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BALANCED SPATIAL DISTRIBUTION OF GREEN AREAS CREATES HEALTHIER URBAN LANDSCAPES

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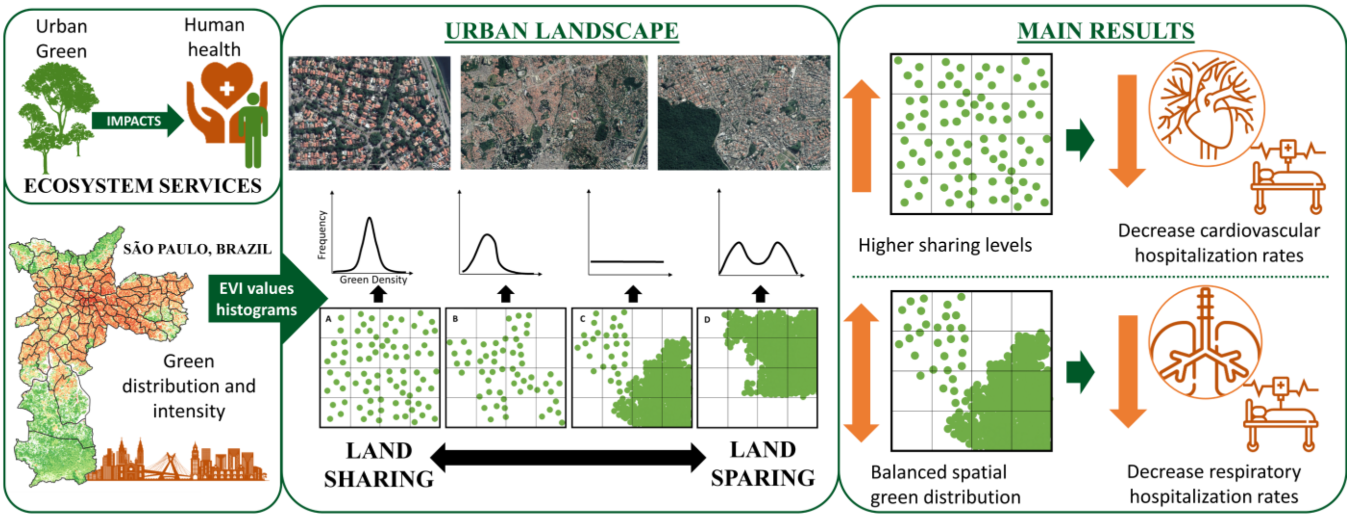
Graphical Abstract



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ABSTRACT

1. The benefits of green infrastructure on human well-being in urban areas are already well established, with strong evidence of the positive effects of the amount and proximity to green areas. However, the understanding of how the spatial distribution and type of green areas affect health is still an open question.
2. Here, through a land sharing and sparing framework, we explore how different spatial configurations of green and built-up areas and how different types of green areas can affect cardiovascular and respiratory hospitalizations in São Paulo city, Brazil.
3. Sharing/sparing indicators were selected as the main explanatory factors in the control of all groups of diseases. Land sharing appeared as a favourable spatial condition to prevent cardiovascular hospitalization, while land sparing and arboreal vegetation were relevant to reduce hospitalization by lower respiratory diseases.
4. For upper respiratory diseases, forests seem to provide a disservice, once they were associated with increased rates of hospitalization by respiratory allergies causes.
5. Considering that hospitalization rates and severity of cardiovascular diseases are substantially higher than those of upper respiratory ones, dense vegetation tends to provide more services than disservices. The land sharing configuration, which is characterized by green areas spread throughout the urban network (in streets, gardens, small squares, or parks), should lead to higher exposure and use of the benefits of green areas, which may then explain the greater prevention of cardiovascular diseases.
6. These novel results indicate that a more balanced distribution of green areas across built-up areas creates healthier urban spaces, and thus can be used as an urban planning strategy to leverage the health benefits provided by green infrastructure.
7. *Policy implications*: Aiming to reduce hospitalizations by cardiovascular and pulmonary causes, urban planning should promote the spreading of green areas across the cities, in order to increase daily contact with natural attributes, giving preference to distribution over total quantity of green in urban landscape.

Key-words: green distribution; landscape structure; human health; urban landscape; land sharing; land sparing; ecosystem services

INTRODUCTION

The association between green infrastructure and human health in cities has been extensively studied, in most cases showing a positive association between the amount of and proximity to green spaces with a reduction of cardiovascular (Moreira et al. 2020) and respiratory diseases (Lotufo 2017, Ferrante et al. 2020). However, the understanding of the effects of green areas' qualities and their spatial arrangement in relation to built-up areas on the provision of health benefits, is still an open question. In particular, it is not clear if it is more beneficial to have large green areas (e.g., well preserved urban parks) or to have the green areas scattered and diffuse in the urban landscape, favouring the proximity to residential areas in relation to their extension and quality.

The benefits of green areas to human health are mediated by ecosystem services, particularly by regulating services, such as air quality and temperature control (Almeida et al. 2018), and cultural services, such as recreation and aesthetic appreciation (Jennings and Gaither 2015, Hegetschweiler et al. 2017, Shi et al. 2020). Urban forests and other green areas can provide both types of service (Roeland et al. 2019), thus favouring cardiovascular, respiratory, and mental health (James et al., 2015; Kondo et al., 2018; Nieuwenhuijsen et al., 2017). Particularly, urban vegetation can reduce respiratory diseases occurrence mostly through the regulation of air pollution (Alcock et al., 2017; Lotufo, 2017; Squillacioti et al., 2020; Tischer et al., 2017). Cultural services, such as recreational activities, sports practice and scenic view appreciation (Tengberg et al. 2012, Kosanic and Petzold 2020) can regulate the production of hormones like cortisol (Roe et al. 2013) and reduce the risk of cardiac diseases (Astell-Burt & Feng, 2020; Moreira et al., 2020; Plans et al., 2019; Yeager et al., 2020). By encouraging outdoor activities and sports practice, green areas near people can reduce cardiovascular risk factors, such as being overweight, hypertension, cholesterol levels, and diabetes (Yeager et al. 2020).

Several factors can mediate the relationships between the potential provision of a service and its contribution to human health, such as the amount of green (Plans et al. 2019), the use of the green areas (Kaczynski et al. 2014, Tamosiunas et al. 2014), the exposure to nature (Shanahan et al., 2015, 2016), the proximity between green and inhabited areas (Kaczynski et al. 2014, Moreira et al. 2020), and the type or quality of vegetation. Green area quality may be related to biodiversity, biomass, or structural complexity parameters, which are known to affect human well-being and health (Schebella et al. 2019; Methorst et al., 2021). For example, green areas and gardens were associated with reductions in asthma hospitalization when pollutant exposures were lower, while tree density had this same effect only when pollutant exposures were higher (Alcock et al. 2017), showing the distinct impact of different types of green areas. Similarly, the spatial arrangement of green areas can modulate the effects on health, but this analysis is generally limited to a proximity effect, disregarding the effects of fragmentation or interspersion between green and built areas (Mitchell et al. 2015, Metzger et al. 2021).

