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Smart Cities and Climate Resilience: The Role of Urban Vegetation in Thermal Regulation and Carbon Sequestration in Ribeirão Preto, SP.

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Cidades Inteligentes e Resiliência Climática: O Papel da Vegetação Urbana na Regulação Térmica e Sequestro de Carbono em Ribeirão Preto, SP

RESUMO

Objetivo - Este estudo visa analisar o papel da vegetação urbana na mitigação das ilhas de calor e no sequestro de carbono (SC) em Ribeirão Preto, SP, Brasil.

Metodologia - Foram utilizadas imagens do satélite Landsat 8, aplicando técnicas de sensoriamento remoto, Sistemas de Informação Geográfica (SIG) e geoprocessamento. Foram calculados o Índice de Vegetação por Diferença Normalizada (NDVI), o fluxo de CO2 (CO2FLUX) e as temperaturas de superfície para avaliar a correlação entre cobertura vegetal, temperatura e sequestro de carbono.

Originalidade/relevância - O estudo preenche uma lacuna na literatura sobre o impacto direto da vegetação urbana na regulação climática em cidades brasileiras de médio porte, oferecendo evidências quantitativas do papel das áreas verdes no SC e na redução das temperaturas urbanas.

Resultados - As áreas com maior cobertura vegetal apresentaram índices elevados de SC e temperaturas superficiais reduzidas, enquanto regiões urbanas e agrícolas com pouca vegetação registraram maior aquecimento.

Contribuições teóricas/metodológicas - O estudo aprimora o uso de técnicas de sensoriamento remoto para avaliação ambiental urbana, demonstrando a eficácia de indicadores como NDVI e CO2FLUX na análise de serviços ecossistêmicos.

Contribuições sociais e ambientais - Os achados sustentam a formulação de políticas públicas voltadas para a ampliação de áreas verdes urbanas, promovendo a sustentabilidade, a qualidade de vida e a mitigação das mudanças climáticas.

PALAVRAS-CHAVE: Sensoriamento Remoto. Sequestro de Carbono. Temperatura de Superfície. Índice de Vegetação. Vegetação Urbana.

Smart Cities and Climate Resilience: The Role of Urban Vegetation in Thermal Regulation and Carbon Sequestration in Ribeirão Preto, SP

ABSTRACT

Objective – This study aims to analyze the role of urban vegetation in mitigating heat islands and carbon sequestration (CS) in Ribeirão Preto, SP, Brazil.

Methodology – Landsat 8 satellite images were used, applying remote sensing techniques, Geographic Information Systems (GIS), and geoprocessing. The Normalized Difference Vegetation Index (NDVI), CO2 flux (CO2FLUX), and surface temperatures were calculated to assess the correlation between vegetation cover, temperature, and carbon sequestration.

Originality/Relevance – This study addresses a gap in the literature regarding the direct impact of urban vegetation on climate regulation in medium-sized Brazilian cities, providing quantitative evidence of the role of green areas in CS and urban temperature reduction.

Results – Areas with greater vegetation cover exhibited higher CS indices and reduced surface temperatures, while urban and agricultural regions with sparse vegetation recorded higher warming levels.

Theoretical/Methodological Contributions – The study enhances the use of remote sensing techniques for urban environmental assessment, demonstrating the effectiveness of indicators such as NDVI and CO_2FLUX in the analysis of ecosystem services.

Social and Environmental Contributions – The findings support the formulation of public policies aimed at expanding urban green areas, promoting sustainability, quality of life, and climate change mitigation.

KEYWORDS: Remote Sensing. Carbon Sequestration. Surface Temperature. Vegetation Index. Urban Vegetation.

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Ciudades Inteligentes y Resiliencia Climática: El Papel de la Vegetación Urbana en la Regulación Térmica y el Secuestro de Carbono en Ribeirão Preto, SP.

RESUMEN

Objetivo – Este estudio tiene como objetivo analizar el papel de la vegetación urbana en la mitigación de las islas de calor y en el secuestro de carbono (SC) en Ribeirão Preto, SP, Brasil.

Metodología – Se utilizaron imágenes del satélite Landsat 8, aplicando técnicas de teledetección, Sistemas de Información Geográfica (SIG) y geoprocesamiento. Se calcularon el Índice de Vegetación de Diferencia Normalizada (NDVI), el flujo de CO2 (CO2FLUX) y las temperaturas de superficie para evaluar la correlación entre la cobertura vegetal, la temperatura y el secuestro de carbono.

Originalidad/Relevancia – El estudio aborda una laguna en la literatura sobre el impacto directo de la vegetación urbana en la regulación climática en ciudades brasileñas de tamaño medio, proporcionando evidencia cuantitativa del papel de las áreas verdes en el SC y la reducción de las temperaturas urbanas.

