

Yes, Trees are the Solution for Thermal Comfort and Environmental Quality in Equatorial Public Squares

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Research Article

Keywords: urban microclimate, urban environments, environmental quality, social organization

Posted Date: October 29th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11192876/v1>

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Additional Declarations: No competing interests reported.

YES, TREES ARE THE SOLUTION FOR THERMAL COMFORT AND ENVIRONMENTAL QUALITY IN EQUATORIAL PUBLIC SQUARES

ABSTRACT

Unregulated urban expansion can diminish green spaces and alter microclimatic conditions, thereby compromising thermal comfort and the quality of life for the population. In this context, urban forestry plays a pivotal role in mitigating warming effects within urban environments. The present study aimed to analyze the influence of urban tree canopy cover on surface temperature and thermal comfort in urban squares within the municipality of Santarém, Pará state, Brazil. To this end, in situ measurements of surface temperature were conducted using an infrared thermometer, alongside assessments of thermal stress and perceived temperature using a heat stress meter equipped with the Wet-Bulb Globe Temperature (WBGT) index. Data were collected in both tree-shaded and unshaded areas across seven city squares at 08:00, 13:00, and 18:00. The results demonstrated that the afternoon period exhibited the highest mean values for surface temperature (40.1 °C), thermal stress (31.6 °C), and perceived temperature (48.3 °C). Areas lacking tree canopy cover recorded higher surface temperatures (39.7 °C), elevated thermal stress (30.5 °C), and greater perceived temperatures (45.4 °C) compared to tree-shaded areas. Among the evaluated sites, Liberdade Square presented the highest mean surface temperature (40.8 °C), while São Raimundo and Três Poderes squares recorded the highest values for thermal stress (31.2 °C) and perceived temperature (48.6 °C). We conclude that the presence of tree canopy cover significantly contributes to lowering surface temperatures and improving thermal comfort conditions, thereby highlighting the critical role of urban forestry in urban planning and the enhancement of urban environmental quality.

Keywords: urban microclimate; urban environments; environmental quality; social organization.

1. INTRODUCTION

The urbanization process entails transformations within the social, economic, and environmental structures of a region, driven primarily by rural-to-urban migration, population growth, infrastructure expansion, and the development of increasingly anthropized landscapes (Chaolin et al., 2012; Zhang et al., 2022). In developing nations like Brazil, this process occurred relatively late, yet rapidly and unevenly, associated with the transition from an agro-export economy to an industrial and urbanized society throughout the 20th century (Martine & McGranahan, 2013; Santos et al., 2020). In the Northern region, particularly within the Amazon, urbanization exhibited a distinct dynamic characterized by state-driven economic frontiers, the expansion of extractive activities, and initial human settlements concentrated along riverbanks. Subsequently, the opening and consolidation of highway networks intensified urban expansion and socio-environmental transformations, most

notably the BR-163 highway, which connects Santarém, in western Pará state, to Cuiabá, in Mato Grosso state (Martine & McGranahan, 2013; Santos et al., 2020).

Costa & Venâncio (2016) contend that this phenomenon of spatial transformation is associated with significant socioeconomic advancements, such as expanded access to healthcare, education, transportation, leisure, infrastructure, technology, and housing, in addition to job creation within the commerce, industrial, and service sectors. However, in the absence of established criteria, comprehensive planning, control, and spatial organization, unregulated urban sprawl can exacerbate social inequalities, amplify infrastructural deficits, and induce environmental impacts that compromise both environmental quality and human well-being (Angel, 2023; Lima et al., 2024). Several authors assert that regions undergoing unprecedented and unplanned urbanization, such as the city of Dhaka, the capital of Bangladesh (Rahaman et al., 2023), Morogoro municipality in Tanzania (Shao et al., 2021), and Belém, in the Northern region of Brazil (Furtado et al., 2024), have exhibited elevated rates of deforestation, alterations in natural land cover, rising temperatures, and shifts in precipitation regimes. Directly or indirectly, these changes have culminated in health risks, environmental challenges, elevated stress levels, and a diminished quality of life for local populations.

The reduction of green spaces, such as squares, parks, and botanical gardens, constitutes one of the primary impacts associated with advancing urbanization and is directly correlated with the replacement of natural surfaces by paved and built environments (Araújo et al., 2019; Oliveira et al., 2019; dos Santos et al., 2021; Semeraro et al., 2021). This transformation alters the surface energy balance, diminishes evapotranspiration facilitated by vegetation, and promotes greater energy absorption and storage by urbanized surfaces (Borges et al., 2022). Furthermore, soil sealing decreases water infiltration and increases surface runoff, which can overwhelm drainage systems and contribute to the occurrence of localized flooding and inundations during periods of intense rainfall (Bezerra et al., 2018).

Consequently, it is imperative to develop studies that generate robust datasets to support informed decision-making regarding the proactive planning or mitigation of urbanization impacts, particularly concerning the protection, maintenance, or establishment of green spaces within urban centers. Such data can underpin the formulation of urban forestry plans that integrate regional landscape and ecological characteristics, while also fostering social acceptance and strengthening the population's sense of belonging to urban public space (dos Santos et al., 2021; Zea-Camaño et al., 2015). However, the availability and quality of such information still pose significant limitations within segments of Brazilian governmental systems, potentially compromising analytical accuracy and the efficacy of urban environmental planning and management initiatives (Kunen & Santos, 2024).

Currently, various methods and tools facilitate data acquisition for assessing urban environmental conditions and guiding decisions related to urban forestry, with particular emphasis on thermal comfort. Prominent among these approaches are remote sensing (Lucena, 2019) and monitoring via stationary or mobile meteorological stations (Campos & Danelichen, 2021; Porangaba et al., 2017) . Nevertheless, despite the potential of remotely sensed data for broad spatial analyses, their spatial resolution may be insufficient to capture the thermal heterogeneity inherent at the local scale, particularly within complex urban environments. Therefore, validating the reliability of these data through in situ measurements becomes necessary, as these are capable of accurately representing the actual thermal conditions experienced within the urban environment.

In this regard, among the indicators that can be employed to assess thermal conditions at the local scale, the Wet-Bulb Globe Temperature (WBGT) index is particularly notable, as it integrates various thermal variables to represent the heat stress conditions to which an individual is subjected (Borges et al., 2016) . In Brazil, the WBGT is utilized for the assessment of occupational heat exposure and is governed by Regulatory Standard No. 15 (NR-15) (Brasil, 2019). Although its application is primarily associated with occupational exposure, the index has also been deployed in outdoor environments, such as agricultural crop areas (Schettino et al., 2018), building facades, and communal living spaces. Consequently, its application within urban public spaces constitutes a robust alternative for characterizing thermal conditions at the local scale, yielding field data that enable the validation of the representativeness of information derived from remote sensing.

Building upon this perspective, elucidating the interplay among microclimate, thermal comfort, and vegetation demands in situ data acquisition and analysis within urban public spaces. The central hypothesis guiding this research is that the presence of urban tree canopy significantly influences local thermal conditions, yielding milder temperatures and enhanced thermal comfort compared to areas devoid of canopy cover. This mitigating effect is primarily attributed to the shading and evapotranspiration facilitated by the vegetation, which conjointly attenuate surface warming and regulate the urban microclimate (Li et al., 2025) .

Understanding these relationships can provide critical insights for municipal environmental planning and management, particularly for guiding urban forestry strategies aimed at enhancing microclimatic conditions in public spaces. Therefore, the objective of this study was to analyze the influence of urban tree canopy cover on temperature and thermal comfort conditions within urban squares in the municipality of Santarém, in the Brazilian Amazon.

2. MATERIALS AND METHODS

2.1. Characterization of the study area

The present research was conducted in public squares within the municipality of Santarém, in the state of Pará, Northern Brazil. According to the Köppen-Geiger climate classification, Santarém falls within the Af climate zone, described as a tropical climate (Alvares et al., 2013), exhibiting a mean annual temperature of 27.2 °C and an annual precipitation of 3,109 mm (Climate Data, 2025). The region is characterized by two distinct seasons, as presented in Table 1.

Table 1. Climatic characterization of the two seasons (winter and summer) in the municipality of Santarém, Pará state, Northern Brazil.

Season	Period	Precipitation	Temperature	Humidity
Winter	December to May	54.8 mm month ⁻¹	24 °C to 30 °C	82 to 86%
Summer	July to November	1,920 mm month ⁻¹	25 °C to 33 °C	71 to 81%

Source: (Climatempo, 2025; INMET, 2025).

To evaluate the influence of urban tree canopy cover on temperature and thermal comfort conditions, seven public squares within the city of Santarém were randomly selected: Liberdade Square, Flores Square, Três Poderes Square, Santarenzinho Square, São Raimundo Square, Tiradentes Square, and Vila Arigó Square (Figure 1).