A broader framework for assessing the spatial distribution of green areas is provided by the land sharing and land sparing strategies (Lin and Fuller 2013, Soga et al. 2014, Stott et al. 2015). Land sparing is a conservation strategy that combines the intensification of human use in some areas (in principle, the most favourable areas for use), with setting aside other areas for conservation of more preserved (with higher quality) native vegetation (Balmford et al., 2012). On the other side, land sharing strategy promotes less intensive use in more extensive areas, leading to shared use of the same space for production and conservation purposes. In urban areas, a land sparing configuration can typically be represented by neighbourhoods with a high population density and with the presence of well-maintained green areas (parks, squares). Land sharing is typically represented by neighbourhoods of lower population densities, with plenty of green areas among households, as occurs in many suburbs of cities in more developed countries. Originally, the sharing-sparing framework was developed to analyse its impacts on species density and biodiversity, both in rural and urban areas (e.g. Soga et al. 2014; Caryl et al. 2016; Geschke et al. 2018; Ibañez-álamo et al. 2019). Here, we expand the application of this framework to understand its effects on human health, which should occur through its effects on the provision of regulating and cultural services. The effect of urban sharing and sparing on duration, frequency and intensity of exposure to nature (Shanahan et al., 2015, 2016), and thus on the provision of ecosystem services and human health, is still an open question, with important implications for landscape urban planning and nature-based solution interventions in cities (Cohen-Shacham et al. 2019).

Our aim here was to evaluate the relative effects of the quantity, type and spatial distribution of green areas in an urban landscape on the frequency of hospitalizations by cardiovascular and respiratory diseases. We tested those relationships using public data of hospitalization rates in one of the world's largest megacities, São Paulo (Brazil), relating them to the level of land sharing and sparing, the amount and type of green areas in a neighbourhood scale. To perform this analysis, we developed new indicators which allow us to assess, in a continuous way, how the landscape structure reflects the level of land sharing and sparing in a particular region (here, a neighbourhood). We expect that: (1) greener neighbourhoods will present lower occurrence of diseases (due to higher provision of regulating and cultural services); (2) more complex/diverse vegetation types will provide more health benefits; and (3) land sharing schemes will provide more benefits than land sparing schemes, if we suppose they allow more frequent exposure of people to green areas.

Materials and methods

Study Area

The study was carried out in São Paulo city, southeastern Brazil. São Paulo megacity is the biggest metropolis in the southern portion of the globe, with an estimated population of 12,325,232 inhabitants in 2020 (IBGE, 2021), and a total area of 1,521.110 km². Its metropolitan region encompasses more than 21,500,000 inhabitants.

São Paulo is located in the Atlantic Rain Forest region, a biodiversity hotspot that was overexploited during the last five centuries, with currently no more than 28% of its natural cover remaining (Rezende et al. 2018). São Paulo city has a significant forest cover within its administrative limits (~33%; SVMA, 2020), in special two state nature reserves (one in the northern region, with ~ 7,916 ha, and another one in the South), that extends beyond the city limits.

We used as the unit of analysis the 96 administrative districts (ranging from 2 to 20000 ha) for which we obtained social and populational data from official sources (Figure 1). These districts present a wide gradient of socio-environmental conditions in terms of green cover and infrastructure, population, socioeconomic condition, and frequency of use of the public health system.

Health Data

We used the public health dataset of hospitalizations (known in Brazil as the Universal Health System, or in Portuguese, *Sistema Único de Saúde* – SUS) for adults with 20 years or more. The SUS is available for all of the Brazilian population, free of charge.

Beyond SUS, there are many private health systems, used mostly by employees with access to private health insurance systems. About 55% of São Paulo's city population are SUS exclusive users, according to an estimation made in 2010 (CEInfo, 2010). This rate changes according to the socioeconomic characteristics and size of the city district, ranging from no more than 30% to more than 70% of SUS users.

All health-related data was available in the dataSUS database (SUS, 2021), and were processed and georeferenced by the Centre of Metropolitan Studies of the University of São Paulo (CEM, 2017). The data is from an open public data source and do not require ethical approval for use, since are completely anonymous. For each hospitalization, the cause of hospital admission (according to the International Classification of Diseases code) and the residence address (by ZIP code) of the patient were recorded. The georeferenced data collection prepared by the Centre of Metropolitan Studies was plotted in São Paulo's districts map, allowing the identification of the numbers of hospitalizations by administrative region. We selected three years of data, 2014, 2015 and 2016, that are the last three years available to download on the CEM's platform (CEM, 2021; https://centrodametropole.fflch.usp.br/pt-br/download-de-dados). As health-related outcomes, we have considered three groups of diseases: cardiovascular, upper and lower respiratory tract (URT and LRT, respectively) diseases (Table S1 – supplementary material).

Once our analyses were restricted to the population that uses SUS, we considered the estimated fraction of SUS users for each district, according to the Health Secretary of the municipality (CEInfo, 2010). According to the last census, from 2010, the population of the whole city was 11,253,203 inhabitants (IBGE, 2010), of which circa 6,100,000 were SUS users (IBGE, 2010; CEInfo, 2010). The population of SUS users for each district was estimated using the Brazilian Census (IBGE, 2010) of each district, and the percentage of SUS users per district (CEInfo, 2010).

