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Effects of landscape changes on urban climate change: A case study in the city of São Paulo

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ABSTRACT

Given the vulnerability of Brazilian cities to climate change, it is imperative to monitor urban areas' susceptibility to temperature fluctuations. In this article, we employ thermal remote sensing and digital image processing techniques to illustrate a substantial rise in surface temperatures across the Northwest Region of São Paulo City over the past three decades. This surge in surface temperature is closely linked to alterations in the urban landscape. Our findings emphasize that one significant environmental consequence of São Paulo City's rapid urbanization is the pronounced increase in surface temperatures. These results also underscore the significance of assessing landscape features, such as vegetation cover, to inform the prudent, sustainable, and resilient management of urban centers, thereby mitigating climate change effects in metropolitan areas.

Keywords: urban heat island, São Paulo City, urban planning, urbanization, SDG 13.

Efeitos de alterações paisagísticas em mudanças climáticas urbanas: um estudo de caso na cidade de São Paulo

RESUMO

Considerando que as cidades brasileiras são vulneráveis às mudanças climáticas, faz-se necessário o monitoramento do grau de exposição das cidades às mudanças de temperatura. Neste artigo, através do uso do sensoriamento remoto termal e de técnicas de processamento digital de imagens, evidenciamos que as temperaturas de superfície registradas para a paisagem da Região Noroeste do Município de São Paulo sofreram um drástico aumento no decorrer dos últimos trinta anos e que o aumento de temperatura de superfície foi fortemente correlacionado a mudanças na estrutura paisagística. Nossos resultados evidenciam que uma importante consequência ambiental da crescente urbanização da Cidade de São Paulo é o rápido aumento da temperatura de superfície. Tais resultados também ressaltam a importância da análise de características paisagísticas, como cobertura vegetal, para o direcionamento do uso racional, adequado e resiliente de um determinado centro urbano, a fim de se mitigar os efeitos das mudanças climáticas nas grandes cidades.

Palavras-chave: ilha de calor urbana, cidade de São Paulo, planejamento urbano, urbanização, ODS 13.

Introduction

Contextualization

Climate change stands as one of the most extensive and intricate environmental challenges of our era. It is widely acknowledged that human activities are unequivocally influencing Earth's climate, amplifying risks for urban areas (PBMC, 2016). Among the consequences of climate change, the Intergovernmental Panel on Climate Change (IPCC, 2014; 2018) emphasizes the anticipated surge in heatwaves within urban settings, characterized by increased frequency, severity, and

duration. Furthermore, alterations in landscape configuration due to urbanization, involving the replacement of natural surfaces with buildings, streets, and avenues, have significantly heightened soil impermeability and the emission of heat into the atmosphere (Costa et al., 2010). Consequently, global warming has garnered escalating attention due to a substantial rise in the global average surface temperature since the late 19th century, particularly in urban centers (Chen et al., 2006;

Costa et al., 2010; Santamouris, 2020; Halder et al., 2021; Thanvisitthpon et al., 2023).

In response to this alarming backdrop, in 2015, the United Nations (UN) introduced the 2030 Agenda, incorporating a Sustainable Development Goal (SDG) solely dedicated to addressing climate change: SDG number 13, “Take urgent action to combat climate change and its impacts.” Given the aforementioned circumstances and the projections outlined by the IPCC (2014; 2018), there exists an urgent imperative for the development of studies and research projects centered on the matter of climate change. These initiatives aim to contribute to the achievement of SDG 13 and the promotion of sustainability, with a particular focus on major urban centers. This study is grounded in this context.

Considering the intricacies of socio-environmental systems, where natural, social, and economic dimensions intersect, an interdisciplinary inquiry concentrated on the sustainability of urban environments becomes indispensable for obtaining a comprehensive perspective on the issue of climate change in cities. It is within this realm of research that the current study resides, addressing climate change with an emphasis on mitigating its repercussions within the São Paulo City.

Research on urban heat islands is emerging as a topic of great importance in the broad field of climate change, gaining relevance both for the scientific community and society at large. This phenomenon, a direct consequence of well-documented global warming, has elevated climate change to a central position in the natural and medical sciences, and more recently, in the social and political sciences. Global warming triggers a series of extreme weather events, including heat islands, droughts, floods, cyclones, and wildfires. The severe heat islands recorded in recent decades have made heat islands a crucial focus of climate change research. This growing interest can be understood both by the increase in temperatures and the intense scientific activity it provokes (Santamouris, 2020; Marx et al., 2021).

The phenomenon of urban overheating is documented in over 400 major cities worldwide. Various experimental data reveal that the average temperature increase can exceed 4-5°C, while at peaks, it can surpass 10°C. This rise in ambient temperature has a significant impact on energy consumption for cooling, peak electricity demand, heat-related mortality and morbidity, urban environmental quality, local vulnerability, and residents' comfort (Santamouris, 2020).

Population pressure, infrastructural development, and economic growth drive the process of urbanization, even amidst urban expansion. Changes in land use, vegetation degradation, and climate alterations are direct consequences of urban heat islands. Land surface temperature is a crucial aspect in studies of global climate change, allowing for the calculation of radiation budgets, conducting heat balance studies, and estimating climate change scenarios (Halder et al., 2021). This temperature refers to the radiative temperature of the land surface, derived from solar radiation, and can impact organisms and ecosystems at local and global scales. Specifically, land surface temperature is closely related to air temperature, making it a common indicator for urban heat islands (Thanvisitthpon et al., 2023).

At the local level, urban climate results from both anthropogenic and geo-environmental actions. As per Oliveira (1988), the primary factors shaping urban climate encompass: (I) solar radiation, (II) urban morphological characteristics (elements of city structure such as roughness, porosity, and thermodynamic properties), and (III) the presence and distribution of green spaces. Variables II and III establish a direct correlation between surface temperature data and the spatial layout of the landscape, as will be substantiated by the findings of this study. Consequently, this research aims to conduct a spatial correlation study between climate variables associated with vegetation and urbanization (land use and land cover mapping) and surface temperature in the São Paulo City, employing geoprocessing of remote sensing data.

Justification

Currently, urban centers generate 80% of the world's wealth, and over 50% of the global population resides in cities, with projections indicating that this figure will rise to 60% by 2030 (UN-Habitat, 2011; 2014). Given that cities both significantly contribute to and are vulnerable to climate change, the importance of studies focused on monitoring and mitigating climate change impacts within urban areas cannot be overstated.

By the end of the 20th century, urban heat islands were predominantly viewed as a recurring meteorological phenomenon, nearly independent of human activities. However, in the last decades, a notable increase in extreme climatic and meteorological events has been observed. Research on climate change has shown that these alterations are clearly linked to human influence, particularly the rise in greenhouse gases in the Earth's atmosphere. Climate extremes such as heat islands, droughts, floods, cyclones, and wildfires

underscore the significant vulnerability of societies to climate change resulting from global warming (Marx et al., 2021; Halder et al., 2021).

The increase in temperature within cities due to the confluence of climate change and urbanization processes is a pressing concern (Venhari et al., 2017). On a national level, most Brazilian cities grapple with environmental issues tied to development patterns and geographical transformations. Moreover, in large cities, the effects of climate change are exacerbated, as they are densely urbanized regions prone to the formation of urban heat islands. The magnitude and extent of these heat islands are directly proportional to population density and urbanization intensity (Hung et al., 2006; Turhan & Akkurt, 2018). According to the IPCC (2018), climate change is expected to lead to extreme heat events, heatwaves, and thermal stress in cities, exposing their residents to life-threatening temperatures. Hence, it is imperative that the academic community rapidly develops the identification of these impacts and the proposition of strategies for their mitigation to support the formulation and implementation of local, regional, and national public policies.

According to a publication by the Brazilian Ministry of the Environment (MMA), conducting scientific research to ascertain the causes and magnitude of climate change is of paramount importance (Silverwood-Cope et al., 2011). Furthermore, scientific advancements can contribute to the development of innovative practices to enable more robust mitigation and adaptation measures in response to climate change (Silverwood-Cope et al., 2011).

Given that Brazilian cities are susceptible to climate change and expected to face numerous impacts in the future (PBMCI, 2016), it is crucial to assess cities' exposure and sensitivity levels to climate change. Moreover, there is an urgent need to formulate urban planning proposals that combat climate change through mitigation and adaptation strategies, enhancing urban resilience. This research's primary objective is to contribute within this scope, with a focus on the Northwest Region of the São Paulo City. As a result of this research, the development of urban planning recommendations to address climate change in São Paulo, while considering the international climate change policy framework and the characteristics of the studied landscape, emerges as a noteworthy outcome.

Due to climate change and the absence of landscape planning, it is anticipated that major cities will confront significant challenges related to the urban heat island phenomenon. This

phenomenon occurs in areas characterized by an excess of buildings and a scarcity of green spaces, resulting in higher temperatures than in neighboring non-urbanized regions (Souza, 2004). Large cities possess structural complexities that make problem identification challenging due to their lack of continuity or homogeneity. They comprise diverse materials that reflect or emit electromagnetic energy differently, presenting a wide spectral range and high spatial frequencies that are difficult to disentangle (Costa et al., 2010). Therefore, the application of tools and methodologies enabling the analysis of each constituent element in various urban areas' contribution to heat island formation is essential (Costa et al., 2010).