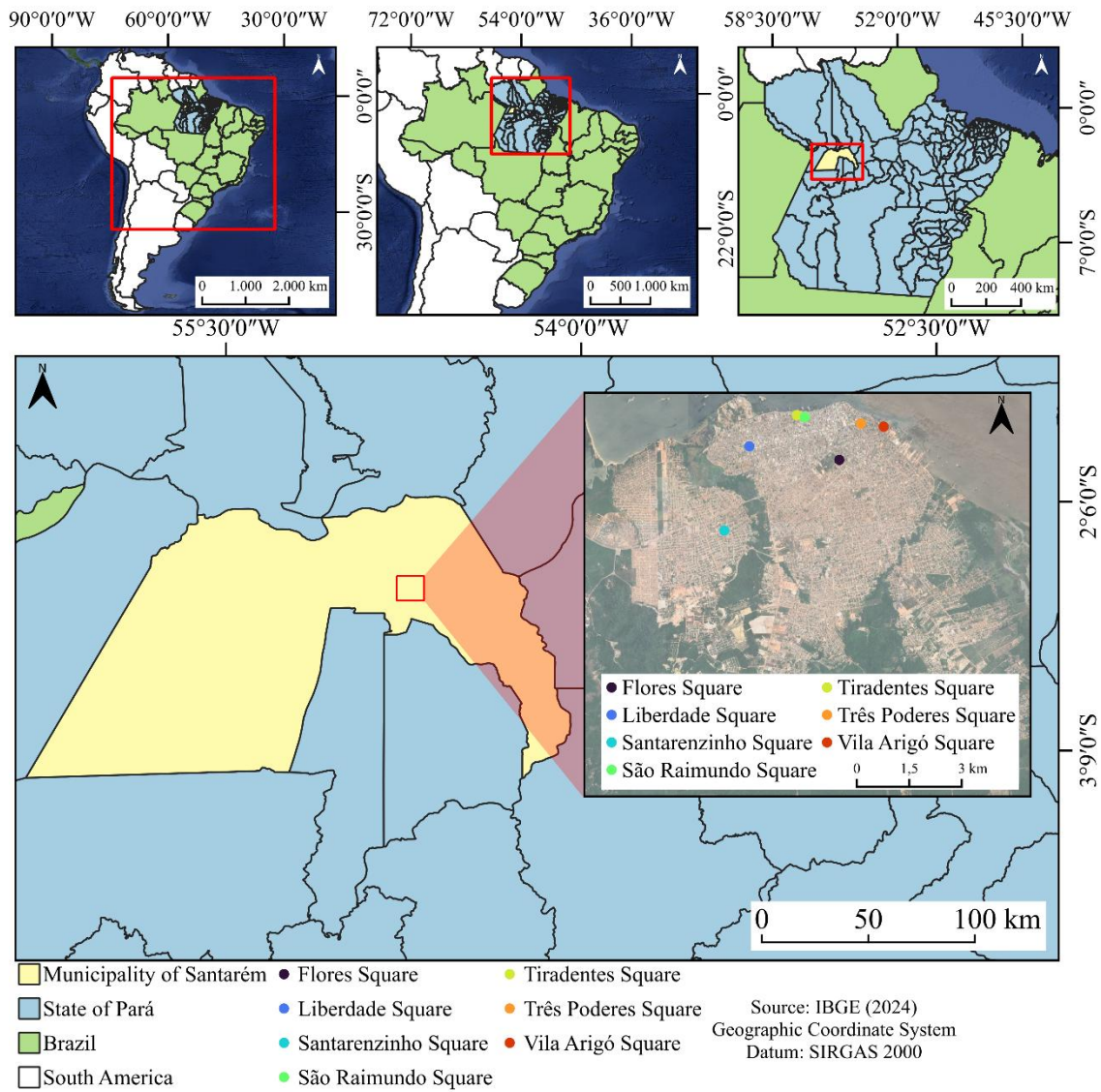


Figure 1. Location map of the seven squares selected to evaluate the influence of urban tree canopy cover on temperature and thermal comfort conditions in the municipality of Santarém, Pará state, Northern Brazil.

2.2. Data collection

For data acquisition, a TGD-400 Heat Stress Meter equipped with a digital dry- and wet-bulb globe thermometer (Figures 2-A and 2-B) and a JSZ-03A digital infrared thermometer (Figure 2-C) were utilized to assess surface temperature variations within the perimeters of the study areas. Additionally, a Garmin eTrex 10 handheld navigation GPS (Figure 2-D) was employed to record the geographic coordinates of the selected sampling points for the subsequent generation of temperature maps across the study areas.



Figure 2. Equipment utilized for data collection. A - Heat Stress Meter: data collection in a tree-shaded environment. B - Heat Stress Meter: data collection in an unshaded environment. C - Infrared Thermometer. D - Garmin eTrex 10 GPS.

The heat stress meter employs a Globe Thermometer to record temperature variations over short time intervals, serving as an indicator of high temperatures, radiant heat, and high relative humidity. It also accounts for factors inducing thermal strain (ambient ventilation, low relative humidity, and low temperatures), which dictate work and rest regimens (Anjos et al., 2023). At each sampling location, the heat stress meter was programmed to capture one measurement every 30 seconds, with the device exposed for a total of 1 minute and 30 seconds per point, in addition to recording the surface temperature using the infrared thermometer at the respective site.

To ensure the statistical representativeness of the data collection points, sampling locations were randomized within the boundary polygons of each square (Figure 3) using QGIS software, version 3.40.6. The sampling points were equally distributed between tree-shaded and unshaded areas, contingent upon in situ availability, avoiding locations with artificial barriers (e.g., kiosks, active or closed sports courts, sheds, outdoor gyms) or natural hazards (e.g., risk of falling trees or branches) that would preclude data logging.

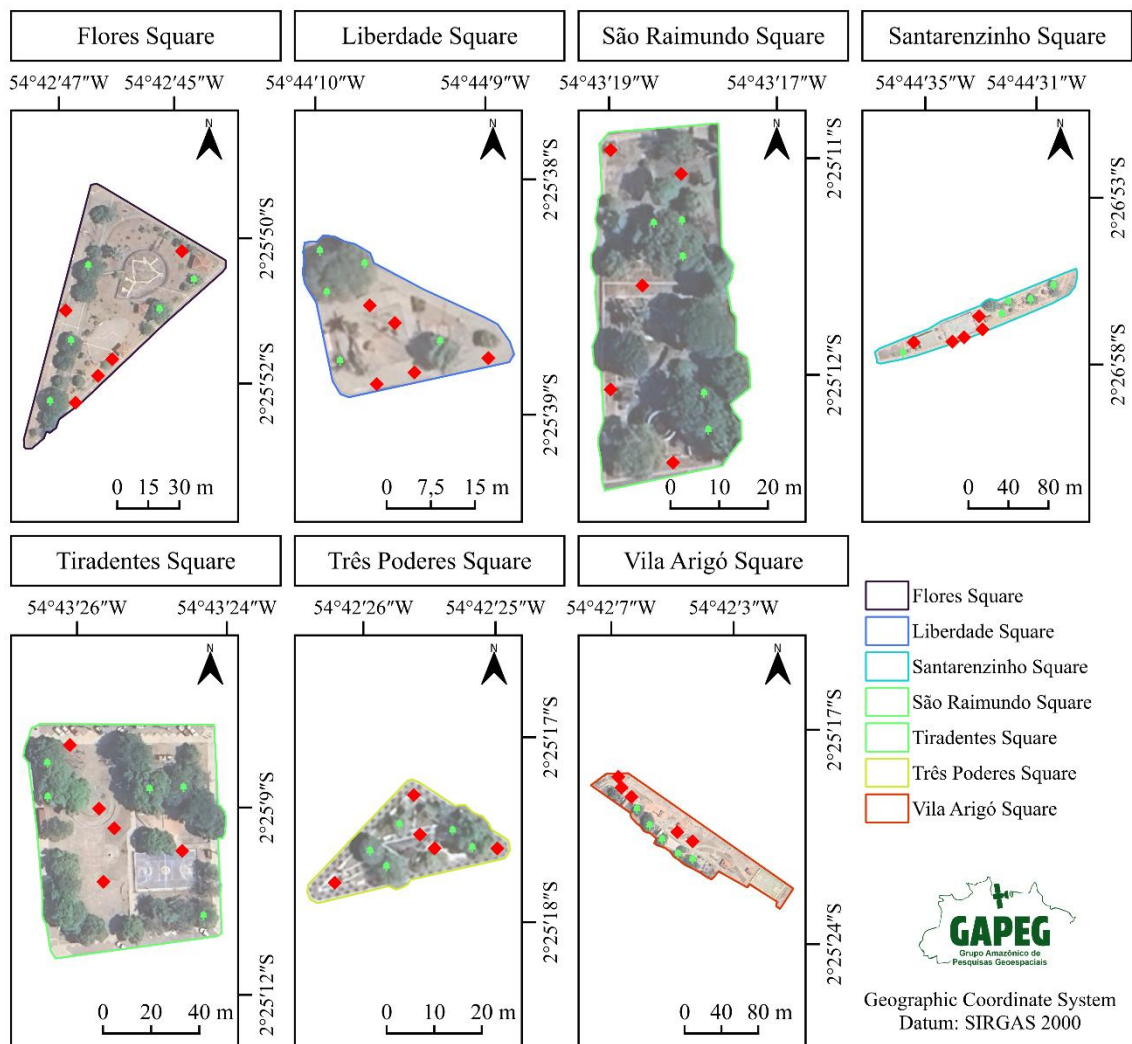


Figure 3. Distribution of data collection sampling points within the selected squares in Santarém, Pará state.