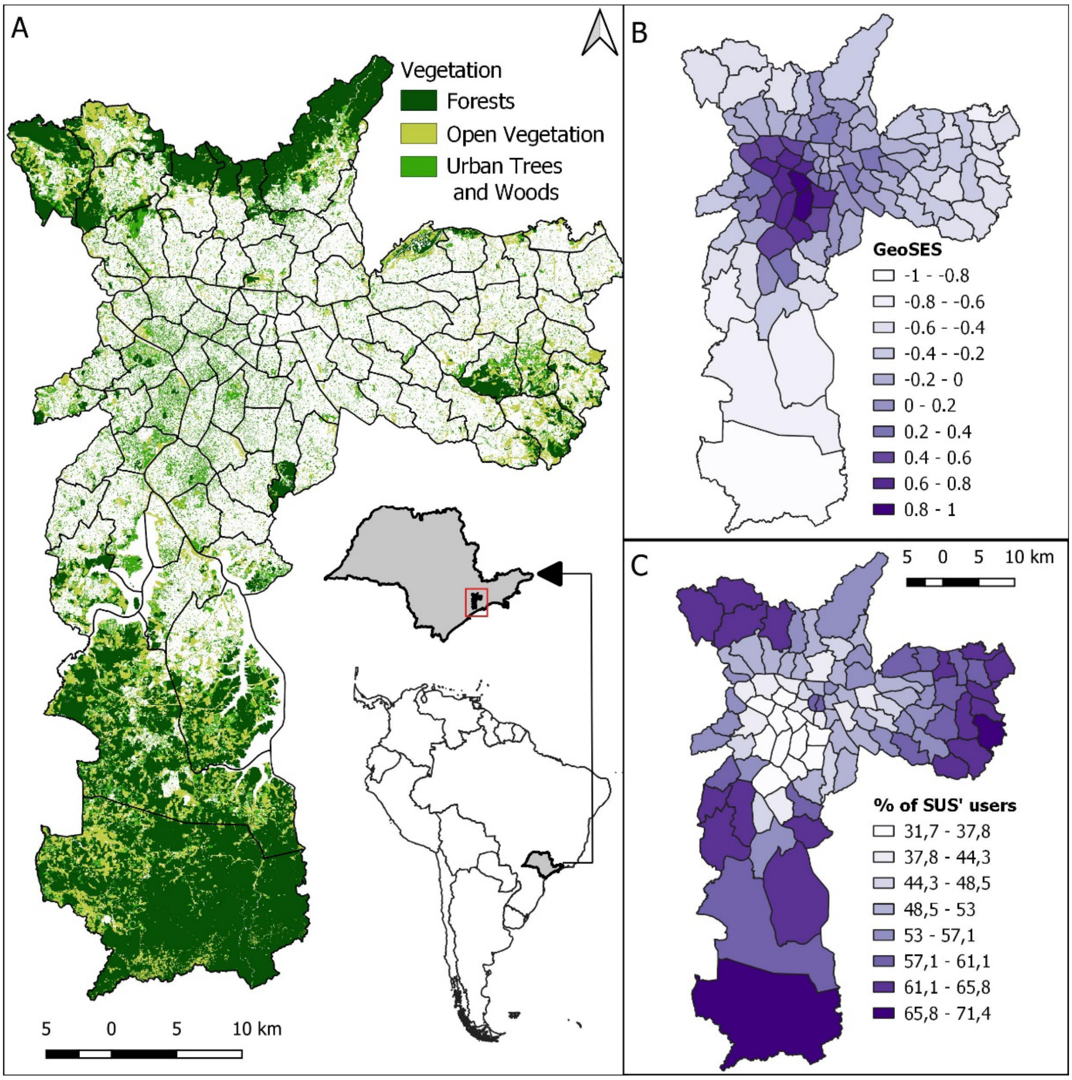

Figure 1. (A) Vegetation cover of the city of São Paulo, per district (polygons defined by black lines), and, in detail, the location of the city in relation to São Paulo State and South America; (B) Social conditions represented by GeoSES Index (Barrozo *et al.* 2019; highest values represent better conditions); and (C) Estimated proportion of Universal Health System (SUS) users.

Socioeconomic Data

To control socioeconomic conditions, we used the GeoSES indicator (Barrozo et al. 2019). This metric was developed as an alternative to the Human Development Index (HDI). It incorporates seven socioeconomic dimensions: education, mobility, poverty, wealth, income, segregation, and deprivation of resources and services. GeoSES has great explanatory power for relative risks of some diseases, and, different from HDI, it does not have a longevity component, avoiding mathematical redundancy for health research (Barrozo et al. 2019). We used GeoSES values obtained for each of the 96 districts with the 2010 Brazilian Census data, as a co-variable for all statistical models.

Landscape and Vegetation Data

For landscape composition analysis, we used the vegetation cover map of São Paulo municipality (SVMA, 2020). The data consists of a vegetation cover vectorization and classification in the resolution of 1:1000 inside the city, and 1:5000 within protected areas, based on orthophotos with 0.12 m of resolution, from 2017, obtained by the municipal environment office. The original data has 15 categories, but for this study, we reclassified it into three types of vegetation (Figure 1). **Forests** represent native arboreal physiognomies, such as dense rainforest, lowland and swampy forests, and heterogeneous or homogeneous non-native formations (e.g. *Eucalyptus* plantations) with native understory vegetation. **Isolated trees and small woods** represent mostly urban green cover outside protected areas and small woods, such as street afforestation, gardens, squares, and urban parks with trees, but mostly without understory vegetation. **Open Vegetation** comprises shrubs and herbaceous vegetation, grasslands (natural and non-natural) and agricultural areas. We also used a georeferenced data of street trees for the entire city. Those variables were obtained through data processing on the ArcGIS (v. 10.8). The vegetation data and other geographic information, such as municipality administrative limits, urban infrastructure and others, are available on GeoSampa portal (São Paulo, 2020).

Land sharing and sparing analysis

Based on Stott *et al.* (2015), we used an Enhanced Vegetation Index (EVI) image to create four land sharing and land sparing indices. EVI values were obtained with a LANDSAT 8 image (30 m resolution), dated from April 2016 (one of the three years of the hospitalization data), that covers the entire city of São Paulo on the same day, without any cloud cover. This image allowed a direct comparison of the districts without day, weather or seasonal variations in the image.

We first divided the histogram with EVI values into three quantiles (Figures 2 and S1 – see below the determination of quantiles): intermediate values correspond to cells with a mix of vegetation and buildings, low values represent mostly built-up areas, and high values correspond mostly to green and forestry areas. Land sharing and land sparing indices are based on rations between these quantiles (Table 1), as presented below. We excluded EVI values lower than zero because they mainly represent water. We also excluded cells that are located in open areas (e.g., grasslands, small fields), since those cells have intermediate values of EVI and can be mistaken with land sharing conditions (see below). Consequently, in this study, land sharing and sparing indices consider only the spatial distribution of arboreal vegetation, and not all green areas in the city.

Determining the quantiles - To determine the three quantiles, we evaluated the values distribution of the entire city and used a sample of 10,000 cells to apply two thresholds. We randomly selected 10,000 random points in built-up areas, and another 10,000 points in areas covered by trees, based on the vegetation cover map of São Paulo municipality (SVMA, 2020), and obtained, for each of these samples, the mean EVI value. The first threshold represents the mean of urban areas (EVI = 0.16) and the second one is the mean of green areas (EVI= 0.56). With these two thresholds, we obtained three quantiles, A, B and C: A represented areas dominated by buildings (urban areas) with all EVI values under 0.1;6; B mixed areas, with all EVI values between 0.16 and 0.56; and C arboreal green areas, with EVI values above 0.56 (Figure 2).

