Artur Lupinetti Cunha

Avaliando o serviço ecossistêmico de regulação climática local e os efeitos da estrutura da paisagem em sua provisão

Assessing the local climate regulation ecosystem service and the landscape structure effects on its provision

São Paulo

2023

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Versão corrigida da dissertação apresentada ao Instituto de Biociências da Universidade de São Paulo, para a obtenção de Título de Mestre em Ciências, na Área de Ecologia.

Orientador: Dr. Jean Paul Metzger
Coorientadora: Dra. Simone R. Freitas

São Paulo

2023

Ficha Catalográfica

Ficha catalográfica elaborada pelo Serviço de Biblioteca do Instituto de Biociências da USP, com os dados fornecidos pelo (a) autor (a) no formulário: 'https://biblioteca.ib.usp.br/ficha-catalografica/src/ficha.php'

Lupinetti Cunha, Artur
Avaliando o serviço ecossistêmico de regulação climática local e os efeitos da estrutura da paisagem em sua provisão / Artur Lupinetti Cunha ; orientador Jean Paul Metzger ; coorientadora Simone Rodrigues de Freitas -- São Paulo, 2023.
53 p.

Dissertação (Mestrado) -- Instituto de Biociências da Universidade de São Paulo. Programa de Pós-Graduação em Ecologia.

1. Calor urbano. 2. Temperatura da superfície. 3. Planejamento urbano. 4. Ecologia urbana. 5. Ecologia da paisagem. I. Metzger, Jean Paul, orient. II. Rodrigues de Freitas, Simone, coorient.

Bibliotecária responsável pela catalogação:
Elisabete da Cruz Neves - CRB - 8/6228

Dedicatória

Dedico este produto ao processo de desenvolvimento do mesmo, e aos ensinamentos e pessoas que ele me trouxe

Agradecimentos

Agradeço as Universidades públicas, gratuitas e de qualidade, que proporcionam a troca e aquisição de conhecimentos que vão muito além do científico. Em especial a Universidade de São Paulo e a Universidade Federal do ABC, que guiaram a minha formação. Agradeço a política de dados abertos, que facilita a produção científica e traz transparência ao meio acadêmico. Tratando-se disso, também expresso minha gratidão à Rede MapBiomas, onde sigo aprendendo a fazer, comunicar e disseminar ciência, dialogando com profissionais de diversas áreas.

Agradeço meus colegas de pós-graduação, que compartilharam conhecimentos e parcerias valiosas. Em especial, agradeço aos colegas do Laboratório de Ecologia da Paisagem e Conservação, cujas sugestões enriqueceram o manuscrito e os momentos descontraídos durante os cafés. Um agradecimento especial para Camila, Douglas, Gabriel e Jonathan, que me auxiliaram nas decisões importantes sobre os métodos, revisaram o texto e contribuíram na elaboração das figuras do trabalho.

Agradeço meu orientador, Dr. Jean Paul Metzger, e minha coorientadora, Dra. Simone Rodrigues de Freitas, por todo o conhecimento transmitido e por me guiarem durante este processo. Agradeço também os membros do meu comitê de acompanhamento - Dra. Denise Helena Silva Duarte, Dra. Vânia Regina Pivello e Dr. Humberto Ribeiro da Rocha - pelos conselhos e ensinamentos durante nossas reuniões.

Agradeço a minha mãe, Meire, e meu pai Antonio, por estarem presentes e interessados na minha carreira acadêmica, me ajudando de todas as formas possíveis continuar no caminho que escolhi seguir. Obrigado ao meu irmão Pedro, que sempre fica feliz em me ver crescer pessoalmente e profissionalmente, além de ser meu leitor externo à academia, sempre me ajudando a buscar clareza na transmissão das ideias.

Agradeço meus amigos Bruno, Douglas, Diego, Jonathan, Juliete, Tatiane. Morar perto de vocês e ter sua companhia foi essencial para que eu chegasse até o fim. Por fim, agradeço mais uma vez meu companheiro de vida, Douglas Cirino. Foi quem me acompanhou mais de perto durante o desenvolvimento da dissertação, desde o surgimento da vontade de entrar em um programa de pós-graduação a este ponto. Viu todos os altos e baixos deste processo e sempre esteve disposto a estender a mão para me ajudar, acreditando mais no meu potencial do que eu mesmo acreditava. Seu apoio constante foi uma verdadeira motivação. Obrigado a todos que contribuíram para o meu crescimento acadêmico e pessoal.

FINANCIAMENTO:

Agradeço a Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) pela bolsa de pós-graduação – processo nº 88887.499676/2020-00

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Introdução Geral

A população mundial cresce em ritmo acelerado, principalmente nos países em desenvolvimento, levando à expansão das áreas urbanas (Cohen, 2006). Atualmente, as cidades constituem a principal forma de organização social humana (McKinney, 2006), o que implica em mudanças demográficas, econômicas e do uso e cobertura da terra que comprometem o funcionamento de ecossistemas naturais e causam impactos negativos sobre as populações e biotas locais (Zhang & Seto, 2011). O aquecimento urbano constitui um dos impactos mais notáveis nas cidades (Grimmond, 2007; Tsoka et al., 2020), ocorrendo devido a liberação de calor por múltiplas atividades, como a queima de combustíveis fósseis e a impermeabilização do solo (Jin et al., 2020). Muitos dos materiais utilizados nas cidades, como o concreto e o asfalto, ainda absorvem uma alta porcentagem da radiação solar incidente, o que leva ao aumento da temperatura do ar a partir da troca de calor com a atmosfera (Gago et al., 2013; Jamei et al., 2019). Se não remediada, a retenção excessiva de calor nas cidades pode gerar um desconforto térmico grave, que diminui a qualidade de vida dos cidadãos e, portanto, representa um problema ambiental importante a ser resolvido nas cidades em expansão.

O processo de aquecimento térmico mais conhecido são as ilhas de calor: um fenômeno em que áreas urbanas apresentam temperaturas mais elevadas do que áreas rurais em seus arredores por perderem calor mais vagarosamente devido à forma com que as cidades são estruturadas (Kong et al., 2017; Oke, 1973, 1982). Em particular, as ilhas de calor de superfície envolvem diferenças de temperatura irradiadas pelas superfícies dos objetos, que podem ser detectadas através de sensores térmicos de satélites (Li et al., 2013; Zhang et al., 2009). A temperatura de superfície terrestre (LST, do inglês *Land Surface Temperature*) influencia a temperatura do ar nas camadas atmosféricas mais baixas, afetando o balanço de energia da superfície e a temperatura no interior das construções, tendo implicações para o conforto térmico e saúde da humana (Voogt & Oke, 2003; Kovats & Hajat, 2007).

O aumento da temperatura média global intensifica a necessidade de mitigar os impactos negativos dos fenômenos de aquecimento urbano sobre a população (Giridharan & Emmanuel, 2018; Wu et al., 2020). Neste contexto, soluções baseadas na natureza (inspiradas ou apoiadas no funcionamento de ecossistemas naturais) vêm ganhando destaque por apresentarem melhor custo-benefício a longo prazo (Bowler et al., 2010;

Morecroft et al., 2019; Yu et al., 2017; Costanza et al., 2017). Entre outras estratégias, aumentar a área de vegetação urbana pode ser uma resposta eficiente e de baixo custo para amenizar a temperatura de superfície (Salmond et al., 2016; Willis & Petrokofsky, 2017). A partir do sombreamento, a vegetação impede que raios solares incidam diretamente sobre o solo, reduzindo o aquecimento (Ng et al., 2012; Speak et al., 2020). Junto a isso, as plantas ainda são capazes de resfriar o ambiente a partir do processo de evapotranspiração, em que as folhas liberam água para o ar na forma de vapor (Vieira et al., 2018). O efeito de resfriamento pela evapotranspiração ainda estende-se além do local no qual a planta está, contribuindo para a melhora do conforto térmico das proximidades (Moss et al., 2019; Spangenberg et al., 2019; Vaz Monteiro et al., 2016).

Diversos fatores modulam a intensidade das funções ecossistêmicas da vegetação urbana sobre a amenização da temperatura: (1) o porte da vegetação (ex: altura e dimensão de copa das árvores; Abreu-Harbich et al., 2015; Rahman et al., 2019, 2020; Helletsgruber et al., 2020; Lehmann et al., 2014; Sun et al., 2017); (2) a quantidade de áreas verdes na cidade (Howe et al., 2017; Ouyang et al., 2020); (3) a geometria das áreas verdes (como formato, área e perímetro; Feyisa et al., 2014; Srivanit & Iamtrakul, 2019); e (4) a proximidade espacial das árvores (Qiu & Jia, 2020; Zhou et al., 2017). Além da vegetação, as características das áreas construídas e a interação espacial destes com a vegetação modulam a intensidade do aquecimento urbano (Masoudi et al., 2019; Nguyen, 2020). A quantidade (Song et al., 2014), configuração (Connors et al., 2013) e a altura de edificações são fatores que influenciam a temperatura da superfície. Por exemplo, em locais de alta quantidade de construções ocorre o maior sombreamento por prédios altos e modificações no fluxo de correntes de ar de acordo com o arranjo espacial das construções (Ferreira & Duarte, 2019; Wu et al., 2019). Desta forma, a configuração espacial da cidade como um todo afeta o serviço de regulação do clima local, incluindo a distribuição espacial de áreas impermeáveis (Estoque et al., 2017).

Considerando os desafios que envolvem a mitigação das temperaturas nas cidades, investigamos o papel da paisagem, tanto em sua composição, quanto em sua configuração, e a interação entre composição e configuração tanto das áreas verdes quanto das áreas construídas na regulação da temperatura local. Usamos um recorte de uma megacidade como modelo de estudo – o município de São Paulo (Brasil), a maior cidade do Hemisfério Sul. Além disso, buscamos não apenas compreender os fatores da paisagem que afetam o serviço ecossistêmico de regulação climática local, como também a distribuição espacial da provisão do mesmo pela cidade ao aplicar o *framework* da cadeia de provisão de serviços ecossistêmicos (Metzger et al. 2021) para entender a ligação entre a oferta, a demanda e o fluxo do serviço de regulação térmica local, permitindo identificar onde há um desbalanço entre oferta e demanda pelo serviço de amenização do calor. A partir da identificação de áreas prioritárias, esperamos que os nossos resultados auxiliem nas tomadas de decisão para um melhor planejamento urbano, principalmente em relação à alocação de novas áreas verdes para aumentar a resiliência climática das cidades.

MANUSCRITO:

Assessing the local climate regulation ecosystem service and the landscape structure effects on its provision

TARGET JOURNAL: Sciece of the Total Environment
IF: 10.7

Assessing the local climate regulation ecosystem service and the landscape structure effects on its provision

Artur Lupinetti-Cunha[a], Simone Rodrigues de Freitas[b], Jean Paul Metzger[a]

[a] Department of Ecology, Biosciences Institute, University of São Paulo, Rua Do Matão, Tv. 14, São Paulo, São Paulo 05508-090, Brazil

[b] Center for Natural and Human Sciences, Federal University of ABC, Av. dos Estados, 5001, Santo André, São Paulo 09210-580, Brazil

Abstract

One prominent consequence of the intensification of urbanization is the occurrence of urban heat islands. Surface urban heat islands, affecting lower layers of the atmosphere, potentially increase energy consumption, and have implications for thermal comfort and human health. Regarding the mitigation or prevention of extreme thermal events and the alleviation of surface urban heat island effects, urban vegetation holds great potential, but in the urban landscape it is also important to take into account the effects of other elements, such as buildings, and their interactions with vegetation. Through a landscape ecology approach and by applying linear mixed models, we assess the provision of the local climate regulation ecosystem service in the city of São Paulo, Brazil, identifying areas with a mismatch between the service supply (landscape capacity of lowering the land surface temperature) and demand (population), and how its supply is affected by landscape structure, focusing on both vegetated and built areas, and on their interaction. Despite composition metrics, especially total vegetation cover, being the ones that better explain the supply of local climate regulation service, configuration metrics also exerts a significant effect on this service. Vegetation edge density showed a positive effect on the service supply, while the opposite happened for buildings edge density. We also found that arboreal volume and the contact between vegetated and built areas helps reduce land surface temperatures and that both those surface types interact with each other. Finally, regions of the city with a mismatch between the supply and demand, which could represent a health risk in a scenario of climate crisis, were identified. Those results can help decision makers and urban planners to think about the city configuration and propose public policy aiming to alleviate the local temperatures, benefiting the population.