Resultados – Las áreas con mayor cobertura vegetal presentaron índices más altos de SC y temperaturas superficiales reducidas, mientras que las regiones urbanas y agrícolas con escasa vegetación registraron un mayor calentamiento.

Contribuciones Teóricas/Metodológicas – El estudio mejora la aplicación de técnicas de teledetección para la evaluación ambiental urbana, demostrando la eficacia de indicadores como NDVI y CO2FLUX en el análisis de servicios ecosistémicos.

Contribuciones Sociales y Ambientales – Los hallazgos respaldan la formulación de políticas públicas orientadas a la expansión de las áreas verdes urbanas, promoviendo la sostenibilidad, mejorando la calidad de vida y mitigando el cambio climático.

PALABRAS CLAVE: Teledetección. Secuestro de Carbono. Temperatura de Superficie. Índice de Vegetación. Vegetación Urbana.

1 INTRODUCTION

Carbon sequestration (CS) is the process of removing carbon dioxide (CO_2) from the atmosphere and storing it in biotic and pedological reservoirs, such as vegetation and soil (IPCC, 2023; Olson et al., 2014; Pan et al., 2011; Smith, 2004). Vegetation plays a key role in this process by converting atmospheric carbon into organic carbon through photosynthesis (Amaral et al., 2017; Trindade et al., 2021). Considered an essential ecosystem service, CS contributes to climate regulation and human well-being, directly supporting the maintenance and stability of ecological processes (Parron; Garcia, 2015; Reid et al., 2005; Westman, 1977).

Discussions on CS date back to the 1970s, with the work of Whittaker and Likens (1973), who analyzed the capacity of forests to remove carbon from the atmosphere and emphasized the importance of terrestrial ecosystems in regulating the carbon cycle. Later, Houghton et al. (1983) demonstrated how land use influences carbon stocks, highlighting the impact of deforestation and the conversion of forested areas on CO_2 emissions. Since the 1990s, CS has gained prominence on the international agenda, driven by agreements such as the Kyoto Protocol, which established targets for reducing greenhouse gas (GHG) emissions (Gomes, 2005; UNITED NATIONS, 1998).

With the worsening of the global climate crisis, CS has become a key strategy for mitigating the effects of rising GHG concentrations. Countries like Brazil have made commitments during the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21), setting emission reduction targets (Brasil, 2021). As the sixth-largest global emitter of GHGs, Brazil holds great potential to contribute to these goals, particularly through the preservation and expansion of green areas (Artaxo, 2022).

In this scenario, the urban context gains relevance as it concentrates the majority of the global population (UNITED NATIONS, 2022) and high levels of GHG emissions (IPCC, 2023). In Brazil, about 85% of the population lives in urban areas (IBGE, 2011), which underscores the need for sustainable strategies in cities. Urban green spaces play a vital role in carbon removal, thermal regulation, and in mitigating urban heat islands (UHI) (Griscom et al., 2018; Jatoi et al., 2022; Leite et al., 2023; Lin et al., 2011; Shishegar, 2014).

The quantification of CS can be conducted using different methodologies, such as field-based methods and remote sensing (Tadese et al., 2019). Field methods include destructive approaches, such as plant biomass analysis (Kong et al., 2014), and non-destructive approaches, such as measurements in sample plots using allometric equations (Montès et al., 2000; Zhao et al., 2023). However, remote sensing has stood out for its ability to collect large-scale data quickly and at low cost, enabling estimates through vegetation indices (NDVI) and carbon fluxes (CO_2FLUX) (Formigoni et al., 2011; Meneses; Almeida, 2012; Zhang; Shao, 2021).

Despite limitations such as the influence of atmospheric conditions and the need for model calibration, the advantages of remote sensing are significant, especially when combining different techniques to quantify environmental variables (Dossa; Miassi, 2024; Formigoni et al., 2011). Additionally, these techniques are widely used in urban and regional planning, allowing for the joint analysis of surface temperature, vegetation, and land use (Almeida, 2010).

In this context, smart cities emerge as promising alternatives by integrating technology, sustainability, and urban planning to address contemporary environmental challenges. Tools such as remote sensing, Geographic Information Systems (GIS), and geoprocessing contribute to monitoring vegetation cover and urban thermal dynamics, providing essential support for the formulation of effective public policies (Pfeiff et al., 2020).

Amid increasing urbanization and emerging environmental demands, it is essential to understand how urban spaces can contribute to mitigating climate impacts through nature-based solutions. Scientific investigation in this field supports the development of more sustainable urban strategies, promoting a balance between development and environmental conservation.

Therefore, this article aims to analyze the influence of urban vegetation on the mitigation of urban heat islands and carbon sequestration in the municipality of Ribeirão Preto (SP). To achieve this, we employed orbital remote sensing, GIS, and geoprocessing techniques, highlighting the importance of these technologies for developing more sustainable and resilient cities.

