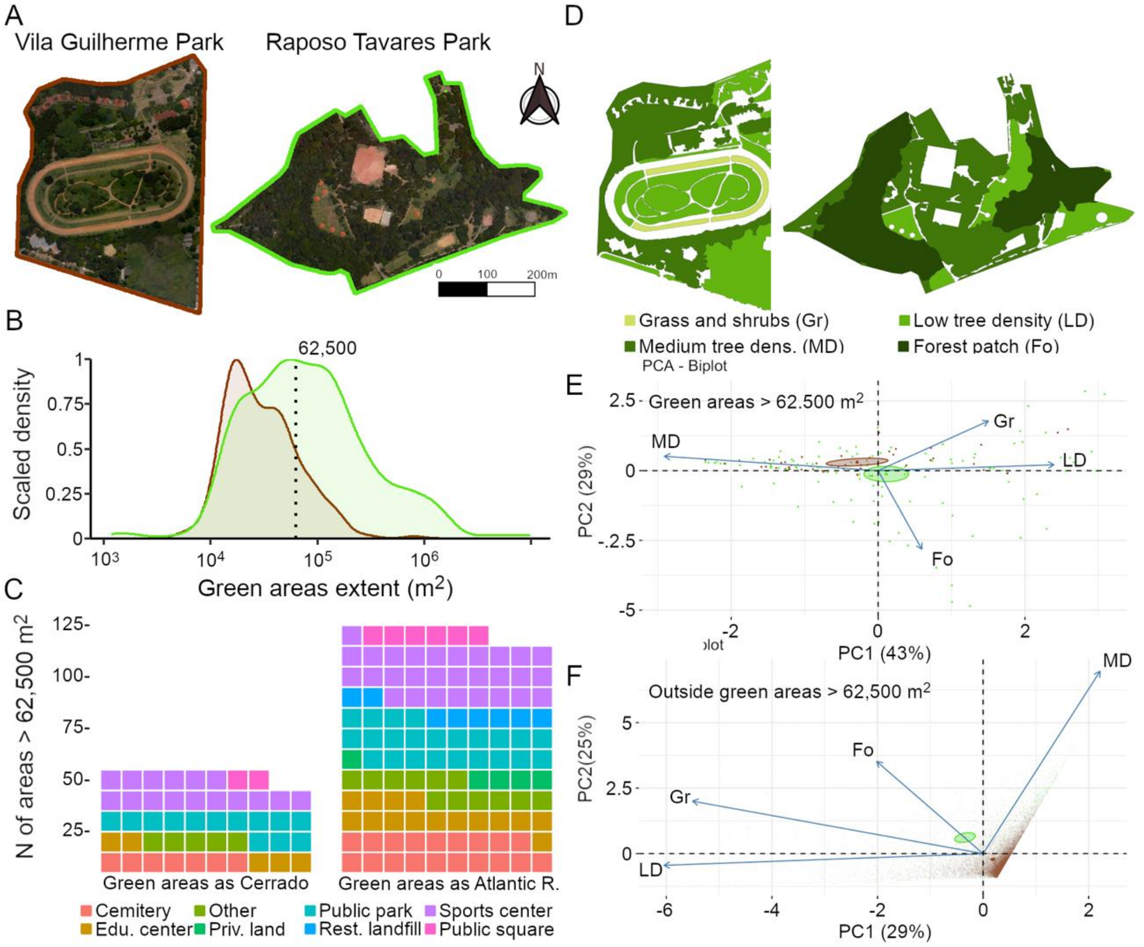

Figure 5: Detailed evaluation of the green spaces from the city of São Paulo, A) with two examples of Public Parks classified as Cerrado (brown outline) and Mata Atlantica (green outline). B) The distribution of green spaces extent is displayed in the density plot, C)

whose land use are described for areas larger than 62.500 m^2. D) An example of the distribution of four types of green cover in two Public Parks, E) and the Principal Component Analyses of the proportion of green cover in green spaces with more than 62,500 m^2 (ellipses indicate 95% confidence interval), and F) of the proportion of green cover outside the green spaces but across the urban fabric (ellipses indicate 95% confidence interval).