In recent years, remote sensing has gained prominence in urban climate change studies due to its high spatial resolution and the ability to provide insights at multiple scales. It also allows the utilization of spectral data in the thermal infrared region within the atmospheric window. This enables sensors operating in this region to convert their data into surface temperatures, a critical parameter in urban climatology research (Voogt & Oke, 2003; Costa et al., 2010). Since surface temperature is closely linked to the surface's conditions under examination, one of the primary applications of remote sensing in urban climate studies is to comprehend the relationships between the spatial structure of urban thermal patterns and urban surface characteristics, which can subsequently inform landscape planning (Chen et al., 2006; Costa et al., 2010).

Although cities have developed climate action plans, there remains a need for more academic research aimed at monitoring and implementing short-term mitigation and adaptation strategies for climate change, as well as long-term urban and regional planning (Rosenzweig et al., 2011; PBMCI, 2016). In this context, during times of climate change and global warming, decision-makers and planners can rely on scientific research to reduce temperatures and enhance climatic comfort (Venhari et al., 2017). Therefore, decision-making grounded in scientific studies can guide cities toward sustainable urban development (Venhari et al., 2017), directly contributing to SDG 13 within major urban centers, including the São Paulo City, the focal area of this research.

Materials and methods

Study area

Given the extensive expanse of São Paulo City, our study focuses exclusively on a specific area: the Northwest Region of São Paulo Municipality (depicted in Figure 1). This region, demarcated by the São Paulo City Hall (2018), encompasses the sub-municipalities of Pirituba, Perus, and Freguesia do Ó. Within these sub-municipalities lie the neighborhoods of Pirituba, Jaraguá, São Domingos, Freguesia do Ó, Vila Brasilândia, Anhanguera, and Perus. This geographical scope was deliberately selected due to its noteworthy concentration of green spaces within

an expanding urban landscape (São Paulo, 2016). For instance, the Perus sub-municipality, a substantial portion of the Northwest Region, boasts the second-highest vegetative cover index in the municipality (247.24 m² per inhabitant) (São Paulo, 2016; Lourenço et al., 2016). Conversely, neighborhoods like Pirituba and Brasilândia exhibit high residential densities, while the Anhanguera neighborhood accommodates numerous industrial complexes (São Paulo, 2016; Lourenço et al., 2016).

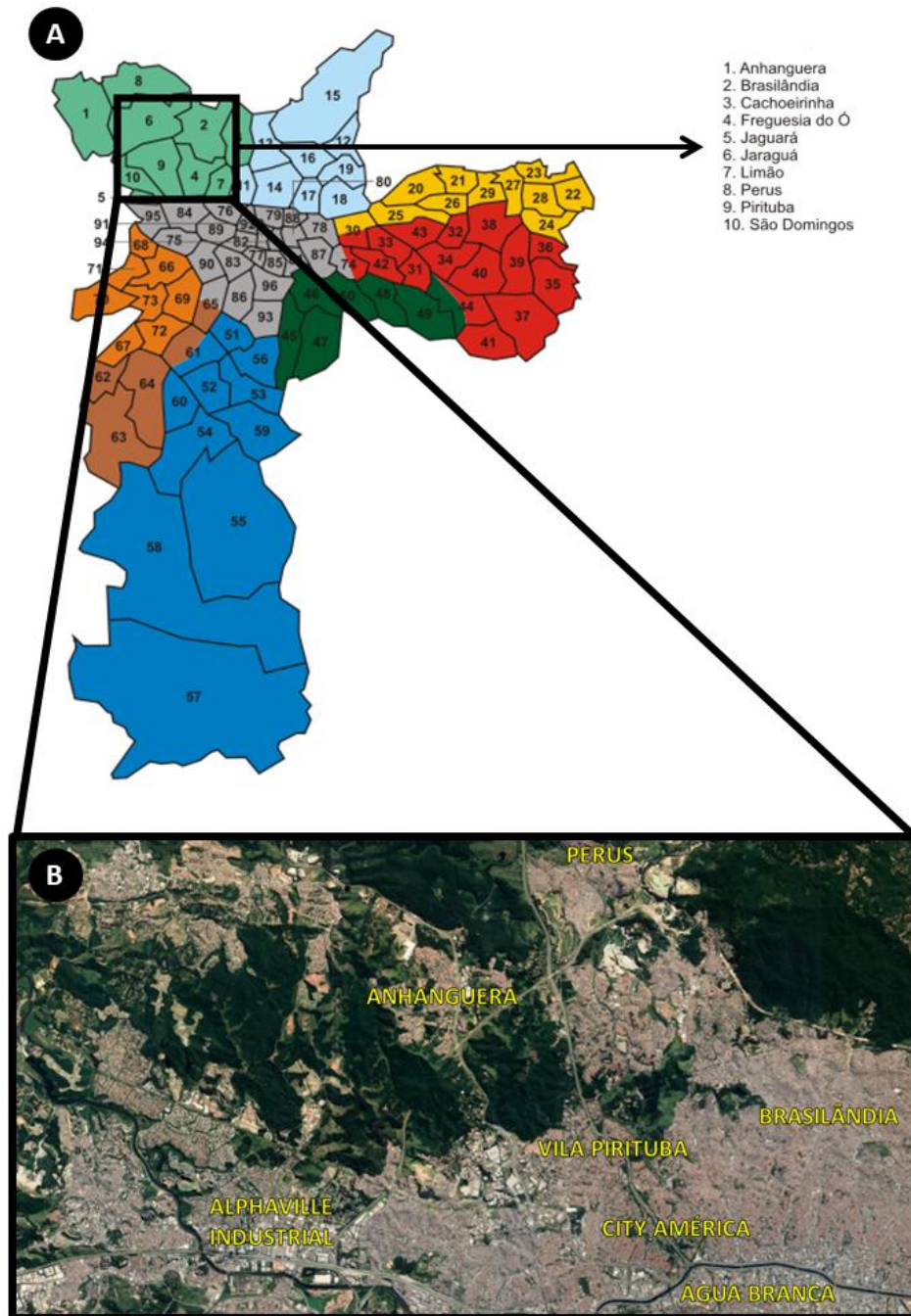


Figure 1. Study Area. (A) Map of São Paulo City, with emphasis on the Northwest Region. (B) Detailed map of the Northwest Region (study area).

Mapping and landscape characterization

To conduct the mapping and spatiotemporal characterization of the study area's landscape, we employed advanced geotechnologies. These included remote sensing imagery, as well as geoprocessing and digital image processing techniques, facilitated through the utilization of Spring (Sistema de Processamento de Informações Georreferenciadas / Georeferenced Information Processing System).

The satellite images essential for this investigation were procured without cost from the Instituto Nacional de Pesquisas Espaciais / National Institute for Space Research (INPE) website. In particular, we utilized an image obtained from the CBERS-4/PAN satellite (as detailed in Table 1) for the year 2018. Additionally, an image sourced from the Landsat-5/TM satellite (as specified in Table 2) for the year 1989 was also integrated into our analysis.

Table 1. Characteristics of spectral bands from CBERS-4/PAN satellite used for landscape mapping and characterization in 2018.

Spectral bands	Spectral resolution	Spatial resolution	Temporal resolution	Imaged area	Radiometric resolution
(B1) Panchromatic	0,51 – 0,85 μm	5 m	26 days	60 km	8 bits
(B2) Green	0,52 – 0,59 μm	10 m			
(B3) Red	0,63 – 0,69 μm				
(B4) Near-infrared	0,77 – 0,89 μm				

Table 2. Characteristics of spectral bands from Landsat-5/TM satellite used for landscape mapping and characterization in 1989.

Spectral bands	Spectral resolution	Spatial resolution	Temporal resolution	Imaged area	Radiometric resolution
(B1) Blue	0,45 – 0,52 μm	30 m	16 days	185 km	8 bits
(B2) Green	0,50 – 0,60 μm				
(B3) Red	0,63 – 0,69 μm				
(B4) Near-infrared	0,76 – 0,90 μm				

For both the 2018 and 1989 images, extensive digital processing was undertaken. This process encompassed various techniques, including the creation of color composites, linear contrast adjustments, principal component analysis, and image fusion. From these techniques, the most optimal color composite was selected to facilitate visual analysis. Subsequently, we generated comprehensive land use and land cover maps for both study years. These maps were crafted through the utilization of the processed images, incorporating a combination of qualitative methods, such as photointerpretation, and quantitative approaches, including supervised classification. Noteworthy references for these techniques include works by Santos et al. (2014), Santos & Bitencourt (2016), and Krizek & Santos (2021). To bring these concepts to life visually, all resultant maps were generated using the Scarta module within the Spring software platform.

Calculation of surface temperature

Remote sensing plays a pivotal role in exploring urban climates, primarily by evaluating the interplay between spatial surface temperature patterns and urban landscape attributes (Chen et al., 2006; Costa et al., 2010). This analytical approach subsequently offers valuable insights into effective land use planning.

In our current study, we leveraged Landsat-5/TM and Landsat-8/TIRS imagery, specifically focusing on thermal infrared bands. These images were employed to estimate surface temperature across the study area for the years 1989 and 2018 (as indicated in Table 3). The specific acquisition dates for these images are August 14, 1989, and August 30, 2018.