Keywords: Urban Heat; Land Surface Temperature; Urban Planning; Urban Ecology; Landscape Ecology.

1. Introduction

The intensification of the urbanization process has profound implications for natural ecosystems and the services they provide to humanity (Mcdonald et al., 2008). One prominent consequence of urbanization is the occurrence of urban heat islands, where cities tend to experience higher temperatures compared to surrounding rural areas (Grimmond, 2007; Tsoka et al., 2020). This is primarily due to the release of anthropogenic heat from human activities and the low albedo of urban materials, which absorb a significant amount of solar radiation (Voogt & Oke, 1998; K. Wang et al., 2018; Jin et al 2020). Depending on the atmospheric layer where the temperature difference is measured, urban heat islands can be classified into three categories: boundary, canopy and surface (Oke, 1976; Voogt & Oke, 2003). While boundary and canopy urban heat islands deal with air temperature differences at higher layers (usually above 1.5 m), surface urban heat islands are characterized by temperature differences between urban and rural surfaces, and can be detected using thermal sensors on satellites (Li et al., 2013; Zhang et al., 2009). The land surface temperature (LST) affects the energy balance of urban areas, potentially increasing energy consumption, and has implications for thermal comfort and human health, elevating the risks of heat strokes and heat exhaustion, especially on children and elderly people (Voogt & Oke, 2003; Kovats & Hajat, 2007; Sagris & Sepp, 2017). Those issues are particularly more harmful in the tropics, where urban heat islands are enhanced by the typically warm weather (Giridharan & Emmanuel, 2018).

In the current scenario of climate change, the concern for mitigating negative impacts of increasing global average temperature is growing (Giridharan & Emmanuel, 2018; Wu et al., 2020). Regarding the mitigation or prevention of extreme thermal events and the alleviation of surface urban heat island effects, urban vegetation holds great potential (Cohen-Shacham et al., 2019). Several factors modulate the intensity of this local climate regulation service (i.e., the service through which urban vegetation alleviates land surface temperature). The effects of the quantity of green areas in the city (i.e. landscape composition) is widely-known to reduce LST (Zhou & Wang, 2011; Alavipanah et al., 2015; Howe et al., 2017; Ouyang et al., 2020). Vegetation configuration also influences LST: aggregated vegetation patches were shown to be more efficient in reducing LST, by facilitating the energy flows and exchange between vegetated and built areas (Zhibin et al., 2015) and by larger and more aggregated patches providing a larger and more intense cooling island effect through evapotranspiration (Gkatsopoulos, 2017; Moss et al., 2019). The cooling potential of green areas is also dependent on their shape, with parks that have more irregular shape having higher cooling distance and more compact parks presenting higher cooling intensities (Feyisa et al., 2014). Fragmentation and edge effects on LST reduction is more complex, exhibiting positive or negative effects on the local climate regulation service depending on the study location, scale, and green coverage, that may be caused by differences in the contributions of shading and evapotranspiration cooling: while more edge can potentially increase the shade provided by trees, it also represents more fragmented patches with reduced evapotranspiration cooling efficiency (Srivanit & Iamtrakul, 2019; Qiu & Jia, 2020; Yao et al., 2020; Zhou et al., 2017). Also, vegetation height and volume reduce LST by providing more shade and expanding the cooling effect range (Helletsgruber et al., 2020).

However, the provision of this ecosystem service is not only influenced by vegetation cover and configuration, but also by the structure of built areas and their spatial interaction with vegetation (Masoudi et al., 2019; Nguyen, 2020). Thus, the overall spatial configuration of the city (i.e. buildings aggregation and proximity to vegetated areas) affects temperature, even in densely built areas (Estoque et al., 2017; Heinl et al., 2015; Howe et al., 2017; Liang et al., 2020). Building positioning and characteristics, such as height and surface area, can lead to increased shading and modifications in airflow patterns (Ferreira & Duarte, 2019; Li et al., 2020; Wu et al., 2019). Considering that both natural and build characteristics influence LST, it is essential to quantify their interactions to better plan resilient cities (Fu et al., 2022). Moreover, few studies on this topic were carried out in developing cities in the global south, where urban growth is intense and less planned, and where green availability to residents is highly unequal between neighborhoods, creating urban landscapes quite distinct from those of the global north (Rigolon et al. 2018). Understanding how the modulation of the climate regulation service takes place in these cities is thus not only functionally important, but also relevant to better plan strategies for adapting to the problems linked to climate warming in cities of the global south (Masoudi et al., 2019).

In light of the growing urbanization and the associated challenges of increasing temperatures in cities, this study aims to deep the understanding on how landscape affects local climate regulation service, with a particular focus on the configuration effects, which are still controversial between different study areas (Zhou et al., 2017; Fu et al., 2022; Liu et al. 2022). We expand the usual studies that look only at vegetation, by focusing on both vegetated and built areas, and on their interaction. It is expected that despite composition being the main factor affecting local climate regulation, configuration of both green and built areas affects the provision of this ecosystem service, with aggregated and less fragmented vegetation having a positive effect, while the inverse is expected of buildings configuration. Moreover, the interplay between both natural and built areas will modulate the intensity of the ecosystem service supply and the effects of each other over it, with vegetation reducing the negative effects of buildings, as well as the other way around, with buildings reducing the positive effects of vegetation. Furthermore, by applying the ecosystem provision chain (Metzger et al., 2021), our objective is to pinpoint areas characterized by a disparity between the supply of local climate regulation service (expectedly by urban green and built areas) and the demand arising from higher population densities. By doing so, the research intends to provide policymakers and city planners with valuable insights to facilitate informed decision-making in relation to the strategic allocation of green spaces and nature-based solutions, thinking about planning urban spaces for greater climate resilience.

2. Methods

2.1. Study area

São Paulo is the most populous metropolis in the South Hemisphere, home to an estimated population of 11,451,245 as of 2022, spanning an area of 1,521 km² (Brazilian Institute of Geography and Statistics - IBGE, 2023). Despite its predominantly urban landscape, the municipality surprisingly retains 48% of vegetation cover, with 21% classified as natural vegetation (SVMA, 2020). The city has a wet subtropical climate (Cfa according to Köppen classification), characterized by warm humid summers and the cool drier winters, with an annual average of 1356 mm of rain per year. It can be further divided by distinct natural mesoclimatic regions, influenced by factors such as proximity to the ocean and topography, which play a role in shaping its climate (Fig. S5 - Tarifa & Armani, 2000). The temperature of the city typically ranges from 11 to 31ºC yearly, but the events of intense cold and heat have increased lately in the region (Alves et al., 2016; Valverde

& Rosa, 2023). The highest temperatures for the city have been registered are now reaching 38ºC (10ºC degrees above the mean maximum temperature for the hot season).

The city's complex mix of natural and built environments, coupled with its diverse land use patterns, presents a rich opportunity to explore the intricate interplay between vegetation cover, built structures, and surface temperatures (Ribeiro et al., 2021). Moreover, being a megacity in a developing country, the city also exhibits high levels of air pollution, impervious surface cover and, consequently, urban heat islands, all of which have been associated with negative health outcomes to the population (Sharovsky et al., 2004; Ikefuti et al., 2018), making it a critical place to explore measures to mitigate climate threats.

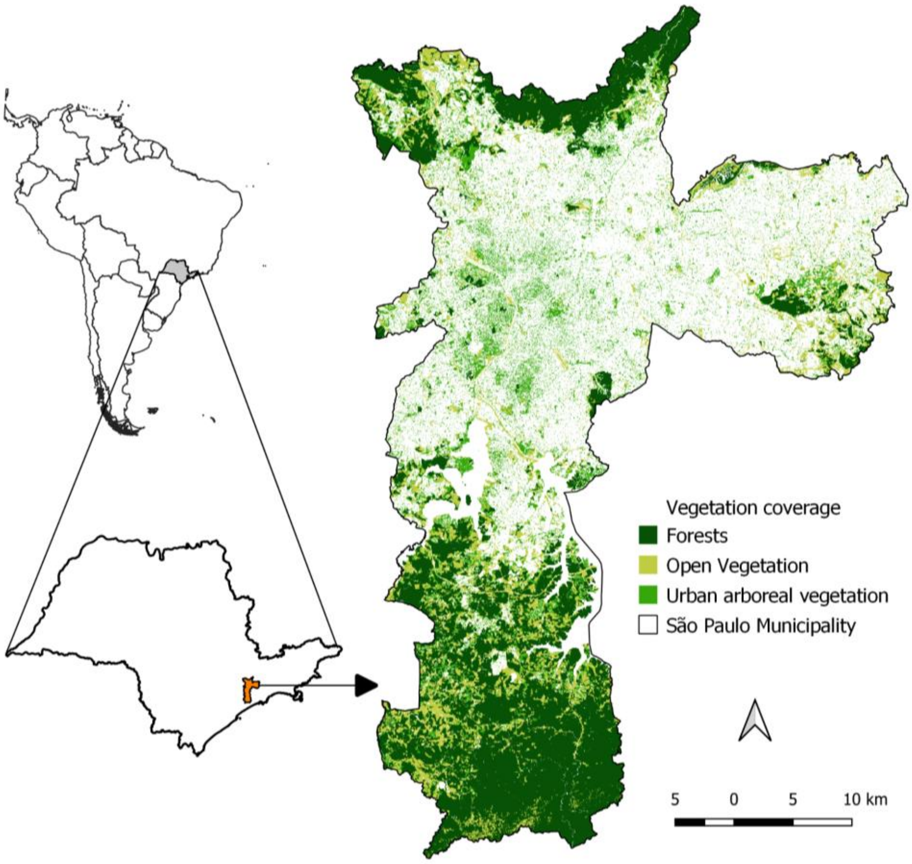

Fig. 1. Location and vegetation cover of the São Paulo municipality. On the left, the location of the city in relation to São Paulo state and South America. On the right the vegetation coverage, divided in three categories.

2.2. Local climate regulation ecosystem service assessment

The assessment of an ecosystem service depends on the understanding of three components of its provision chain: the service supply, demand and flow (Villamagna et al. 2013). The supply represents the potential of ecosystems (here, urban landscapes) to generate specific services, such as local climate regulation. The demand represents the societal need or desire for a particular ecosystem service, while the flow encompasses the biotic or abiotic processes that connect areas of supply and demand, effectively providing the benefits associated with the ecosystem service (Villamagna et al., 2013).

To characterize the supply of the local climate regulation service, we used Landsat 8 satellite images (30 m of spatial resolution), provided by the United States Geological Survey (www.usgs.gov). Using the Google Earth Engine platform, LST was retrieved using the script developed by Ermida et al. (2020). This script employs a sequence of equations utilizing the spectral bands red (B4), near infra-red (B5), the thermal band (B10), and atmospheric parameters to convert satellite-captured radiation into LST. We selected three images (September 23, 2015, November 15, 2017 and January 21, 2019) based on low cloud cover, absence of rain, and season (spring or summer, since in these periods differences in LST between different surfaces are accentuated) for the supply characterization analysis, in order to check its temporal consistency and avoid using only one period that could be affected by a climatic anomaly (Figure S1-S3 for the LST maps and information on the weather on the date each image was captured). All images were captured at 10 A.M. (BRT).