2 OBJECTIVE

This study aims to analyze the influence of urban vegetation on the mitigation of urban heat islands and carbon sequestration in the municipality of Ribeirão Preto (SP). Specifically, it seeks to understand the role of urban green areas in the removal of CO_2 from the atmosphere and in the thermal regulation of urban environments, using advanced techniques of remote sensing, Geographic Information Systems (GIS), and geoprocessing to quantify these processes.

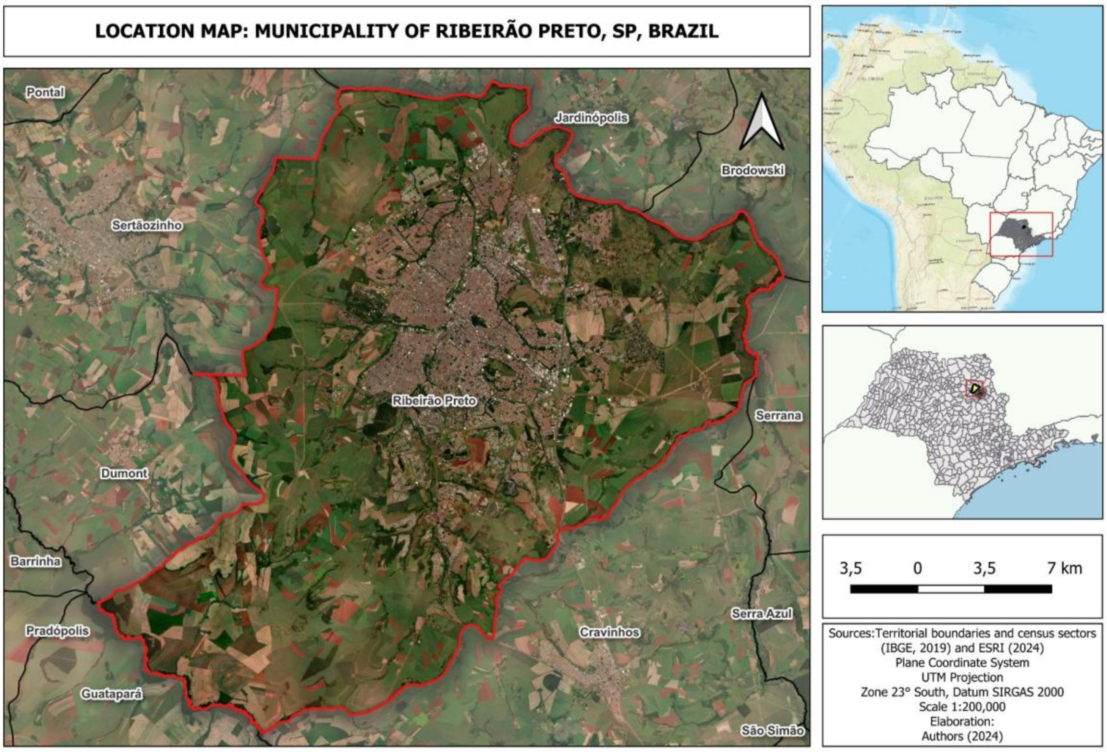
The relevance of this work lies in its contribution to the development of strategies for mitigating the effects of climate change in urban areas, particularly in Brazilian cities. The analysis of sustainable urban planning practices, combined with the use of environmental monitoring technologies, is essential for promoting more resilient and sustainable urban growth. In this way, the results obtained may support the formulation of public policies that prioritize the expansion of urban green cover, not only as a tool for mitigating heat islands but also as a resource for carbon capture, in alignment with Brazil's commitments in the fight against climate change.

3 METHOD

3.1 Study Area

The study was conducted in the municipality of Ribeirão Preto, located in the northeastern region of the State of São Paulo, southeastern Brazil, with a total area of 651 km² (Figure 1). The estimated population is 698,642 inhabitants, making it the eighth most populous municipality in the state (IBGE, 2024). According to data from IBGE, the vast majority of the population (99.7%) resides in the urban area of the municipality (Ribeirão Preto, 2024a).

Figure 1 – Map of the Municipality of Ribeirão Preto (SP), Brazil.



Source: the authors.

Ribeirão Preto is located in a transitional zone between the Seasonal Semideciduous Forest and the Cerrado (Brazilian savanna). The local vegetation is characterized by leaf shedding during periods of intense drought (Kotchetkoff-Henriques, 2003; Veloso et al., 1991). The climate is tropical, with rainy summers and dry winters. Average temperatures range from 19 °C in winter to 25 °C in summer (Rolim et al., 2007). Annual precipitation is approximately 1400 mm, with 80% of rainfall occurring between October and March, while the June–August period is drier (5% of rainfall) (IPT, 1999).

