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REGULAR ARTICLE

Thermal stress in an Agroforestry System: a case study of the use of a thermal sensor and unmanned aerial vehicle.

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LPM: Conceptualization; Experimental data collection; Data storage; Data analysis; Literature review; Manuscript writing. JAO: Experimental data collection; Data analysis; Literature review. MAP: Experimental data collection; Data analysis. ADS: Experimental data collection; Data analysis; Manuscript revision; Supervision; Funding acquisition.

Abstract

An agroforestry system (AFS) is a multifaceted agricultural practice that integrates the cultivation of shade-providing trees and understory crops. These systems have been shown to play a crucial role in mitigating extreme temperatures, reducing soil evapotranspiration, and shielding crops from wind damage. Effective management practices, including pruning, ensure optimal light distribution and temperature regulation in the AFS. The employment of unmanned aerial vehicles (UAVs) has led to significant advancements in the evaluation of crop traits, including the assessment of heat stress. However, research addressing thermal stress and temperature variations across AFS areas is limited. It is evident that thermal stress exerts a substantial influence on the physiological and genetic processes within plants. The present study investigated the relationship between temperature, insolation, and thermal stress in a 0.5-hectare AFS at Universidade Federal de São Carlos, Brazil. A Unmanned Aerial Vehicle (UAV) equipped with a thermal sensor was utilized to capture thermal and RGB images in four regions. These images were then analyzed with software such as Agisoft Metashape and QGIS to calculate the Thermal Condition Index (TCI). This index enabled the quantification of plant stress. The findings indicated that the midday period experienced the highest levels of stress, particularly in open pasture areas. The correlation between insolation exposure and higher surface temperatures (up to 40.56 °C) was significant in these areas. In contrast, tree-covered areas demonstrated a lower level of stress. TCI variations have been shown to align with temperature trends, underscoring the significance of microclimatic data for optimizing AFS management practices, including pruning and crop selection.

Keywords

Thermal Condition Index; Remote Sensing; Multifunctionality; Solar Radiation.

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Introduction

An agroforestry system (AFS) is characterized by the presence of cover trees that provide shade and understory plants that receive shade (Kumar et al., 2021). A salient benefit of these systems is their multifunctionality, which refers to their capacity to serve purposes beyond food production. Multifunctionality, as defined by the OECD (2001), refers to the capacity of agriculture to modify landscapes, assist in water and soil conservation, and contribute to the cultural and socio-economic maintenance of diverse regions.

The inclusion of trees in the growing area has been demonstrated to help reduce extreme temperatures, decrease soil evapotranspiration, and provide protection from the wind (Kumar et al., 2021). Furthermore, the configuration of these systems, in various forms, has been demonstrated to modify the light environment and the incidence of solar radiation (Sgarbossa et al., 2021). Maintaining the productivity of both trees and understory crops necessitates monitoring plant growth and management practices, such as pruning (Jose et al., 2004). Pruning is a labor-intensive practice that facilitates light penetration into the understory (Nicodemo et al., 2016) and modifies the temperature within these environments.

The advent and increased utilization of unmanned aerial vehicles (UAVs) has enabled the expeditious measurement of crop phenotype characteristics (Xie and Yang, 2020). In Agroforestry Systems, there are studies to measure forage production (Santos et al., 2024), above-ground biomass (Liang et al., 2022), and body temperature of heifers in a silvopastoral system (Thomsen et al., 2024). Some authors have also demonstrated the potential of using thermal cameras to monitor different crops (Viana et al., 2018). However, studies that measure thermal stress at different points in the AFS, as well as surface temperature variation and its relationship with insolation, are rare in these systems.

Thermal stress affects different processes that occur in crops, such as physiological, morphological and genetic processes (Mikó et al., 2025). Different crops, and forms of production, will be affected in different ways by heat and heat stress. In agroforestry systems, the presence of trees has been shown to minimize temperature extremes and reduce the average temperature over time (Rosisca et al., 2022). Furthermore, AFS has been demonstrated to mitigate the loss of crop productivity resulting from elevated temperatures, as evidenced by studies conducted on wheat (Singh et al., 2024).