It is important to note that all values and surface temperature depictions presented within this study were derived through calculations and methodologies established by Krizek & Santos (2022). This standardized protocol was employed to ensure rigor and consistency throughout our analyses.

Table 3. Characteristics of the thermal spectral bands used for surface temperature calculation in 1989 and 2018. *Although the original spatial resolution of TIRS bands is 120 m, in this study, we chose to use band 10 from an orthorectified TIRS image with a spatial resolution of 30 m.

Date	Satellite	Spectral bands	Spectral resolution	Spatial resolution	Temporal resolution	Imaged area	Radiometric resolution
1989	Landsat-5/TM	(B6) Thermal infrared	10,4 – 12,5 μm	120 m	16 days	185 km	8 bits
2018	Landsat-8/TIRS	(B10) Thermal infrared 1	10,3 – 11,3 μm	30 m*	16 days	185 km	12 bits

Statistical analysis

The statistical analysis hinged on surface temperature data derived from distinct land cover categories: tree vegetation, ground vegetation, and urban areas. For every one of these categories, the mean surface temperature in 1989 was computed using temperature values ($^{\circ}\text{C}$) obtained from twenty randomly selected points situated within the designated category for that particular year. Correspondingly, the mean temperature for 2018 was determined from the temperature values ($^{\circ}\text{C}$) sourced from the same set of twenty sample points. In essence, the sample points were meticulously paired, ensuring that the average surface temperatures for each category in 1989 and 2018 were derived from identical pixel samples.

The accrued sample data for each of the aforementioned classes, captured in both 1989 and 2018, were meticulously organized within Excel spreadsheets. Subsequently, this data was transferred to the GraphPad Prism 5 software for comprehensive statistical analysis.

To assess the conformity of the data to a Gaussian distribution curve, we applied the Shapiro-Wilk normality test. This test, known for its appropriateness concerning the sample size in question (Miot, 2017), was chosen to ascertain the distribution nature of the data. Given the non-normal distribution pattern identified, the statistical methodology employed to compare the two interdependent paired samples (1989 and 2018) for each class was the Wilcoxon test. All analytical procedures were executed with a predetermined level of statistical significance set at 5%.

Proposal for urban planning to combat climate change

The escalating influence of human-induced climate change presents substantial perils to urban areas, necessitating consistent engagement from local authorities to bolster urban resilience (Rosenzweig et al., 2018; PBMC, 2016). In response to this pressing concern, and drawing from the established methodology and resulting outcomes, a series of urban planning proposals have been crafted. These proposals have been

strategically devised for regional implementation, with the overarching goal of mitigating the unfavorable ramifications of climate change within São Paulo.

The core objective of these proposals is to offer comprehensive guidance to fellow researchers and decision-makers. By doing so, they facilitate the identification and execution of measures geared towards both climate change mitigation and adaptation in the context of São Paulo. These proposals take into account not only the global policy framework for addressing climate change, such as the Planning for Climate Change initiative by UN-Habitat (2014), but also the distinctive attributes of the city under study.

Results and discussion

Landscape changes

The dynamics behind landscape transformations in the São Paulo City are multifaceted, encompassing processes such as urban expansion, suburbanization, and peri-urbanization (Alves et al., 2010; Follmann, 2022). This ever-evolving alteration of the landscape carries substantial societal and environmental ramifications, making it a focal point of interest for numerous researchers. However, up until the early 2000s, remote sensing and geoprocessing research predominantly concentrated on natural areas, with limited attention directed towards comprehending urban development and its expansion. Nevertheless, the paradigm shifted with the advent of high-resolution satellite imagery, leading to a marked escalation in the utilization of geotechnologies within the study of urban landscapes (Alves et al., 2010; Liu & Yang, 2015). This technological progression ushered in new possibilities for integrating orbital images into research endeavors that aimed to untangle the intricate processes underpinning landscape shifts within major cities like São Paulo. These advanced technologies harbor the potential to yield outcomes that are instrumental in fostering judicious and sustainable urban planning practices (Blaschke & Kux, 2005; Pfeffer et al., 2015).

Figures 2 and 3 illustrate thematic maps crafted through the utilization of the supervised maximum likelihood classification technique for the years 1989 and 2018, respectively. These visual representations provide insights into the arrangement and dispersal of five distinct object classes across the landscape in both analyzed years. These classes encompass urbanized areas, exposed soil, water bodies, ground vegetation, and tree vegetation.

The classification process carried out for the year 1989 yielded an impressive overall accuracy of 92.16%, alongside a Kappa coefficient value of 84.23%. Correspondingly, the classification performed for the year 2018 achieved a commendable overall accuracy of 92.19%, accompanied by a Kappa coefficient value of 84.54%. Notably, both of these classification outcomes are deemed exceptional in terms of their precision parameters, adhering to the standards outlined by Landis and Koch (1977).

Leveraging the outcomes of these classifications, we were able to quantify the extent of various landscape elements during the two specified years (detailed in Table 4). As indicated by the acquired data, urbanized areas and tree vegetation regions emerged as the dominant features within the study area for both time periods. Additionally, Figures 2 and 3 highlight that ground vegetation regions often abut urbanized areas, appearing less frequently and in smaller sizes within vegetated patches.

One plausible hypothesis to interpret the observed distribution pattern of ground vegetation areas is the edge effect. In fragmented landscapes, newly formed fragment perimeters experience heightened exposure to sunlight, elevated temperatures, intensified wind, and increased rates of evaporation. This phenomenon can result in distinct edge characteristics, including differential diurnal temperature fluctuations, humidity variances between edge and interior areas, and in certain instances, deviations in CO₂ concentrations. These transformations can render the perimeter of a fragment less conducive for forest-dwelling species and more favorable for grass species (Gurevitch et al., 2006). Moreover, this edge effect would likely be more pronounced within smaller, isolated fragments, aligning with the patterns evident in the provided figures.

Figure 4 presents a comparative diagram that showcases the proportional areas (expressed in %) of distinct landscape features in the years 1989 and 2018. This comparison is based on outcomes derived from the supervised maximum likelihood classification process. It becomes evident from the graph that the collective area of tree vegetation

underwent a considerable decrease of 21.2% over the examined timeframe. To elaborate, in 1989, tree vegetation covered 39.0% of the total landscape extent. In stark contrast, by 2018, this coverage had contracted to occupy merely 30.8% of the landscape (Figure 4). This decline can be attributed, at least partially, to the expansion of urban areas, which grew by 10.5% in relation to their 1989 extent. By 1989, urbanized areas constituted 42.4% of the landscape, and this figure surged to 46.8% in 2018 (Figure 4). It is noteworthy that while fragmentation is a natural phenomenon within ecosystems, human-driven activities — particularly urbanization — have greatly amplified this process.

In congruence with this urban expansion, there was a concurrent expansion in the overall expanse of ground vegetation, particularly along the perimeters of fragments. This aligns with the previously discussed edge effect hypothesis. The total area covered by ground vegetation witnessed a substantial 52.7% augmentation in 2018 compared to its expanse in 1989. To elucidate further, ground vegetation constituted 12.8% of the landscape in 1989, and this figure escalated to 19.5% in 2018 (Figure 4).

The transition from tree vegetation to ground vegetation at the periphery of vegetation fragments is a significant outcome of the fragmentation process (Gurevitch et al., 2006). Ecological literature underscores a conspicuous asymmetry between areas near the edges and the more central interior segments of fragments. For instance, areas farther away from edges tend to exhibit greater species richness and diversity in comparison to border regions, which typically feature diminished diversity and heightened prevalence of pioneering and regenerative species (Oliveira et al., 2015). Furthermore, a fragment's dimensions and configuration are intrinsically intertwined with the manifestation of the edge effect. Smaller or elongated fragments generally experience more pronounced edge effects due to a reduction in the interior-to-edge ratio. This ratio engenders constraints on sustaining populations of specific species by modifying spatial factors with noteworthy ecological consequences (Perico et al., 2005). An extensive body of research on habitat fragmentation underscores the edge effect as a principal menace to various biological groups due to the attendant physical and biological modifications (Bierregaard et al., 2001; Yarnall et al., 2021).

Presently, habitat loss and fragmentation rank among the foremost threats to global biodiversity. The findings of this study unequivocally highlight the rapid urban expansion

witnessed in the Northwest Region of the Municipality of São Paulo over the past three decades. This expansion has had repercussions on the quality of natural ecosystems, primarily manifested through the fragmentation of tree vegetation habitats and the escalation of the edge effect. These outcomes, in turn, contribute to the depletion of richness and diversity among forest species. In the absence of landscape-oriented environmental planning that prioritizes conservation and sustainability, steered by geographically informed monitoring studies, natural ecosystems face the prospect of undergoing profound transformations that compromise their structural integrity and ecological contributions. This highlights the significance of underscoring that geotechnologies play a pivotal role in expediting urban planning and management processes, particularly those that hinge on the analysis of spatial and temporal environmental data and insights. These technologies have assumed a pivotal position as instrumental tools in forging and nurturing resilient and sustainable urban centers.

