



URBAN EXPANSION, VEGETATION COVER, AND LAND SURFACE
TEMPERATURE IN A MEDIUM-SIZED BRAZILIAN CITY: AN INTRA-URBAN
ANALYSIS OF VITÓRIA DA CONQUISTA, BAHIA

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Abstract *This study analyzed the relationships among urban expansion, vegetation cover, and land surface temperature (LST) across the neighborhoods of Vitória da Conquista, Bahia, Brazil, between 2019 and 2025. Land-use and land-cover data, the Normalized Difference Vegetation Index (NDVI), and LST were analyzed using temporal trend analyses, Spearman correlations, and neighborhood and year fixed-effects models. During the study period, the urbanized area increased by 31.1%, while native vegetation decreased by 15.6%, although these changes occurred heterogeneously across neighborhoods. The intensity of urban expansion was not significantly associated with changes in vegetation, NDVI, or LST. However, neighborhoods with a higher initial proportion of native vegetation tended to experience greater losses of this cover ($p = -0.568$; $p = 0.004$), highlighting the importance of pre-existing landscape conditions in shaping environmental trajectories. After controlling for interannual variability, native vegetation showed the strongest negative association with LST ($p = -0.440$; $p < 0.001$), whereas the relationship between urbanized area and temperature was weaker ($p = 0.154$; $p = 0.046$). However, the longitudinal models did not identify significant within-neighborhood effects. The results highlight the importance of conserving vegetation cover during urban expansion and reinforce the need to consider initial landscape conditions and distinguish spatial patterns from temporal responses.*

Keywords: *NDVI; remote sensing; landscape dynamics; thermal environment; territorial planning.*

EXPANSÃO URBANA, COBERTURA VEGETAL E TEMPERATURA DE
SUPERFÍCIE EM UMA CIDADE MÉDIA BRASILEIRA: UMA ANÁLISE
INTRAURBANA DE VITÓRIA DA CONQUISTA, BAHIA

Resumo Este estudo analisou as relações entre expansão urbana, cobertura vegetal e temperatura de superfície terrestre (LST) nos bairros de Vitória da Conquista, Bahia, entre 2019 e 2025. Foram utilizados dados de uso e cobertura da terra, Índice de Vegetação por Diferença Normalizada (NDVI) e LST, combinados com análises de tendência temporal, correlações de Spearman e modelos com efeitos fixos de bairro e ano. No período, a área urbanizada aumentou 31,1%, enquanto a vegetação nativa diminuiu 15,6%, embora essas transformações tenham ocorrido de forma heterogênea entre os bairros. A intensidade da expansão urbana não apresentou associação significativa com as mudanças na vegetação, no NDVI ou na LST. Entretanto, bairros com maior proporção inicial de vegetação nativa tenderam a apresentar perdas mais acentuadas dessa cobertura ($p = -0,568$; $p = 0,004$), evidenciando a importância das condições preexistentes da paisagem para as trajetórias ambientais. Após o controle da variabilidade interanual, a vegetação nativa apresentou a associação negativa mais forte com a LST ($p = -0,440$; $p < 0,001$), enquanto a relação entre área urbanizada e temperatura foi mais fraca ($p = 0,154$; $p = 0,046$). Os modelos longitudinais, contudo, não identificaram efeitos significativos dentro dos bairros. Os resultados destacam a importância da conservação da cobertura vegetal durante a expansão urbana e reforçam a necessidade de considerar as condições iniciais da paisagem e distinguir padrões espaciais de respostas temporais.

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Palavras-chave: NDVI; Sensoriamento remoto; Dinâmica da paisagem; Ambiente térmico; Planejamento territorial.

1 Introduction

Urban expansion is one of the main contemporary processes driving landscape transformation, altering the distribution of natural land cover and the environmental structure of cities (Richards; Belcher, 2020). The expansion of built-up areas is often accompanied by the conversion or fragmentation of vegetated areas, although the intensity of these changes varies both among cities and within the same urban area (Barrera; Henríquez, 2017). Richards and Belcher (2020) demonstrated that urbanization and vegetation cover may follow distinct trajectories, including vegetation loss, persistence, or localized gains. This heterogeneity was also identified by Barrera and Henríquez (2017), indicating that urban expansion does not necessarily produce spatially uniform environmental changes.

Among the consequences of these transformations are changes in the urban thermal environment (Estoque; Murayama; Myint, 2017). The replacement of vegetated surfaces with built-up materials alters the energy balance, evapotranspiration, and heat storage. In this context, vegetation plays an important role in thermal regulation through shading and evapotranspiration (Shiflett *et al.*, 2017). Studies conducted in different urban environments have identified a negative association between vegetation indices and land surface temperature (LST), with more vegetated areas generally exhibiting relatively lower temperatures (Shiflett *et al.*, 2017). Estoque, Murayama, and Myint (2017) further demonstrated that not only the amount but also the composition and configuration of the landscape influence the spatial distribution of LST.

The relationship between urbanization and vegetation, however, is not necessarily linear (Yang *et al.*, 2021). The thermal response to urbanization also depends on characteristics such as building density, imperviousness, vegetation distribution, and the spatial configuration of land cover (Meng *et al.*, 2022). Meng *et al.* (2022) showed that the influence of landscape components on LST also depends on the scale and spatial configuration considered. Moreover, neighborhoods experiencing similar levels of urban expansion may follow different trajectories of vegetation conservation or loss (Barrera; Henríquez, 2017; Richards; Belcher, 2020), making it insufficient to interpret environmental changes solely on the basis of the extent of land converted to urban uses.

Another important issue concerns the temporal dimension of these relationships. LST is highly sensitive to meteorological conditions and interannual variability (Yao *et al.*, 2018; Guo *et al.*, 2022), which may hinder the identification of trends associated with changes in land cover. Shu *et al.* (2024), for example, identified substantial temporal variation in the relationship between vegetation and LST. Consequently, spatial associations between more vegetated neighborhoods



and lower temperatures do not necessarily imply that short-term changes in vegetation produce equivalent thermal changes within those same neighborhoods.

This distinction has received comparatively less attention in studies based predominantly on spatial associations or multitemporal comparisons between land cover and LST, particularly given the high temporal variability of these relationships (Shu *et al.*, 2024). Using an approach based on intra-urban changes, Jun *et al.* (2024) demonstrated that changes in vegetation and impervious surfaces may contribute to changes in LST, highlighting the importance of distinguishing spatial patterns from temporal relationships.

In this context, this study analyzes the relationships among urban expansion, vegetation cover, and land surface temperature across the neighborhoods of Vitória da Conquista, Bahia, Brazil, between 2019 and 2025. The study seeks to identify environmental trajectories associated with urban growth and to assess how urbanized area, native vegetation, and the Normalized Difference Vegetation Index (NDVI) relate to intra-urban thermal differentiation. In addition, spatial and longitudinal associations are compared to assess whether environmental differences among neighborhoods are also manifested as changes over time within the same territorial units.