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However, even within an agroforestry system, there are different temperature levels, with places having greater or lesser exposure. Consequently, outlining the behavior of each area within the system can facilitate management, such as the type and timing of pruning, and planting choices to optimize production. One way to assess heat stress in plants is by using the Thermal Condition Index (TCI) proposed by Kogan (1997). This index uses surface temperature in its calculation and indicates optimal (100) or non-optimal (0) values for crop development. Therefore, this paper presents preliminary results of a methodology for measuring surface temperature and insolation data for an AFS. It also evaluates thermal stress at different points in the system, using data obtained with a thermal sensor attached to a UAV.

Materials and methods

The area selected for analysis was a small agroforestry system (0.5 ha) situated at the Federal University of São Carlos (UFSCar) in the city of Araras, São Paulo state, Brazil (latitude 22°21'25" south and longitude 47°23'03" west, at an altitude of 646 meters).

To obtain the requisite images, both thermal and RGB, flights were conducted with a Matrice 300, loaded with a Zenmuse H20T, which is capable of radiometric temperature measurement with a resolution of 640*512. Six flights were conducted at a relative height of 40 meters, with one on June 25th and five on June 27th. The flight on June 25th commenced at 10 a.m. and was utilized to obtain RGB images for the digital elevation model (DEM). On June 27th, the five flights were conducted at the following times: 8:00 a.m., 10:00 a.m., 12:00 p.m., 2:00 p.m., and 4:00 p.m. The times were selected according to sunrise and sunset. According to data from the local weather station, the sun rises (on average) at 6 a.m. and sets at 5 p.m. Therefore, to capture the temperature, the start time was set at 8 a.m. and the end time at 4 p.m. so that images could still be captured. Due to battery charging limitations, a two-hour interval between flights was established to ensure that the batteries were fully operational.

The thermal images obtained from the flights were then converted into TIFF files according to the methodology of Irujo (2022). For calibration, the method established by the sensor manufacturer was used. According to the manual's recommendations, the data obtained from the images can be directly converted into temperature. Before and after each flight, the reflected ambient temperature was recorded and calculated by measuring a pre-established point in the image (concrete cover) with a handheld infrared thermometer (model MT-395, MINIPA ELECTRONICS INC, Texas, USA). As there was no significant difference between the manually measured value and that obtained in the image, no corrections were made. The images were processed in the Agisoft Metashape Professional Edition (v. 1.5.5.9097, Agisoft LLC, St. Petersburg, Russia) to obtain the DEM (RGB images) and the orthomosaics (thermal images). The simulation of the incidence of solar radiation (obtaining direct, diffuse and total insolation values) was carried out using open-source packages, SAGA GIS (Conrad et al. 2015), based on DEM.

The average temperature and insolation values were obtained using QGIS software (QGIS 2024). To achieve this objective, nine points were selected from four distinct regions within the analyzed area. These regions included the tree line (T1-T9), the area between the lines (B1-B9), the bare pasture area (P1-P9), and the shaded pasture area (S1-S9) (Figure 1). The areas between the trees were cultivated with vegetables at the time of the analysis (cabbage, herbs and spices). Solar radiation and air temperature data from a weather station located on the campus of the Federal University of São Carlos in Araras-SP were also used. Using the data obtained, graphs were produced showing the evolution of temperature and insolation over time.

Data from the weather station was also used to measure heat stress. The average maximum temperature and average minimum temperature were calculated for June 27, using data from the last ten years. These data were entered into Equation 1 to calculate the TCI (The Thermal Condition Index) (KOGAN, 1997), an index that measures the condition of the plant, with values ranging from 0 (inadequate condition) to 100 (optimum condition of the plant in relation to temperature).

$$TCI = 100 * \left(\frac{T_{max} - T}{T_{max} - T_{min}}\right) \qquad \text{Equation 1}$$

where T_{max} is the average maximum temperature over the last ten years for the date evaluated, T_{min} is the average minimum temperature for the same period, and T is the temperature measured at the point evaluated on the date and at the time the flights were made.

To evaluate the correlation between TCI values and temperature/radiation Pearson's correlation was performed. This test measures the relationship between two continuous variables and assigns a value between −1 and 1, where 0 indicates no correlation, 1 indicates total positive correlation, and −1 indicates total negative correlation (Equation 2).

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\left(\sum_{i=1}^{n}(x_i - \bar{x})^2\right)}\sqrt{\left(\sum_{i=1}^{n}(y_i - \bar{y})^2\right)}} \qquad \text{Equation 2}$$

To compare the average values of the index between the locations analyzed and the times evaluated, an ANOVA test was performed to verify whether there was a difference between the averages, followed by a Tukey test.