Due to the necessity for manual operation of the equipment and the spatial distance between sites, simultaneous data collection across the squares was unfeasible. Consequently, the procedure was executed over five field expeditions (Table 2). Data collection was conducted under conditions of atmospheric stability, specifically during sunny periods with moderate cloud cover. Additionally, owing to technical complications that necessitated equipment maintenance, the third expedition occurred over a distinct temporal interval relative to the other data collection campaigns.

Table 2. Schedule of data collection expeditions in the selected squares to evaluate the influence of urban tree canopy cover on temperature and thermal comfort conditions in the municipality of Santarém, Pará state, Northern Brazil.

Expeditions	Dates	Squares	Time
1	27/08/2025	Liberdade Square	08:00 13:00 18:00

2	28/08/2025	Santarenzinho Square	08:00	13:00	18:00
3	29/08/2025	Flores Square	08:00	13:00	18:00
4	03/11/2025	Três Poderes Square and Vila Arigó Square	08:00	13:00	18:00
5	04/11/2025	Tiradentes Square and São Raimundo Square	08:00	13:00	18:00

138 Data regarding air temperature, relative humidity, and wind speed corresponding to the specific days and
139 times of data collection (Figure 4) were acquired from historical meteorological records provided by the
140 WeatherSpark platform, utilizing data from the Maestro Wilson Fonseca Airport meteorological station in
141 Santarém, Pará state (Weather Spark, 2025).

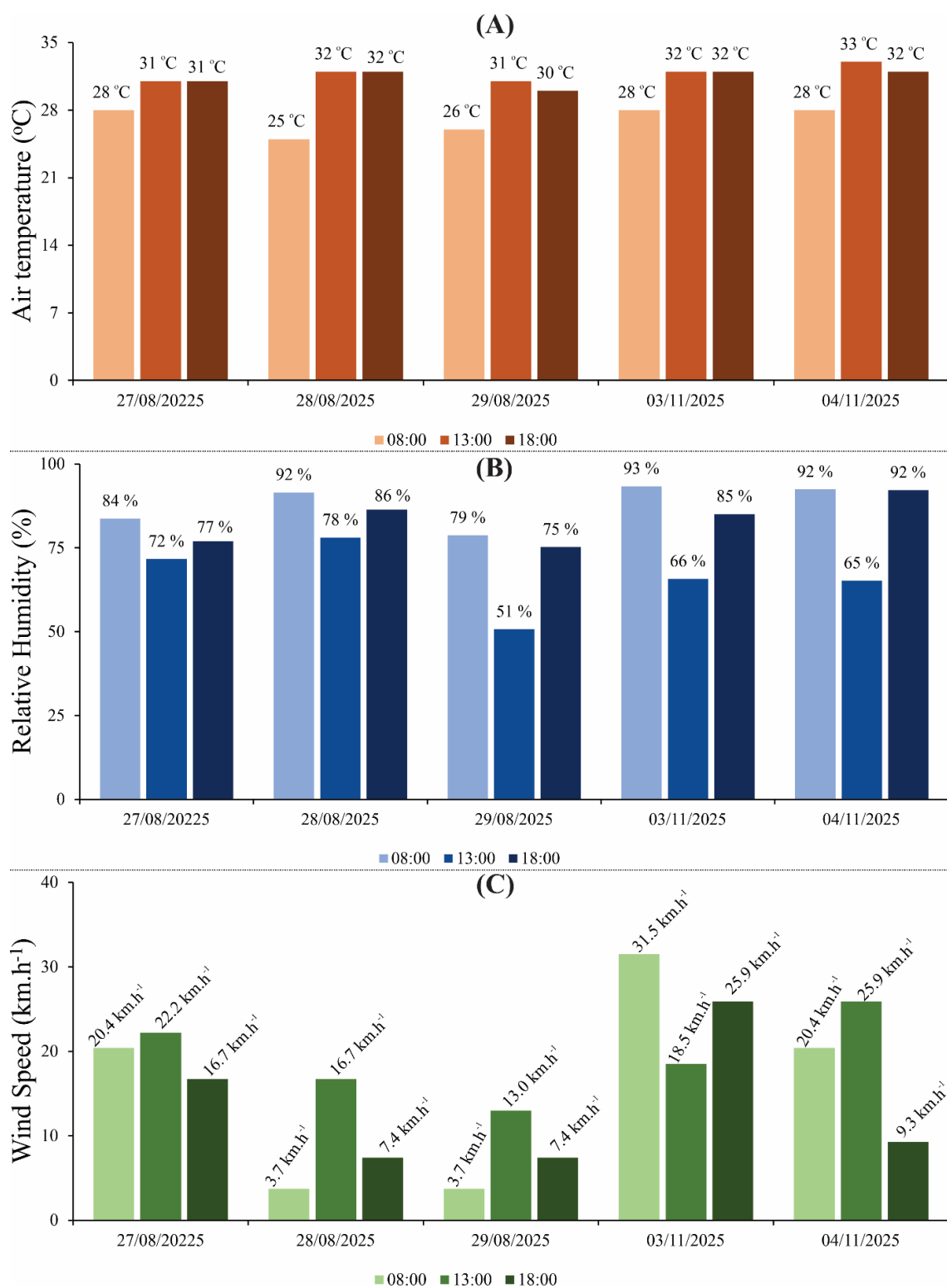


Figure 4. Air temperature (A), relative humidity (B), and wind speed (C) corresponding to the days and times of data collection in the selected squares to evaluate the influence of urban tree canopy cover on temperature and thermal comfort conditions in the municipality of Santarém, Pará state, Northern Brazil.

Source: (Weather Spark, 2025).

2.3. Data processing

The data collected using the heat stress meter and the thermometer were inputted into Microsoft Excel software (Office 16), where thermal assessments were conducted based on the outdoor WBGT (heat stress), the heat index (perceived temperature), and the temperature recorded by the thermometer. The WBGT values for outdoor environments under solar load and the heat index are determined by the device utilizing Equations 1 and 2.

$$WBGT = 0.7T_{wb} \times 0.1T_{db} \times 0.2T_g \quad (1)$$

Where WBGT is Wet Bulb Globe Temperature, T_{wb} is Wet-bulb temperature ($^{\circ}\text{C}$), T_{db} is Dry-bulb temperature ($^{\circ}\text{C}$), and T_g is Globe temperature ($^{\circ}\text{C}$).

$$HI = c_1 + c_2T_a + c_3R + c_4T_aR + c_5T_a^2 + c_6R^2 + c_7T_a^2R + c_8T_aR^2 + c_9T_a^2R^2 \quad (2)$$

Where c_1 – c_9 are fixed constants stored in the circuit memory, T_a is the dry-bulb air temperature ($^{\circ}\text{C}$), and R is the relative humidity (%).

For the analysis of the heat index (HI), the alert levels were compared (Table 3).

Table 3. Heat index alert levels.

Alert Level	Heat Index
No alert	$< 27^{\circ}\text{C}$
Caution	27.1°C to 32°C
Extreme Caution	32.1°C to 41°C
Danger	41.1°C to 54°C
Extreme Danger	$> 54^{\circ}\text{C}$

Source: Adapted from Moreira et al. (2023).

2.4. Statistical analysis

For the statistical analysis, means were calculated by square, by the presence of tree canopy, and by time of day. Subsequently, the Shapiro-Wilk normality test was conducted at a 5% significance level, which indicated the non-normality of the data. To ensure data normality, a logarithmic transformation was applied (Equation 3).

$$x' = \log(x) \quad (3)$$

Where x' represents the transformed data value and x represents the original data value.

Following data transformation, an Analysis of Variance (ANOVA) was conducted to determine the presence of statistically significant differences among the means. When a significant difference was indicated, the Scott-Knott test was applied at a 5% significance level for the comparison of means.

3. RESULTS

Figure 5 presents the results for the mean values of surface temperature, thermal stress, and perceived temperature during the morning, afternoon, and evening periods, both in the presence and absence of tree canopy cover, across each of the seven analyzed squares. The afternoon period exhibited the highest values, differing statistically from the other periods. The morning period, in turn, presented the lowest values, demonstrating statistical differences in surface temperature and perceived temperature, but with thermal stress values statistically equivalent to those recorded during the evening period.