2 Materials and Methods

2.1 Study area and units of analysis

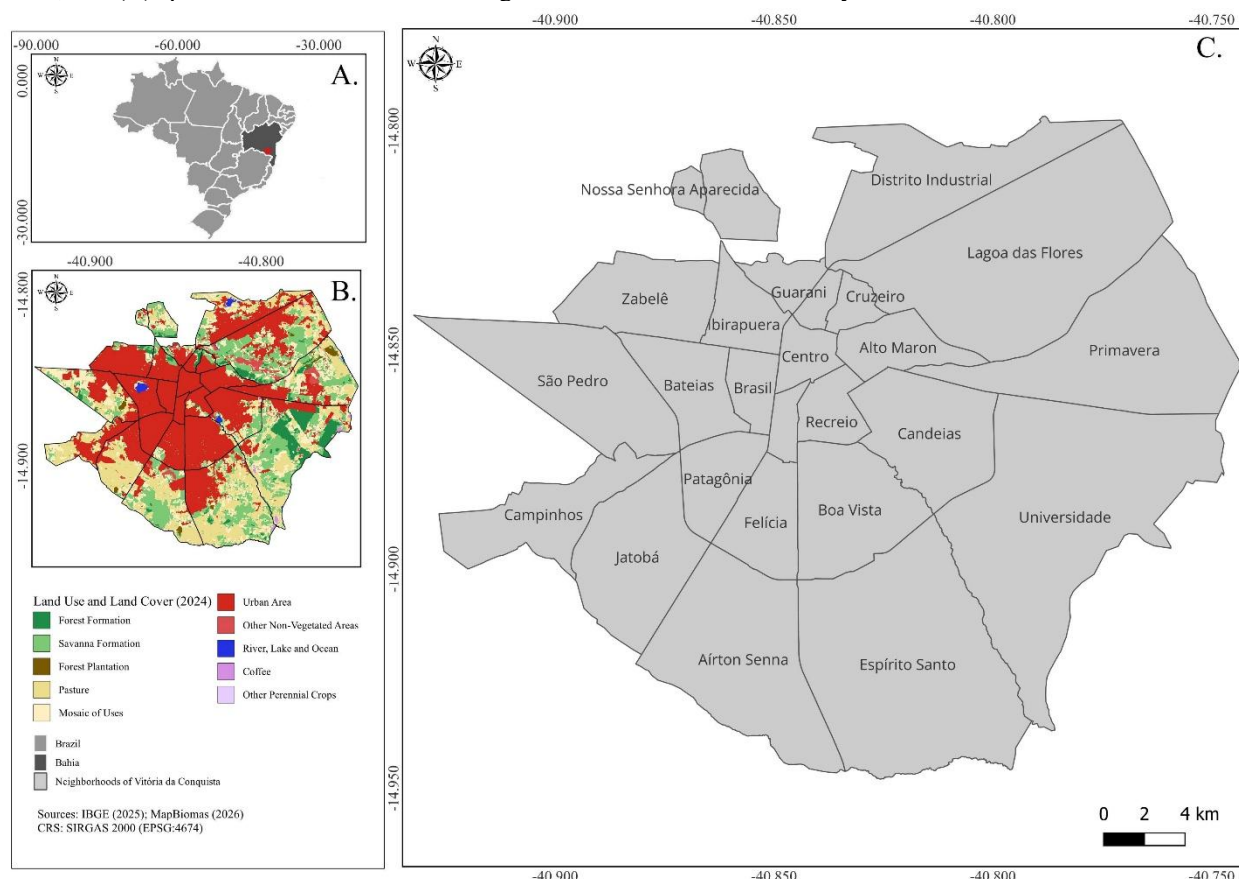
The study was conducted in Vitória da Conquista, a municipality located in southwestern Bahia, Brazil (Figure 1). According to the 2022 Population Census, the municipality had a population of 370,879 inhabitants, a population density of 113.97 inhabitants km⁻², and an urbanized area of 97.13 km². Within the Brazilian urban hierarchy, Vitória da Conquista is classified as a Regional Capital B and serves as an important regional center for commerce, services, education, and healthcare (IBGE, 2026; Porto; Santana Júnior; Nascimento, 2017). Characterized as a medium-sized city, Vitória da Conquista has undergone an urbanization process marked by the expansion of the urban fabric and spatially differentiated transformations between consolidated areas and areas of more recent growth (Chaves, 2016; Santos; Ferraz, 2020; Oliveira, 2026).

The analysis included the 24 neighborhoods comprising the urban area examined in this study. Neighborhood boundaries were obtained from the neighborhood spatial dataset provided by the Brazilian Institute of Geography and Statistics (IBGE), associated with the 2022 Population Census (IBGE, 2024). Neighborhoods were adopted as the spatial units for integrating and comparing information on land use and land cover, vegetation, and land surface temperature.

The spatial datasets were clipped to neighborhood boundaries and organized into a panel data structure covering the period from 2019 to 2025. Each neighborhood was assessed annually,

resulting in a total of 168 neighborhood-year observations. This structure allowed us to examine both environmental differences among neighborhoods and changes within neighborhoods over time.

Figure 1. Location of the study area and spatial characterization of Vitória da Conquista, Bahia, Brazil. (A) Location of the municipality within the state of Bahia and Brazil; (B) land use and land cover in the urban area in 2024; and (C) spatial distribution of the 24 neighborhoods included in the analyses.



Source: Prepared by the authors based on data from IBGE (2024) and MapBiomas (2026).

2.2 Environmental data and variable processing

Land use and land cover dynamics were analyzed using annual data from MapBiomas 10 m, Collection 4, at a spatial resolution of 10 m, for the period from 2019 to 2025. The classifications were clipped to the boundaries of the 24 neighborhoods and used to quantify the area occupied by forest, savanna formation, forest plantation, pasture, temporary and perennial crops, mosaic of uses, urbanized area, non-vegetated areas, and water bodies. MapBiomas produces land use and land cover time series from remote sensing imagery and automated classification procedures, enabling the monitoring of landscape transformations at high spatial resolution (MapBiomas, 2026).

For the main analyses, two landscape components were defined. Native vegetation corresponded to the sum of class 3, Forest, and class 4, Savanna Formation, whereas urbanized



area was represented by class 24. For each neighborhood and year, areas were calculated in hectares based on pixel area and subsequently converted into proportions of the total neighborhood area. This procedure allowed comparisons among spatial units of different sizes and enabled temporal changes to also be expressed in percentage points.