3.2 Remote Sensing Analyses

As The analyses were conducted using high spatial resolution images obtained from the Landsat 8 satellite, sensors OLI (Operational Land Imager) and TIRS (Thermal Infrared Sensor), made available through the EarthExplorer platform of the United States Geological Survey (USGS) (USGS, 2024). The Landsat Program aims to continuously monitor the Earth's surface, with applications in areas such as the environment, land use, agriculture, hydrology, geology, forestry, and urban areas (Acharya; Yang, 2015).

Para For this study, the following Landsat 8 spectral bands were used:

- Band 2 - Blue (0.450 - 0.51 µm) 30 m;
- Banda 3 - Green (0.53 - 0.59 µm) 30 m;
- Banda 4 - Red (0.64 - 0.67 µm) 30 m;
- Banda 5 – Near Infrared (0.85 - 0.88 µm) 30 m;

- Banda 10 – Termal Infrared/TIRS 1 (10.6 - 11.19 µm) 100 m resolution, resampled to 30 m.

The images were processed using QGIS software, including steps such as reprojection, study area clipping, and radiometric calibration (Coelho; Correa, 2013).

3.2.1 Land Surface Temperature

Landsat 8 Band 10 was used to generate the land surface temperature (LST) map. First, atmospheric correction of the image was performed. Then, the brightness temperature was converted into land surface temperature using physical models that take into account the surface's thermal properties (Coelho; Correa, 2013). For Landsat 8 thermal Band 10, a commonly used equation is:

$$LST = \frac{K2}{ln\left(\frac{K1}{(DN \, * \, M + A)} + 1\right)} - 273.$$

Where:
LST: Land Surface Temperature.
DN: Digital number of the thermal band.
M e A: Calibration coefficients to convert the digital number into spectral radiance.

3.2.2 Normalized Difference Vegetation Index (NDVI)

NDVI, an indicator of vegetation quantity and vigor, was calculated using Bands 4 (Red) and 5 (Near Infrared) of Landsat 8. NDVI is associated with biomass and the carbon sequestration potential and is calculated using the following equation:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

Where:
NDVI: Normalized Difference Vegetation Index.
NIR: Reflectance in the Near Infrared band.
Red: Reflectance in the Red band.

NDVI values range from -1 to 1. Values near 1 indicate high vegetation density, while values close to -1 correspond to areas with little or no vegetation (such as water bodies or bare soil). Values around zero indicate areas with cloud cover or soil exposure.

3.2.3 Simplified Photochemical Reflectance Index (sPRI)

The Photochemical Reflectance Index (PRI) (Santos, 2017) is used in vegetation studies and employs blue and green spectral bands from satellite imagery to estimate the photosynthetic activity of plants. It is particularly sensitive to changes in photosynthetic pigments such as chlorophyll and carotenoids and is linked to light use efficiency during photosynthesis (Baptista, 2003). Variations in the ratio of these pigments may indicate changes in photosynthetic efficiency. PRI values must be rescaled to avoid negative data, resulting in the Simplified Spectral Photosynthesis Index (sPRI).

$$PRI = \frac{(Blue - Green)}{(Blue + Green)}$$

$$sPRI = \frac{(PRI \ + 1)}{2}$$

Where:
PRI: Photochemical Reflectance Index.
sPRI: Simplified Spectral Photosynthesis Index.
Band 2 (Blue): Sensitive to changes in carotenoid pigments, related to photosynthesis.
Band 3 (Green): Also used in PRI calculation, together with the blue band.

3.2.4 CO_2 Flux (CO2FLUX)

The CarbonFlux method is based on the combination of remote sensing data and in situ measurements to estimate carbon fluxes, allowing the identification of net photosynthetic rates in vegetated landscapes such as urban parks (Rahman et al., 2000).

The estimate is built upon the combination of two parameters:

- Absorbed Photosynthetically Active Radiation (APAR): Represented by the NDVI, which quantifies light absorption by vegetation.
- Light Use Efficiency (LUE): Represented by the PRI, which reflects variations in xanthophyll pigments, indicators of photosynthetic activity.

CO2FLUX is an important indicator of the photosynthetic capacity of vegetation and, consequently, its carbon sequestration potential. This tool has proven useful for analyzing remote sensing data. This spectral index is calculated using NDVI and sPRI (Rahman et al., 2000). It aims to determine the relative rate of photosynthetic capacity, establishing a direct connection with atmospheric carbon capture and fixation processes.

$$CO2FLUX = NDVI \ * \ sPRI$$

Where:
CO2FLUX: CO_2 Flux.
NDVI: Normalized Difference Vegetation Index.
sPRI: Simplified Photochemical Reflectance Index.