A grid system with a resolution of 100 m x 100 m (1 ha) was employed as the sampling unit, dividing the city into 137,604 cells, which were considered as different landscapes for the subsequent analysis. The choice of this spatial extent is due to the expected limited range of influence of vegetation and building configuration metrics on local climate (Chen et al., 2022). Each cell was further categorized based on its mesoclimatic region (Tarifa & Armani, 2000). Then, the mean LST value of the Landsat pixels inside each sampling unit was extracted (LSTi) and the LST difference (ΔLSTi) between each cell "i" and the cell with the highest temperature (LSTmax) within the same mesoclimatic region was calculated (Equation 1). Given that cells within the same mesoclimatic region experience similar effects from natural variables operating at larger scales (such as the influence of the ocean, altitude, topography, and the two largest forest continuums in São Paulo), differences in LST within these cells primarily arise from variations in landscape structure and anthropic activities, as well as from the direction and orientation of the relief, albeit with a slightly lesser intensity. Consequently, ΔLST serves as a proxy for quantifying the supply of the local climate regulation ecosystem service provided by the urban landscape in each cell.

$$\Delta LSTi = LSTmax - LSTi \quad (1)$$

The estimation of the demand for local climate regulation service was based on the population within each cell, considering the number of individuals who would benefit from lower surface temperatures (Norton et al., 2015). To obtain this information, data from the most recent available Demographic Census conducted in 2010 (IBGE, 2010) was projected to the year 2017 to align with the year of the vegetation and building maps. The population of each sample unit was calculated by summing the populations of the sectors (tracts) that overlap with the grid cell. To achieve this, we first computed the population density of each sector and determined the area of each tract that intersected with each respective sample unit. Next, for each sample unit, we multiplied the area of each sector within it by the population density of that sector. This calculation was performed for all sectors overlapping with the sample unit. Finally, we summed these products to obtain the population estimate for each sample unit (Ribeiro et al, 2019). Finally, due to the nature of the LST (Zhang et al., 2017), this ecosystem service has a local flow (within each cell), considering thus that people only benefit from this service when they share space or are immediately near the supply.

Subsequently, the balance between supply and demand was calculated to obtain a variable indicating areas where there is a service mismatch, or inversely, an equilibrium, following Equation 2 (Xue et al., 2022). Since the demand (population) and supply (ΔLST) variables were measured on different scales, normalization was performed using the z-score transformation (Patro & Sahu, 2015), resulting in values ranging from 0 to 1. Cells composed mostly of water were also removed from this analysis.

$$Balance = \frac{Supply - Demand}{Supply + Demand} \quad (2)$$

Values range from -1 to 1, where negative values represent more demand in relation to supply, while positive values indicate the opposite. Values closer to zero indicate a more balanced provision of service. Furthermore, a bivariate map was made in order to pinpoint areas with different combinations of supply and demand levels, classified into low, medium and high using the Jenks optimization method (using the R package “biscale” – Prener et al., 2022).

2.3. Influence of landscape structure on the local climate regulation ecosystem service supply

To analyze how different landscape parameters influence the supply of local climate regulation, we measured both compositional and configurational variables. Landscape composition was obtained from manually classified orthophotos of São Paulo municipality from 2017, with a resolution of 0.12 m (SVMA, 2020), available in the GeoSampa portal (www.geosampa.prefeitura.sp.gov.br). We considered three land use and land cover classes: vegetation, buildings and water. Vegetation was divided into four classes: (1) forests, representing native arboreal phytophysiognomies with native understory vegetation, (2) open vegetation, representing grasslands, shrubs, and herbaceous vegetation, (3) arboreal vegetation, which includes street afforestation and trees within gardens, squares, and parks, mostly without understory vegetation, and (4) all vegetation, encompassing the aforementioned classes as well as non-natural vegetation (e.g., agricultural areas).

Landscape configuration was measured based on four metrics, calculated using the software FRAGSTAT 4.2 (McGarigal & Marks, 1995; McGarigal, 2015) for the arboreal vegetation and buildings classes: (1) edge density, (2) mean proximity index, (3) normalized landscape shape index and (4) edge contact between trees and buildings, calculated separately for the combination of the classes forest and arboreal vegetation (representing areas mainly covered by trees) and buildings (Table 1). Each sample unit was treated as a distinct landscape for the analysis. Additionally, to incorporate 3D information about the landscape structure, building and vegetation heights of São Paulo city were included. These heights were derived from LiDAR data collected in 2017, with a precision of 10 cm and a mean point density of 10 points per m². Gomes (2022) provided raster-format models of building and vegetation heights at a resolution of 50 cm, where each pixel represented the height relative to the maximum value within the intersecting LiDAR dataset. Mean arboreal vegetation height and mean building height were extracted for each sample unit, and the total volume of buildings and arboreal vegetation was calculated by intersecting the height and area layers. All geospatial processing was performed using QuantumGIS 3.28.3.

Table 1. Landscape composition and configuration metrics, their range and description.

Landscape metric	Range	Description
Composition		
Forest cover (FC)	0 ≤ FC ≤ 1	Percentage of the landscape belonging to class "forest".
Open vegetation cover (OC)	0 ≤ OC ≤ 1	Percentage of the landscape belonging to class "open vegetation".
Arboral vegetation cover (AC)	0 ≤ AC ≤ 1	Percentage of the landscape belonging to class "arboreal vegetation".
Total vegetation cover (VC)	0 ≤ VC ≤ 1	Percentage of the landscape belonging to class "all vegetation".
Water cover (WC)	0 ≤ WC ≤ 1	Percentage of the landscape belonging to class "water".
Buildings cover (BC)	0 ≤ BC ≤ 1	Percentage of the landscape belonging to class "buildings".
Configuration		
Edge density (ED)	ED ≥ 0, without limit	Sum of all edges of the forest and arboreal vegetation or building classes in relation to the landscape area.
Mean proximity index (MPI)	PROX_MN ≥ 0	Average proximity index (sum of patch area (m^2) divided by the nearest edge-to-edge distance squared (m^2) between each forest and arboreal vegetation or building class patch and all patches of the same class whose edges are within the landscape).
Normalized landscape shape index (NLSI)	0 ≤ NLSI ≤ 1	The ratio of the actual edge length of patches of the forest and arboreal vegetation or building classes in relation to the hypothetical range of possible edge lengths of the class. It is a measure of how aggregated patches are in the landscape. The closer to 1 this metric is, more disaggregated and randomly are the patches of the focal class distributed on the landscape.
Edge contact between trees and buildings (TBED)	TBED ≥ 0, without limit	Sum of all edges involving patches of forest or arboreal vegetation and building classes in relation to the landscape area.
Height/Volume		

Mean height (HEIGHT_MN)	HEIGHT_MN ≥ 0, without limit	Average height of forest and arboreal vegetation or building features in the landscape
Volume (VOL)	VOL ≥ 0, without limit	Total volume of forest and arboreal vegetation or building features in the landscape

2.4. Statistical analysis

To evaluate the influence of landscape structure, in terms of composition and configuration of built and vegetated areas, as well as the interplay of both factors on the supply of local climate regulation ecosystem service, we constructed linear mixed models (LMM) using the R environment and the following packages: (1) bbmle (Bolker, 2022), (2) numDeriv (Gilbert & Varadhan, 2019), (3) foreign (R Core Team, 2022), and (4) lme4 (Bates et al., 2015). The response variable in all models was ΔLST (i.e. the service supply), the predictor variables were landscape metrics (17 in total), and the cell's mesoclimatic region was incorporated as a random intercept. Additionally, models were generated by combining pairs and trios of landscape variables that exhibited less than 60% of correlation (Fig. S4). In these cases, we considered the interaction between two variables to investigate how one predictor variable influences the effect of another on the response variable. All variables were scaled before being input in the models (see Table S2 for the complete list of generated models).

The selection of the best models was based on the Akaike Information Criteria (AIC), which balances model complexity and goodness of fit (Burnham & Anderson, 2002). The model with the lowest AIC value was considered the best-fitting model among the alternatives. However, models with a difference of less than 2 AIC units compared to the lowest AIC (ΔAIC) were considered equally plausible (Burnham & Anderson, 2002). AIC weights (wAIC) were also examined to provide a relative measure of the evidence strength for each model in the comparison set. Furthermore, a null model (~1) was included to ensure the consistency of the selected models.

With a model selection procedure, we tested two sets of models: 1) considering all the variables, including composition ones - which are known to have stronger effect on LST; and 2) excluding the composition variables and keeping only configuration and height/volume metrics, in order to better understand their effects on the local climate regulation ES. Also, to assess the consistency of the selected models, all analyses were repeated using the ΔLST values from the three images. This approach aimed to evaluate if the landscape variables included in the selected models exhibited consistent relationships across different time periods. As the landscape data was available only for 2017, it was assumed that significant landscape modifications did not occur between 2015 and 2019. In that way, a total of six model selection rounds were run in the end.

3. Results

The mean ΔLST values for São Paulo were (7.17 ± 3.20) °C for 2015, (8.13 ± 3.88) °C for 2017, and (7.35 ± 3.34) °C for 2019. ΔLST also varied between different mesoclimatic regions, implying greater amplitudes depending on the location (Fig. S5). The regions with higher landscape heterogeneity - with more mixed-use patterns, such as areas with both dense building occupation and parks or urban green in the landscape - tend to have higher amplitudes. On the other hand, regions mostly covered by vegetation (e.g. dense forests in north and south of São Paulo) showed lower amplitudes (Fig. S5). This heterogeneity of land use and land cover not only between, but also inside the different mesoclimatic regions of São Paulo, allowed us to test our hypotheses and identify patterns relating landscape structure and the local climate regulation service supply.

The best models to explain ΔLST variation in the three analyzed years were similar, with exactly the same predictive variables selected by AIC in all best models (Table 2). Considering all landscape variables, including composition metrics - that are known to have a greater effect on LST -, a consistent positive effect of the percentage of vegetation cover on ΔLST was observed. Increasing 10% of the total vegetation cover represents decreasing the local surface temperature by an average of 0.58 ºC in 2015, 0.83 ºC in 2017 and 0.76 ºC in 2019 (Table 2). The best model for the 2015 image included a non-significant positive effect of buildings normalized landscape shape index (NLSI – representing how aggregated or randomly distributed on the landscape the buildings are), as well as a positive additive effect and positive interaction between total vegetation cover and vegetation edge density (ED). Both the 2017 and 2019 images shared the same best model, which featured the aforementioned positive effect of total vegetation cover, a positive effect of edge contact between vegetation and buildings, a positive effect of buildings' NLSI, and a negative interaction between the latter two variables. The observed relationships between ΔLST and landscape composition and configuration for the 2015, 2017 and 2019 images are illustrated in Fig. 2-4, respectively.

Excluding composition variables, the best models for all images included a positive effect of vegetation edge density and of total vegetation volume, and a negative effect of buildings edge density (Table 2). The exact same model was selected for 2015 and 2017, which also included a negative interaction between buildings' edge density and vegetation volume (Fig. 2-4). In contrast, for 2019, the best model included the interaction between vegetation edge density and vegetation volume, also with a negative effect. According to the 2017 model data, a 1000 m/ha increase in vegetation edge density was associated with a 1.3 °C decrease in the local surface temperature (1.1 °C in 2015 and 1.3 °C in 2019). For building's edge density, a 1000 m/ha increase leads to an average increase of 0.1 °C on the local climate in 2015 and 2017 and of 1.0 °C in 2019.