Vegetation condition was estimated using the Normalized Difference Vegetation Index (NDVI), calculated from Sentinel-2 Surface Reflectance Harmonized imagery from the COPERNICUS/S2_SR_HARMONIZED collection. The index was calculated as the normalized difference between the near-infrared and red bands, B8 and B4, respectively, following the formulation proposed by Rouse *et al.* (1974). Before calculation, cloud and shadow masking was performed using the Scene Classification Layer (SCL), excluding pixels classified as cloud shadows, medium- and high-probability clouds, cirrus, and snow/ice. Only images with less than 60% cloud cover were included.

To reduce seasonal effects and ensure comparability among years, only images acquired between July and October were considered. After applying the selection criteria, 30 images were used in 2019, 30 in 2020, 27 in 2021, 24 in 2022, 34 in 2023, 24 in 2024, and 39 in 2025. For each year, a composite was generated using the median NDVI values, after which the mean, median, and 10th and 90th percentiles were extracted for each neighborhood. Although the original processing covered the period from 2017 to 2025, the main analyses were restricted to 2019–2025, corresponding to the interval with greater consistency of observations across the sensors used.

Land surface temperature (LST) was obtained from the Landsat 8 and Landsat 9 Collection 2, Tier 1, Level 2 collections, LANDSAT/LC08/C02/T1_L2 and LANDSAT/LC09/C02/T1_L2. Quality control was performed using the QA_PIXEL band, removing pixels classified as dilated cloud, cirrus, cloud, and cloud shadow. LST was derived from the ST_B10 thermal band by applying the scale factor of 0.00341802 and the offset of 149.0, followed by conversion from Kelvin to degrees Celsius, according to the specifications of the Landsat Collection 2 Level 2 product (USGS, 2024).

As with NDVI, only images acquired between July and October of each year were used. After image selection and quality-control procedures, 21 images were used in 2019, 19 in 2020, 19 in 2021, 46 in 2022, 38 in 2023, 40 in 2024, and 42 in 2025. The images were combined using annual median composites, and the mean, median, and 10th and 90th percentiles of LST were calculated for each neighborhood. Zonal statistics were obtained at a spatial resolution of 30 m, consistent with the processing of the Landsat thermal bands.

All geospatial processing was performed in Google Earth Engine, a cloud-based computing platform designed for the analysis of large geospatial datasets (Gorelick *et al.*, 2017). Annual information on land use and land cover, native vegetation, urbanized area, NDVI, and LST was



integrated using the unique identifier of each neighborhood, resulting in a longitudinal dataset comprising 168 neighborhood-year observations for the 24 neighborhoods monitored from 2019 to 2025.

2.3 Analysis of spatiotemporal changes

Changes in urbanized area, native vegetation, NDVI, and land surface temperature were assessed between 2019 and 2025, considering both the overall dynamics of the study area and the individual trajectories of the 24 neighborhoods. For variables expressed as proportions of neighborhood area, changes between the initial and final years were calculated in percentage points. For NDVI and LST, changes were calculated as the differences between the corresponding annual values.

Temporal trends were assessed using the nonparametric Mann–Kendall test, which allows the detection of monotonic trends without requiring normally distributed data (Mann, 1945; Kendall, 1975). The direction and strength of the trend were represented by Kendall's τ coefficient, with statistical significance assessed at $p < 0.05$. To quantify the magnitude of changes over time, Sen's slope estimator (Sen, 1968) was used, expressed in the original unit of each variable per year. The analyses were conducted for the overall time series and separately for each neighborhood, depending on the variable analyzed.

LST was additionally analyzed using annual anomalies to reduce the influence of thermal fluctuations common to the entire study area and distinguish them from neighborhood-specific changes. For each neighborhood-year observation, the anomaly was calculated as the difference between the neighborhood LST and the mean LST of the 24 neighborhoods in the corresponding year. Thus, positive values indicated neighborhoods that were relatively warmer, whereas negative values indicated neighborhoods that were relatively cooler compared with the citywide annual thermal pattern. Trends in these anomalies were then assessed using the Mann–Kendall test to determine whether persistent thermal changes occurred independently of the common interannual variability.

To investigate whether the intensity of urban expansion was associated with other environmental transformations, changes between 2019 and 2025 were calculated for each neighborhood, and their relationships with changes in native vegetation, NDVI, and LST were assessed using Spearman's rank correlation coefficient (Spearman, 1904). The same procedure was used to examine the association between urban expansion and trends in thermal anomalies. In addition, we assessed whether initial landscape conditions were associated with the magnitude of subsequent transformations by relating the proportion of native vegetation in 2019 to its change between 2019 and 2025, and the initial proportion of urbanized area to the expansion observed



over the study period. The use of a nonparametric measure allowed monotonic relationships to be assessed without assuming linearity or normally distributed variables.

These procedures allowed us to distinguish three complementary dimensions of intra-urban dynamics: the direction and magnitude of trends over the study period, the cumulative changes between 2019 and 2025, and differences in the environmental trajectories of the neighborhoods. This approach made it possible to assess not only whether neighborhoods experiencing similar intensities of urban expansion exhibited similar responses in vegetation cover and thermal conditions, but also whether these transformations were associated with the land-cover conditions present at the beginning of the study period.

2.4 Relationships Between Landscape Cover and Land Surface Temperature

The relationships among urbanized area, native vegetation, NDVI, and land surface temperature were initially assessed using Spearman's rank correlation coefficient (Spearman, 1904). This nonparametric approach was used to identify the direction and strength of the associations among variables across the full set of neighborhood-year observations. The relationships between LST and NDVI, native vegetation, and urbanized area were examined, as were the associations among the landscape components themselves.

Because LST exhibited substantial interannual variability shared across neighborhoods, the associations were also estimated after controlling for year effects. To this end, the shared temporal variability was removed from the variables before calculating the correlations, allowing us to assess whether differences among neighborhoods remained associated independently of annual fluctuations. This analysis was used to distinguish predominantly spatial relationships from associations influenced by year-specific conditions.

To investigate whether the relationships observed among neighborhoods were also manifested over time within the same spatial units, neighborhood and year fixed-effects models were estimated using a two-way fixed effects (TWFE) specification. This approach controls for time-invariant neighborhood characteristics and temporal factors common to all units, allowing the coefficients to be estimated from changes occurring within each neighborhood over time (Wooldridge, 2010).

LST was defined as the dependent variable, while NDVI, the proportion of native vegetation, and the proportion of urbanized area were evaluated as explanatory variables. Separate models were estimated for each environmental variable to avoid simultaneously including strongly correlated predictors and thereby reduce potential multicollinearity. The general specification was expressed in Equation 1:

$$LST_{it} = \beta X_{it} + \alpha_i + \lambda_t + \varepsilon_{it} \quad (1)$$

where LST_{it} represents the land surface temperature of neighborhood i in year t , X_{it} corresponds to the environmental variable analyzed, β represents the coefficient associated with within-neighborhood changes in that variable, α_i represents neighborhood fixed effects, λ_t represents year fixed effects, and ε_{it} is the error term.