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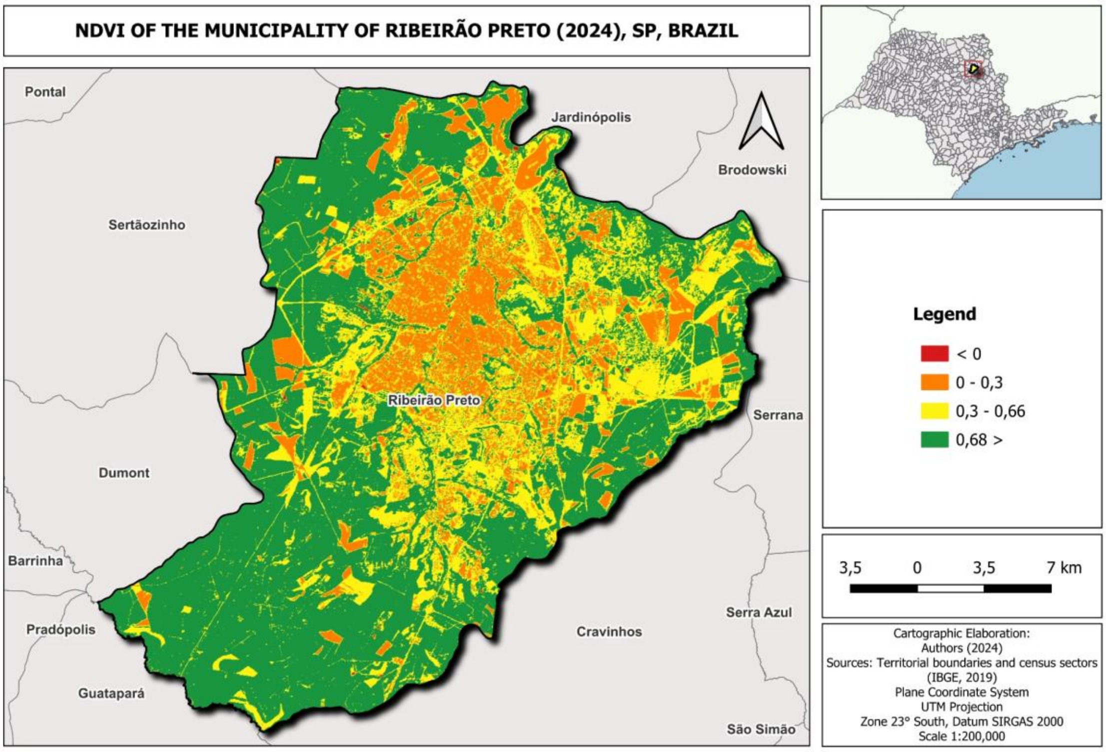
4. RESULTS E DISCUSSION

This study analyzed the role of urban vegetation in mitigating urban heat islands and carbon sequestration in Ribeirão Preto (SP), using remote sensing techniques, Geographic Information Systems (GIS), and geoprocessing. Based on the analysis of spectral indices such as the NDVI (Normalized Difference Vegetation Index) and CO2FLUX, as well as surface temperature, it was possible to identify correlations between vegetation cover density, carbon sequestration potential, and urban thermal regulation.

The NDVI results (Figure 2) revealed significant variability in vegetation cover across the municipality.

Figure 2 – Normalized Difference Vegetation Index map for Ribeirão Preto (SP), Brazil.



Source: the authors.

NDVI values (Figure 2) were classified into four intervals: values below zero indicate non-vegetated targets or vegetation with no activity, such as exposed soil and highly paved urban areas; values between 0 and 0.3 (orange) represent areas with sparse vegetation, such as paved and built-up urban and industrial zones, early-stage crop fields, and partially exposed soil; values from 0.3 to 0.66 (yellow) indicate moderate vegetation density, such as crops at intermediate growth stages and urban vegetation in parks and squares; and values from 0.66 to 1 (green) indicate fully healthy vegetation or vegetation in advanced stages of development, including forest mosaics, protected areas such as conservation units, riparian vegetation, and advanced-stage crop fields.