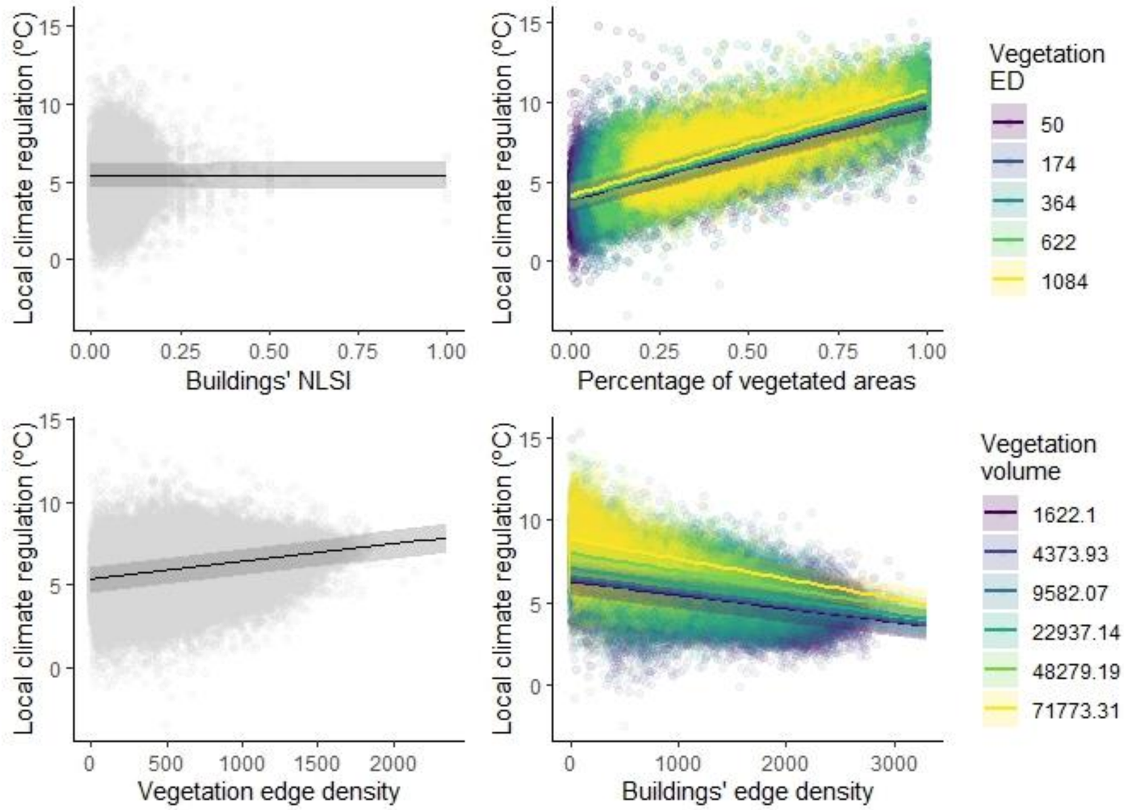

Fig. 2. Plots of the main relationships observed between the supply of local climate regulation service (ΔLST) and landscape structural parameters (composition and configuration) for the 2015 image. The plots on top represent the best model considering composition and configuration variables: the effects of building NLSI (with lower values representing more aggregated buildings and higher values more randomly distributed on the landscape) and percentage of total vegetation cover (interacting with vegetation edge density) over local climate regulation supply, respectively. Bottom plots represent the best model without composition variables: the effects of vegetation edge density and buildings edge density (interacting with arboreal vegetation volume, with higher volumes decreasing the negative effect of buildings' edge density over the ecosystem service supply) over local climate regulation supply, respectively. NLSI = normalized landscape shape index; ED = edge density.

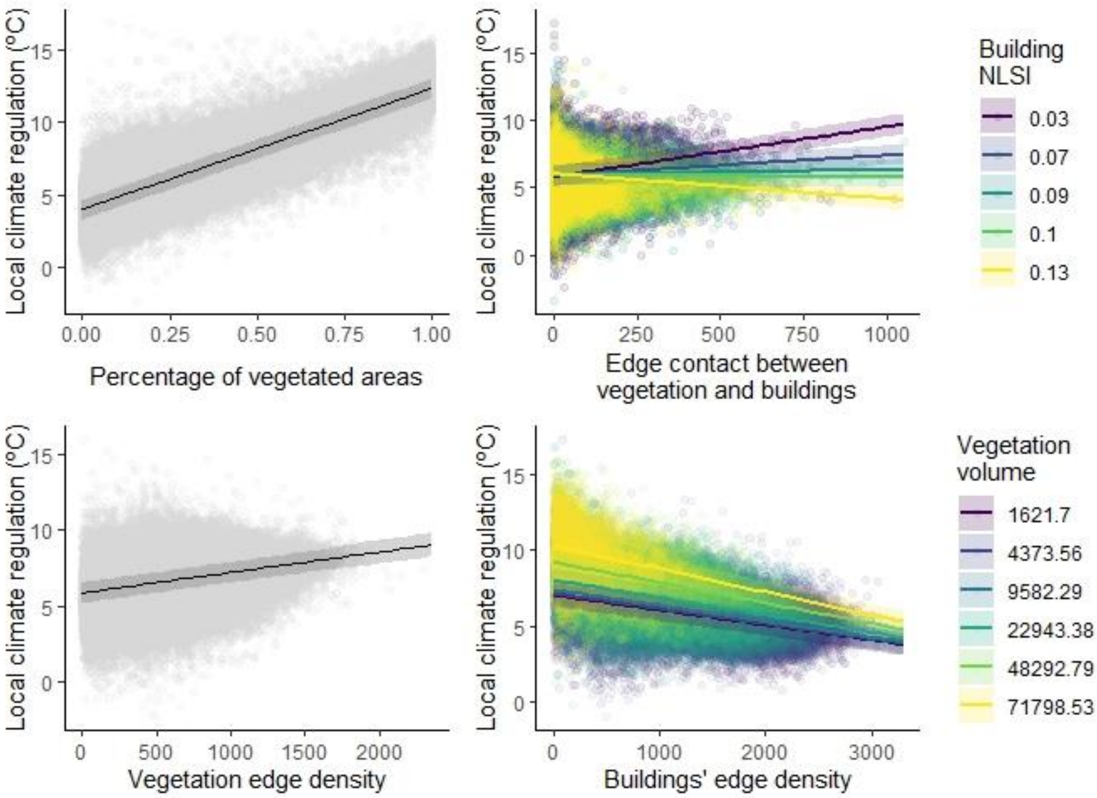

Fig. 3. Plots of the main relationships observed between the supply of local climate regulation service (ΔLST) and landscape structural parameters (composition and configuration) for the 2017 image. The plots on top represent the best model considering composition and configuration variables: the effects of percentage of total vegetation cover and edge contact between vegetation and buildings (interacting with building NLSI, with lower values representing more aggregated buildings and higher values more randomly distributed on the landscape) over local climate regulation supply, respectively. Bottom plots represent the best model without composition variables: the effects of vegetation edge density and buildings edge density (interacting with arboreal vegetation volume, with higher volumes decreasing the negative effect of buildings' edge density over the ecosystem service supply) over local climate regulation supply, respectively. NLSI = normalized landscape shape index.

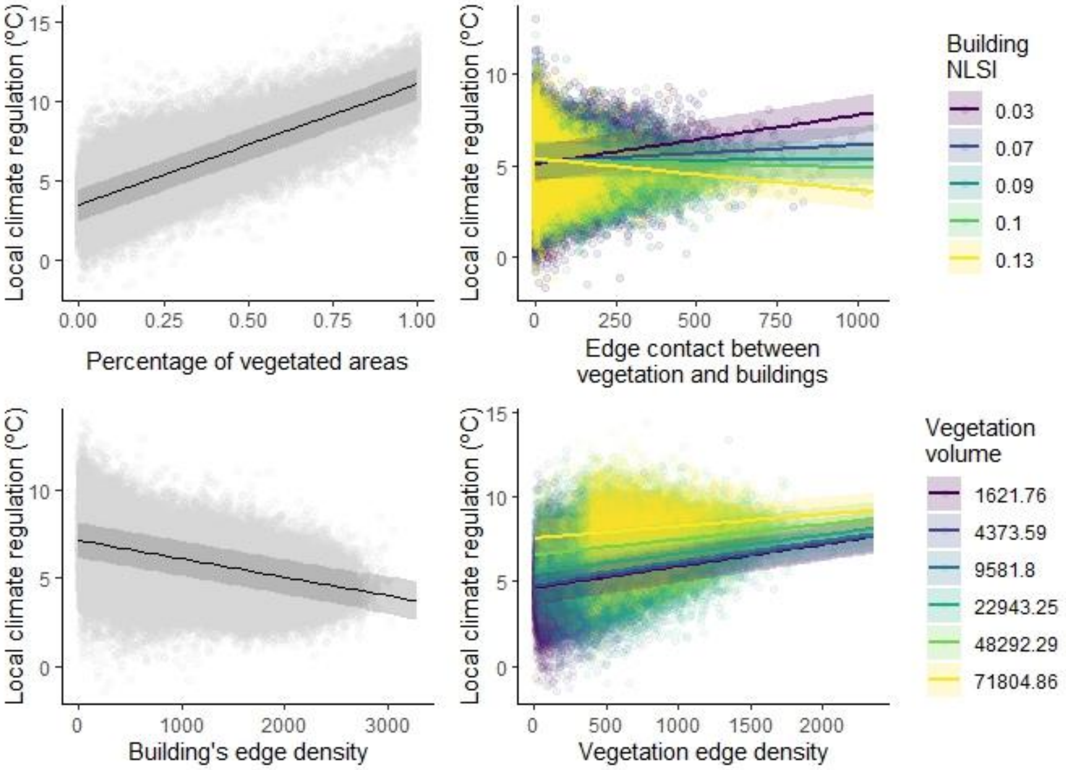

Fig. 4. Plots of the main relationships observed between the supply of local climate regulation service (ΔLST) and landscape structural parameters (composition and configuration) for the 2019 image. The plots on top represent the best model considering composition and configuration variables: the effects of percentage of total vegetation cover and edge contact between vegetation and buildings (interacting with building NLSI, with lower values representing more aggregated buildings and higher values more randomly distributed on the landscape) over local climate regulation supply, respectively. Bottom plots represent the best model without composition variables: the effects of buildings' edge density and vegetation edge density (interacting with arboreal vegetation volume, with higher volumes increasing the positive effect of arboreal vegetation edge density over the ecosystem service supply) over local climate regulation supply, respectively. NLSI = normalized landscape shape index.

Table 2. Best models selected for each year, considering or not composition landscape variables. *AIC* is the Akaike information criteria. *Coefficient* is the estimated value for the effect size for each variable included in the model, along with its standard error (*SDT*) and *p-value*. Since only one model was selected by set, the ΔAIC of all shown models is 0 and wAIC is 1. ":" denotes an interaction between two variables.