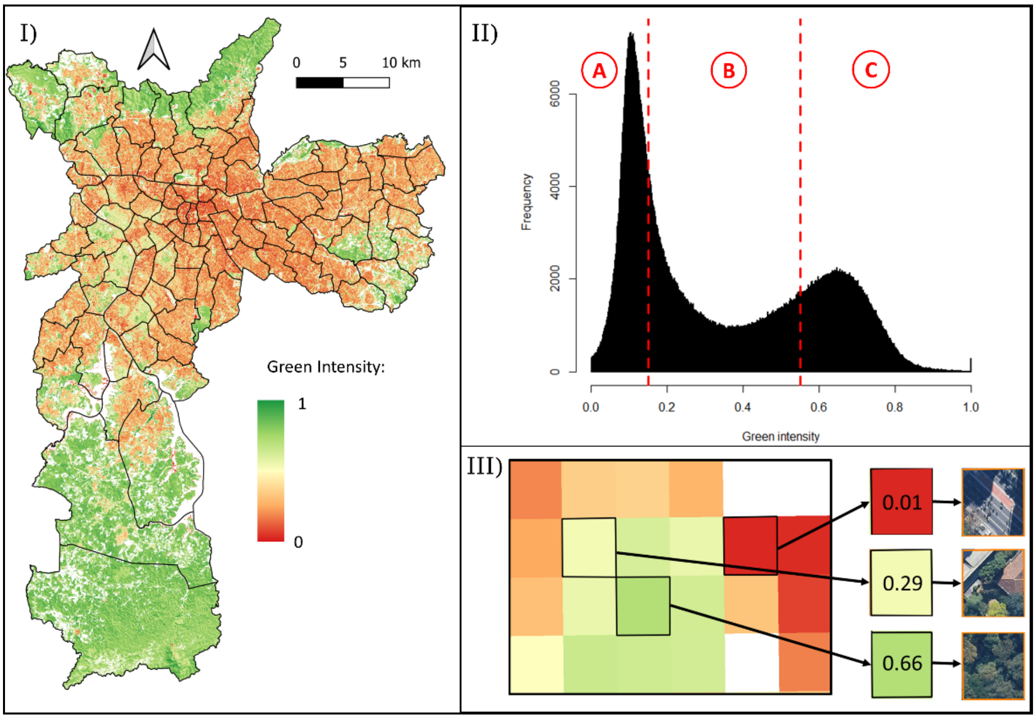

Figure 2 – EVI data and quantiles used to calculate land sharing and sparing indices. I) EVI image for São Paulo city, without water and open areas (both represented in white); II) Distribution of EVI values and thresholds – red dashed lines – establishing the three quantiles: A – Urban areas; B – Mixed areas and C – Green areas; III) A sample of the EVI image presenting low, intermediate, and high EVI conditions into the 30 m pixels.

For a given region composed of a set of cells with EVI values, land sharing and land sparing patterns can be inferred based on the frequency of cells in different green intensities (Soga et al, 2014). A single central peak in the intermediary values represents a land sharing pattern because intermediary values are related to mixed regions with green and urban infrastructure (Figure 3-A, B). On the other side, a bimodal distribution, with one peak in low values of EVI (high presence of urban areas) and another peak in high values of EVI represents a land sparing pattern (Figure 3-D). Land sharing and land sparing in this approach is a continuous gradient, with intermediate situations, that are not land sharing nor land sparing, or can be a mix of conditions (Figure 3-C). This procedure can be replicable for other cities or systems, which will have different threshold values, but will anyway allow identifying the conditions of the three quantiles (predominantly green or human-modified areas, or intermediate mixed conditions).

Calculating the land sharing and land sparing indices: To consider a landscape as a sharing area we need to have some degree of mixture, in terms of green and non-green, which can be easily identified by observing the proportion of values on the B portion of the histogram, which is represented by the **Sharing Vegetation Index (SVI)** (Table 1; Box 1). On the other hand, it is more complicated to assume a degree of land sparing, requiring more than one metric to evaluate it, depending on the evenness and unevenness in the quantities between the green and urban pixels, as illustrated in Figure 3 E-H and Box 2.

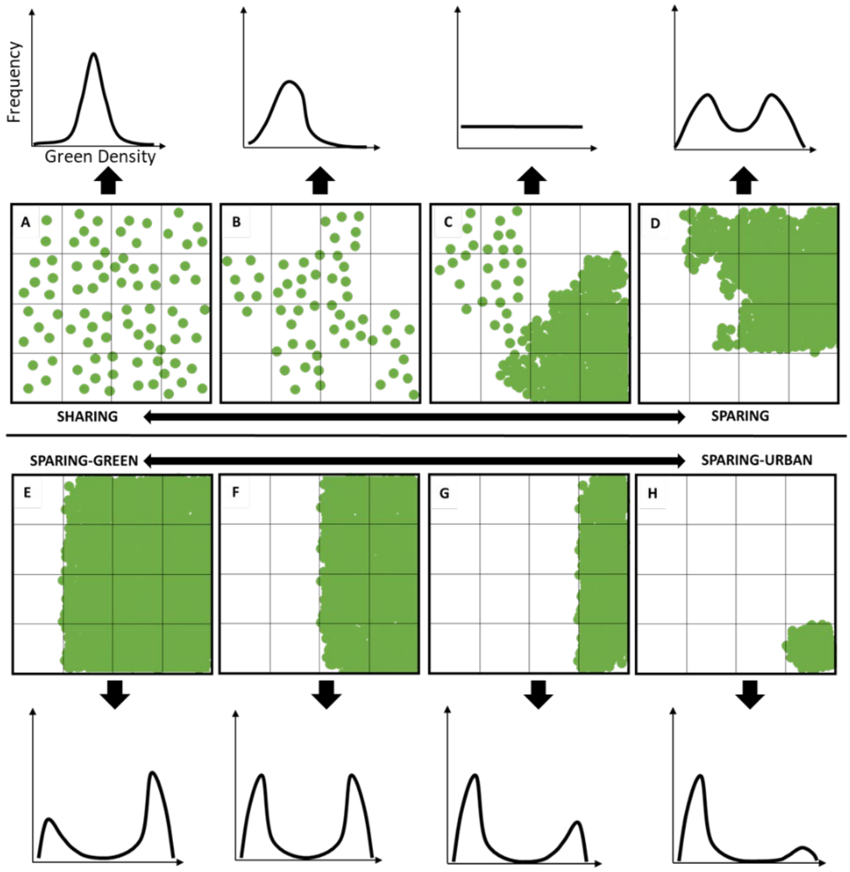

Figure 3 – Land sharing and sparing patterns, defined by sharing/sparing level and evenness between green and built areas. The first four examples (A to D) represent a gradient of landscapes from sharing (one central peak on EVI distribution) to sparing (two peaks separated by a valley on the EVI distribution) patterns. At intermediate conditions, no clear sharing and sparing pattern appears (C). The following examples (E to H) represent different land sparing conditions within a continuous gradient in terms of evenness, from sparing green (E) – where the majority of pixels are green – to a sparing urban – where the majority of pixels are grey, i.e., housing or built areas (G and H).