The interpretation of the models focused on the β coefficient, allowing us to assess whether within-neighborhood changes in vegetation, NDVI, or urbanized area were associated with changes in LST after controlling for time-invariant differences among neighborhoods and temporal variations common to all neighborhoods. This strategy enabled a comparison between the spatial associations identified by the correlation analyses and the longitudinal relationships estimated from intra-urban changes.

All statistical analyses were performed in R version 4.6.1 (R Core Team, 2026), adopting a 5% significance level ($p < 0.05$).

3 Results

3.1 Spatiotemporal dynamics of urbanization and vegetation cover

Between 2019 and 2025, Vitória da Conquista experienced a continuous expansion of urbanized areas accompanied by a reduction in native vegetation (Figure 2a). The urbanized area increased from 5,826.36 to 7,636.32 ha, representing an increase of 1,809.96 ha (31.1%). The trend was positive and statistically significant ($\tau = 1.000$; $p < 0.001$), with an estimated increase of 262.84 ha year⁻¹ according to Sen's slope estimator. Conversely, native vegetation decreased from 4,216.71 to 3,560.98 ha, representing a loss of 655.73 ha (15.6%), with a significant negative trend ($\tau = -0.905$; $p = 0.003$) and an estimated decline of 89.49 ha year⁻¹. This pattern is consistent with processes observed in other Brazilian cities, where the expansion of built-up areas has occurred concurrently with the reduction of vegetated areas. Rocha *et al.* (2024), for example, identified urban expansion in João Pessoa accompanied by a reduction in non-built-up land cover, demonstrating how urban growth can rapidly alter landscape structure.

At the intra-urban scale, the mean proportion of urbanized area increased from 50.37% to 57.89%, an increase of 7.52 percentage points (p.p.), while native vegetation decreased from 12.99% to 11.25% (-1.74 p.p.). Urban expansion was spatially widespread, with significant positive trends in 22 of the 24 neighborhoods, although its intensity varied considerably. This heterogeneity is an important feature of urban transformations, as growth does not occur uniformly within cities. Remote sensing studies have shown that different urban sectors may follow distinct trajectories of expansion, land-cover conversion, and persistence of vegetation fragments (Reba;



Seto, 2020).

The largest increases in urbanized area occurred in Boa Vista (+20.85 p.p.), Distrito Industrial (+16.03 p.p.), São Pedro (+14.24 p.p.), Bateias (+13.72 p.p.), and Candeias (+12.82 p.p.). Primavera (+10.36 p.p.) and Lagoa das Flores (+10.19 p.p.) also experienced substantial expansion. In contrast, Centro (+0.004 p.p.) and Jurema (+0.23 p.p.) remained virtually stable, highlighting the coexistence of consolidated areas and neighborhoods undergoing more intense transformations. This contrast reinforces the importance of the intra-urban scale, as citywide aggregate analyses may obscure relevant spatial differences in the intensity and location of land-cover changes.

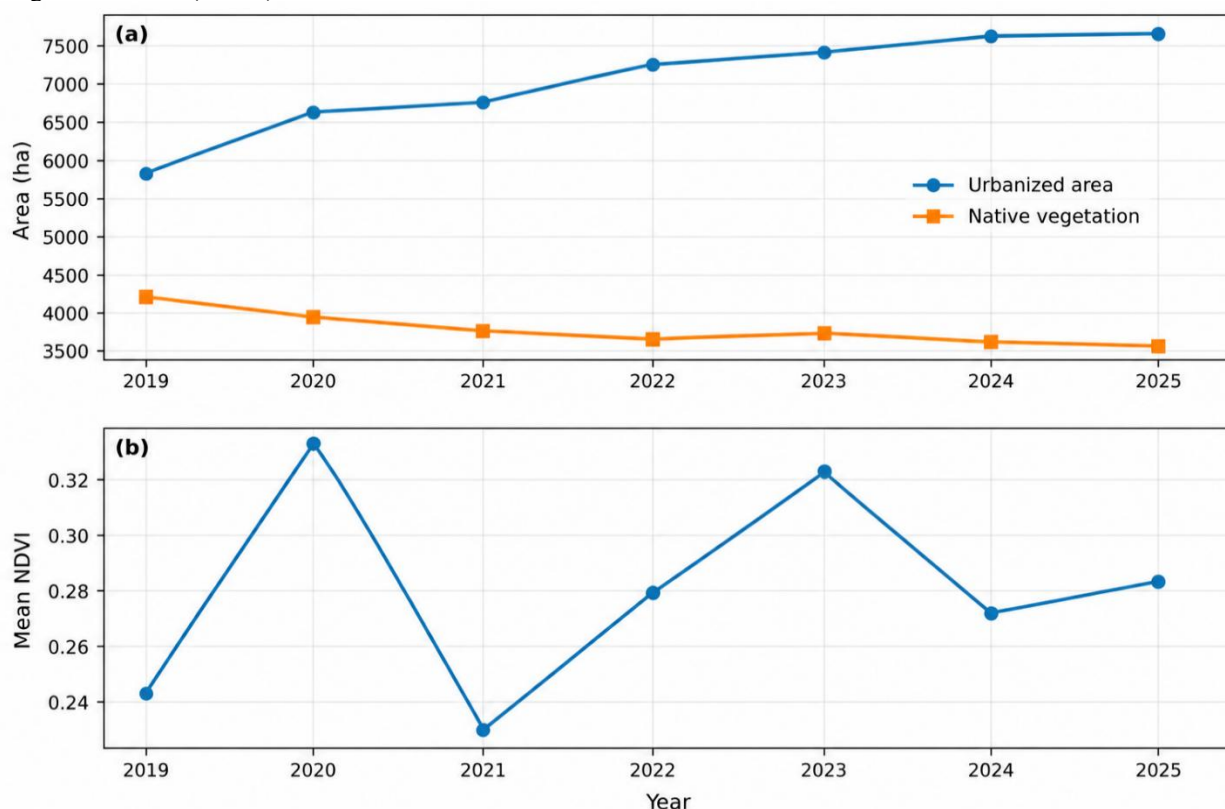
Native vegetation exhibited even greater spatial heterogeneity. The largest declines occurred in Primavera (−11.53 p.p.), Aírton Senna (−5.65 p.p.), Universidade (−5.58 p.p.), Lagoa das Flores (−4.97 p.p.), and Cruzeiro (−4.22 p.p.). However, vegetation loss did not occur proportionally to urban expansion. Bateias, for example, experienced a 13.72 p.p. increase in urbanized area but virtually no change in native vegetation (−0.02 p.p.), whereas Alto Maron combined urban expansion (+4.17 p.p.) with an increase in native vegetation (+1.34 p.p.). Thus, the expansion of urbanized areas does not necessarily imply a direct conversion of native vegetation in the same proportion, as it may involve other land-cover classes and different trajectories of landscape transformation. This nonlinear dynamic has also been identified in multitemporal studies, in which urbanization, vegetation loss, and localized increases in vegetation cover may occur simultaneously (Chaudhuri; Mainali; Mishra, 2022).