Year	Model (Variables)	AIC	Coefficient	SDT	p-value
	Considering all variables, including composition variables				
2015	Total vegetation cover	266.427	2.4500	0.0103	< 0.001
	Vegetation edge density		0.1677	0.0059	< 0.001

	Buildings dissagregation (NLSI)		0.0006	0.0050	0.907
	Total vegetation cover: Vegetation edge density		0.0839	0.0078	< 0.001
2017	Total vegetation cover	277.831	3.3350	0.0095	< 0.001
	Edge contact between trees and buildings		0.0055	0.0050	< 0.001
	Buildings disaggregation (NLSI)		- 0.0003	0.0054	0.580
	Edge contact between trees and buildings: Buildings disaggregation		- 0.1571	0.0057	< 0.001
2019	Total vegetation cover	267.377	3.0510	0.0089	< 0.001
	Edge contact between trees and buildings		0.0228	0.0047	< 0.001
	Buildings disaggregation (NLSI)		0.0373	0.0050	< 0.001
	Edge contact between trees and buildings: Buildings disaggregation		- 0.1229	0.0053	< 0.001
	Without composition variables				
2015	Vegetation edge density	271.369	0.2976	0.0060	< 0.001
	Buildings edge density		- 0.7333	0.0137	< 0.001
	Vegetation volume		1.4680	0.0282	< 0.001
	Buildings edge density : Vegetation volume		- 0.1921	0.0179	< 0.001
2017	Vegetation edge density	289.676	0.3738	0.0068	< 0.001
	Buildings edge density		- 0.9229	0.0154	< 0.001
	Vegetation volume		1.8480	0.0317	< 0.001
	Buildings edge density : Vegetation volume		- 0.2750	0.0201	< 0.001
2019	Vegetation edge density	283.724	0.2603	0.0070	< 0.001
	Buildings edge density		- 0.7291	0.0065	< 0.001
	Vegetation volume		1.8840	0.0142	< 0.001
	Vegetation edge density : Vegetation volume		- 0.1149	0.0105	< 0.001

Intersecting the supply and demand of local climate regulation ecosystem service revealed a substantial mismatch between these two parameters (Fig. 5 a-d). Areas inside São Paulo urban area lack climate regulation supply, while areas outside have surplus supply but little to no demand. The balance between supply and demand for São Paulo reveals that some sample units exhibit more supply than demand, while there are others with more demand than supply. In general, regions depicted in yellow in Fig. 5-c and in dark purple in Fig. 5-d represent the main localities where the aforementioned supply-demand mismatch can lead to adverse outcomes for residents, while areas in dark green in Fig. 5-d represents areas with high supply and low demand, where the service is not benefiting people.

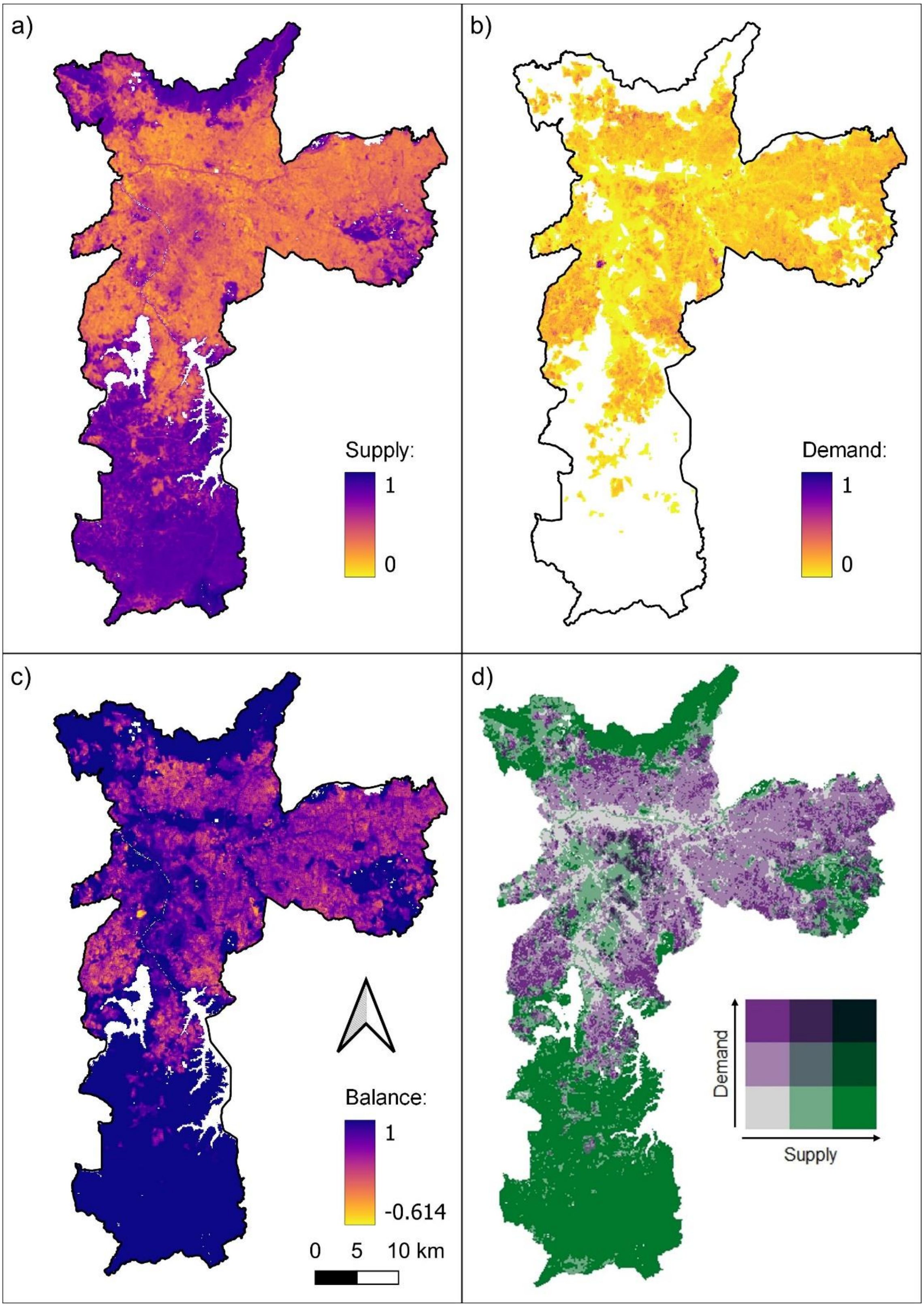

Fig. 5. Spatial representation of the local climate regulation supply (a), demand, where areas in white represent cells without residents (b), balance (c), and the relation between different levels of supply and demand (d) in the city of São Paulo.

4. Discussion

As expected, composition metrics are the ones that better explain the supply of local climate regulation service. However, our analysis revealed that configuration metrics also exerts a significant effect on this service. This service supply was positively affected by total vegetation cover, by arboreal vegetation volume and edge density, the latter representing the extension of edges on the landscape, in other words, the amount of arboreal vegetation in contact with other land uses, and also being a proxy of vegetation fragmentation, and by the amount of contact between trees and buildings. On the other hand, it was negatively affected by buildings' edge density, which means that a fragmented arrangement of built-up areas reduces the supply of local climate regulation service. Interactions between vegetation and buildings were also found to modulate the effects of each of those landscape features over the service supply. Overall, similar models and variables were selected as best predictors of local climate regulation ecosystem service supply across different years, indicating consistency on the effects of landscape structure on service over time.

Total vegetation cover consistently appeared in all models considering composition, suggesting that the presence of all vegetation classes - not only arboreal or natural vegetation – contributes to local climate regulation. This result expands the possibilities of urban green spaces that could be implemented to enhance thermal comfort, by pointing out that urban agriculture and grasslands can also play an important role in climate mitigation (Gál et al., 2021). However, it's worth noting that while a variety of vegetation types contribute to local climate regulation, trees have been consistently found to be more effective in this regard (Onishi et al. 2010; Schwaab et al. 2021). Nevertheless, it is important to consider that vegetation volume was also a complementary factor, and that local climatic conditions may affect vegetation effects on climate regulation. For example, in drier climates the expansion of herbaceous vegetation may provide fewer substantial benefits in terms of temperature alleviation, since its efficacy depends on high soil humidity (Hopkins & Del Prado 2007; Gomez-Casanovas et al. 2018).

Disregarding the effect of composition variables, arboreal vegetation edge density was consistently included in all selected models. Increased edge density implies fragmented patches of vegetation, and larger surface areas directly exposed to solar radiation (edge areas of vegetation). More vegetation edge indicates less aggregation of trees in the landscape and more shading on other surface types, especially impervious ones, which could be benefiting from the shading, which shields the areas adjacent to tree canopies from direct sunlight, thus reducing LST (Ng et al., 2012; Speak et al., 2020; Yu et al., 2020). Buildings' edge density was also included in the models along with arboreal vegetation edge density. Buildings usually have low albedo and absorb heat, leading to temperature increases, negatively affecting the service supply - and more edge density indicates more building surface exposed to the sun rays (Connors et al., 2013, Gago et al., 2013; Jamei et al., 2019). Apart from elevating LST, increased surface temperatures of buildings can negatively impact the thermal comfort of occupants and raise energy consumption for interior cooling (Simpson 2002; Voogt & Oke, 2003).

The selected models also bring forth interactions between vegetation and buildings affecting their respective impacts on local climate regulation supply. In the model considering all landscape variables, including composition, the positive effect of the edge contact between trees and buildings on the supply of local climate regulation service is modulated by buildings' disaggregation in 2017 and 2019. When buildings are more aggregated, the supply of climate regulation service is higher during daytime, probably because the aggregation also means less impervious areas directly exposed to sunlight (Berry et al., 2013). There could also be an effect caused by one building shade over another – contrary to the effect of trees, where fragmentation was positively associated with the supply, when buildings are aggregated there is a higher possibility of they shading each other – given that the shading of impervious surface is what matters mostly for LST reduction, fragmented buildings shading other types of surfaces, like vegetation or water, should not significantly affect the supply.

The other interaction found was between buildings' edge density and vegetation volume, where increased vegetation volume reduces the negative effect of buildings' edge density on climate regulation. As higher building edge density means more building surface exposed to solar radiation, the negative interaction could be due to enhanced shading on building walls by those trees, particularly when considering higher vegetation volume as a proxy of taller trees (Fig. 6), emphasizing the importance of including tridimensional metrics in LST analysis (Lyu et al., 2023).

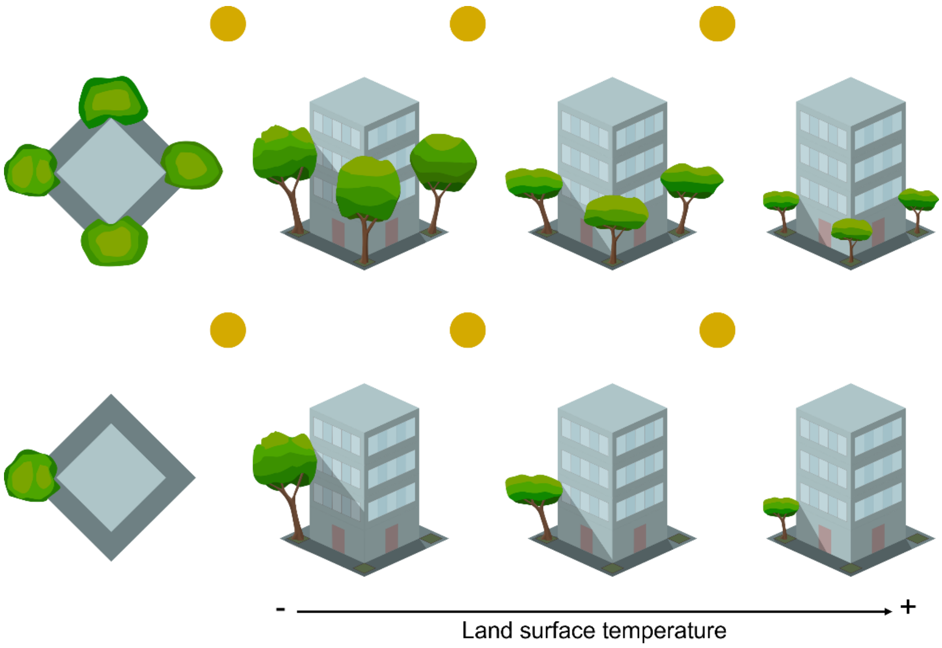

Fig. 6. Diagram showing how the negative effect of building' edge density could be modulated by the volume of tree vegetation. Even when building edge is the same when observed in 2D (upper view), different arboreal vegetation volume and height exert different shade amounts on the impervious surfaces, which can only be observed when considering a 3D landscape, reducing land surface temperature in different intensities.