We evaluate the land sparing in three terms (see the formula in Table 1): (1) green level of sparing– **Sparing Green Vegetation Index (SGVI)**; (2) urban level of sparing –

Sparing Urban Vegetation Index (SUVI); and (3) how even is the distribution between them – **Sparing Unevenness Vegetation Index (SEVI)**. The methodology is an adaptation of ideas described by other authors (Soga et al. 2014, Stott et al. 2015) and developed to allow a statistical analysis. We applied this methodology to the 96 districts of São Paulo city (Boxes 1 and 2; Figure S1). For the estimation of quantiles and the proportion of pixels in each quantile, we used R (v. 3.5.3) with the packages *raster, rgdal* and *bbmle*. Examples of sharing-sparing districts and unevenness conditions with more detailed application can be accessed in supplementary material (Boxes S1 and S2).

Table 1 – Land sharing and sparing indices and formulas. A, B and C represents the number of pixels in each quantile of the EVI histogram (Figure 2II).

Name	**Formula**	**Description**
Sharing Vegetation Index	$SVI = \frac{B}{A+B+C}$	Proportion (varying from 0 to 1) in the whole landscape of pixels with values in B quantile, representing the level of land sharing
Sparing-Green Vegetation Index	$SGVI = \frac{C}{A+B+C}$	Proportion (varying from 0 to 1) in the whole landscape of pixels with values in quantile C – sparing with high green density.
Sparing-Urban Vegetation Index	$SUVI = \frac{A}{A+B+C}$	Proportion (varying from 0 to 1) in the whole landscape of pixels with values in quantile A – sparing with high urban density
Sparing-Unevenness Vegetation Index	$SEVI = \left\|\frac{A-C}{A+C}\right\|$	Absolute normalized difference between quantiles A and C, representing the unevenness between green and urban areas, varying from zero to one with low values representing sparing conditions with more even contributions of green and urban areas.

Statistical analysis

We investigated how hospitalization rates of cardiovascular, upper and lower respiratory tract diseases responded to different green quantities, vegetation types and green distribution with *Generalized Linear Models* (GLM). Models were constructed in R, using the *binomial* family (Richardson et al., 2015). Our response variable was a "rate of hospitalization", defined by the ratio between the number of hospitalizations in each of the 96 districts, for each of the three diseases groups (Table S1), in relation to the estimated number of SUS users in each district. We used the function *cbind* (base R package 3.6) to construct a matrix of success (number of hospitalizations) and non-success (number of SUS users minus number of hospitalizations). The predictive variables were the four sharing and sparing indices (SVI, SUVI, SGI and SEVI), the cover of the three vegetation classes (forests (5), isolated trees and small woods (6), and open vegetation (7)), the total arboreal cover (5 + 6) (8), the total green cover (5 + 6 + 7) (9), and the density of street trees points in each district (10). For all models we used the GeoSES index for the district as a co-variable, building additive multiple GLM. We also made additive models combining pairs of landscape variables with less than 70% of correlation between them (Table S2). All landscape values vary from zero to one and the GeoSES score varies from minus one to one. We built a null model – response variables adjusted to 1 – to test the null hypothesis. We present the analyses considering all years and seasons together, but we also did the same analyses considering separated years and the four seasons – Summer from January to March; Autumn from April to June; Winter July to September; Spring from October to December. There was no significant difference between years and seasons, so we decided to present the results in the main text using all data together. For more detailed information about effects of years and seasons see supplementary material. (Figure S2 and Table S3).

We selected the best model by *Akaike Information Criteria* (AIC, Burnham & Anderson, 2002), and considered models equally plausible if $\Delta AIC \leq 2$; the best model was the one with the lowest value of AIC. We used as a measure of goodness of the models the "weight" given by the comparative approach between multiple models by Akaike criteria. We also present the p-value of each variable in each of the selected best models. We run Pearson's correlation between socioeconomic factor (GeoSES), sharing-sparing indices and the cover of vegetation classes to confirm the effect of the social indicator on green distribution (Table S4).

We tested for spatial autocorrelation using three methods for the best models of each disease group, resulting in a negligible spatial effect (Table S5). We also built models considering a spatial component, by including the centroid of each district as a random variable in the Generalized Linear Mixed Models (glmm). Those models do not change greatly from models without spatial components (below); for more information, check supplementary material (Table S6).

RESULTS

From 2014 to 2016, 32,726 hospitalizations were registered for cardiovascular causes, 766 for URT causes and 1,828 for LRT causes, considering adults with 20 years or more and the disease codes presented in Table S1. These hospitalizations were unevenly distributed across the city of São Paulo, with a tendency for higher rates in marginal areas of the city (Figure 4 A, B, C). All rates presented high standard deviations, suggesting that the districts and regions of São Paulo city are highly different in terms of hospitalization rates, as it is in terms of socioeconomic conditions and SUS users (Figure 1).