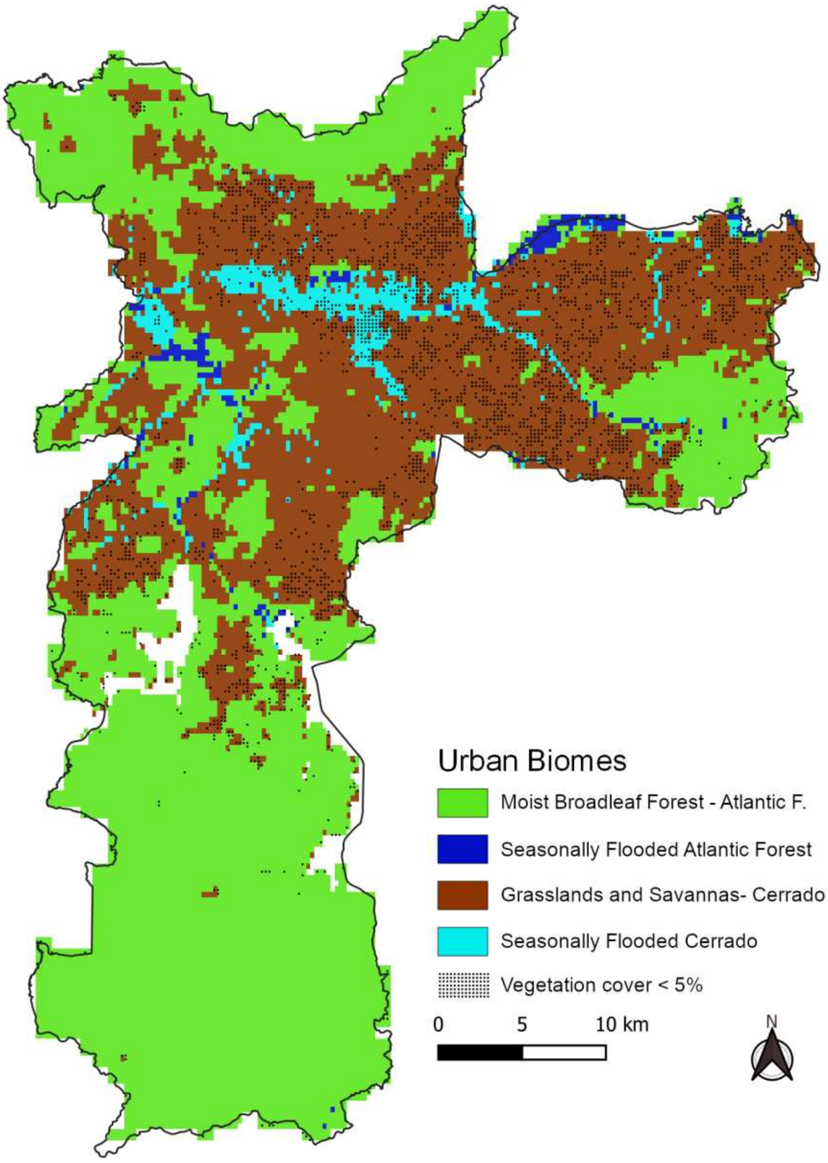

Figure 6: Classification of the city of São Paulo in the Urban Biomes (refer to Figure 1), according to the extant climate conditions and vegetation structure. Seasonally flooded areas in each biome are based on the overlaying naturally flooding areas of the main rivers in the city (Flood Areas map from GeoSampa).