The evaluation of supply-demand reveals important mismatches between locations of supply and demand of local climate regulation service, which follows specific patterns. For instance, areas with insufficient supply often coincide with high-density localities and low-income regions (Arantes et al., 2021), such as city borders (peripheries) and slums (Fig. 7). Those places have a very low vegetation cover and are mostly composed of low-rise buildings (limited shading), suffering from a severe lack of climate regulation service supply. Interestingly, this scarcity of green areas in certain city regions aligns with a land sparing pattern (Linn & Fuller, 2013): regions with high population density, mostly composed of impervious surfaces, which are adjacent to large green areas. In the context of local climate regulation supply, the land sparing approach appears to have limited benefits due to a spatial decoupling of supply and demand, differing from previous studies (Stott et al., 2015). These inconsistent results may be related to the fact that we are considering a local flow (within the cell) for this service. However, for São Paulo, these land sparing regions are also areas with higher risk of hospitalization due to cardiovascular causes (Cirino et al., 2022), which could be potentially linked to higher temperatures and lower climate regulation (Michelozzi et al., 2009). These findings underscore the direct connection between the landscape, the provision of ecosystem services, and human health and well-being.

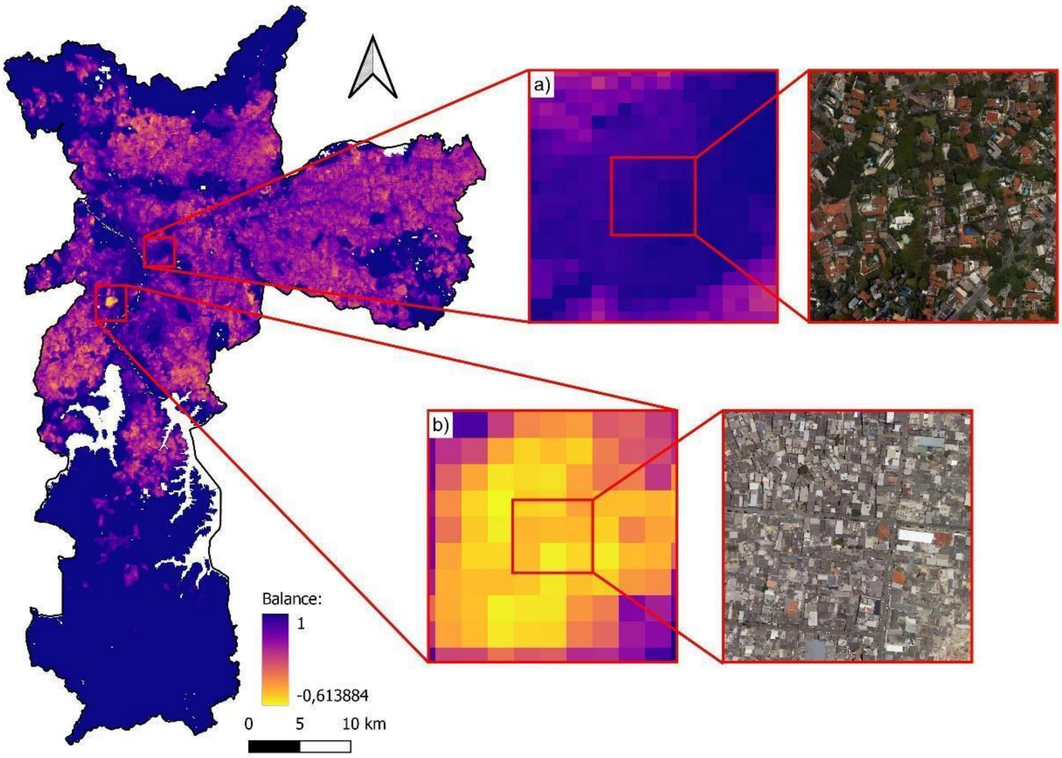

Fig. 7. Examples of areas in São Paulo that exhibit a supply-demand mismatch in the local climate regulation ecosystem service. a) *Jardins* district, characterized by its wealth and abundant street afforestation, represents an area with high levels of supply and low demand. b) *Paraisópolis*, a slum marked by its lack of green spaces, represents an area where the demand significantly surpasses the available supply.

The identification of areas with a supply-demand mismatch and the presence of contrasting patterns in different regions further emphasize the need for targeted policy interventions (Weber et al., 2015). In general, places with high building densities, especially with low-rise buildings, with no vegetation between them, often present high socio-economic vulnerabilities (air-conditioning is unaffordable, houses are built using non-energy-efficient materials) and a lack of local climate regulation service (Ferreira & Duarte, 2019). To reduce city inequalities in local climate regulation provision, decision-makers should prioritize the development of public policies aimed at mitigating the consequences of urban heating in these areas, such as the implementation of nature-based solutions (such as tree planting, green roofs), which are supported by the functioning of natural ecosystems (Bowler et al., 2010; Liu et al., 2021; Morecroft et al., 2019; Yu et al., 2017). By strategically implementing green spaces and promoting the growth of trees and plants, while involving the residents in those process, cities can enhance their resilience to rising temperatures and create more comfortable urban environments (Arghavani et al., 2020; Feyisa et al., 2014; Salmond et al., 2016; Willis & Petrokofsky, 2017). Moreover, it is crucial to involve residents from these underserved areas actively in afforestation projects, since community engagement not only fosters a sense of ownership but also enhances the efficiency of these initiatives (Pincetl, 2013). On the other hand, places with low population density or with high population density but highly verticalized buildings with vegetation in between them, in a land sharing configuration, present the highest levels of the local climate regulation supply through vegetation and edge-to-edge contact between buildings and green. However, there are only a few regions like that, where both supply and demand are high (colored in black in Fig. 5-d), which could inspire further densification of the city without losing the provision of the climate regulation service.

These findings reinforce the importance of considering landscape configuration when addressing the complex dynamics of local climate regulation ecosystem service. Increasing the vegetation amount should be coupled with the planning of the distribution of new green areas and street afforestation in the cityscape, focusing especially on their fragmentation and promoting their contact with buildings, given the interaction between vegetated and built areas. In other words, fragmented buildings without nearby vegetated areas represent the worst scenarios for controlling urban heating. Also, knowing the positive effect of arboreal vegetation volume on the local climate regulation supply contributes to the planning of the species used on urban afforestation and their spatial positioning to more efficiently provide the service. By using configuration effects on ecosystem service provision, as presented above, urban planners could improve the service provision in already densely built regions of the city, where it is hard to greatly increase the quantity of green areas.

5. Conclusion

By analyzing landscape configuration, vegetation and building interactions, and supply-demand distribution, we unveiled the intricate dynamics of local climate regulation in urban areas. The implementation of green areas, as means of increasing vegetation coverage, should be coupled with the planning of trees and buildings configuration, aiming to promote the contact between both, spreading the green area throughout the city in a more fragmented configuration, expanding the area of shading they provide, and reducing impervious surfaces exposed to direct sunlight. The tridimensional configuration of the landscape, mainly in terms of vegetation volume, was also important for increasing the supply of local climate regulation service. Moreover, the identification of supply-demand mismatch in certain regions revealed the need for targeted interventions in areas characterized by high demand and low supply. These areas would gain from the implementation of nature-based solutions (such as linear parks and rain gardens) between the buildings. Urban planning based on these landscape composition and configuration effects should result in more efficient urban landscapes to deal with the challenges of urban heat waves, which are becoming more frequent and intense with global climate change. Our result should thus contribute to planning more resilient cities that effectively address the challenges of urban heating and promote equitable access to ecosystem services, and the overall well-being of urban residents.

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Discussão Geral e Conclusões

O presente trabalho investigou o papel da estrutura da paisagem na oferta do serviço ecossistêmico de regulação da temperatura local. Conforme esperado, as métricas de composição foram as que melhor explicaram a oferta do serviço, com destaque para o efeito positivo quantidade de vegetação total sobre a amenização da temperatura. No entanto, nossa análise revelou que a configuração da paisagem também exerce influência sobre a temperatura local. A oferta da amenização térmica esteve positivamente relacionada com a cobertura vegetal total, o volume de vegetação arbórea e a densidade de bordas da vegetação, sendo esta última uma medida da fragmentação da vegetação, bem como pela quantidade de contato entre árvores e edifícios. Por outro lado, a densidade de bordas dos edifícios teve um efeito negativo na oferta do serviço, o que significa que um arranjo fragmentado das áreas construídas reduz a oferta do serviço de regulação climática local. Também foram encontradas interações entre a vegetação e os edifícios que modulam os efeitos de cada um destes elementos da paisagem na oferta do serviço, mostrando a complexidade na compreensão da dinâmica por trás da provisão da regulação climática local em áreas urbanas.

Com base nos resultados, a implementação de áreas verdes como meio de aumentar a cobertura vegetal, deve ser combinada com o planejamento da disposição de árvores e edifícios, visando promover o contato entre ambos, distribuindo as áreas verdes por toda a cidade em uma configuração mais fragmentada e compartilhada, ampliando a área de sombreamento que eles proporcionam e reduzindo as superfícies impermeáveis expostas à luz solar direta. Além disso, o conhecimento do efeito positivo do volume de vegetação arbórea no fornecimento da regulação climática local contribui para o planejamento das espécies utilizadas na arborização urbana e sua posição espacial para fornecer o serviço de forma mais eficiente.

A identificação de áreas com desequilíbrio entre oferta e demanda e a presença de padrões contrastantes em diferentes regiões ressaltam ainda mais a necessidade de intervenções políticas direcionadas. Em geral, locais com alta densidade de edifícios, especialmente com construções de baixo porte e sem vegetação entre as habitações, frequentemente apresentam altas vulnerabilidades socioeconômicas e falta de serviço de regulação climática local. Para reduzir as desigualdades na provisão de regulação climática local na cidade, os tomadores de decisão devem priorizar o desenvolvimento de políticas públicas voltadas para mitigar as consequências do aquecimento urbano nessas áreas, como a implementação de soluções baseadas na natureza e vegetação entre as edificações.

O planejamento urbano com base nos efeitos da composição e configuração da paisagem deverá resultar em paisagens urbanas mais eficientes para lidar com os desafios das ondas de calor urbano, que estão se tornando mais frequentes e intensas com as mudanças climáticas globais. Nossos resultados devem contribuir, assim, para o planejamento de cidades mais resilientes que enfrentem efetivamente os desafios do aquecimento urbano e promovam o acesso equitativo aos serviços ecossistêmicos e o bem-estar geral dos residentes urbanos.