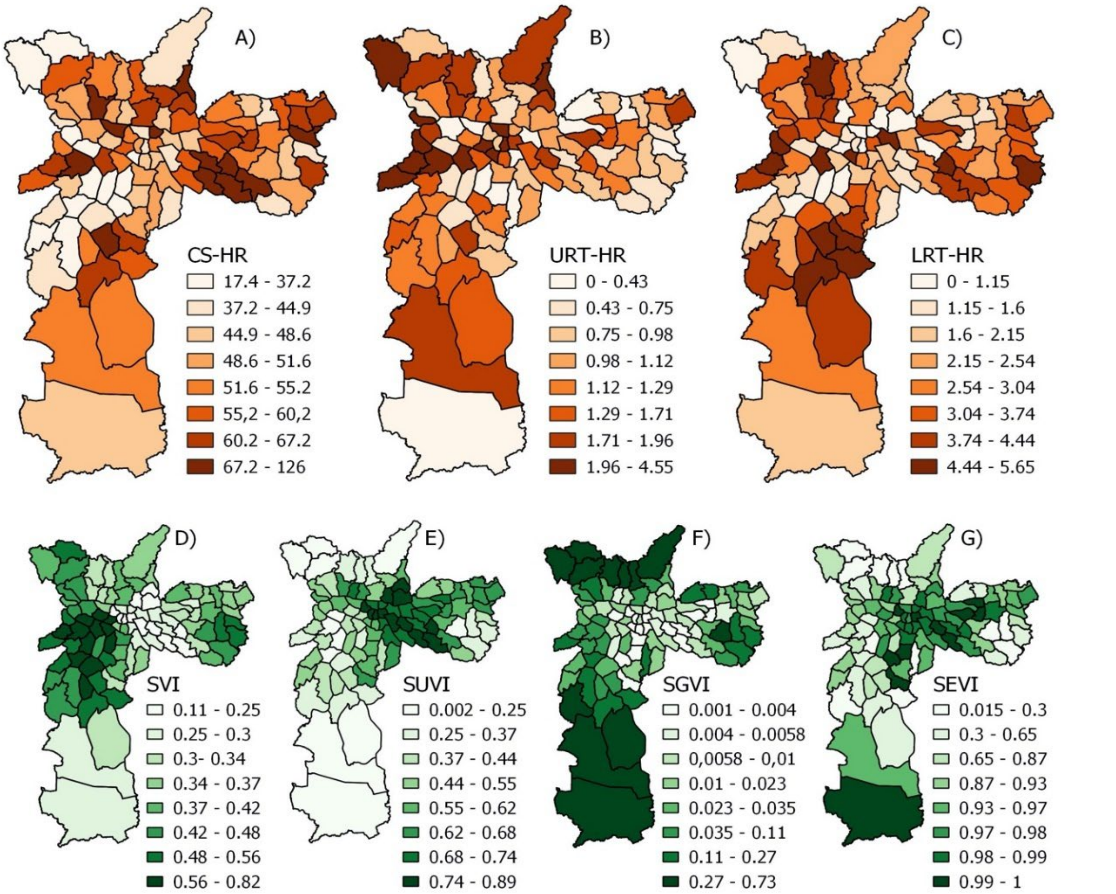

Figure 4– The distribution of hospitalizations per 10,000 SUS's users in the districts and sharing and sparing indices. A) Cardiovascular system hospitalization rate (CS-HR); B) Upper respiratory tract hospitalization rate (URT-HR); C) Lower respiratory tract hospitalization rate (LRT-HR); D) Sharing Vegetation Index (SVI); E) Sparing Urban Vegetation index (SUVI); F) Sparing Green Vegetation Index (SGVI); G) Sparing Unevenness Vegetation Index (SEVI).

The model selection resulted in a different set of explanatory variables for each disease group (Table 2, Figure 5). For cardiovascular diseases, only one model was selected, showing a negative effect on the hospitalization rate of both total arboreal cover and the sharing index. For URT diseases, three models were selected, all having a negative relationship between open vegetation areas and hospitalization rates, but also including a positive effect of sparing green and forests on hospitalization rate. For LRT, the best model shows a decrease in the hospitalization rate with the increment of isolated trees and small woods, and also with an increase in sparing unevenness.

Table 2 –Best models selected for each disease group. AICc is the Akaike Information Criteria corrected; ΔAIC is the difference of AIC between a given model and the best model; df is the degree of freedom; weight represents the

strength of the model in relation to the others. Only the models with dAICc ≤ 2 are presented. The estimate is the value non-transformed (logit link binomial glm) of the size of effect for each variable.

Model	AICc	ΔAIC	df	weight	estimate	sd	p-value
CARDIOVASCULAR							
Total Arboreal Cover +					-0.30975	0.0393	<0.001
Sharing	2377.5	0	4	0.9953	-0.83377	0.05423	< 0.001
GeoSES					-0.03740	0.01678	0.0259
URT							
Open Vegetation +					-2.46005	0.86407	0.00441
Sparing Urban	580.5	0	4	0.2385	-0.67905	0.23072	0.00325
GeoSES					-0.1080	0.1209	0.37145
Open Vegetation +					-1.88944	0.77028	0.01417
Sparing Green	580.9	0.4	4	0.198	0.75036	0.25677	0.00347
GeoSES					0.04389	0.12519	0.72589
Open Vegetation +					-1.43535	0.71185	0.04376
Forests	582.5	2	4	0.0873	0.67752	0.25709	0.00841
GeoSES					0.02862	0.12515	0.81911
LRT							
Isolated Trees and Small Woods +					-1.795	0.6562	0.00623
Sparing Unevenness	765.2	0	4	0.7117	-0.37	0.1665	0.02627
GeoSES					-0.10993	0.09285	0.23639