Furthermore, it was observed that all means differed statistically from one another in the analysis regarding the presence or absence of trees. Areas lacking tree canopy cover exhibited higher surface temperature (39.7 °C), thermal stress (30.5 °C), and perceived temperature (45.4 °C). Additionally, the perceived temperature was classified within the danger threshold (41.1 °C to 54 °C) under both scenarios.

Regarding surface temperature, Liberdade Square recorded the highest mean (40.8 °C). In contrast, Vila Arigó Square presented the lowest mean (33.4 °C). For thermal stress, São Raimundo and Três Poderes squares, both at 31.2 °C, exhibited the highest indices, whereas Liberdade (29.7 °C), Flores (29.7 °C), and Santarenzinho (29.6 °C) squares demonstrated the lowest values.

Perceived temperature ranged from Extreme Caution to Danger, with Liberdade (40.9 °C), Flores (40.9 °C), and Santarenzinho (40.7 °C) squares registering the lowest indices, while Três Poderes (48.8 °C) and São Raimundo (48.6 °C) squares recorded the highest values.

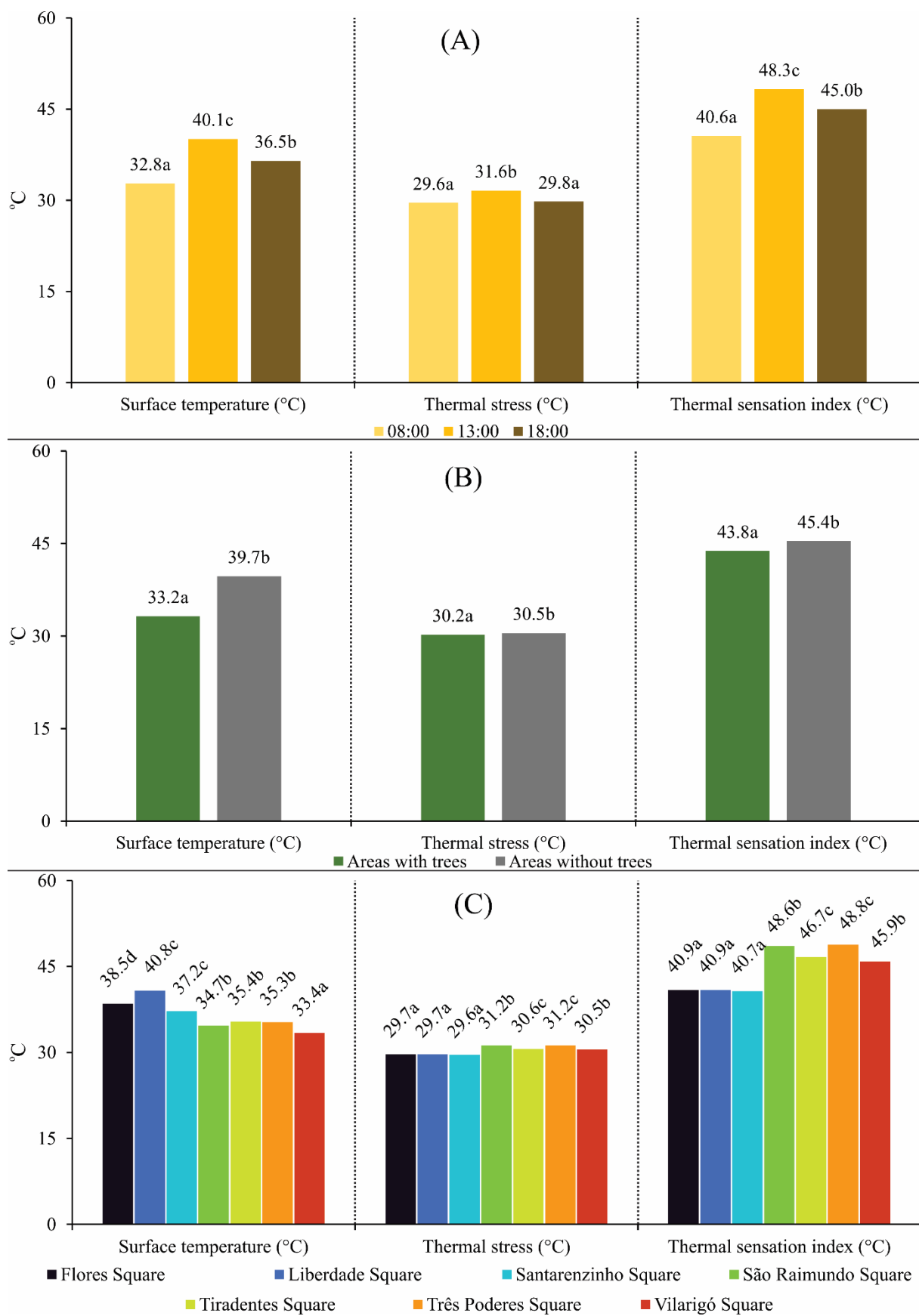


Figure 5. Mean values of surface temperature, thermal stress, and perceived temperature during morning, afternoon, and evening periods (A), in areas with the presence and absence of trees (B), and for each of the studied

squares (C) in the municipality of Santarém, Pará state, Brazil. Different letters indicate statistically significant differences according to the Scott-Knott test at a 5% significance level.

Regarding surface temperature, thermal stress, and perceived temperature across the squares and evaluated times, considering environments with the presence (PT) and absence of trees (AT) (Figure 6). In relation to surface temperature, among environments with PT, the highest value was observed in Liberdade Square (38.9 °C). In environments with AT, Liberdade (42.7 °C), Flores (42.3 °C), Santarenzinho (40.3 °C), and Tiradentes (39.3 °C) squares exhibited the highest values, with no statistical difference among them.

Concerning thermal stress, Três Poderes and São Raimundo squares presented the highest values in environments with PT (31.3 °C and 31.1 °C, respectively) and also stood out in environments with AT (31.1 °C and 30.7 °C, respectively), with no statistical difference between them. For perceived temperature, in environments with PT, the highest values were recorded in Três Poderes (49.1 °C) and São Raimundo (47.5 °C) squares. In the absence of trees, Tiradentes (47.7 °C), São Raimundo (49.7 °C), Três Poderes (48.5 °C), and Vila Arigó (46.9 °C) squares presented the highest values, with no statistical difference among them.

The temporal analysis revealed that the afternoon period exhibited the most elevated thermal conditions. Surface temperature reached 34.8 °C in environments with PT and 45.3 °C in those with AT, whereas the lowest values were observed during the morning period, at 30.6 °C and 34.9 °C, respectively. For thermal stress, the highest values also occurred in the afternoon, both in the presence (31.5 °C) and absence of trees (31.8 °C). The lowest values were recorded in the morning for environments with PT (29.3 °C) and in the evening for those with AT (29.8 °C).

A similar behavioral pattern was observed for perceived temperature, where the highest values occurred in the afternoon period, reaching 47.6 °C in environments with PT and 49.0 °C in environments with AT. During the morning period, the lowest values were recorded, at 39.1 °C and 42.2 °C, respectively. In general, the results demonstrate higher values for the thermal variables during the afternoon period and, notably for surface temperature, in unshaded environments.