NDVI exhibited a pattern distinct from the observed land-cover changes (Figure 2b). Although the mean increased from 0.243 in 2019 to 0.283 in 2025, no significant temporal trend was detected ($\tau = 0.143$; $p = 0.773$). Likewise, none of the 24 neighborhoods showed a significant NDVI trend, indicating greater interannual variability in this indicator compared with the persistent changes in urbanized area and native vegetation. This finding is particularly relevant because it demonstrates that an increase in mean NDVI cannot be directly interpreted as an increase in vegetation extent. Studies conducted in Brazilian cities have also identified distinct trajectories between structural land-cover changes and variations in NDVI. In Brasília, for example, Oliveira *et al.* (2023) observed an increase in NDVI over the time series, whereas studies in Garanhuns identified a stable mean accompanied by greater spatial variability (Bezerra *et al.*, 2021). NDVI reflects the vigor and photosynthetic activity of existing vegetation and may therefore vary in response to seasonal and climatic factors without necessarily representing equivalent changes in the extent of vegetation cover.

Overall, Vitória da Conquista underwent a rapid yet spatially uneven transformation of its landscape between 2019 and 2025. The 31.1% expansion of urbanized area alongside a 15.6%

reduction in native vegetation indicates a trajectory of intensifying urban occupation; however, differences among neighborhoods demonstrate that this process does not follow a simple replacement relationship between built-up surfaces and vegetation. The absence of a significant NDVI trend further supports this interpretation and indicates that vegetation-cover extent and the spectral condition of vegetation represent distinct dimensions of urban environmental quality, supporting their complementary analysis in the subsequent sections.

Figure 2. Temporal dynamics of urbanization and vegetation in Vitória da Conquista, Bahia, Brazil, between 2019 and 2025. (a) Changes in urbanized area and native vegetation; (b) variation in mean Normalized Difference Vegetation Index (NDVI).



Source: Prepared by the authors (2026).

3.2 Temporal and spatial patterns of land surface temperature

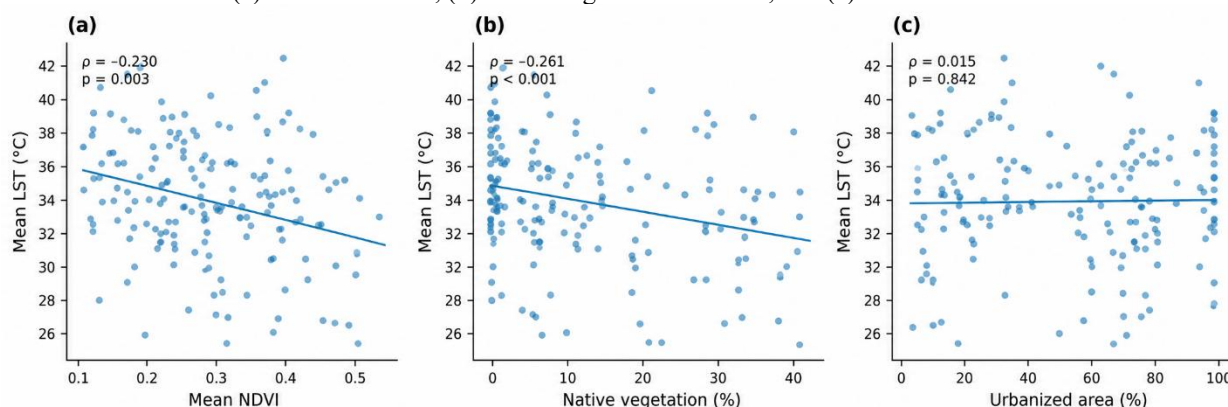
Land surface temperature (LST) exhibited substantial interannual variability between 2019 and 2025, with similar patterns across the neighborhoods of Vitória da Conquista. Differences among years were more pronounced than the trends observed within individual neighborhoods, indicating a strong influence of annual meteorological conditions on intra-urban thermal dynamics. This pattern is consistent with studies showing that urban LST responds not only to urbanization but also to precipitation, solar radiation, and background temperature, and may therefore exhibit substantial fluctuations between consecutive years (Yao *et al.*, 2018; Guo *et al.*, 2022).

Between 2019 and 2025, LST decreased in all 24 neighborhoods, with reductions ranging

from -3.24°C in Zabelê to -8.45°C in Espírito Santo. However, this widespread decrease does not necessarily represent a persistent urban cooling process. After removing the common temporal variability using LST anomalies, none of the 24 neighborhoods exhibited a statistically significant trend ($p > 0.05$). Similar results have been observed in urban thermal time series in which interannual climate variability masks or exceeds short-term local trends, reinforcing the need to distinguish common temporal variability from structural landscape changes (Guo *et al.*, 2022).

Despite this temporal variability, thermal differences among neighborhoods were associated with land-cover characteristics (Figure 3). NDVI was negatively associated with LST ($\rho = -0.230$; $p = 0.003$), as was the proportion of native vegetation ($\rho = -0.261$; $p < 0.001$). In contrast, urbanized area was not significantly associated with LST in the unadjusted analysis ($\rho = 0.015$; $p = 0.842$). The inverse relationship between vegetation and temperature is widely documented in urban environments, where greater vegetation cover tends to reduce surface heating through shading and evapotranspiration (Shiflett *et al.*, 2017; Ziter *et al.*, 2019).

Figure 3. Relationships between land surface temperature (LST), NDVI, native vegetation, and urbanized area across the neighborhoods of Vitória da Conquista, Bahia, Brazil, between 2019 and 2025. The panels show the associations between (a) NDVI and LST, (b) native vegetation and LST, and (c) urbanized area and LST.



Source: Prepared by the authors (2026).

The relatively moderate magnitude of the correlations indicates, however, that vegetation alone does not explain intra-urban thermal differentiation. Studies have shown that LST also responds to building density and height, imperviousness, construction materials, moisture conditions, and the spatial configuration of vegetation cover (Estoque; Murayama; Myint, 2017; Meng *et al.*, 2022). Thus, neighborhoods with greater vegetation cover tend to exhibit relatively more favorable thermal conditions, although this effect depends on the physical and environmental structure of the urban fabric.