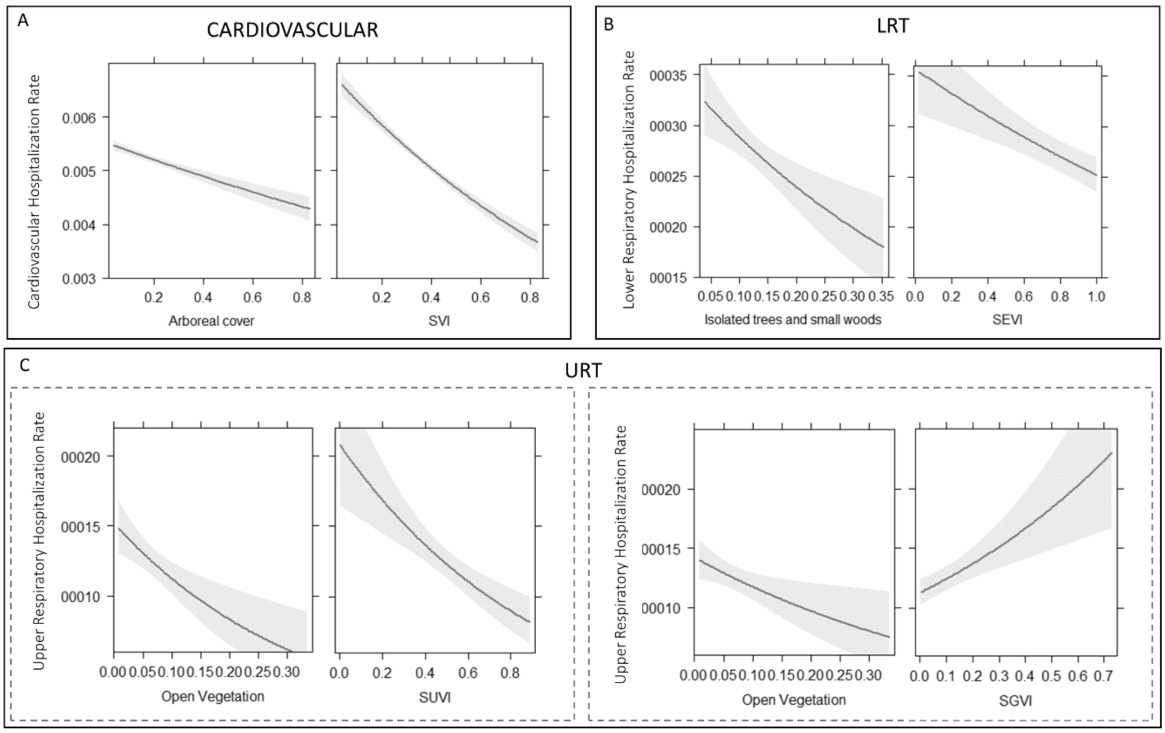

Figure 5 – Main relationships between hospitalization rates and green area explanatory variables according to the selected models for each group of diseases. Cardiovascular (A); Lower Respiratory (B) and Upper Respiratory (C). For upper respiratory diseases the graphics represent the two best models. SVI, SUVI, SEVI, SGVI represents sharing green, sparing urban, sparing unevenness, and sparing green indexes, respectively. Grey shadows in graphics represent the confidence intervals.

The Pearson’s correlation between GeoSES and sharing-sparing indexes shows a significant positive correlation between street trees density, SVI and isolated trees and small woods with GeoSES (R = 0.79, 0.35, 0.6 respectively; Table S4). On the other hand, the total green coverage has a negative correlation with the GeoSES (R = -0.3), as do forests and SGVI (R = -0.42, -0.47, respectively; Table S4).

DISCUSSION

We found consistent patterns that associate the reduction of cardiovascular and respiratory hospitalization rates with green areas in an urban environment, considering not only the quantity but also their spatial distribution and vegetation type. Innovatively, we have shown that hospitalization rates for cardiovascular diseases are more related to the distribution of, rather than to the amount of, green or arboreal areas, with a land sharing pattern favouring the reduction in hospitalization due to those diseases. Green areas can have a contrasting effect depending on the type of diseases (e.g., upper respiratory vs cardiovascular diseases), showing that different vegetation types have different responses for each disease group.

Land sharing districts presented a lower frequency of cardiovascular diseases hospitalizations than land sparing. The increase in each 10% of sharing level was associated with an average decrease of 8% in hospitalization rates by cardiovascular outcomes in the district population. Similarly, in a study in Tokyo, Japan, people in land sharing regions respond to having better life quality and use more green areas than those in land sparing regions (Soga et al. 2015). The beneficial aspects of land sharing design can be explained by a wider spatial distribution of ecosystem services that benefit people's health, thereby bringing the service supply closer to those who demand it (Metzger et al., 2021). Services such as scenic view, tree shading, noise control, heat control, and also other recreational and cultural activities, are services that have been shown to improve overall health (Coutts & Hahn, 2015; Kabisch et al., 2017; Roe et al., 2013; Sandifer et al., 2015). The proximity between demand areas (in this case, inhabited areas) and supply areas can be a crucial factor for these ecosystem service provisions (Metzger et al. 2020, 2021), which could be favoured by a sharing configuration. Regions of the city with land sharing patterns can represent more pleasant landscapes because of well-maintained gardens, public green areas, and street trees. Furthermore, the proximity to green areas should also increase the frequency and intensity of use of those areas, by providing propitious conditions to walk, for sports practice, gardening, and other outdoor activities in the neighbourhood (Dennis & James, 2016; Samuelsson et al., 2018; Soga et al., 2015, 2017). As a consequence, this may result in higher "nature doses" (Shanahan et al. 2015) and lower "extinction of experience" between people and nature (Soga et al. 2015, Soga and Gaston 2016). Within a land sharing design, all those benefits from green areas are provided more homogeneously in space, increasing the exposure and experience of nature, and thus positively influencing a larger portion of the inhabitants of the cities (Bratman et al. 2019, Marselle et al. 2020).

Likewise, the decrease in hospitalization rates due to LRT diseases was associated with isolated trees and small woods, with the increment of 10% of this land cover decreasing the hospitalization rates by 17%. This land cover category consists of non-forest arboreal coverage (without understory), as urban small woods, urban parks, squares, and street afforestation. The other parameter of the best model for LRT consists of a land sparing factor related to the unevenness between green and grey - high SEVI associated with isolated trees and small woods. This means that districts with the majority of land cover composed of green in the form of isolated trees and small woods, are better than those with the majority composed of grey. That shows the importance of sparing some green areas, such as small woods and parks, balancing the effect between sharing and sparing, since the best variables selected are not pure land sharing or pure land sparing.

For LRT diseases, neighbourhoods in an intermediary level of the continuum land-sharing-sparing (like Figures 3-C and 3-E) seem to be better than those predominantly sharing, sparing, or grey. Together, small segregated urban woods (that to some degree configures a land sparing pattern) and isolated trees (that to some degree can contribute to increasing land sharing levels) results in landscapes in between the continuous, but that brings the green as a key factor on decreasing LRT hospitalizations. This landscape configuration could play a role in the air quality control (Janhäll 2015), through the presence of denser and more developed vegetation (sparing small woods), but also with some isolated trees in the landscape. Greener regions can lower the particle matter in air through leaves deposition and air depuration (Janhäll, 2015), depending on forest designs (Nowak et al. 2018), proximity and management of urban tree canopy (Nowak et al. 2006). Complementarily, street trees reduced suspended particular matter nearby the source (Vailshery et al. 2013), so isolated trees can have a potential role in regulating air quality. That can be related to the control of lung diseases that we found, by controlling pollutants, offering cultural ecosystem services, and stimulating sporting practices and recreational activities which can in the long-term also benefit lung health.

Contrasting effects of green on human health

Despite health services of green cover decreasing cardiovascular and LRT hospitalization rates, on the other hand, we found an opposite effect for URT – green areas and sparing green (SGVI) configuration appears to present a potential disservice. According to the selected models, the increase of 10% in SGVI level increases 10% of hospitalization rate, and the increase of 10% in forest cover increases 9% of hospitalization rate. The diseases selected in the upper respiratory tract health category

(Table S1) are all related to potential respiratory allergies, which can be caused by higher humidity, air pollen, fungus, and mites in regions nearby forests (Parmes et al. 2020). Little is known about pollen and plant induced allergies in tropical environments (Caraballo et al., 2016; Johnston et al., 2009), but in temperate climates the relations between the proximity of forest environments and respiratory allergies are better established (Parmes et al. 2020). This potential explanation is reinforced by the fact that hospitalizations by URT causes were higher in spring (Figure S2), when there are more pollen particles in the air and the weather is humid, favouring the increase of organisms like mites and fungus that can cause allergies. Conversely, an increment of 10% of open vegetation and urban areas reduces the hospitalization rate by 25% and 10%, respectively (Table 2 - URT), which can be related to the higher insolation and less favourable environments for the development of fungus and mites, having a lower presence of them by the lack of forests (Dudek et al., 2018; Parmes et al., 2020). Forests can thus represent a disservice to human health in terms of allergies (Dudek et al. 2018), while open vegetation and urban areas are a service, but these correlations still lack clear scientific evidence of causal relationships, especially in the tropics.