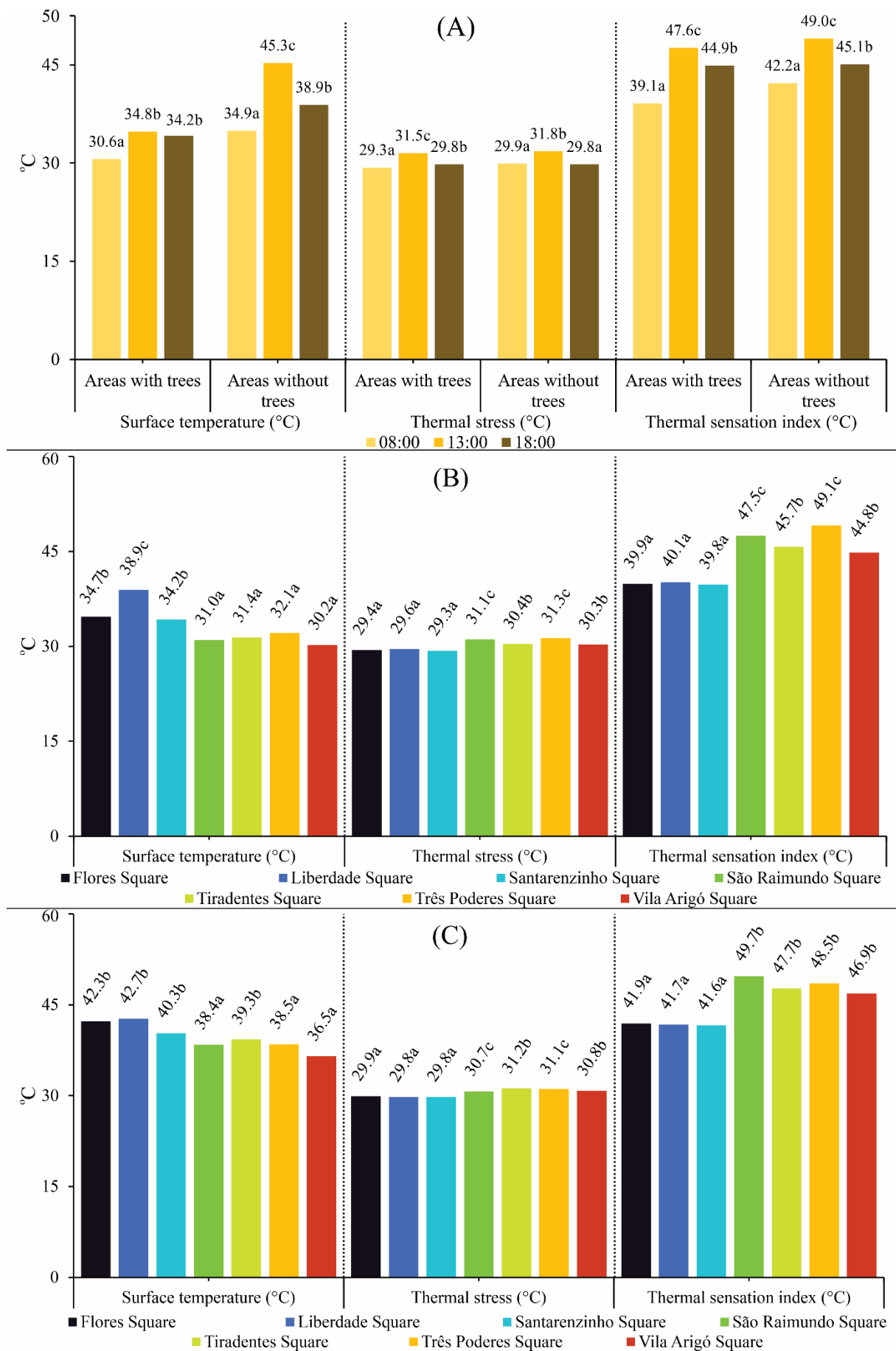


Figure 6. Mean values of surface temperature, thermal stress, and perceived temperature index at each evaluation time (08:00, 13:00, and 18:00) in areas with and without tree canopy cover (A), and in each of the squares in areas with the presence of trees (B) and absence of trees (C) within the municipality of Santarém, Pará state, Brazil. Different letters indicate statistically significant differences according to the Scott-Knott test at a 5% significance level.

Figure 7 presents the mean values for surface temperature, thermal stress, and perceived temperature at each evaluated time, categorized by the studied square. During the morning period, the squares exhibited no statistically significant differences among themselves regarding surface temperature. Conversely, Liberdade (44.2 °C), Santarenzinho (42.7 °C), and Flores (41.4 °C) squares registered peak temperatures during the afternoon period, with no statistical difference among them. During the evening period, Liberdade Square recorded the highest temperature (44.2 °C), followed by Flores Square (39.6 °C). None of the evaluated time periods presented statistical differences among themselves in the breakdown by square.

Regarding thermal stress, it was observed that during the morning, Três Poderes (30.4 °C) and Vila Arigó (30.7 °C) squares presented the highest values. In the afternoon period, Três Poderes Square exhibited the highest thermal stress index (32.9 °C), whereas Tiradentes (29.9 °C) and Flores (30.1 °C) squares recorded the lowest. During the evening period, Tiradentes (33.3 °C) and São Raimundo (32.9 °C) squares stood out with the highest thermal stress indices.

As for perceived temperature, during the morning period, Vila Arigó Square presented the highest temperature (46.8 °C), while Tiradentes, Liberdade, Flores, Santarenzinho, and São Raimundo squares recorded the most favorable thermal comfort indices. In the afternoon period, Três Poderes Square (63.1 °C) exhibited the most severe heat index, whereas Flores (30.1 °C) and Tiradentes (29.9 °C) squares demonstrated the lowest values. During the evening, Tiradentes (60.5 °C) and São Raimundo (58.3 °C) squares recorded the poorest perceived temperature, differing statistically from the others. Regarding the temporal variation within each square, it was observed that Liberdade, Flores, Santarenzinho, and Vila Arigó squares did not differ significantly across the evaluated times. São Raimundo Square exhibited a statistical difference between the morning and the other time periods. Tiradentes Square demonstrated the most severe index during the evening, differing statistically from the others, whereas Três Poderes Square presented the worst-case conditions during the afternoon, also exhibiting statistical divergence.

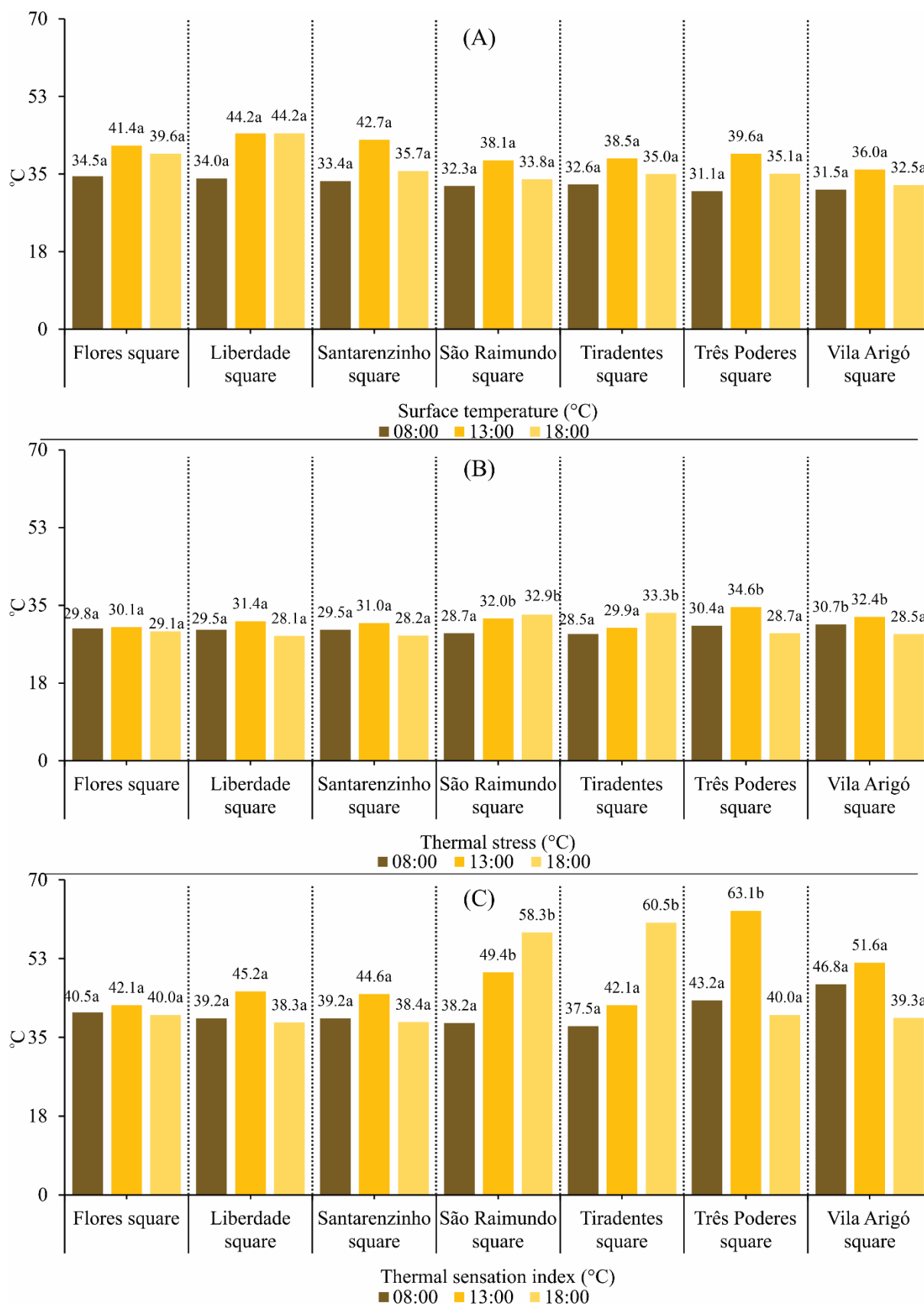


Figure 7. Mean values of surface temperature (A), thermal stress (B), and perceived temperature index (C) at each evaluation time (08:00, 13:00, and 18:00) for each of the squares in the municipality of Santarém, Pará state,

Brazil. Different letters indicate statistically significant differences according to the Scott-Knott test at a 5% significance level.

Figure 8 presents the mean values for surface temperature, thermal stress, and perceived temperature at each evaluation time according to the studied square. During the morning period, surface temperatures did not differ statistically among the squares. Regarding thermal stress, Três Poderes (30.4 °C) and Vila Arigó (30.7 °C) squares exhibited the highest indices, differing statistically from the others. For perceived temperature, Vila Arigó Square (46.8 °C) recorded the highest value.