The absence of a significant association between the overall proportion of urbanized area and LST in the unadjusted analysis should also be interpreted in this context. Urbanized area is an aggregate measure and does not directly represent the degree of imperviousness, urban geometry,



or the spatial distribution of vegetation fragments. Meng *et al.* (2022) emphasize that neighborhoods with similar proportions of urban development may exhibit different thermal responses because of differences in the spatial configuration and structure of the built environment. This helps explain why, in Vitória da Conquista, vegetation exhibited a clearer relationship with thermal conditions than the proportion of urbanized area alone.

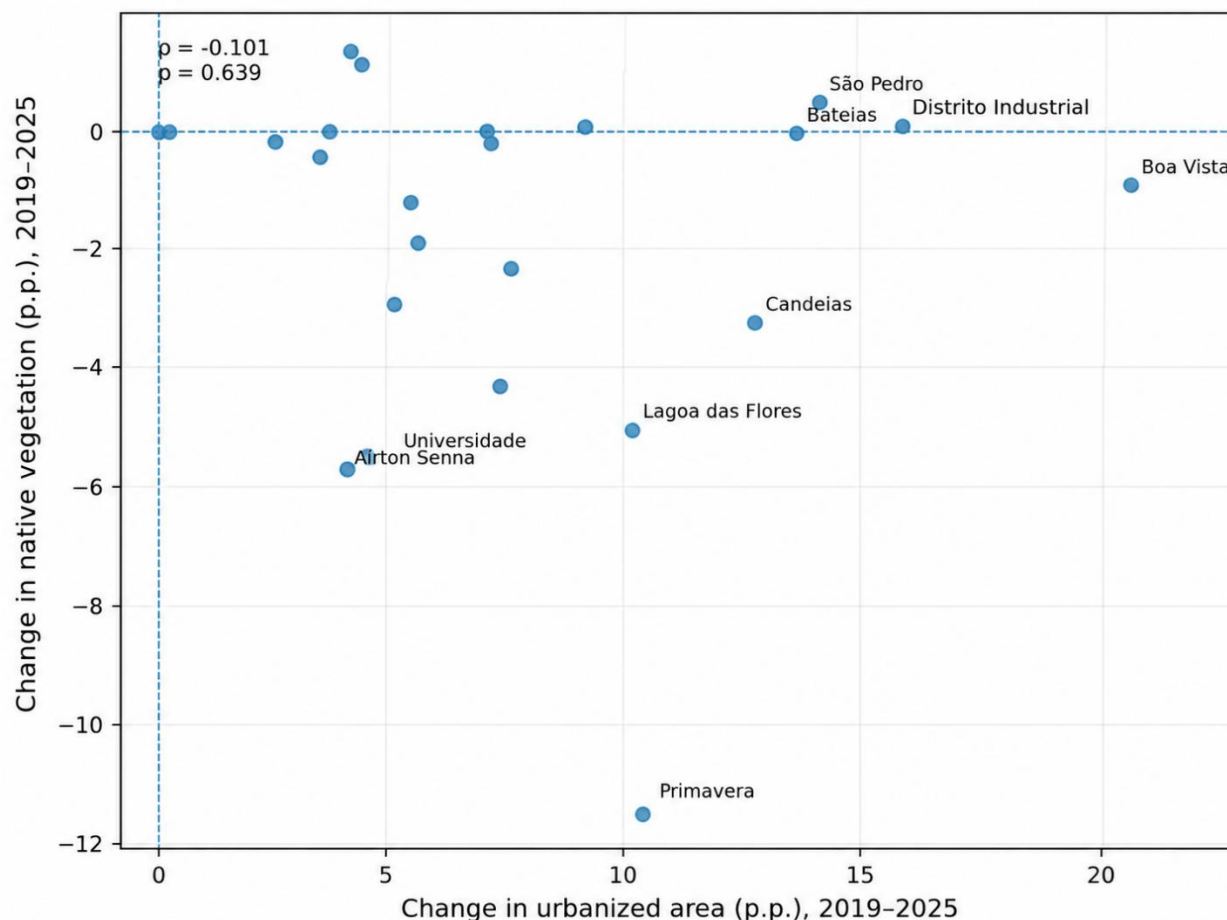
Overall, the results reveal greater spatial thermal differentiation than persistent temporal trends. While LST anomalies showed no significant trends across neighborhoods, higher NDVI values and greater proportions of native vegetation were associated with relatively lower temperatures. This distinction reinforces the understanding that the urban thermal environment results from the interaction among vegetation cover, built-environment structure, and atmospheric variability, rather than solely from the total amount of urbanized area.

3.3 Environmental trajectories of neighborhoods under urban expansion

The analysis of changes between 2019 and 2025 revealed that urban expansion did not produce uniform environmental responses across the neighborhoods of Vitória da Conquista. The magnitude of growth in urbanized area was not significantly associated with changes in native vegetation ($\rho = -0.101$; $p = 0.639$), NDVI ($\rho = 0.257$; $p = 0.226$), or LST ($\rho = 0.072$; $p = 0.738$). Thus, neighborhoods experiencing similar intensities of urban expansion followed distinct environmental trajectories, particularly in terms of vegetation conservation or loss (Figure 4). This heterogeneity is consistent with studies showing that urbanization can produce different trajectories of vegetation-cover change within the same city, depending on the form and location of urban expansion and on pre-existing landscape characteristics (Barrera; Henríquez, 2017; Richards; Belcher, 2020).

These contrasts are particularly evident among the neighborhoods that experienced the greatest urban expansion. Boa Vista showed the largest increase in urbanized area (+20.85 p.p.), but only a 0.88 p.p. reduction in native vegetation and an increase in NDVI (+0.038). Distrito Industrial (+16.03 p.p. in urbanized area), São Pedro (+14.24 p.p.), and Bateias (+13.72 p.p.) also exhibited little change in native vegetation (+0.12, +0.50, and -0.02 p.p., respectively). These cases demonstrate that the expansion of urbanized areas did not necessarily result in vegetation loss of an equivalent magnitude. Intra-urban studies have also shown that the conversion of green areas can vary substantially among areas undergoing urbanization, indicating that local characteristics of the urban development process influence the intensity of vegetation loss (Kadhim; Salih, 2025).

Figure 4. Relationship between changes in urbanized area and native vegetation across the neighborhoods of Vitória da Conquista, Bahia, Brazil, between 2019 and 2025. The highlighted neighborhoods illustrate contrasting trajectories of urban expansion and vegetation conservation or loss. ρ = Spearman's rank correlation coefficient.