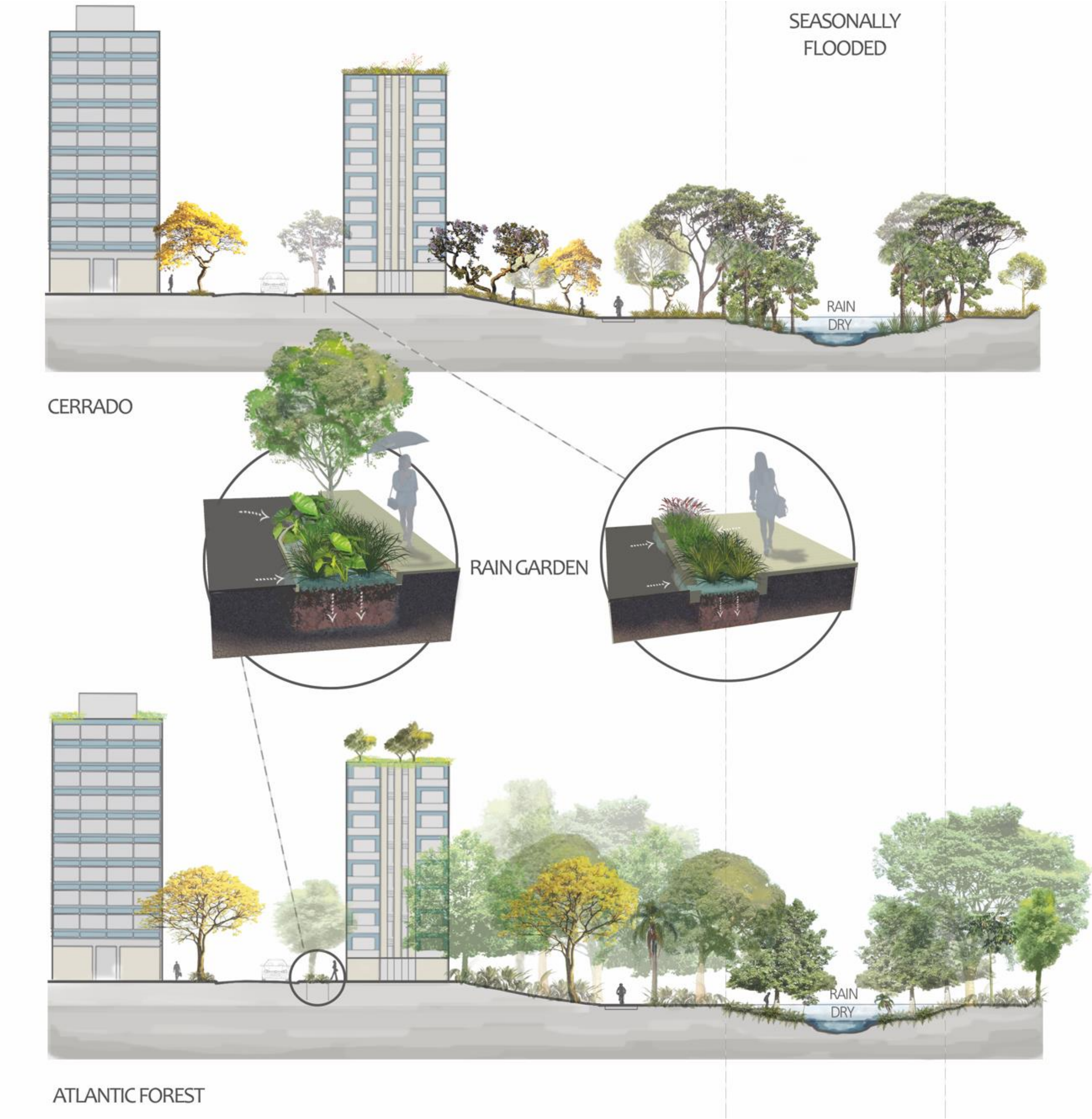

Figure 7: Examples of possible interventions of green infrastructure according to the four Urban Biomes in the city of São Paulo.

Table 1: Coefficients of Linear Discriminant Analysis used to classify Official Brazilian Biomes.

Variables	LD1	LD2	LD3
Mean NDVI	-0.13	0.48	0.38
Ratio NDVI (max NDVI / min NDVI)	-0.09	-0.24	0.25
Annual mean temperature	0.92	0.42	-0.84
Mean temp. of the warmest quarter	1.58	2.13	-0.83
Annual precipitation	-1.20	0.80	-1.16
Precipitation of the driest month	0.26	-0.37	0.84
Precipitation of the coldest quarter	0.01	0.42	0.75