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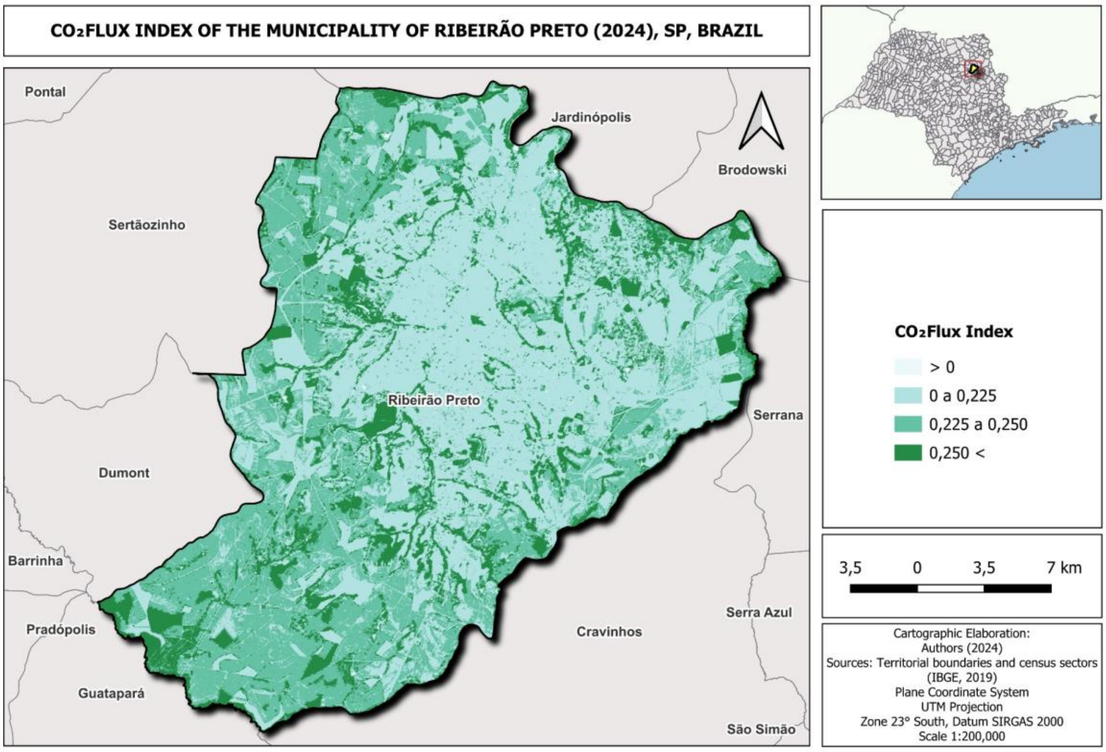
Based on the NDVI and sPRI indices, the CO2FLUX Index was generated (Figure 3), indicating areas with the highest potential for carbon sequestration in the municipality.

Figure 3 – CO2FLUX Index map for Ribeirão Preto (SP), Brazil



Source: the authors.

The results corroborate the findings of Yin et al. (2022), who observed higher carbon sequestration in forested areas compared to agricultural and pasture lands. It was observed that the highest CO2FLUX index values were found along the fringes of the city's urban core. The areas with the highest levels of carbon sequestration are: the southern zone, represented by the Ribeirão Preto Ecological Station, which spans 154 hectares (São Paulo, 2010); the western zone, including the University of São Paulo (USP) campus, with approximately 168.95 hectares of vegetation (USP, 2017; Varanda et al., 2005); and portions of the eastern region, where the Municipal Park "Prefeito Luiz Roberto Jábali" and other vegetation fragments and riparian forests with strong vitality are located.

Another area with high CO2FLUX values is located near the city center, consisting of two conservation units: the Municipal Environmental Protection Area (APA) "Morro do São Bento" and the State APA "Morro do São Bento" (Ribeirão Preto, 2024b; São Paulo, 2024). The results observed in these densely forested areas indicate greater carbon sequestration efficiency, consistent with findings by Andrade et al. (2023) in preservation areas in São Gonçalo (RJ), and Baptista (2003) in tropical cerrado environments. Rowntree and Nowak (1991) also observed a relationship between carbon sequestration and forest cover levels in urban forests in the United States, highlighting that areas with greater tree density have a higher capacity to store and sequester carbon.