Despite the contrasting effects of forest cover and sharing/sparing configuration, green areas and sharing configuration prevent the occurrence of diseases that are much more frequent than those that can be enhanced by arboreal vegetation. On average, there are 13,184 adult hospitalizations per year in the public system by diseases that seems to be decreased by green coverage (cardiovascular and LRT), and just 255 for upper respiratory diseases that seem to be increased by green coverage. In that way, the services of green areas are proportionally greater than the disservices for human health, at least for the city of São Paulo.

Socioeconomic factors of green distribution

For this study, we controlled socioeconomic variations, which are very evident in the city of São Paulo. São Paulo city has a spatial pattern where richer districts frequently have high levels of land sharing, higher availability of parks and green areas, and higher tree cover along streets, whilst poorer districts with dense populations have fewer street trees and low availability of green between the households (Arantes et al., 2021). This pattern is not uncommon in Latin American cities, indicating a greater social inequality and insufficient urban planning to reduce these inequalities (Dobbs et al., 2018). On the other hand, some peripheral regions of the city of São Paulo have more areas with dense green coverage, composed of forest remnants, but in most cases those areas do not have public access or are considered dangerous places, resulting in little use of the space for recreation and leisure activities. Consequently, besides the socio-economic conditions being worse in peripheral areas, the offer or access to recreational green areas is more limited, which could be related to lower ecosystem services provision and higher hospitalization rates.

Implications for Urban-planning and decision-makers

The health benefits provided by green areas, particularly of forested areas in land sharing configurations, can be used in the planning of healthier urban landscapes. Increasing land sharing seems to be an interesting target for urban planning to provide an evenly spatial distribution of ecosystem services provision, and potentially prevent the occurrence of some diseases, particularly in the case of cardiovascular disease.

Enabling the provision of ecosystem services through nature-based solutions (Cohen-Shacham et al. 2019) is a powerful tool to increase the health quality of citizens, alleviating some of the problems of urban life (Bush and Doyon 2019). Land sharing configuration is part of these solutions. The land sharing indicator (SVI) is not only related to the density of street trees in the district ($R=0.4$; $p<0.001$), but also to the vegetation composed of isolated trees and small urban woods ($R=0.8$; $p<0.001$). To increase land sharing, we should stimulate the creation or recovery of green areas, both in public and private lands, including the expansion of street afforestation, the creation of public squares, and the establishment of gardens and trees inside private land – all these actions can help to make cities greener (Miller & Montalto, 2019). The most favourable landscape configurations are those with high total green coverage, distributed in the landscape in dense green patches (parks and protected areas), but also with street afforestation and small urban woods in between the households, ensuring the provision of both cultural and regulating ecosystem services.

Although our sharing and sparing indicators are based only on arboreal vegetation, open vegetation can also have positive effects on health (as we showed here for upper respiratory diseases). Open vegetation may be prevalent in other cities, and thus a major natural component in the provision of ecosystem services that benefit human health. In these cases, it would be fundamental to develop procedures that allow the analysis of the sharing and sparing of this open vegetation.

Considering that green infrastructure in cities has recognised effects on biodiversity (Alvey 2006; Soga et al. 2014; Ibañez-álamo et al. 2019) and that this biodiversity (or the perceived biodiversity; Schebella et al. 2019) in turn can enhance benefits to human health, interventions aimed at expanding green areas can leverage synergies between biodiversity and human well-being. Depending on the type of ecosystem service and disease considered (Stott et al. (2015), a more sharing or sparing configuration, or an intermediate condition, may be preferred.

Interventions to increase or redistribute green areas should prioritize regions with less social resources, which are regions with a higher proportion of public health system users. In Latin American cities, those regions are mostly situated at the periphery, and usually lack green areas, or have green areas in a sparing configuration but with restricted or dangerous access. In those regions, creating parks is not enough – existing parks need to be safer and more suitable for use, in addition to the development of projects focused on increasing the density of trees in streets.

As some regions of the cities have low availability of land to implement new green areas, environmental interventions should focus on the multiplication of small initiatives, such as planting trees on small spaces, like central avenue beds, sidewalks and street traffic circles, the implementation of green roofs and facades, and bioswale (Miller & Montalto, 2019). The sum of these small lots in the middle of urbanized regions matters to improve the total green cover, increasing land sharing intensity and thus spreading ecosystem services supply nearby who demands it (Metzger et al. 2021).

The regulation of human health through the expansion of green areas and land sharing configuration can improve the quality of life and health of people in cities (van den Bosch & Ode Sang 2017). These can both save health costs and provide long-term and resilient solutions if those solutions are perpetuated in the landscape and used by several generations of city dwellers.

CONCLUSIONS

Not just the amount but also the type and distribution of green coverage matters in efforts to prevent cardiovascular, upper and lower respiratory diseases. Our data shows that the configuration of urban green seems to be as important as total green coverage. Land sharing configuration was associated with lower cardiovascular system hospitalization rates, probably by providing greater exposure to and usufruct of regulating and cultural ecosystem services that act on human health. The amount of dense tree canopy reduces lower tract respiratory hospitalization rates, but potentially increases allergy-based hospitalizations. In general, the services provided by forests and urban woods on human health, particularly a land sharing configuration, seem to be bigger than their disservices. Thus, the increase of green areas and the intensification of sharing configuration are relevant targets for urban planning, in particular through multiple small interventions scattered throughout the urban landscape. Those interventions can be more efficient, cheaper and lasting, since green areas can remain for generations on urban landscapes and can benefit the population in the long term.

AUTHORS CONTRIBUTIONS

Douglas William Cirino conceived the original idea, was responsible for the acquisition, treatment and analysis of data, developed the methodology and wrote the manuscript; Leandro R. Tambosi, Simone R. de Freitas, Thais Mauad and Jean Paul Metzger interpreted the data and results and critically reviewed the content with important intellectual contribution; Jean Paul Metzger supervise the research project since the idea conception to results interpretation, and contributed in the writing of the manuscript.

CONFLIT OF INTEREST

The authors declare that they have no conflict of interest.

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DATA AVAIABILITY

Data available via the Dryad Repository: https://doi.org/10.5061/dryad.7sqv9s4v6 (Cirino et al, 2022)

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