The observed alterations in the landscape can also exert an influence on water dynamics within the studied region. This stems from the reduction in tree vegetation areas, which hold a crucial role in contributing to atmospheric moisture and regional precipitation. Indirectly, these vegetation areas impact water flow by intercepting precipitation, mitigating the impact of rainfall on the ground, and curbing surface runoff (Gurevitch et al., 2006). The shift from vegetation areas to urbanized expanses, as discerned in the study area's evolution over the past thirty years (as depicted in Figures 2-3), can result in a notable surge in surface runoff and soil erosion, especially in rugged or mountainous terrain. This, in turn, can escalate the risk of flooding and mudslides, inflicting additional harm on vegetation and posing hazards to human lives. In sum, the substitution of vegetation with impermeable surfaces carries implications ranging from diminished precipitation and heightened soil warming to the instigation of desertification (Schlesinger et al., 1990; Dirmeyer & Shukla, 1996; Gurevitch et al., 2006).

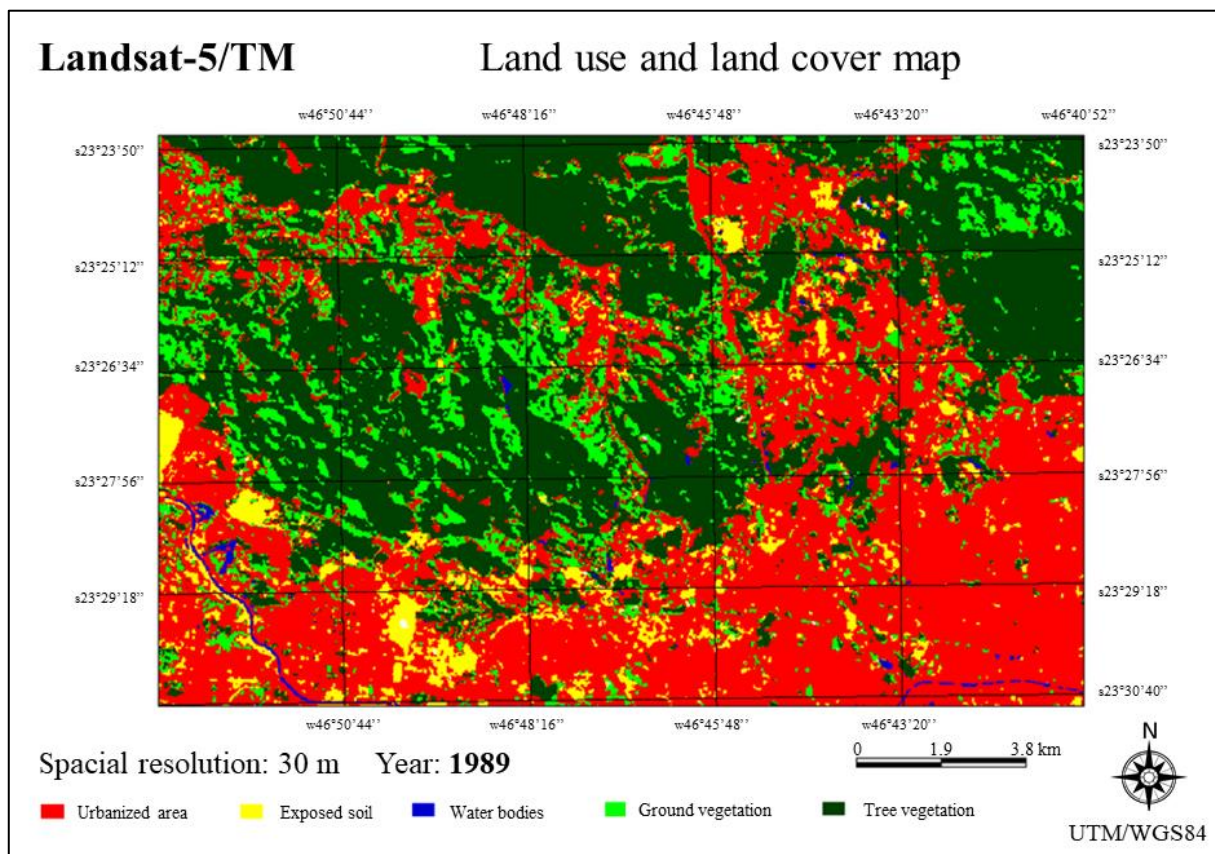


Figure 2. Land use and land cover map obtained using the supervised maximum likelihood classification technique for the study area in the year 1989.

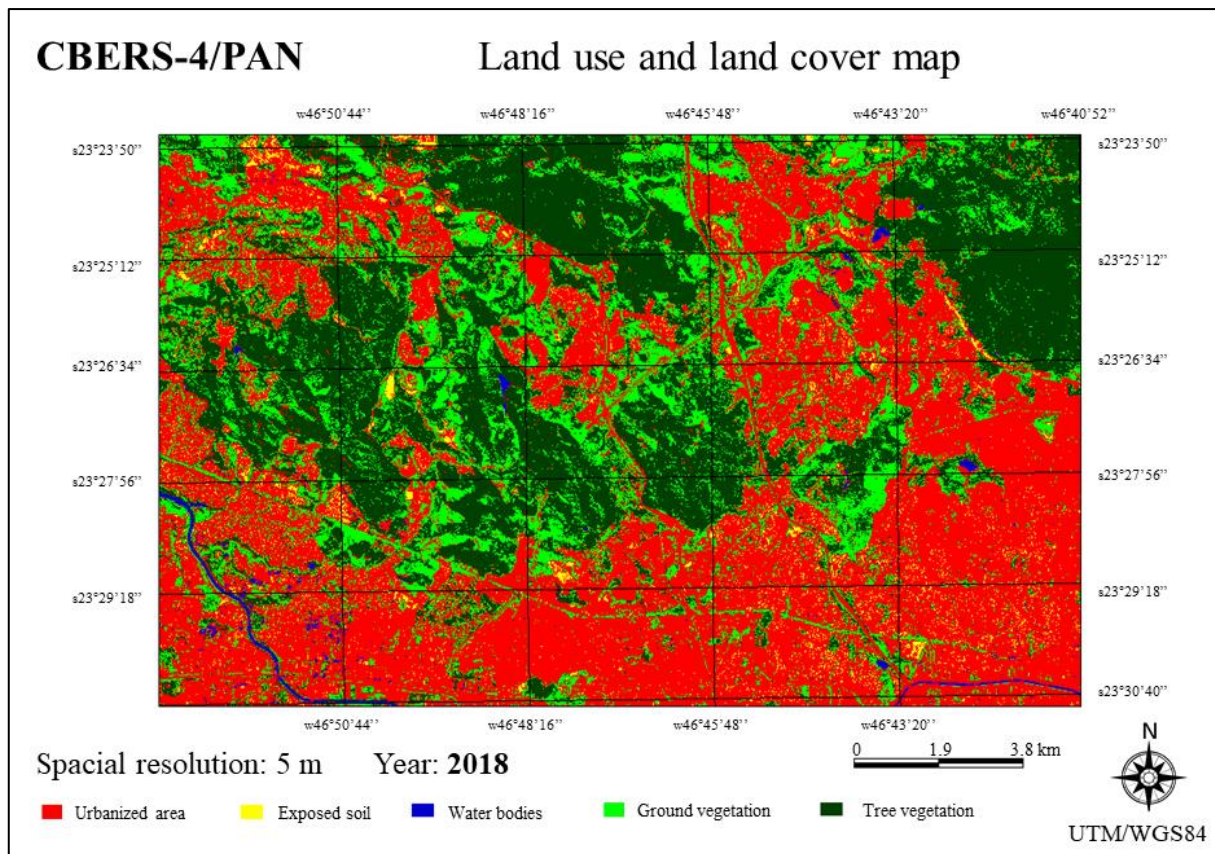


Figure 3. Land use and land cover map obtained using the supervised maximum likelihood classification technique for the study area in the year 2018.

Table 4. Approximate area (hectares) of different landscape targets in the years 1989 and 2018, based on the results of supervised maximum likelihood classification.

Landscape target	Approximate area (hectares)		Difference
	1989	2018	
Urbanized area	11 467,2	12 668,3	$\approx + 10,5\%$
Exposed soil	1 385,5	566,9	$\approx - 59,1\%$
Water bodies	152,8	183,6	$\approx + 20,0\%$
Ground vegetation	3 464,3	5 291,9	$\approx + 52,7\%$
Tree vegetation	10 554,4	8 318,1	$\approx - 21,2\%$
Total area of classes	27 024,2	27 028,8	X
Total unclassified area	36,3	17,3	
Total map area	27 060,5	27 046,1	