During the afternoon period, concerning surface temperature, Flores (41.4 °C), Liberdade (44.2 °C), and Santarenzinho (42.7 °C) squares presented the highest values. For thermal stress, Três Poderes Square (34.6 °C) registered the highest heat index. Regarding perceived temperature among the sites, Três Poderes Square (63.1 °C) exhibited the highest values.

For the evening period, in relation to surface temperature, Liberdade Square (44.2 °C) recorded the highest temperature, differing statistically from the other locations. Concerning thermal stress, Tiradentes (33.3 °C) and São Raimundo (32.9 °C) squares exhibited the highest values, also demonstrating statistical differences from the remaining sites. Regarding perceived temperature, Tiradentes (60.5 °C) and São Raimundo (58.3 °C) squares recorded the most severe thermal conditions, differing statistically from the others.

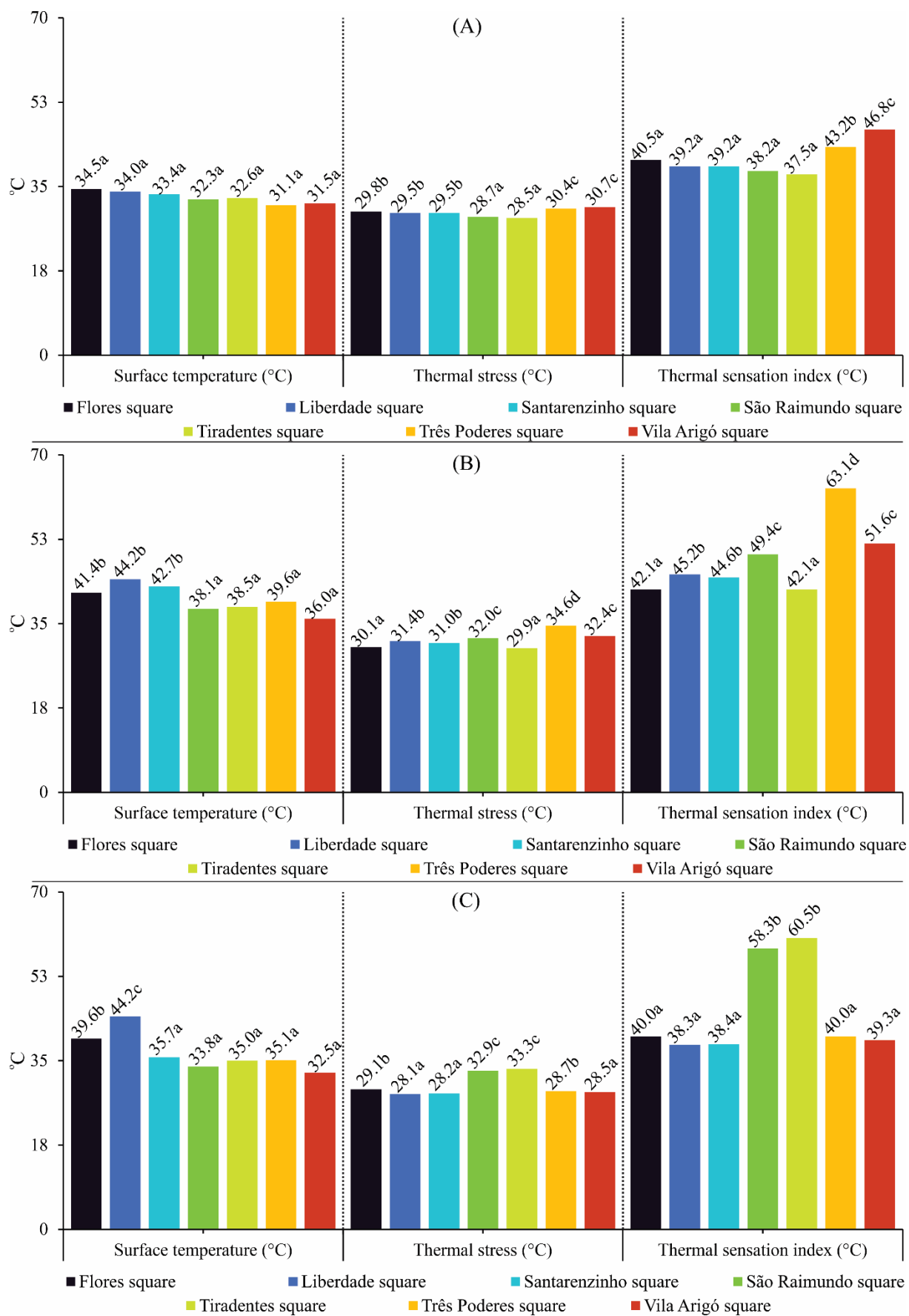


Figure 8. Mean values of surface temperature, thermal stress, and perceived temperature index at 08:00 (A), 13:00 (B), and 18:00 (C) for each of the squares in the municipality of Santarém, Pará state, Brazil. Different letters indicate statistically significant differences according to the Scott-Knott test at a 5% significance level.

4. DISCUSSIONS

Maioli et al. (2023) investigated diurnal temperature variations in squares within the city of Vitória, Espírito Santo state, and observed identical dynamics, characterized by peak temperatures in the afternoon, followed by a decline during the evening and morning periods, corroborating the findings of this study. Furthermore, Lisboa et al. (2024), in evaluating thermal stress (WBGT) variations across squares in the cities of Barbalha, Crato, and Juazeiro do Norte, Ceará state, identified a range of 23.7 °C to 40 °C, with peaks occurring during periods of maximum sun exposure. This pattern can be attributed to the incidence of direct solar radiation throughout the day. In the early afternoon (13:00), the period exhibiting the greatest thermal amplitude, all squares are subjected to more intense solar irradiation, resulting in temperature elevations. However, as the apparent position of the Sun shifts, portions of these areas begin to receive less direct solar incidence, facilitating a gradual reduction in air temperature.

Regarding perceived temperature, it was noted that the temperatures across the three evaluated times ranged from 32.8 °C to 36.5 °C, falling within the classifications of extreme caution (32.1 °C to 41 °C) and danger (41.1 °C to 54 °C). According to Moreira et al. (2023), the elevation in perceived temperature is directly correlated with the anthropization process, which drives landscape alterations through soil exposure and sealing, in addition to modifying the spatial configuration of the urban environment. Within this context, the adequate planning of public spaces becomes paramount, necessitating the adoption of architectural solutions and materials that minimize heat absorption and storage. Consequently, it is possible to create more comfortable environments capable of mitigating the effects of urban warming and alleviating the thermal discomfort experienced by the population.

The highest values of the analyzed variables in environments with AT (absence of trees) can be explained by the greater incidence of direct solar radiation on the surface, given the lack of vegetation cover capable of providing shading. This condition promotes the heating of the soil and urban structures, thereby raising the air temperature and exacerbating thermal discomfort. Furthermore, the lack of vegetation diminishes evapotranspiration processes, contributing to lower relative air humidity values Araújo et al. (2019). The influence of urban tree canopy on temperature was also observed by Anjos et al. (2023), who identified elevated indices in locations with greater exposure to solar radiation. In a study on thermal variability between tree-shaded and unshaded areas in the municipality of Manicoré, Amazonas state, (de Oliveira et al., 2023), concluded that urban

forestry exerts a significant influence on the climatic behavior of the urban environment. The authors verified that the presence of tree species reduces the incidence of direct solar radiation, contributing to temperature attenuation and providing improved thermal comfort conditions. These findings corroborate the results of the present study, reinforcing the critical role of arboreal vegetation in the regulation of the urban microclimate.

The temperatures of the evaluated squares are influenced by factors such as the presence of vegetation, land cover type, and the degree of urbanization in the immediate surroundings. Concrete and asphalt surfaces exhibit a higher capacity for energy absorption and storage, promoting heat accumulation and elevating the environmental thermal load (de Oliveira & Alves, 2013). In this context, Liberdade Square, characterized by its reduced vegetation cover and its location within a highly urbanized sector of Santarém, exhibited elevated temperature values (40.8 °C).

Regarding the thermal stress index, Zamproni et al. (2013) similarly found no statistical difference in their study of tree-shaded and unshaded areas in Curitiba, Paraná state, indicating that both environments exhibit comparable thermal comfort. Cardoso & Martini (2023), in studies of squares in Viçosa, Minas Gerais state, utilizing heat stress meters, recorded temperatures similar to this study, with a minimum of 29 °C and a maximum of 33.64 °C. The thermal influence of tree-shaded versus unshaded environments is driven by the shading provided by tree canopies, which directly affects temperature (Shinzato & Duarte, 2018), in addition to land cover type; grass-covered surfaces facilitate an improvement in thermal comfort (Cavalcante et al., 2025), which is not the case for the evaluated squares, as they are predominantly composed of concrete surfaces. The remaining squares are influenced by their immediate surroundings, given that among the studied sites, Santarenzinho Square is situated in an unpaved area, while Vila Arigó Square borders the Tapajós River.