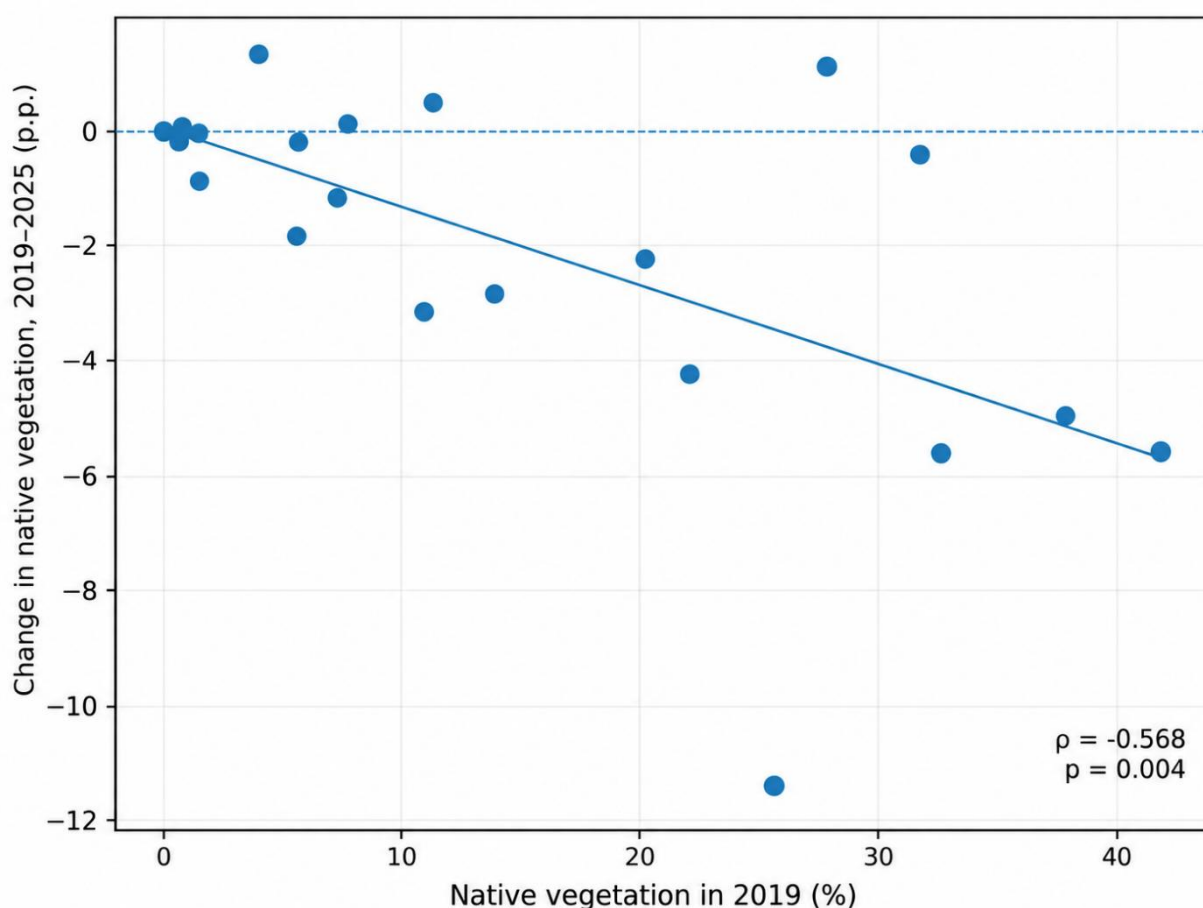
Source: Prepared by the authors (2026).

Primavera followed a distinct trajectory, with a 10.36 p.p. increase in urbanized area accompanied by the largest reduction in native vegetation among the neighborhoods (−11.53 p.p.) and a decrease in NDVI (−0.041). Lagoa das Flores also experienced both urban expansion (+10.19 p.p.) and vegetation loss (−4.97 p.p.), while Candeias showed changes of +12.82 and −3.16 p.p., respectively. Universidade and Aírton Senna recorded losses of more than 5 p.p. of native vegetation despite more moderate urban expansion (+4.66 and +4.04 p.p., respectively). The intensity of vegetation loss, therefore, cannot be attributed solely to the magnitude of urban expansion. The coexistence of areas experiencing vegetation loss, persistence, or localized gains has been observed in other cities and demonstrates that urban expansion and vegetation-cover change do not necessarily follow a linear or spatially homogeneous trajectory (Barrera; Henríquez, 2017; Richards; Belcher, 2020).

Initial land-cover conditions helped explain part of this heterogeneity. The proportion of native vegetation present in 2019 showed a significant negative association with its change

between 2019 and 2025 ($\rho = -0.568$; $p = 0.004$), indicating that neighborhoods with a higher initial proportion of native vegetation tended to experience greater losses over the study period (Figure 5). Conversely, neighborhoods with low initial vegetation cover had less potential to experience substantial losses of this land-cover class. The proportion of urbanized area in 2019 was also negatively associated with the expansion observed through 2025 ($\rho = -0.460$; $p = 0.024$), indicating lower proportional growth in neighborhoods that were already more highly urbanized at the beginning of the study period. These results show that the observed trajectories depend not only on the magnitude of urban expansion but also on pre-existing land-cover conditions.

Figure 5. Relationship between the proportion of native vegetation in 2019 and its change between 2019 and 2025 across the neighborhoods of Vitória da Conquista, Bahia, Brazil. Changes in native vegetation are expressed in percentage points (p.p.). The solid line represents the overall trend in the data, and the dashed line indicates no change over the study period. ρ = Spearman's rank correlation coefficient.



Source: Prepared by the authors (2026).

The thermal response further reinforces this heterogeneity. Although LST decreased in all neighborhoods between the initial and final years, with reductions ranging from -3.24°C in Zabelê to -8.45°C in Espírito Santo, none of the 24 neighborhoods exhibited a significant trend in LST anomalies ($p > 0.05$). Furthermore, the intensity of urban expansion was not associated with the trend in thermal anomalies ($\rho = -0.112$; $p = 0.602$). The absence of this direct relationship is



consistent with evidence that the thermal response to urbanization may vary according to the density and configuration of built-up surfaces, as well as the composition and spatial organization of the landscape (Meng *et al.*, 2022). Thus, the amount of urbanized area alone does not capture the full thermal complexity of the urban expansion process.

The trajectories identified demonstrate that the magnitude of urban expansion alone is insufficient to explain environmental changes at the intra-urban scale. Although the municipality experienced substantial urban expansion and a reduction in native vegetation during the study period, neighborhoods with similar growth intensities exhibited outcomes ranging from vegetation persistence to substantial vegetation loss, without proportional thermal responses. The association between initial vegetation cover and its subsequent change further indicates that pre-existing landscape conditions are related to the magnitude of these transformations. Neighborhoods with a higher initial proportion of native vegetation tended to experience greater losses, whereas those that were initially more urbanized showed lower proportional expansion. Thus, rather than the amount of land incorporated into the urban fabric alone, the results highlight the importance of initial landscape conditions, the way in which urban expansion occurs, and the conservation of vegetation cover throughout this process.