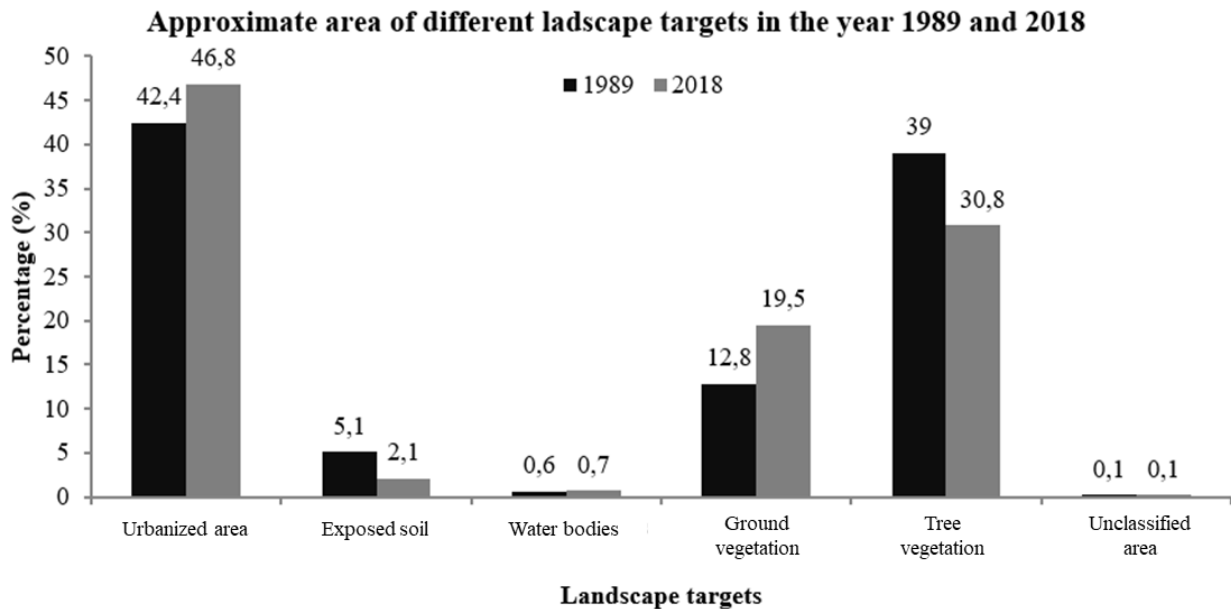


Figure 4. Graph depicting the approximate area of different landscape targets in the years 1989 and 2018, based on the results of supervised maximum likelihood classification.

Surface temperature

In Figure 5, the surface temperature derived from the Landsat-5/TM image of 1989 is depicted. Across the landscape, the recorded surface temperatures spanned from a minimum of 4.2°C to a maximum of 25.7°C. It becomes evident that the urbanized area predominantly featured temperatures ranging between 14°C and 18°C. Conversely, vegetated regions generally exhibited temperatures that were consistently lower than 14°C.

Shifting attention to the surface temperature computation from the Landsat-8/TIRS image of 2018 (Figure 6), an altered behavior is observable. This year exhibited higher temperatures on the whole when compared to the conditions of 1989. In 2018, the lowest surface temperature observed in the landscape was 16.0°C, while the highest reached 36.6°C. A substantial segment of the urbanized expanse registered temperatures ranging from 26°C to 30°C. An adjacent microregion of the urbanized area, situated near vegetated zones, predominantly presented slightly cooler temperatures within the range of 22°C to 26°C. Intriguingly, this temperature range aligned with a considerable portion of the vegetation areas. Within the central sectors of vegetated regions, positioned further from the urban periphery, even lower temperatures were evident, spanning from 18°C to 22°C. Unlike the scenario in 1989 (Figure 5), only a few points in the landscape exhibited temperatures between 16°C and 18°C in 2018, and no point featured a surface temperature lower than 16°C.

Figures 7-9 illustrate graphical representations of the average surface temperatures calculated from the collected sample points for the years 1989 and 2018. These averages are segregated by class: tree vegetation (Figure 7), ground vegetation (Figure 8), and urbanized area (Figure 9). In these visualizations, the error bars signify the standard deviation, and varying letters on the bars indicate statistically distinct means as determined by the Wilcoxon test ($p < 0.05$).

Evidently, all three classes exhibited discernibly different average surface temperatures across the two examined years. Notably, the year 2018 consistently showcased higher average surface temperatures — distinct from those observed in 1989. Furthermore, both in 1989 and 2018, the tree vegetation areas (Figure 7) exhibited comparatively lower average surface temperatures in contrast to the ground vegetation areas (Figure 8). Similarly, the ground vegetation areas demonstrated lower average surface temperatures when juxtaposed with the urbanized areas (Figure 9).

Delving into the specifics of the sampled points within the “tree vegetation” class (Figure 7), the averages were 13°C (1989) and 21.6°C (2018). For the “ground vegetation” class (Figure 8), the averages were 14°C (1989) and 24.5°C (2018). Lastly, for the “urbanized area” class (Figure 9), the averages were 16°C (1989) and 27°C (2018). These disparities vividly underscore the evolving thermal characteristics of these landscape segments over the years.

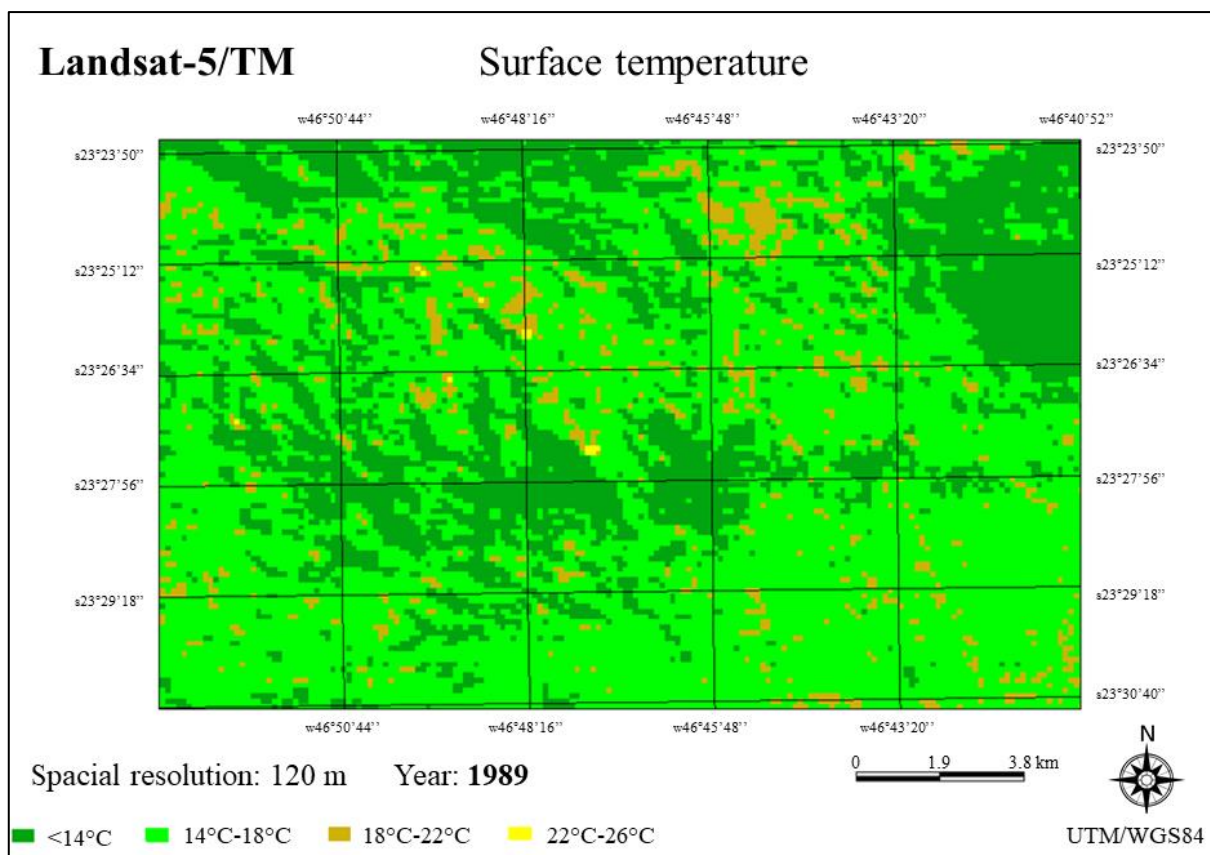


Figure 5. Map related to surface temperature calculated from Landsat-5/TM image (1989) for the study area.