Martelli & dos Santos Jr. (2015), in investigating the differences in air temperature and relative humidity across areas within the municipality of Itapira, São Paulo state, assert that urban forestry influences the urban perimeter, acting as a determinant for thermal comfort. Neres et al. (2021), in their research in Gurupi, Tocantins state, while analyzing temperature variations across distinct sites, also observed temperature reductions promoted by the shading of urban trees during morning, afternoon, and evening periods, all of which corroborate the findings of the present study.

The comparison of means demonstrates that the afternoon period presents the highest temperatures, statistically greater than the others, whereas evening and morning temperatures are milder. Thermal stress in outdoor environments is influenced by humidity and globe temperature (surface radiation); at night, the environment exhibits higher humidity levels, and the squares, being predominantly surrounded by concrete, emit

thermal radiation during the nocturnal period. The high humidity, absence of wind, and intense surface radiation collectively elevate nocturnal thermal stress, creating an extreme environment.

Among the evaluated sites, São Raimundo and Tiradentes squares differ from the others by exhibiting peak thermal stress during the nocturnal period. In contrast, the remaining squares demonstrate a typical thermal cycle characterized by peak thermal stress in the afternoon, followed by energy dissipation at night. Statistically, Vila Arigó, Santarenzinho, Três Poderes, and Liberdade squares recorded their most favorable values during the evening, whereas Flores Square did so in the morning. Anjos et al. (2023) also reported irregularities concerning peak temperature times in their study, attributing this to insufficient vegetation cover coupled with a high density of vehicles, buildings, and residences. These anthropogenic factors heavily influence the environmental thermal comfort, particularly because urban surfaces predominantly absorb solar radiation and re-emit it as sensible heat at specific times of the day, thereby driving ambient temperature increases.

São Raimundo and Tiradentes squares presented the most severe perceived temperature indices during the nocturnal period (58.3 °C and 60.5 °C, respectively), falling into the extreme danger classification. Flores Square exhibited minimal variation in perceived temperature, with no statistical differences across periods, consistently remaining within the extreme caution and danger thresholds. Liberdade, Santarenzinho, Três Poderes, Vila Arigó, and Flores squares recorded their peak values during the afternoon and lower values in the morning and evening, fluctuating between the Extreme Caution and Danger categories. In a study conducted in the city of Belém, Barbosa et al. (2015) found that vegetated areas promote a reduction in the heat index (HI), whereas highly urbanized areas exhibit elevated values, primarily during the afternoon (11:00 to 17:00), peaking at 14:00. Similarly, G. P. dos Santos et al. (2018), in a study within the municipality of Santarém, determined that perceived temperatures between 11:00 and 18:00 fall within the extreme caution interval for the heat index. This is explained by the fact that the net solar radiation balance only becomes negative after 20:00, a finding that corroborates the present study.

5. CONCLUSION

This study unequivocally demonstrates that urban trees are not merely aesthetic landscape elements, but critical public health infrastructure in equatorial cities. Our in situ empirical data prove that the absence of tree canopy cover pushes public spaces into "Danger" and "Extreme Danger" categories for thermal stress, with perceived temperatures reaching critical peaks of up to 63.1 °C in unshaded environments like Três Poderes Square at 13:00.

In contrast, tree-shaded areas significantly buffered surface temperatures and thermal stress, acting as a direct and immediate solution to mitigate the severe urban microclimate. Heavily concreted and unshaded areas, such as Liberdade Square, exemplify the thermal inefficiency of urban environments that prioritize grey infrastructure, creating localized extreme heat zones that actively restrict public use.

Ultimately, we conclude that urban forestry must transition from an optional landscaping feature to a mandatory climate resilience strategy. In Amazonian cities and other equatorial regions, implementing, preserving, and expanding tree canopy cover is the definitive, evidence-based solution to regulate urban microclimates, ensure acceptable thermal comfort, and protect human well-being against extreme urban heat.

6. REFERENCES

- Alvares, C. A., Stape, J. L., Sentelhas, P. C., De Moraes Gonçalves, J. L., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, 22(6), 711–728. <https://doi.org/10.1127/0941-2948/2013/0507>
- Angel, S. (2023). Urban expansion: theory, evidence and practice. *Buildings and Cities*, 4(1), 124–138. <https://doi.org/10.5334/bc.348>
- Anjos, L. S. dos, Anjos, R. S. dos, Luna, V. F., Mendes, T. G. de L., & Nóbrega, R. S. (2023). Arborização e conforto térmico no espaço urbano: estudo de caso em praças públicas de Recife-PA. *Revista Da Casa Da Geografia de Sobral (RCGS)*, 25(3), 107–135. <https://doi.org/10.35701/rcgs.v25.923>
- Araújo, K. L. de, Santos, K. J. R. dos, & Pereira Júnior, A. (2019). Influência de áreas verdes na temperatura do ar urbana: estudo de áreas adjacentes ao Parque Ambiental - Paragominas - PA. In *As múltiplas visões do meio ambiente e os impactos ambientais* (pp. 119–145). Simplíssimo. <https://doi.org/10.4322/978-85-455202-1-4-07>
- Barbosa, P. H. D., Costa, A. C. L. da, Cunha, A. C. da, & Silva Junior, J. D. A. (2015). Weather elements of variability and thermal comfort in different environments in the Brazilian Amazon. *Revista Brasileira de Climatologia*, 17. <https://doi.org/10.5380/abclima.v17i0.43048>
- Bezerra, P. E. S., De Moraes, E. T. I., & Soares, I. R. da C. (2018). Análise da Temperatura de Superfície e do índice de Vegetação no Município de Belém na Identificação das Ilhas de Calor. *Revista Brasileira de Cartografia*, 70(3), 803–818. <https://doi.org/10.14393/rbcv70n3-45701>
- Borges, D. A., Paiva, E. C. R., Sarmiento, A. P., & de Resende, A. A. (2016). Análise de condições térmicas nos blocos didáticos da Universidade Federal de Goiás - Regional Catalão. *REEC - Revista Eletrônica de Engenharia Civil*, 11(3). <https://doi.org/10.5216/reec.v11i3.38144>

382 Borges, V. O., Nascimento, G. C., Celuppi, M. C., Lúcio, P. S., Tejas, G. T., & Gobo, J. P. A. (2022). Zonas climáticas
383 locais e as ilhas de calor urbanas: uma revisão sistemática. *Revista Brasileira de Climatologia*, 31, 98–127.
384 <https://doi.org/10.55761/abclima.v31i18.15755>

385 Campos, M. B. de L. M. B., & Danelichen, V. H. de M. (2021). Sensoriamento Remoto e Estudos de Clima Urbano.
386 *Ensaio e Ciência C Biológicas Agrárias e Da Saúde*, 25(2), 195–199. [https://doi.org/10.17921/1415-](https://doi.org/10.17921/1415-6938.2021v25n2p195-199)
387 [6938.2021v25n2p195-199](https://doi.org/10.17921/1415-6938.2021v25n2p195-199)

388 Cardoso, H. M., & Martini, A. (2023). Benefício microclimático proporcionado pelas áreas verdes de Viçosa –
389 MG. *GEOFRONTER*, 9. <https://doi.org/10.61389/geofronter.v9i1.7400>

390 Cavalcante, L. L., Costa, C. E. A. de S., de Melo, A. M. Q., da Silva, R. C. P., & Moreira, M. L. R. (2025).
391 Influência da floresta urbana no microclima urbano do município de Tucuruí-PA. *Revista Da Sociedade*
392 *Brasileira de Arborização Urbana*, 20. <https://doi.org/10.5380/revsbau.v20.98763>

393 Chaolin, G., Liya, W., & Cook, I. (2012). Progress in research on Chinese urbanization. *Frontiers of Architectural*
394 *Research*, 1(2), 101–149. <https://doi.org/10.1016/j.foar.2012.02.013>

395 Climate Data. (2025). *Clima Santarém*. Climate Data.

396 Climatempo. (2025). *Climatologia em Santarém, BR*. Climatempo.

397 Costa, B. S., & Venâncio, S. R. (2016).
398 A social function of city and the right to housing fit as urban development assumptions sustainable.
399 *Revista Direito Ambiental e Sociedade*, 6(2), 106–136.

400 de Oliveira, H. M., Querino, J. K., Alves, P. V., Pagani, C. H., & Querino, C. A. (2023). Avaliação dos efeitos da
401 arborização nas variáveis de temperatura e umidade relativa do ar na cidade de Manicoré, Amazonas, Brasil.
402 *Revista Brasileira de Climatologia*, 32, 292–310. <https://doi.org/10.55761/abclima.v32i19.16453>

403 de Oliveira, M. M., & Alves, W. S. (2013). A influência da vegetação no clima urbano de cidades pequenas: um
404 estudo sobre as praças públicas de Iporá-GO. *Revista Territorial*, 2(2), 61–77.