3.4 Vegetation and intra-urban thermal differentiation

The integrated analysis confirmed that urbanization, vegetation cover, and temperature exhibit distinct relationships within the intra-urban landscape of Vitória da Conquista. After controlling for interannual variability, native vegetation showed the strongest negative association with LST ($\rho = -0.440$; $p < 0.001$), followed by NDVI ($\rho = -0.318$; $p < 0.001$). Urbanized area showed a positive but weaker association with temperature ($\rho = 0.154$; $p = 0.046$) (Table 1). The predominance of negative associations between vegetation and LST is consistent with studies conducted across different urban contexts, in which areas with greater vegetation cover or higher vegetation index values exhibit relatively lower land surface temperatures (Shiflett *et al.*, 2017; Kaiser *et al.*, 2022).

Table 1. Relationships among land cover, vegetation, and land surface temperature across the neighborhoods of Vitória da Conquista, Bahia, Brazil, between 2019 and 2025

Relationship	Spearman's ρ	p	ρ controlling for year	p controlling
NDVI $\times$ LST	-0.230	0.003	-0.318	<0.001
Native vegetation $\times$ LST	-0.261	<0.001	-0.440	<0.001
Urbanized area $\times$ LST	0.015	0.842	0.154	0.046
Urbanized area $\times$ NDVI	-0.822	<0.001	-0.902	<0.001



Relationship	Spearman's ρ	p	ρ controlling for year	p controlling
Native vegetation $\times$ NDVI	0.811	<0.001	0.838	<0.001
Urbanized area $\times$ native vegetation	-0.763	<0.001	-0.742	<0.001

Source: Prepared by the authors (2026).

Note: ρ = Spearman's rank correlation coefficient. Correlations controlling for year represent associations estimated after removing temporal variability shared across observations.

The strongest associations were observed among the landscape components themselves. Urbanized area showed a strong negative relationship with NDVI ($\rho = -0.902$; $p < 0.001$) and native vegetation ($\rho = -0.742$; $p < 0.001$), whereas native vegetation and NDVI were positively associated ($\rho = 0.838$; $p < 0.001$). Urbanization was therefore more strongly associated with the reconfiguration of vegetation cover than with thermal differentiation among neighborhoods. This finding reinforces the interpretation that the thermal response to urbanization depends not only on the amount of urbanized surface but also on the characteristics of the remaining vegetation cover and the environmental configuration resulting from the urban transformation process.

The differences in the magnitude of the associations with LST are also noteworthy. Native vegetation exhibited a stronger relationship with thermal conditions than NDVI and, particularly, than the proportion of urbanized area. This pattern is consistent with the role of vegetation cover in modulating the urban thermal environment and with evidence that vegetation–LST relationships remain spatially consistent even when their strength varies across years and urban contexts (Shiflett *et al.*, 2017; Kaiser *et al.*, 2022). Thus, the presence and persistence of vegetation appear to better differentiate thermal conditions among neighborhoods than the total extent of urbanized area.

The longitudinal analysis, however, revealed a different pattern. In the neighborhood and year fixed-effects models (TWFE), NDVI showed a negative coefficient in relation to LST ($\beta = -13.707$), but the association was not statistically significant ($p = 0.184$). The same pattern was observed for native vegetation ($\beta = -0.118$; $p = 0.091$) and urbanized area ($\beta = 0.041$; $p = 0.492$). Thus, although neighborhoods with structurally greater vegetation cover exhibited relatively lower temperatures, changes occurring within individual neighborhoods between 2019 and 2025 were not accompanied by statistically detectable changes in LST.

This difference between spatial and longitudinal associations does not represent contradictory findings but rather reflects distinct dimensions of the relationship between landscape and temperature. Spatiotemporal studies have shown that the relationship between vegetation indices and LST can vary considerably across years and seasons (Shu *et al.*, 2024). At the same time, longitudinal evidence indicates that changes in vegetation and impervious surfaces can produce thermal changes when longer time series and sufficiently substantial transformations are



considered, as observed by Jun *et al.* (2024) in the Seoul Metropolitan Area. In Vitória da Conquista, the seven-year time series and the high interannual variability in LST may have reduced the ability to detect thermal responses associated with changes occurring within neighborhoods.

This distinction also highlights an important methodological issue, as a substantial proportion of studies on vegetation and LST rely on spatial associations or multitemporal comparisons, whereas longitudinal approaches that simultaneously control for persistent differences among spatial units and temporal variations common across years are less frequent (Jun *et al.*, 2024). The TWFE models adopted in this study allow these two dimensions to be distinguished and demonstrate that a robust spatial association does not necessarily imply that short-term changes in vegetation produce equivalent thermal changes within the same spatial units.

The maintenance of vegetation cover therefore emerges as an important component of intra-urban environmental differentiation, although its thermal effects should be interpreted in light of the temporal scale and spatial structure of the analysis. In Vitória da Conquista, vegetation more clearly differentiated thermal conditions among neighborhoods than it explained thermal changes occurring within them over the study period. This finding reinforces the importance of conserving vegetation cover during urban expansion while avoiding the attribution of a causal relationship between short-term vegetation changes and LST that was not supported by the longitudinal models.

4 Conclusions

Urban expansion in Vitória da Conquista was accompanied by substantial landscape transformation between 2019 and 2025, with a 31.1% increase in urbanized area and a 15.6% reduction in native vegetation. However, the different trajectories observed across neighborhoods demonstrate that the intensity of urban expansion alone does not determine vegetation loss or thermal responses. The initial proportion of native vegetation was associated with the magnitude of its subsequent change, with greater losses occurring in neighborhoods that had higher vegetation cover at the beginning of the study period. Likewise, neighborhoods that were initially more urbanized experienced lower proportional expansion. These findings demonstrate that pre-existing landscape conditions are important for understanding different trajectories of intra-urban transformation.

Vegetation emerged as the most relevant component of intra-urban thermal differentiation, showing a stronger association with lower temperatures ($p = -0.440$; $p < 0.001$) than urbanized area itself. This relationship, however, was predominantly spatial, as the longitudinal models did not detect significant thermal responses to changes occurring within neighborhoods. Thus, neighborhoods with greater vegetation cover tended to exhibit more favorable thermal conditions,



but the results do not support attributing proportional thermal responses to short-term changes in vegetation.

These findings reinforce the need to incorporate vegetation conservation into the urban expansion process. Rather than considering only the amount of newly urbanized land, urban planning should account for pre-existing landscape conditions and guide how and where expansion occurs, seeking to preserve vegetation cover as a component of environmental and thermal quality at the intra-urban scale.

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