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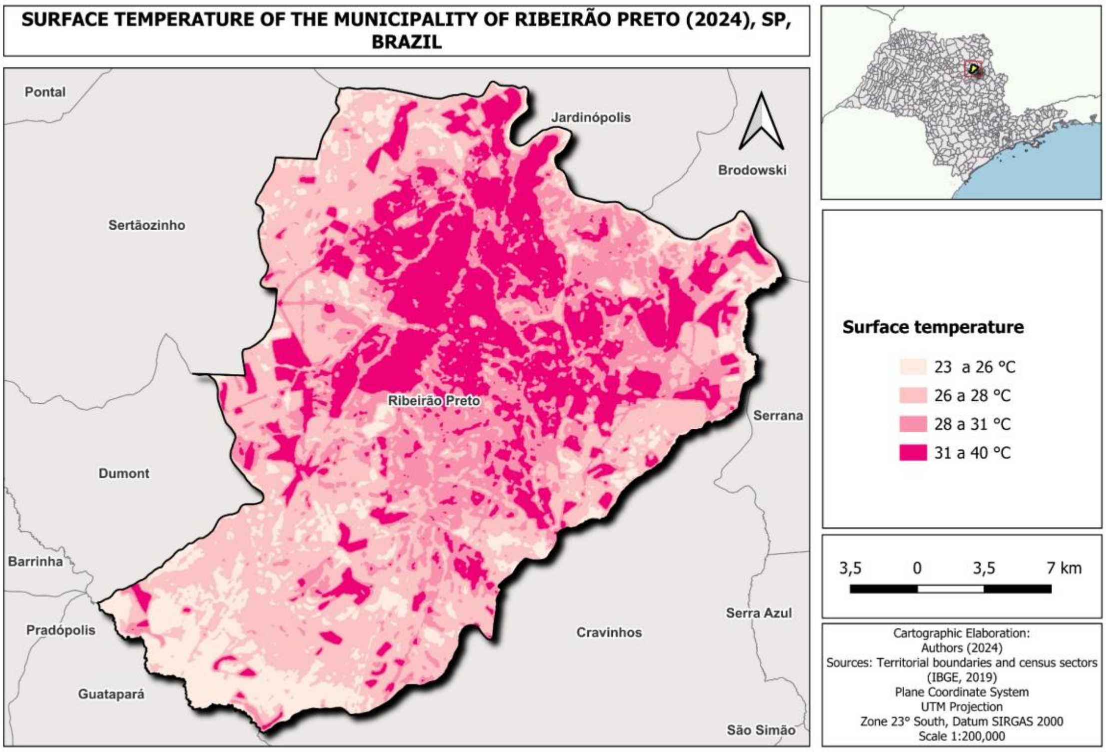
Figure 4 – Land Surface Temperature map for Ribeirão Preto (SP), Brazil.



Source: the authors.

The land surface temperature map (Figure 4) reveals the occurrence of urban heat islands in Ribeirão Preto. The temperature mapping was also categorized into four classes using equal count (quartiles): 23–26 °C, 26–28 °C, 28–31 °C, and 31–40 °C. The highest temperatures (dark pink) were concentrated in areas with greater urban density and in agricultural zones with exposed soil, corroborating the findings of Gomes et al. (2021). Conversely, areas with denser vegetation cover, especially in the southern, far western, and eastern zones of the municipality, showed lower temperatures, forming so-called cool islands.

To better understand the spatial correlation between the two variables—CO2FLUX and surface temperature—a bivariate legend map was generated (Figure 5), allowing the intensity of each variable to be interpreted according to the tonal scale.

By analyzing the CO2FLUX index and surface temperatures together, a strong correlation becomes apparent between carbon sequestration levels and surface temperatures. Areas with denser vegetation cover, especially those with tree canopies, tend to exhibit lower surface temperatures and higher levels of carbon storage, as indicated by the CO2FLUX index. These areas act as thermal regulators and contribute to mitigating the urban heat island effect by lowering local temperatures and enhancing carbon sequestration.

Meanwhile, areas with higher population densities—particularly in the northern, western, central, and part of the eastern regions—present higher surface temperatures. These areas have low vegetation cover, resulting in greater absorption and retention of heat due to

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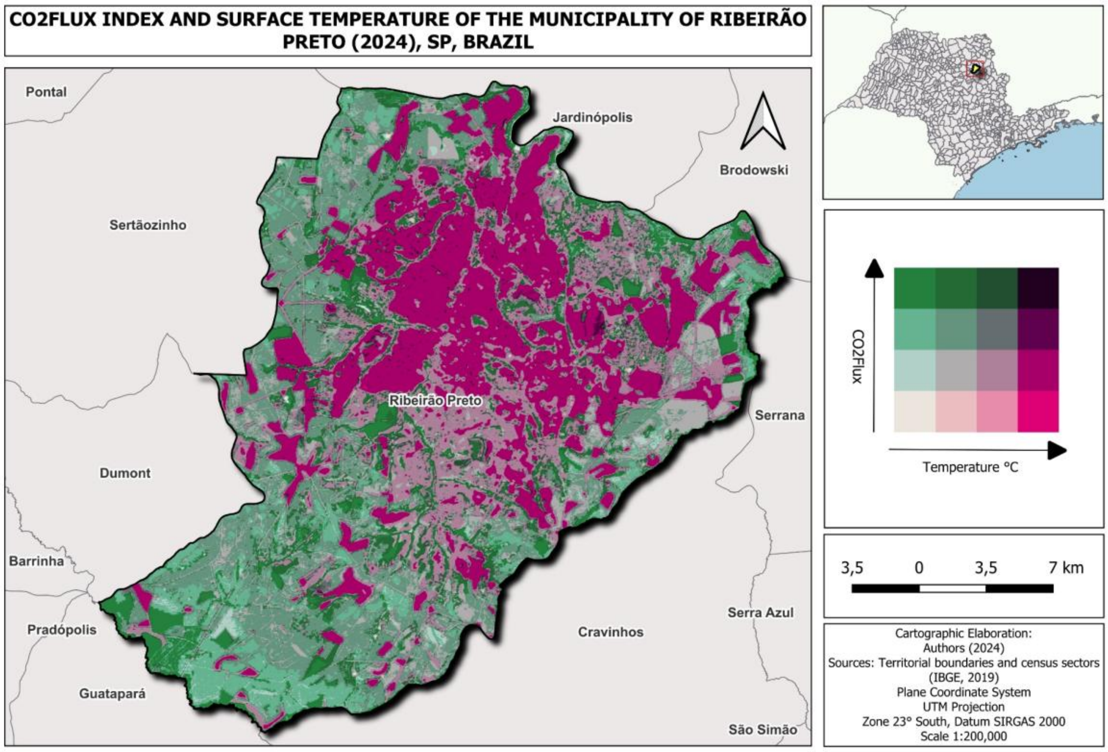
the predominance of built surfaces such as concrete and asphalt, which have high thermal storage capacity and low reflectance (Jabbar et al., 2023; Stewart; Oke, 2010).