405 Furtado, L. S., Pereira, R. V. S., & de Souza, E. B. (2024). Hemeroby Mapping of the Belém Landscape in Eastern
406 Amazon and Impact Study of Urbanization on the Local Climate. *Urban Science*, 8(1), 15.
407 <https://doi.org/10.3390/urbansci8010015>

408 INMET. (2025). *INMET: Clima*. INMET: Clima. <https://clima.inmet.gov.br/GraficosClimatologicos/>

409 Kunen, A., & Santos, G. D. (2024). Gestão de florestas urbanas nas capitais brasileiras: análise dos planos diretores
410 de arborização. *Observatório de La Economía Latinoamericana*, 22(11), e8004.
411 <https://doi.org/10.55905/oelv22n11-255>

Li, W., Pan, P., Fang, D., & Guo, C. (2025). Effects of Plant Communities in Urban Green Spaces on Microclimate and Thermal Comfort. *Forests*, 16(5), 799. <https://doi.org/10.3390/f16050799>

Lima, F. F. O., Konrad, O., & Feitosa, A. K. (2024). Process of urbanization and urban occupation and its environmental, social and economic impacts. *Observatório de La Economía Latinoamericana*, 22(2), e3281. <https://doi.org/10.55905/oelv22n2-131>

Lisboa, M. A. N., da Silva, L. V. A., Nascimento, A. da S., Silva, A. de O., Teixeira, M. R. A., Ferreira, M. F. R., Ferreira, S. C., da Silva, A. C. V., Colares, A. V., & Calixto Júnior, J. T. (2024). Diversity, structure, and carbon sequestration potential of the woody flora of urban squares in the Brazilian semiarid region. *Trees, Forests and People*, 16, 100561. <https://doi.org/10.1016/j.tfp.2024.100561>

Lucena, A. (2019). Uma análise de técnicas nos estudos de clima urbano para a região metropolitana do Rio de Janeiro. *Geo UERJ*, (34), e40954. <https://doi.org/10.12957/geouerj.2019.40954>

Maioli, R. N., Gomes, E., Martinuzzo, P., & Trindade, F. (2023). Análise da influência da vegetação em praças na mitigação de ilhas de calor urbano. *EuroELECS*, 1(1), 1–10.

Martelli, A., & dos Santos Jr., A. R. (2015). Arborização Urbana do município de Itapira –SP: perspectivas para educação ambiental e sua influência no conforto térmico. *REGET*, 19(2), 1018–1031.

Martine, G., & McGranahan, G. (2013). The legacy of inequality and negligence in Brazil’s unfinished urban transition: lessons for other developing regions. *International Journal of Urban Sustainable Development*, 5(1), 7–24. <https://doi.org/10.1080/19463138.2012.735236>

Moreira, P. H. O., Costa, A. C. L. da, Silva Júnior, J. de A., & Cunha, A. C. da. (2023). Variações sazonais do Índice de Temperatura Efetiva (ITE) e Índice de Calor (IC) com o uso do solo em zona urbana na Amazônia Oriental. *Caminhos de Geografia*, 24(93), 01–17. <https://doi.org/10.14393/RCG249365649>

Neres, D. L., Silva, L. R. C. da, & Pereira, M. A. B. (2021). Influência da vegetação no conforto térmico urbano em município do Sul do Tocantins. *Research, Society and Development*, 10(6), e47810615999. <https://doi.org/10.33448/rsd-v10i6.15999>

Oliveira, G. P., Maia, J. de O., Albuquerque, A. R., & Pereira Júnior, A. (2019). Influência da urbanização em Área de Preservação Permanente (APP) no bairro Filadélfia–Marabá (Brasil). *Revista Brasileira de Meio Ambiente*, 5(1), 39–54.

Porangaba, G. F. O., Teixeira, D. C. F., & Amorim, M. C. de C. T. (2017). Procedimentos metodológicos para análise das Ilhas de Calor em cidades de pequeno e médio porte. *Revista Brasileira de Climatologia*, 21. <https://doi.org/10.5380/abclima.v21i0.48832>

442 Portaria Nº 1.359, de 9 de Dezembro de 2019 (2019).

443 Rahaman, M. A., Kalam, A., & Al-Mamun, Md. (2023). Unplanned urbanization and health risks of Dhaka City
 444 in Bangladesh: uncovering the associations between urban environment and public health. *Frontiers in*
 445 *Public Health*, 11. <https://doi.org/10.3389/fpubh.2023.1269362>

446 Santos, A. M. S. P., Da Silva, A. P. V., Mattos, C. S., Lima, M. F. V., Nacur, E., Deschamps, L., Amaral, L., & Brás,
 447 V. (2020). O município e os desafios da política urbana em aglomerados urbanos: a experiência da metrópole
 448 fluminense. *Geo UERJ*, (36), e47268. <https://doi.org/10.12957/geouerj.2020.47268>

449 Santos, G. P. dos, Almeida, R. M., Moura, E. R. da S., & Oliveira, L. L. (2021). Sensação térmica urbana em área
 450 residencial planejada no município de Santarém – Pará, Amazônia, Brasil. *Revista Brasileira de Geografia*
 451 *Física*, 14(3), 1333–1351. <https://doi.org/10.26848/rbgf.v14.3.p1333-1351>

452 Santos, G. P. dos, Oliveira, L. L., Silva, J. A. C. da, Barreto, N. de J. da C., & Almeida, R. M. (2018). Desconforto
 453 térmico durante a estação seca em uma cidade de Clima Tropical Chuvoso na Amazônia. *Revista Ibero-*
 454 *Americana de Ciências Ambientais*, 9(6), 169–179. <https://doi.org/10.6008/CBPC2179-6858.2018.006.0018>

455 Schettino, S., Minette, L. J., Soranso, D. R., Camarinha, A. C. M., & Schettino, C. F. (2018). Avaliação ergonômica
 456 da colheita florestal em área com madeira danificada pelo vento. *Agropecuária Científica No Semiárido*,
 457 14(1), 70–78. <https://doi.org/10.30969/acsa.v14i1.986>

458 Semeraro, T., Scarano, A., Buccolieri, R., Santino, A., & Aarrevaara, E. (2021). Planning of Urban Green Spaces:
 459 An Ecological Perspective on Human Benefits. *Land*, 10(2), 105. <https://doi.org/10.3390/land10020105>

460 Shao, Z., Sumari, N. S., Portnov, A., Ujoh, F., Musakwa, W., & Mandela, P. J. (2021). Urban sprawl and its impact
 461 on sustainable urban development: a combination of remote sensing and social media data. *Geo-Spatial*
 462 *Information Science*, 24(2), 241–255. <https://doi.org/10.1080/10095020.2020.1787800>

463 Shinzato, P., & Duarte, D. H. S. (2018). Impacto da vegetação nos microclimas urbanos e no conforto térmico em
 464 espaços abertos em função das interações solo-vegetação-atmosfera. *Ambiente Construído*, 18(2), 197–215.
 465 <https://doi.org/10.1590/s1678-86212018000200250>

466 Weather Spark. (2025). *Clima e condições meteorológicas médias no Santarém-Maestro Wilson Fonseca Airport*
 467 *no ano todo, Pará, Brasil*. Weather Spark. [https://pt.weatherspark.com/y/147556/Clima-](https://pt.weatherspark.com/y/147556/Clima-caracter%C3%ADstico-no-Santar%C3%A9m-Maestro-Wilson-Fonseca-Airport-Par%C3%A1-Brasil-durante-o-ano)
 468 [caracter%C3%ADstico-no-Santar%C3%A9m-Maestro-Wilson-Fonseca-Airport-Par%C3%A1-Brasil-](https://pt.weatherspark.com/y/147556/Clima-caracter%C3%ADstico-no-Santar%C3%A9m-Maestro-Wilson-Fonseca-Airport-Par%C3%A1-Brasil-durante-o-ano)
 469 [durante-o-ano](https://pt.weatherspark.com/y/147556/Clima-caracter%C3%ADstico-no-Santar%C3%A9m-Maestro-Wilson-Fonseca-Airport-Par%C3%A1-Brasil-durante-o-ano)

470 Zamproni, K., Biondi, D., & Martini, A. (2013). Conforto térmico de uma rua arborizada com *Tabebuia*
471 *chrysotricha* (Mart. Ex DC.) Standl. na cidade de Curitiba-PR. *Revista Geografar*, 8(2), 8.
472 <https://doi.org/10.5380/geografar.v8i2.30607>

473 Zea-Camaño, J. D., Barroso, R. F., Souto, P. C., & Souto, J. S. (2015). Levantamento e diversidade da arborização
474 urbana de Santa Helena, no semiárido da Paraíba. *Agropecuária Científica No Semiárido*, 11(4), 54–62.

475 Zhang, Y., Jiang, T., Sun, J., Fu, Z., & Yu, Y. (2022). Sustainable Development of Urbanization: From the
476 Perspective of Social Security and Social Attitude for Migration. *Sustainability*, 14(17), 10777.
477 <https://doi.org/10.3390/su141710777>

478