Resumo

Uma consequência proeminente da intensificação da urbanização é a ocorrência das ilhas de calor. As ilhas de calor de superfície, que são aquelas que afetam as camadas inferiores da atmosfera, afetam a população ao aumentar o consumo de energia e têm implicações para o conforto térmico e a saúde humana. Em relação à mitigação ou prevenção de eventos térmicos extremos e à redução dos efeitos das ilhas de calor de superfície, a vegetação urbana possui grande potencial, mas no contexto das áreas urbanas também é importante levar em conta os efeitos de outros elementos da paisagem, como edifícios, e suas interações com a vegetação. Por meio de uma abordagem de ecologia da paisagem e aplicando modelos lineares generalizados, avaliamos a prestação do serviço ecossistêmico de regulação climática local na cidade de São Paulo, Brasil, identificando áreas com desequilíbrio entre a oferta e a demanda desse serviço, e como a oferta do serviço é afetada pela estrutura da paisagem, focando tanto em áreas vegetadas quanto construídas, e em sua interação. Apesar das métricas de composição, especialmente a cobertura total de vegetação, serem as que melhor explicam a oferta do serviço de regulação climática local, as métricas de configuração também exercem um efeito significativo sobre esse serviço. A densidade de bordas de vegetação mostrou um efeito positivo na oferta do serviço, enquanto o oposto ocorreu para a densidade de bordas de edifícios. O volume arbóreo e o contato entre áreas vegetadas e construídas também se mostraram parâmetros que ajudam a reduzir as temperaturas da superfície, e que os efeitos da vegetação e das edificações interagem entre si, modulando um ao outro. Por fim, foram identificadas regiões da cidade com desequilíbrio entre a oferta e a demanda desse serviço, o que poderia representar um risco à saúde em um cenário de crise climática. Esses resultados podem ajudar tomadores de decisão e urbanistas a pensar na configuração da cidade e propor políticas públicas com o objetivo de amenizar as temperaturas locais, beneficiando a população.

Abstract

One prominent consequence of the intensification of urbanization is the occurrence of urban heat islands. Surface urban heat islands, affecting lower layers of the atmosphere, increase energy consumption, and have implications for thermal comfort and human health. Regarding the mitigation or prevention of extreme thermal events and the alleviation of surface urban heat island effects, urban vegetation holds great potential, but in the urban landscape it is also important to take into account the effects of other elements, such as buildings, and their interactions with vegetation. Through a landscape ecology approach and by applying generalized linear models, we assess the provision of the local climate regulation ecosystem service in the city of São Paulo, Brazil, identifying areas with a mismatch between the service supply and demand, and how its supply is affected by landscape structure, focusing on both vegetated and built areas, and on their interaction. Despite composition metrics, especially total vegetation cover, being the ones that better explain the supply of local climate regulation service, configuration metrics also exerts a significant effect on this service. Vegetation edge density showed a positive effect on the service supply, while the opposite happened for buildings edge density. We also found that arboreal volume and the contact between vegetated and built areas helps reduce land surface temperatures and that both those surface types interact with each other, changing their effects. Finally, regions of the city with a mismatch between the supply and demand, which could represent a health risk in a scenario of climate crisis, were identified. Those results can help decision makers and urban planners to think about the city configuration and propose public policy aiming to alleviate the local temperatures, benefiting the population.

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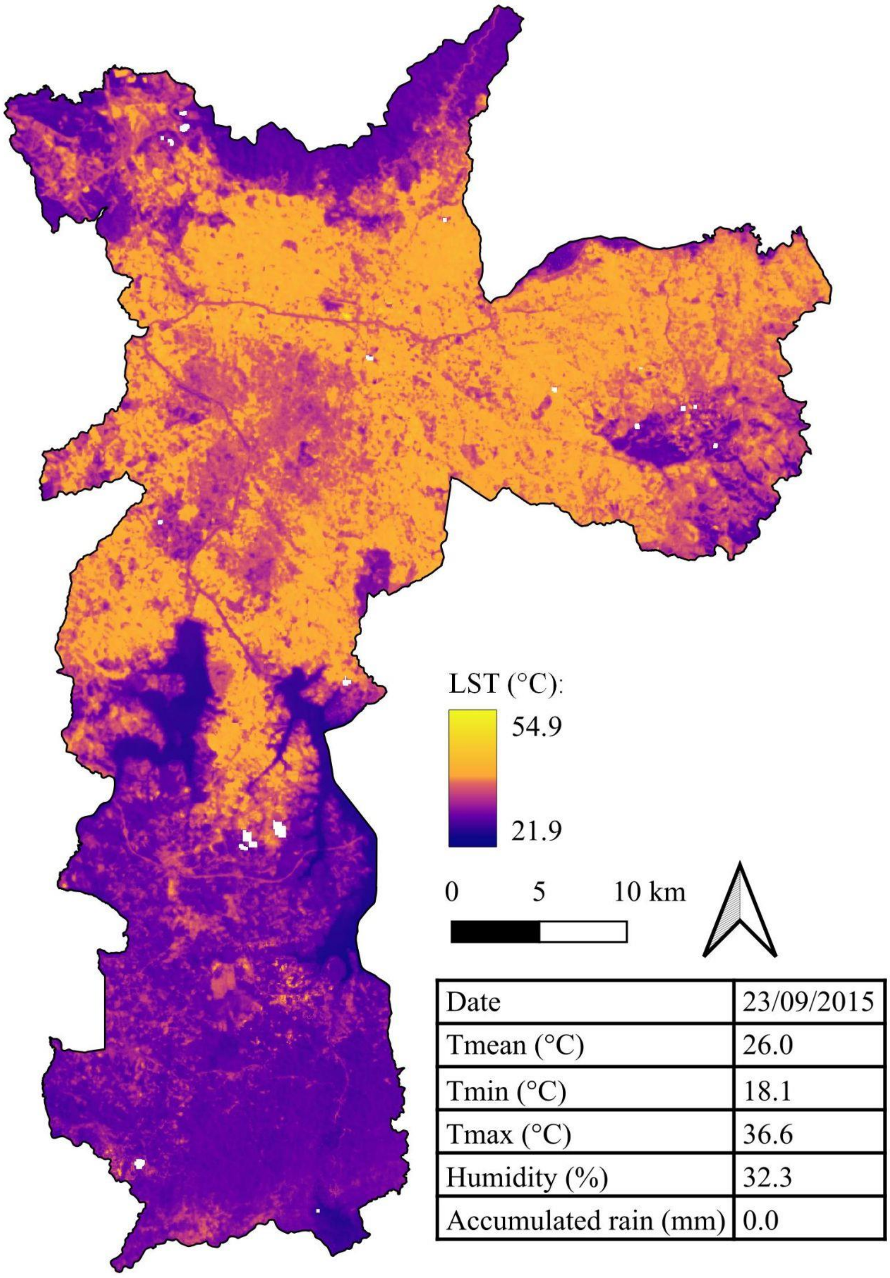
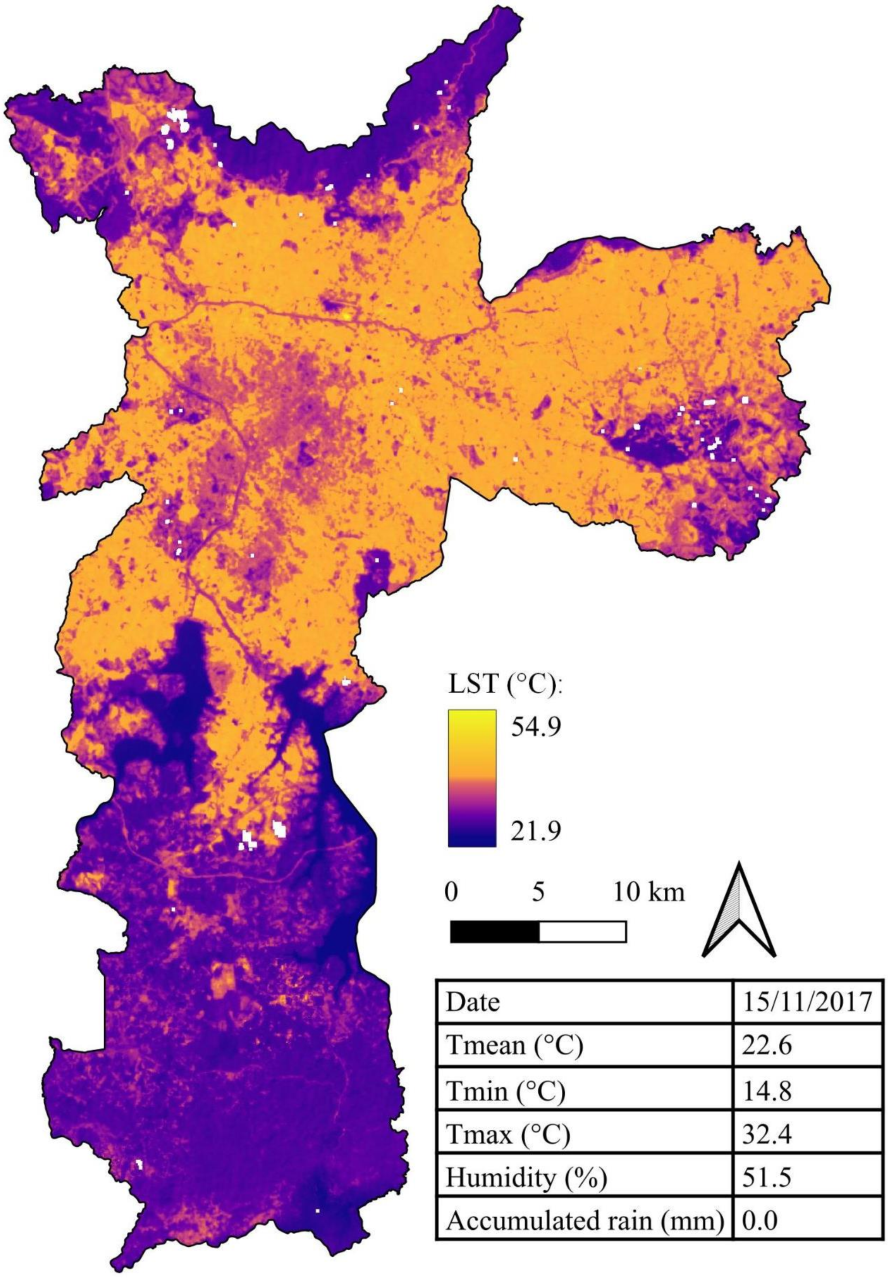
Anexos e Apêndices