Figure 5 – Map representing the correlation between Land Surface Temperature and CO2FLUX in Ribeirão Preto (SP), Brazil.



Source: the authors.

This inverse relationship between vegetation, carbon sequestration, and surface temperature was also observed by Zhang et al. (2020), who studied the watershed of the Ludila and Guanyinyan hydroelectric plants in China, as well as by Nova et al. (2021), who analyzed the relationship between heat islands and vegetation indices in Recife (PE).

Similarly, Terra-Oliveira, Ganem e Baptista (2017) demonstrated the importance of vegetated areas in reducing surface temperatures in urban zones, emphasizing the role of carbon sequestration in this process in the cities of São Paulo, Rio de Janeiro, Belo Horizonte, and Brasília.

5. FINAL CONSIDERATIONS

This study highlighted the importance of urban vegetation in mitigating heat islands and promoting carbon sequestration in Ribeirão Preto (SP), emphasizing the crucial role of green areas in urban climate regulation. The use of remote sensing techniques, Geographic Information Systems (GIS), and geoprocessing proved to be an effective approach for environmental monitoring, providing valuable input for sustainable urban planning.

The results showed that areas with greater vegetation cover presented higher levels of carbon sequestration and significantly lower surface temperatures. In contrast, densely built-up urban areas with limited vegetation registered higher temperatures, confirming the presence of urban heat islands. These findings reinforce the need to expand and preserve green spaces in cities as a key strategy for promoting urban resilience and improving quality of life.

In the context of smart cities, this study contributes to the integration of advanced technologies in environmental monitoring and management. The application of tools such as remote sensing and GIS allows for precise, real-time analysis of environmental conditions, facilitating evidence-based decision-making. Furthermore, the results can support the development of innovative public policies aimed at urban sustainability, fostering socio-environmental equity and addressing climate change.

The contributions of this study go beyond the academic field, directly impacting urban planning and the formulation of strategies for the development of more sustainable and resilient cities. The experience of Ribeirão Preto can serve as a reference for other mid-sized cities in Brazil and around the world, demonstrating the importance of integrating technology, the environment, and urban planning.

Thus, it is concluded that promoting urban sustainability largely depends on the ability of cities to integrate technological solutions with the efficient management of natural resources, thereby strengthening resilience and the quality of life of the urban population. Encouraging the expansion of green areas and the use of environmental monitoring technologies should be viewed as a priority in the agenda for smart and sustainable urban development.

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DECLARATIONS

AUTHORS' CONTRIBUTIONS

Cristiano Capellani Quaresma was responsible for the conception and design of the study, including the definition of the central research objectives. The definition of the methodologies employed involved the participation of all authors. Data collection and processing, as well as mapping procedures, were led by Patrícia do Prado Oliveira. The development of the theoretical framework was carried out by Matheus Felipe Conceição Alves de Lima and Cristiano Capellani Quaresma. The first draft of the manuscript, including the writing and discussion of the results in light of the literature, was prepared by Matheus Felipe Conceição Alves de Lima. The critical revision of the text, aimed at deepening the discussions and enhancing the clarity and coherence of the manuscript, was conducted by Cristiano Capellani Quaresma, with contributions from the other authors. The final version of the article was reviewed and revised by all authors.

CONFLICT OF INTEREST STATEMENT

We, Matheus Felipe Conceição Alves de Lima, Patrícia do Prado Oliveira, and Cristiano Capellani Quaresma, declare that there are no financial, professional, or personal conflicts of interest related to the content of the manuscript entitled "Smart Cities and Climate Resilience: The Role of Urban Vegetation in Thermal Regulation and Carbon Sequestration in Ribeirão Preto, SP." This work was funded by a Research Productivity Grant (CNPq 316808/2023-7) awarded to Cristiano Capellani Quaresma and a Master's scholarship from CAPES granted to Matheus Felipe Conceição Alves de Lima, with no influence on the results or interpretations presented.