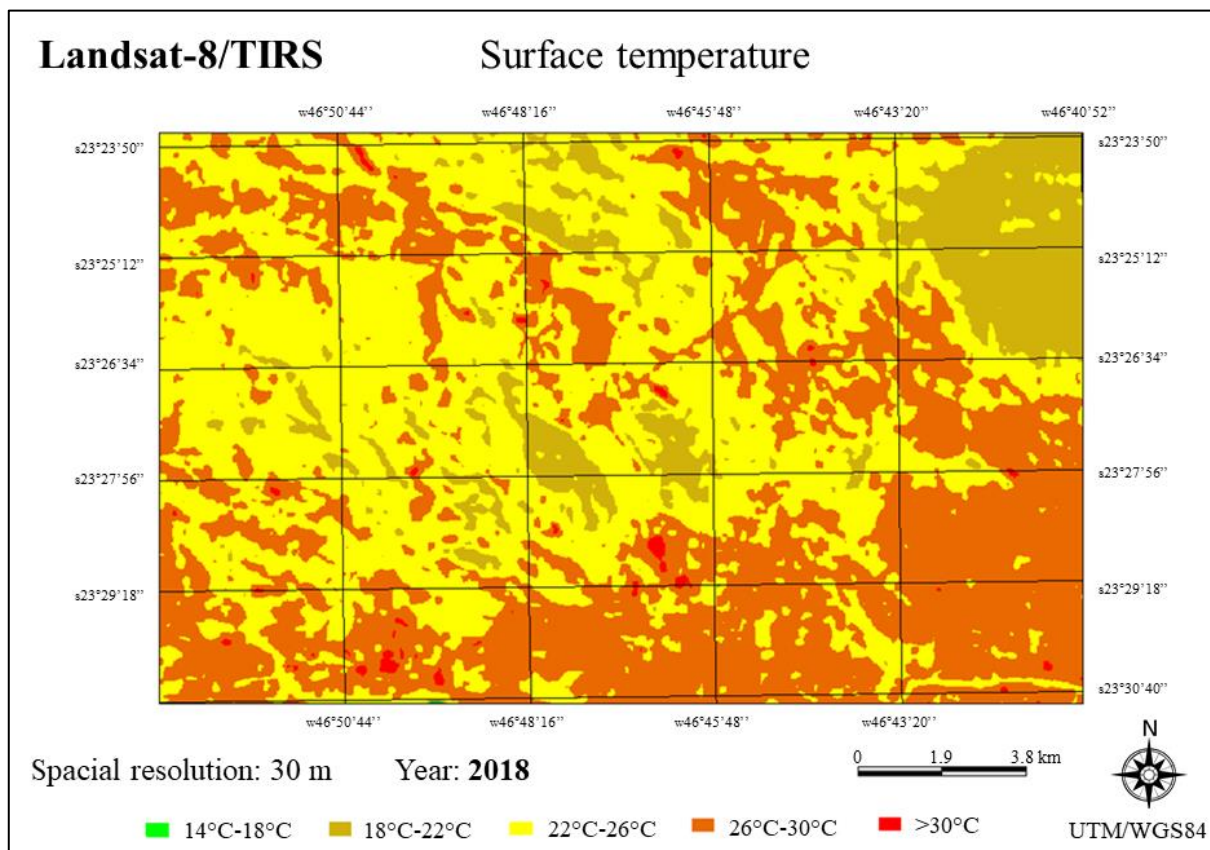


Figure 6. Map related to surface temperature calculated from Landsat-8/TIRS image (2018) for the study area.

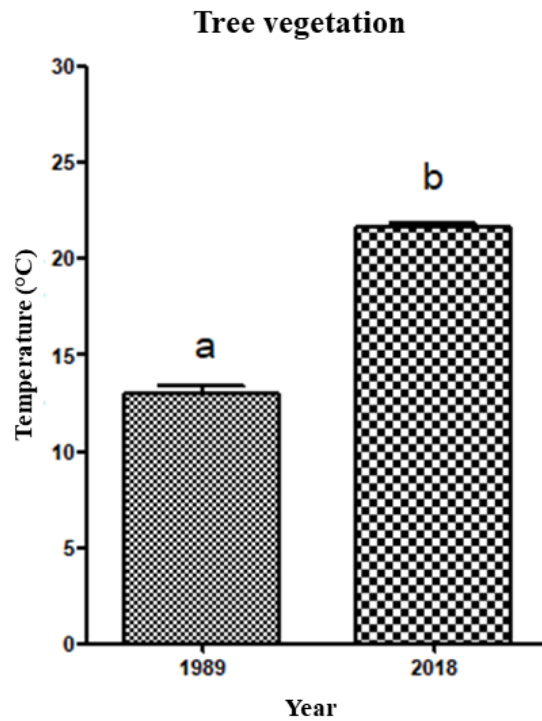


Figure 7. Graph of average surface temperature of tree vegetation areas, calculated from the obtained sample points, for the years 1989 and 2018. Different letters on the bars indicate statistically different means (Wilcoxon test, $p < 0.05$).

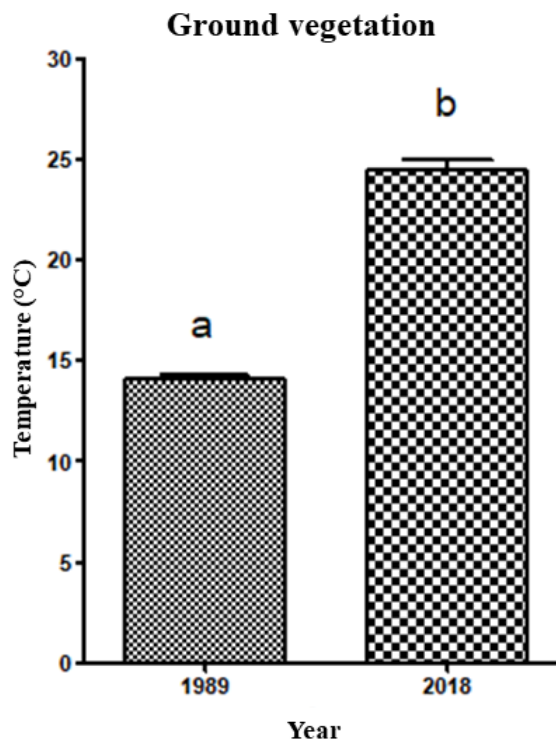


Figure 8. Graph of average surface temperature of ground vegetation areas, calculated from the obtained sample points, for the years 1989 and 2018. Different letters on the bars indicate statistically different means (Wilcoxon test, $p < 0.05$).

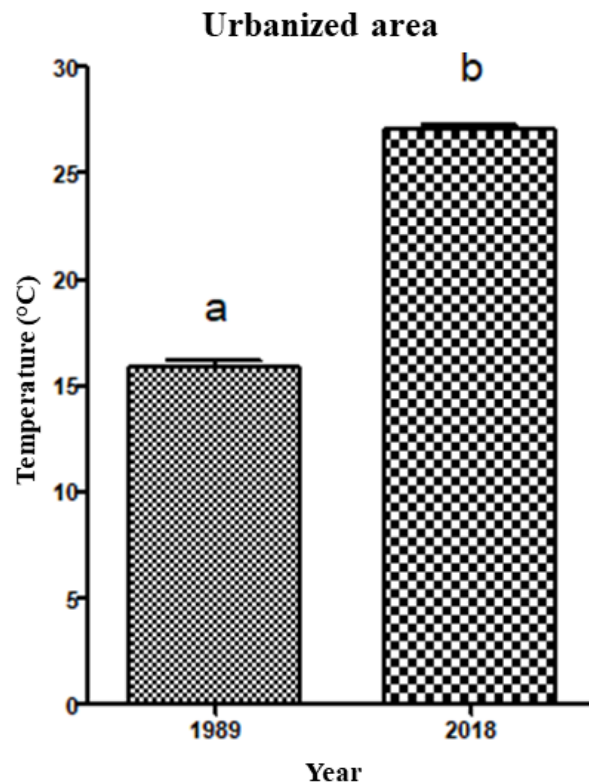


Figure 9. Graph of average surface temperature of urbanized areas, calculated from the obtained sample points, for the years 1989 and 2018. Different letters on the bars indicate statistically different means (Wilcoxon test, $p < 0.05$).

The notable elevation in temperature observed within the “urbanized area” class can be attributed to the replacement of natural surfaces, including vegetation and exposed soil, with impermeable materials such as asphalt and concrete. These transformations not only diminish vegetation coverage but also significantly modify the impermeability, radiative properties, thermal attributes, and aerodynamics of the urban milieu (Costa et al., 2010). This underscores the pivotal role of vegetation in curtailing surface temperatures (Alexander, 2021). Beyond providing shade, vegetation leverages the process of evapotranspiration to lower air temperatures, thus ameliorating heat-related impacts within vegetated domains (Costa et al., 2010).

The presence of green leaves and stems within vegetation curtails the extent of solar radiation that reaches the surface. This is achieved through the absorption of a portion of incident solar radiation by the foliage, which is subsequently utilized in photosynthesis. An additional fraction of radiation is reflected back into the atmosphere. This twofold process contributes to surface cooling: the shade reduces surface temperature, and the cooler surfaces subsequently diminish the heat transferred to buildings and the surrounding atmosphere (Costa et al., 2010). The research

conducted by Akbari et al. (1997) and Scott et al. (1999) underscored that the shading afforded by vegetation can substantially decrease wall and roof temperatures by as much as 20°C.

Moreover, the transformation from natural surfaces — such as vegetation and exposed soil — to impermeable, non-evaporative materials like asphalt and concrete, as observed in the study area’s evolution over the past thirty years, accelerates the runoff of rainwater. A portion of this runoff is collected by urban drainage systems, resulting in a reduced availability of water and a curtailed period for evaporation (Oke, 1982). In stark contrast, tree vegetation areas consistently exhibit the lowest temperatures across both assessed years. This phenomenon can be ascribed to the direct shading effect, as discussed earlier, and the robust latent heat flux generated due to the augmented availability of water for evaporation and evapotranspiration processes (Oke, 1982; Costa et al., 2010).

The outcomes derived from this study unequivocally validate that various elements within a landscape wield distinct influences on surface temperature. Impermeable artificial surfaces like concrete, characteristic of the “urbanized area” class, can be perceived as “heat sources” within urban environs. Conversely,

multilayered vegetation encompassing grass, shrubs, and trees substantially amplify the cooling effect, typified by the “vegetated area” class (Yang & Zhao, 2016). Furthermore, the radiative and thermal characteristics of materials constituting the “urbanized area” class—particularly parameters like albedo, emissivity, thermal capacity, and conductivity — play a pivotal role in dictating surface temperature. This is rooted in their capacity to govern the reflection, absorption, emission, and storage of both shortwave and longwave radiation (Costa et al., 2010).