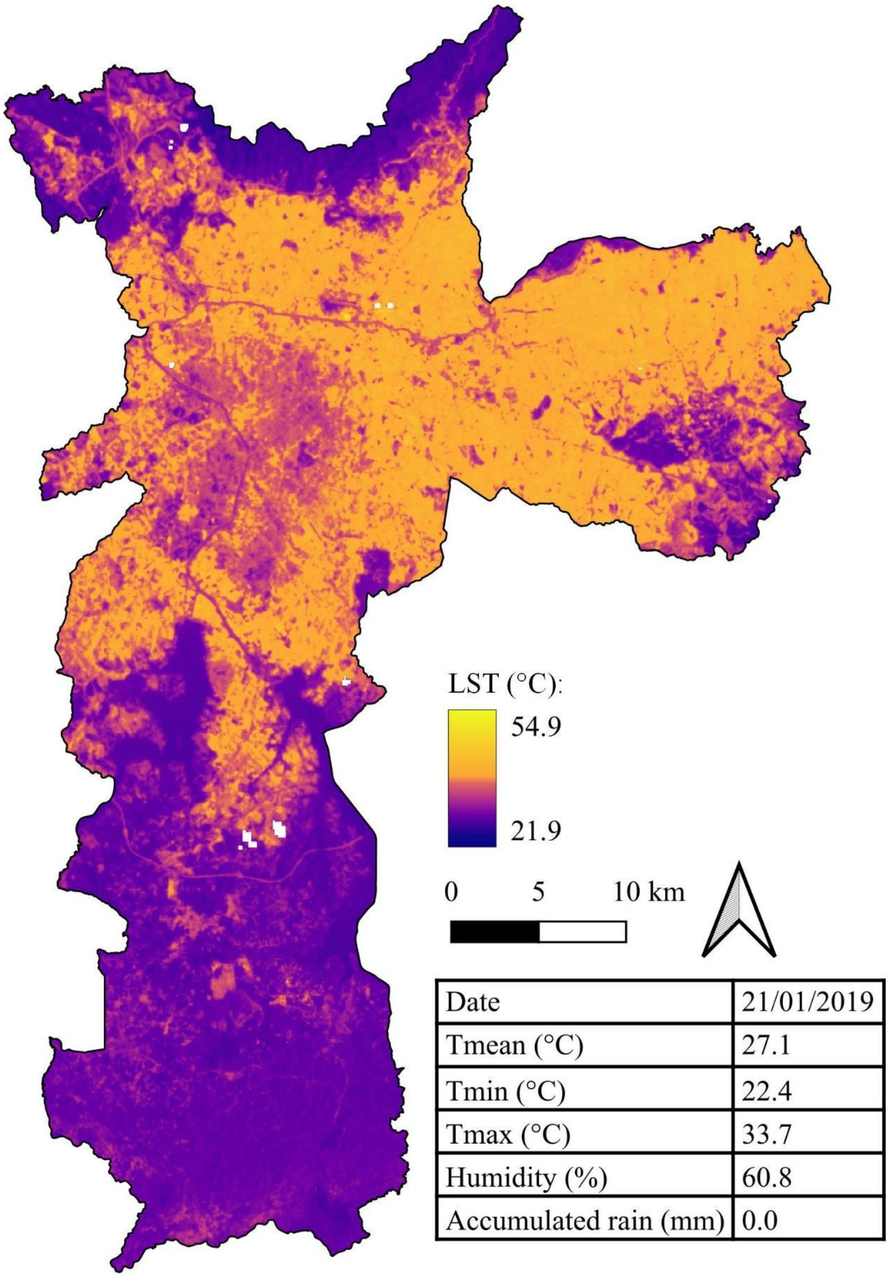
Date	23/09/2015
Tmean (°C)	26.0
Tmin (°C)	18.1
Tmax (°C)	36.6
Humidity (%)	32.3
Accumulated rain (mm)	0.0

Fig. S1. Land surface temperature (LST) and weather condition in São Paulo on September 23, 2015.



Date	15/11/2017
Tmean (°C)	22.6
Tmin (°C)	14.8
Tmax (°C)	32.4
Humidity (%)	51.5
Accumulated rain (mm)	0.0

Fig. S2. Land surface temperature (LST) and weather condition in São Paulo on November 15, 2017.



Date	21/01/2019
Tmean (°C)	27.1
Tmin (°C)	22.4
Tmax (°C)	33.7
Humidity (%)	60.8
Accumulated rain (mm)	0.0

Fig. S3. Land surface temperature (LST) and weather condition in São Paulo on January 21, 2019.

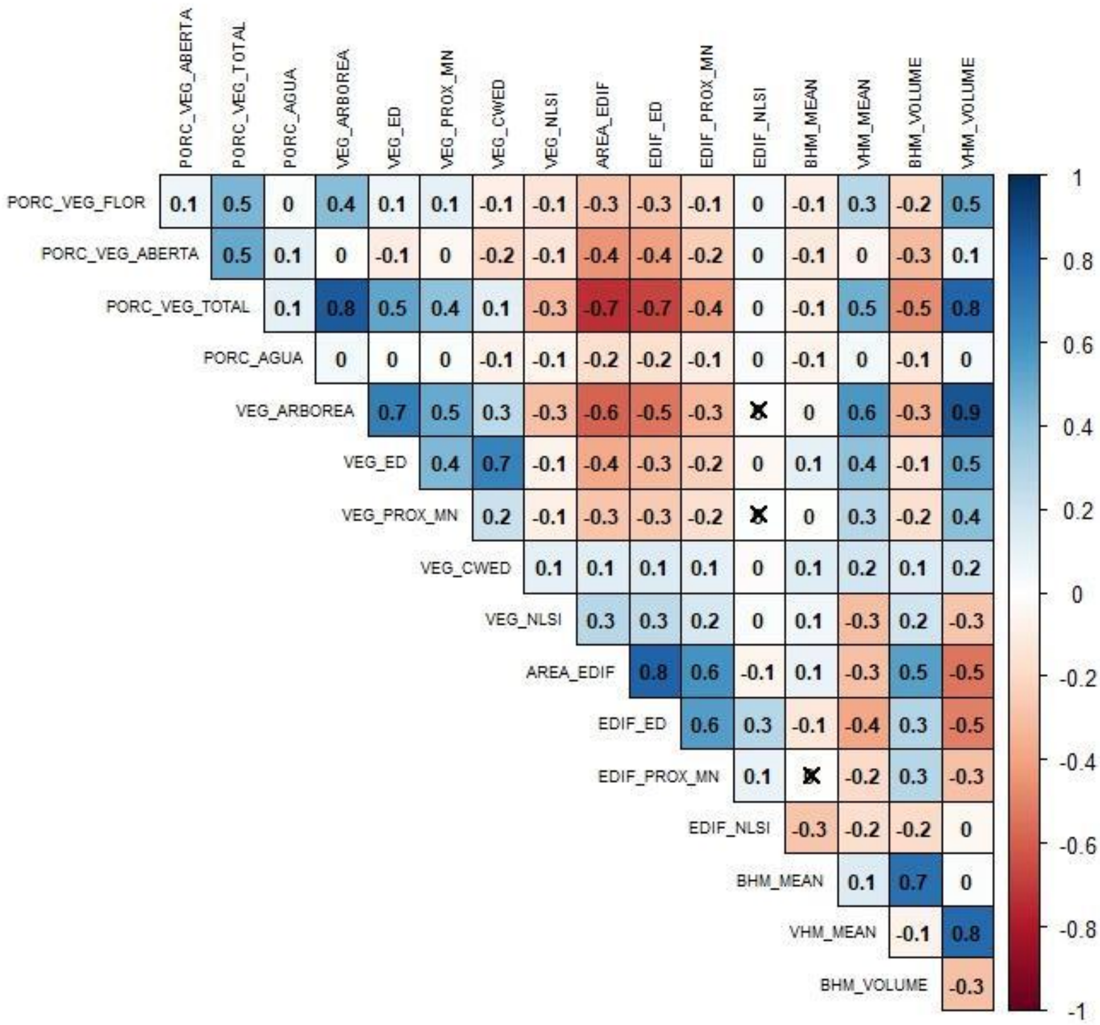


Fig. S4. Correlation plot between landscape variables considering. Darker shades represent stronger correlation, with red representing negative correlation and blue representing positive correlation. Values in each cell are the Spearman correlation coefficient for the pair of variables. Cells with an "X" are values with no statistical significance (p-value > 0.05). PORC_VEG_FLOR = Forest cover; PORC_VEG_ABERTA = Open vegetation cover; VEG_ARBOREA = Arboreal vegetation cover; PORC_VEG_TOTAL = Total vegetation cover; PORC_AGUA = Water cover; VEG_ED = Arboreal vegetation edge density; VEG_PROX_MN = Arboreal vegetation mean proximity index; VEG_CWED = Edge contact between trees and buildings ; VEG_NLSI = Arboreal vegetation normalized landscape shape index; AREA_EDIF = Buildings cover; EDIF_ED = Buildings edge density; EDIF_PROX_MN = Buildings mean proximity index; EDIF_NLSI = Buildings normalized landscape shape index; BHM_MEAN = Mean building height; BHM_VOLUME = Building volume; VHM_MEAN = Mean arboreal vegetation height; VHM_VOLUME = Arboreal vegetation volume.

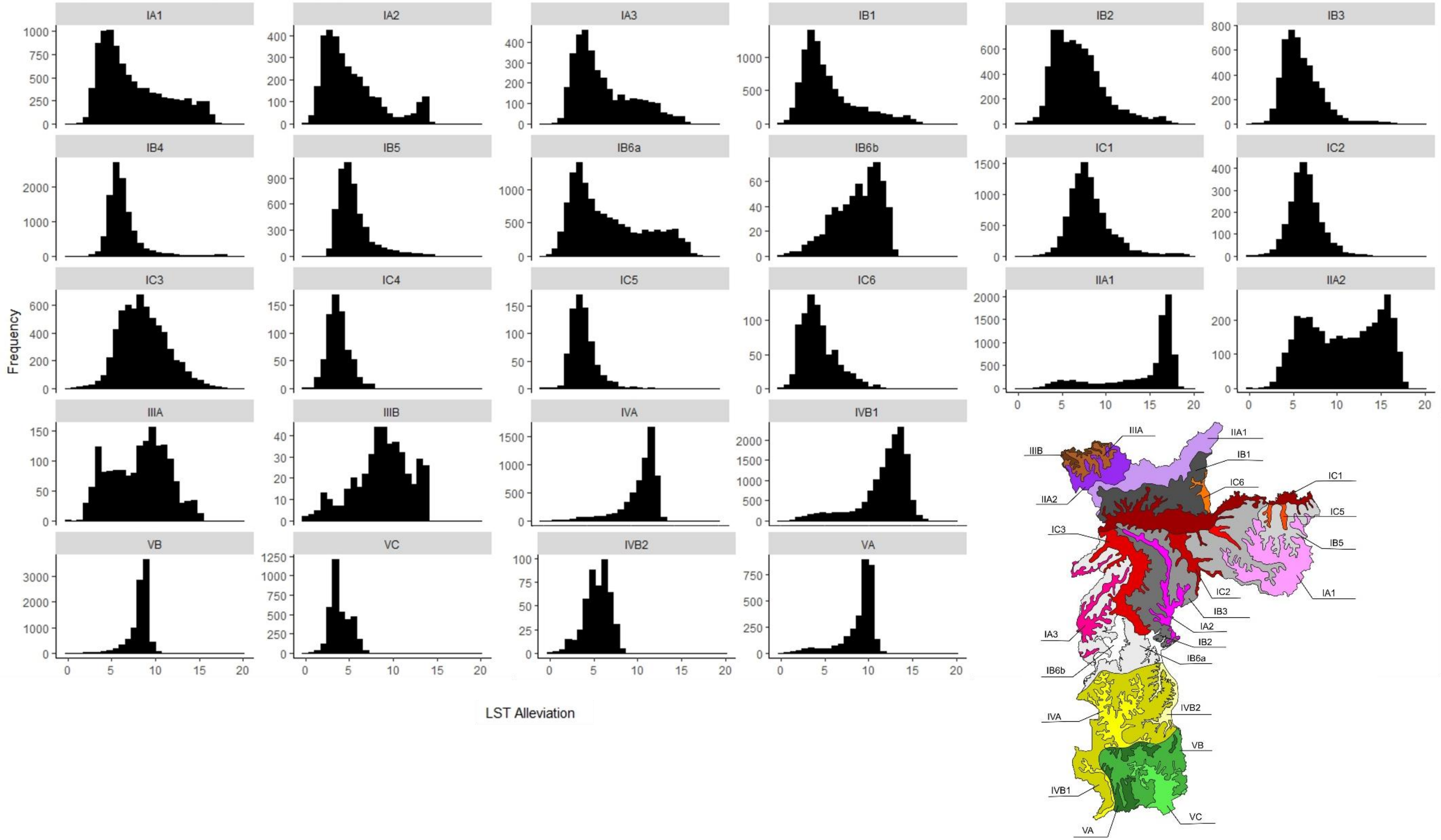


Fig. S5. Histograms of local climate regulation (ΔLST) for each mesoclimatic region of São Paulo municipality (Tarifa & Armani, 2000).