Albedo, representing a surface’s reflective attribute and quantified as the percentage of incoming solar radiation that is reflected, hinges on the surface’s color, texture, and the angle of incidence (Christopherson & Birkeland, 2015). The dissimilarities in reflectivity, absorptivity, and emissivity among substances stem from their inherent characteristics. The particle structure, size, and molecular composition collectively furnish each substance with a unique spectral signature (Spångmyr, 2010). Urban materials frequently encountered, such as roofs, concrete, and asphalt, tend to exhibit low albedo values. Consequently, urban domains tend to reflect less and absorb a higher proportion of solar radiation, contributing to elevated surface temperatures. It is noteworthy that while the albedo of urban materials might not be markedly lower than that of vegetated areas, the cumulative albedo of an urbanized expanse can be exceedingly diminished. The intricate geometry of surfaces and layers in the urban landscape facilitates numerous reflections, with each surface encountering radiation and absorbing a share of it (Oke, 1987; Zekar et al., 2023). Hence, the land surface’s geometry exerts a palpable impact on the albedo of the entire surface system, working in conjunction with the distinct attributes of individual surfaces (Spångmyr, 2010).

Additionally, different construction materials, such as steel and stone, exhibit higher thermal capacity when compared to natural materials commonly found in rural locales, like bare soil and sand. This implies that urbanized regions possess enhanced efficacy in retaining solar energy, encompassing heat, within their

internal structures. In fact, they can absorb and store up to twice as much heat as neighboring vegetated zones (Christen & Vogt, 2004; Costa et al., 2010; Zekar et al., 2023). Notably, these artificial materials also tend to possess elevated thermal conductivity, thereby facilitating the swifter and more efficient transmission of heat to various strata of construction (Kato & Yamaguchi, 2005; Costa et al., 2010).

As discernible in Figure 10, a substantial fraction of the scrutinized landscape has encountered an elevation in surface temperature ranging from 5°C to 15°C over the past three decades. In certain regions, surface temperatures even escalated by as much as 24°C (Figure 10). These findings harmonize with a range of research endeavors (Streutker, 2003; Voogt & Oke, 2003; Weng et al., 2004; Xian & Crane, 2006; Costa et al., 2010), underscoring the environmental outcome of urbanization: a discernible upswing in surface temperatures within urban domains, resulting in heightened temperatures compared to the adjoining non-urbanized expanses. These outcomes further underscore the imperative of scrutinizing attributes such as vegetation cover, pivotal for steering judicious, apt, and resilient utilization of a given landscape (Campos et al., 2004).

The present study corroborates that elevated surface temperatures tend to cluster in areas with reduced tree vegetation and heightened building density. The temperature differentials observed within the study area mirror those documented by Price (1979), who established that numerous cities in the New York region exhibited temperatures 10°C to 15°C warmer than the surrounding rural tracts. Findings reported by Karl et al. (1988) similarly indicated that locales housing populations of 10,000 or more experienced hotter conditions than rural areas inhabited by fewer than 2,000 individuals. Moreover, this study’s outcomes unveil a pronounced correlation between temperature patterns and land cover types, a concurrence also substantiated by Roth et al. (1989) in their analysis of data acquired via satellite sensors.

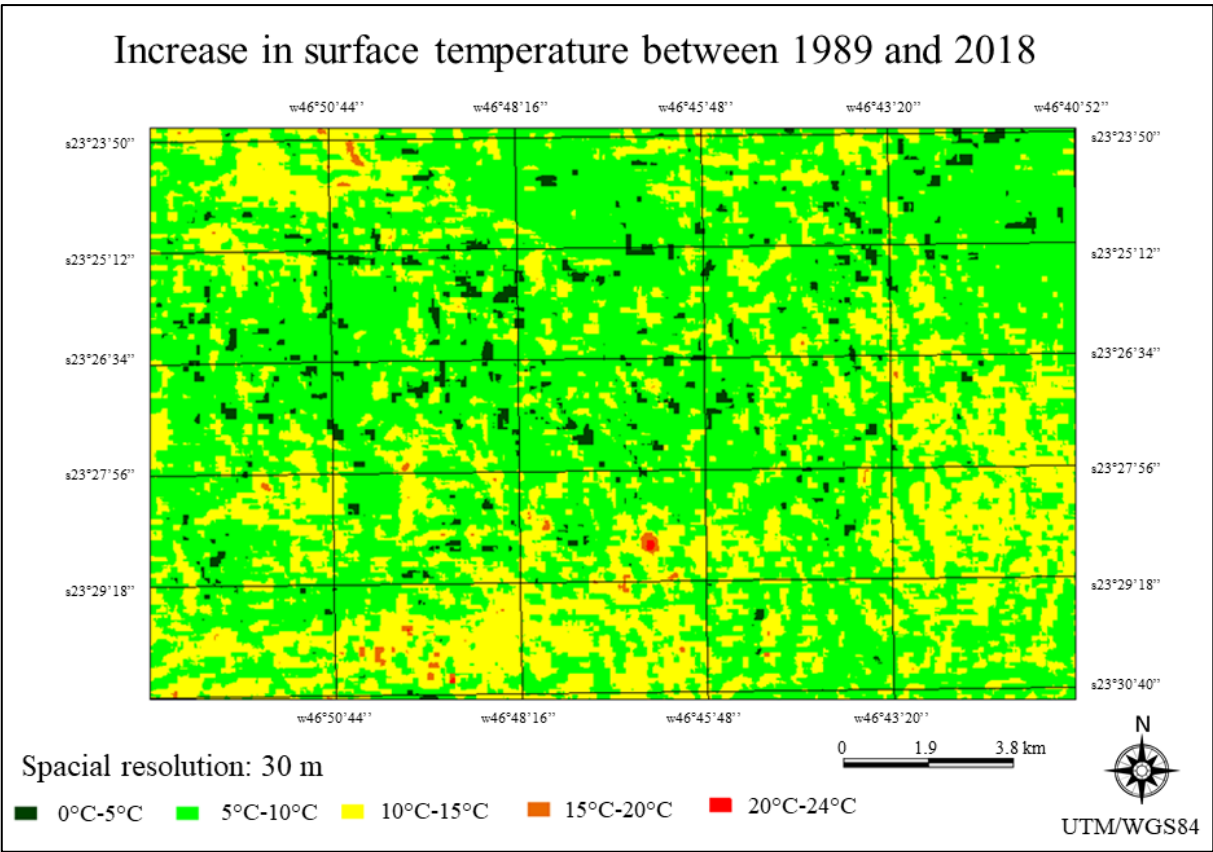


Figure 10. Map illustrating the increase in surface temperature between 1989 and 2018 in the studied landscape.

Guidelines for urban planning to combat climate change

As per the classification proposed by Fialho & Imbroisi (2005), the urban climate is shaped by a multitude of factors that can be categorized into various classes, including

architectural factors, urbanization factors, and geoecological factors. Table 5 enumerates an array of heat island-forming factors that were taken into account in this study to formulate urban planning recommendations aimed at mitigating climate change impacts within the study area.

Table 5. Heat island-forming factors considered in the development of a proposal for urban planning guidelines to combat climate change in the study area.

Categories	Heat island forming factors
Architectural	Urban geometry
	Thermal properties of construction materials
	Albedo
Urbanization	Reduction of evapotranspiration
	Land use and land cover
	Reduction of intraurban vegetation
Geoecological	Vegetation cover

The monitoring and assessment of changes in the factors presented in Table 5 within the Northwest Region of the São Paulo City serve as indicators of socio-economic and environmental transformations that have unfolded in the local urban dynamics, encompassing both historical and contemporary processes. For instance, the reduction in evapotranspiration, when examined in isolation, can be linked to a decline in vegetated

areas. However, when these factors are integrated with data pertaining to land use, land cover, and soil permeability, the resultant analysis facilitates a more profound exploration of the environmental and climatic mechanisms operative in the studied area. Such insights possess substantial potential to inform urban planning by offering diverse pathways that reflect varying degrees of environmental degradation. In this context, Table 6

encapsulates the primary findings gleaned from this research, while Table 7 delineates the crucial guidelines imperative for mitigating climate change within the study area. These guidelines are

formulated based on the assessment of climate and environmental alterations that transpired between 1989 and 2018.

Table 6. Main environmental and climatic changes identified in the studied landscape, occurring between 1989 and 2018, according to the various heat island-forming factors. The superscript numbers indicate references: ¹Oke (1987); ²Oke (1982); ³Oliveira et al. (2015); ⁴Yang & Zhao (2016).

Factor	Diagnosis of changes (between 1989-2018)
Urban geometry	(1) Changes in urban geometry due to the replacement of natural surfaces with construction materials such as asphalt and concrete
Thermal properties of construction materials	(2) The expansion of the urban area has led to the replacement of vegetated areas with construction materials of higher thermal capacity and high thermal conductivity
Albedo	(3) Likely decrease in total albedo and the resulting increase in surface temperature due to the replacement of vegetated areas with construction materials such as concrete, roofs, and asphalt ¹ (4) Likely decrease in total albedo due to the multiple layers and surfaces in the urban environment's geometry ¹
Evapotranspiration	(5) Likely reduction in evapotranspiration due to a decrease in vegetation cover ²
Land use and land cover	(6) Expansion of the total urban area by 10.5% (7) Contraction of the total area of tree vegetation by 21.2% (8) Expansion of the total area of ground vegetation by 52.7% (9) The highest surface temperatures were concentrated in areas with a lower amount of tree vegetation and higher building density (10) The replacement of natural surfaces with impermeable materials likely has resulted in faster runoff of rainwater, leading to a reduction in evaporation time ²
Intraurban vegetation	(11) Contraction of the total area of tree vegetation by 21.2%
Vegetation cover	(12) Transformation of the floristic structure at the edge of vegetation patches (from tree vegetation to ground vegetation) (13) Likely decrease in species richness due to the process of fragmentation and the consequent replacement of diverse tree vegetation areas with less diverse ground vegetation areas ³ (14) Likely decrease in the cooling effect due to the replacement of multi-layered tree vegetation areas with ground vegetation areas ⁴

Table 7. Recommended guidelines for mitigating climate change in the studied landscape, based on the main diagnoses obtained in this research. Author's own compilation, drawing from LCCP (2005), Barton (2009), UN-Habitat (2014), PBMC (2016), and Raven et al. (2018).

Key strategies for local urban planning
Reduce the size of the urban heat island effect through passive approaches, such as green and reflective roofs, and permeable pavements, thereby minimizing thermal stress on all citizens.
Modify the shape and layout of buildings and urban districts to provide cooling and ventilation that reduces energy use and enables citizens to cope with higher temperatures and increased runoff.
Utilize building construction that incorporates appropriate techniques and mechanisms for passive ventilation and cooling systems, has thermal mass for the expected use and occupancy, can incorporate green roofs or walls, and reduces summer heat buildup through surface treatments that reflect heat, such as light-colored paints.
Promote increased urban tree canopy coverage and the creation of green spaces, which simultaneously reduces outdoor temperatures, building cooling demand, runoff, and pollution, while enhancing carbon sequestration.
Design a suitable range of public and private spaces that prioritize the presence of shade, vegetation, and water, ensuring that surface design takes into account more intensive uses, permeability, potential dust generation, and soil erosion.
Provide a rainwater harvesting/graywater recycling system to irrigate gardens, green spaces, and landscaping areas.
Utilize eco-efficient buildings and sustainable materials. The selection of low heat capacity construction materials and reflective coatings can enhance building performance by managing surface heat exchange.
Implementation, by the government, of legislation defining an appropriate ratio between built space and green area.
Reduce urban sprawl by increasing population density.

According to PBMC (2016), it is crucial for cities to undergo remodeling and planning in alignment with existing priorities, with the overarching goal of fortifying their resilience to climate change. Strategies aimed at bolstering climate resilience in urban areas encompass a spectrum of approaches, including urban and land use planning, innovative urban design, financial mechanisms and public-private partnerships, the management and enhancement of ecosystem services, the establishment of robust institutions, the development of community capacities, and the formulation of resilient post-disaster recovery and reconstruction plans (ROSENZWEIG et al., 2015; PBMC, 2016).

The *ARC3.2 Summary for City Leaders* (ROSENZWEIG et al., 2015) delineates key strategies that urban planners and designers should adopt to facilitate climate change mitigation and adaptation in cities: (a) Reducing residual heat and greenhouse gas emissions through initiatives focused on energy efficiency, the promotion of public transportation, and the encouragement of walking; (b) Modifying building and urban district shapes and layouts to optimize climate resilience; (c) Employing heat-resistant construction materials

and reflective surface coatings to mitigate heat absorption; (d) Augmenting vegetation cover within urban environments.

These strategies, as outlined in Table 7, serve as a foundation for guiding urban planning and design initiatives. Notably, among these strategies, urban green space planning warrants special attention. The presence of green spaces in cities can contribute to carbon sequestration, involving the removal of carbon from the atmosphere and its storage in carbon sinks, such as forests. Urban tree vegetation, in particular, serves as an effective means of carbon storage. Urban agriculture, encompassing cultivation within or around cities, also provides green spaces and offers advantages for carbon capture.

Green areas offer a plethora of benefits spanning a wide array of domains. Green roofs and facades, for instance, can help cool buildings during summer months and provide insulation during winter, resulting in reduced energy consumption. Trees offer shade for buildings and mitigate the urban heat island effect. Furthermore, green spaces and planning can enhance rainwater drainage, thereby mitigating water-related issues during extreme weather events. Additionally, green

space planning yields substantial secondary benefits, such as the reduction of air and noise pollution in urban environments. Public green spaces like parks enhance the quality of life for city residents and are easily accessible to everyone. Moreover, urban agriculture can positively impact food security and alleviate urban poverty (UN-Habitat, 2011; 2013; 2014; 2015).

The design and construction of buildings play a pivotal role in their energy requirements and, consequently, their emissions levels. A well-thought-out building design can significantly reduce the need for air conditioning or heating, leading to reduced energy consumption and lower emissions. Additionally, building design and construction practices influence a building's resilience to extreme weather events and other climate change-related impacts. Some building materials and designs possess better thermal properties, making them more suitable for regions with high temperatures (UN-Habitat, 2012).

In light of the findings from this study, safeguarding residential spaces from both internal heat sources and external solar radiation becomes of paramount importance. Incorporating elements that allow for natural airflow, such as open house designs, is essential. The strategic use of shading, including roofs, balconies, and trees, is vital for preventing direct solar heat gain (UN-Habitat, 2012).

The layout of settlements should emphasize the provision of adequate spaces between buildings, which should be organized in a loose and independent manner to maximize air circulation and minimize enclosed spaces. Tall canopy trees can be strategically planted to provide shade while facilitating airflow. In densely populated urban areas, prioritizing building height over increasing ground surface area is crucial, as taller structures can enhance air circulation (Snell & Callahan, 2005; UN-Habitat, 2012).

Internally, buildings can be designed to optimize air movement through the use of open wall structures. Employing "lightweight" construction materials like wood can reduce heat storage within the building. Designing large openings on opposite sides of a room enables horizontal cross-ventilation. Furthermore, curtains, blinds, and shading screens can be employed for effective shading. The shape of the roof also plays a role in directing air movement: round shapes attract air, while pointed roofs can divert air away (Koch-Nielsen, 2002; Snell & Callahan, 2005; UN-Habitat, 2012; Ozariso, 2022).

Developing climate change mitigation and adaptation strategies with a focus on local-level planning is essential for several reasons. Climate

impacts are most acutely felt at the local level, where decisions about planning and investment are often made. Urbanization, a key driver of climate change impacts, also primarily occurs at the local level. Furthermore, climate change directly affects the services provided by local entities, such as water supply, transportation, and emergency response.

Climate change influences numerous aspects of urban life, and as such, it should be factored into nearly all urban policies, plans, or programs. Integrating climate change considerations into urban planning can enhance the effectiveness of these initiatives and ensure that cities are prepared to mitigate climate impacts and take necessary actions. Such integration also helps ensure that climate change is not viewed as a temporary issue but is continuously addressed in urban development and governance (UN-Habitat, 2012).

Conclusions

The key conclusions drawn from this study are as follows:

- **Urbanization and Reduced Tree Vegetation:** The urbanization and reduction of tree vegetation in the Northwest Region of São Paulo City have led to an increase in urban surface temperatures. This underscores the importance of considering vegetation coverage when planning and developing landscapes in a rational, appropriate, and resilient manner.

- **Decrease in Tree Vegetation:** Over the past thirty years, there has been a noticeable decline in the total area covered by tree vegetation in the Northwest Region of São Paulo City. This reduction has been accompanied by urban expansion and an expansion of ground-level vegetation, particularly along the edges of vegetated areas.

- **Drastic Temperature Increase:** Surface temperatures in the landscape of the Northwest Region of São Paulo Municipality have significantly risen over the past three decades. The year 2018 recorded considerably higher average surface temperatures compared to those in 1989.

- **Temperature Variation by Land Cover:** Tree vegetation areas exhibit lower average surface temperatures compared to ground-level vegetation areas, which, in turn, have lower average surface temperatures than urbanized areas. In essence, the temperature pattern is closely associated with the type of ground cover. Areas experiencing higher heat concentrations are predominantly found in the urban perimeter and areas with higher urban density.

• **Impact of Land Cover Types:**

Different land cover types within a landscape can exert varying impacts on surface temperatures. Impermeable artificial surfaces like concrete, prevalent in the “urbanized area” class, act as heat sources for the urban environment. In contrast, multi-layered vegetation comprising grass, shrubs, and trees contributes to effective cooling in the “vegetated area” class.

• **Distribution of Ground-Level**

Vegetation: Ground-level vegetation areas are more commonly located near urbanized areas, occurring less frequently and in smaller sizes within vegetated fragments. This distribution pattern of ground-level vegetation areas can be partially explained by the edge effect.

• **Role of Geotechnologies:**

The use of geotechnologies, including satellite imagery and GIS, in researching landscape change processes in large cities demonstrates significant potential for producing results that contribute to responsible and sustainable urban planning, as evidenced by this study.

These conclusions highlight the complex relationship between urbanization, land cover types, and surface temperatures in the studied region. Understanding these dynamics is critical for informed urban planning and climate resilience efforts in São Paulo City.

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