Results and discussion

The maximum and minimum air temperatures in the area, averaged over the last ten years (2015 to 2024), are 25.3 and 13.2°C, respectively. On the evaluation date, the temperature ranged from 18.2°C to 26.8°C from 8am to 4pm, with the highest temperature reached at 2pm. Therefore, both the minimum and maximum temperatures were above average for the last ten years for the same date (1.5°C above the maximum temperature). Figure 2 shows the variation in air temperature measurements, solar radiation, average total insolation (obtained by simulation) and the surface temperature in the area obtained with the thermal sensor. As illustrated in Figure, the simulated insolation value demonstrates a comparable trend to the radiation data obtained from the weather station, thereby validating the methodology for assessing solar radiation. When the simulation data is utilized exclusively for the pasture area (a condition akin to that under which the weather station obtains its data), the discrepancy between the simulation and the actual data is diminished. The observed solar radiation at peak time was found to be 666 W.m^{-2}, whereas the simulated value was 693 W.m^{-2}.

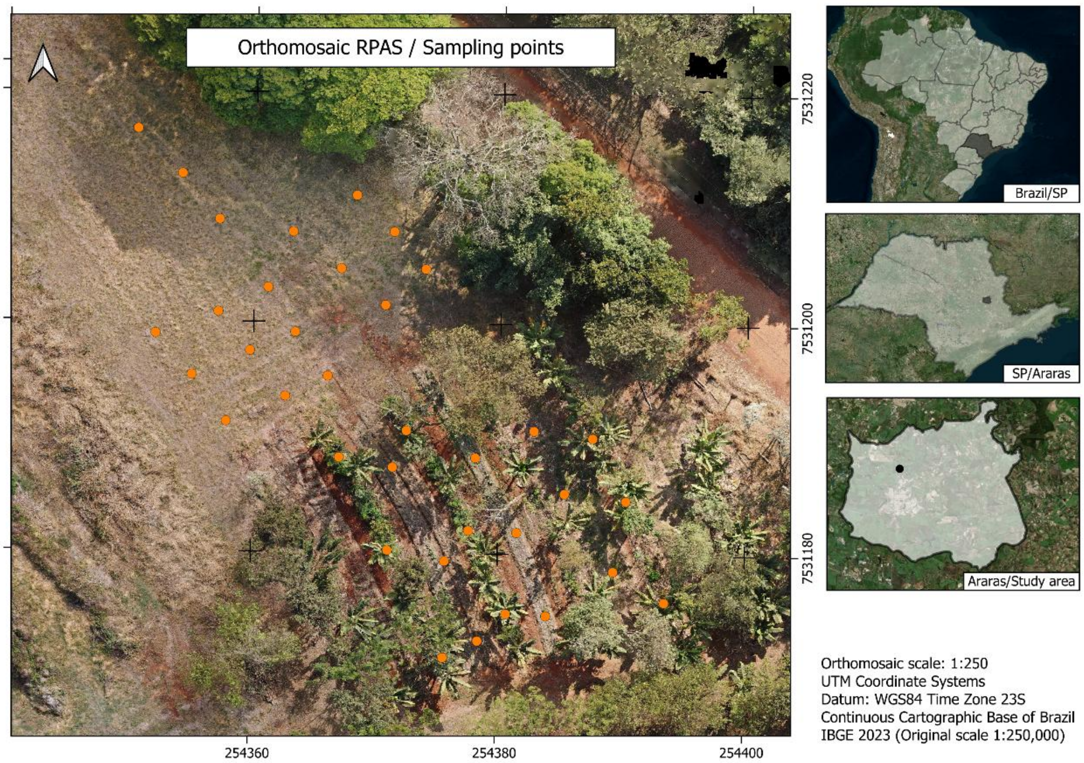

Figure 1. Location of the area analyzed with sampling points

Figure 2 shows that the surface temperature in the area analyzed (orange line) follows the increase in solar radiation, with an increase in surface temperature as the radiation falls on the plants. Using simulated insolation data as a basis, temperature has a similar relationship with direct, diffuse and total insolation (correlation of 0.56, 0.56 and 0.58 respectively). However, these relationships change as the time of analysis changes. At 10 a.m., the temperature has almost zero correlation with diffuse insolation and a higher correlation (0.48) with direct insolation. At 2 p.m., diffuse insolation has a higher correlation (0.56), while the influence of direct insolation decreases (0.43). The correlation values for the 2 p.m. hour can be seen in Figure 3.

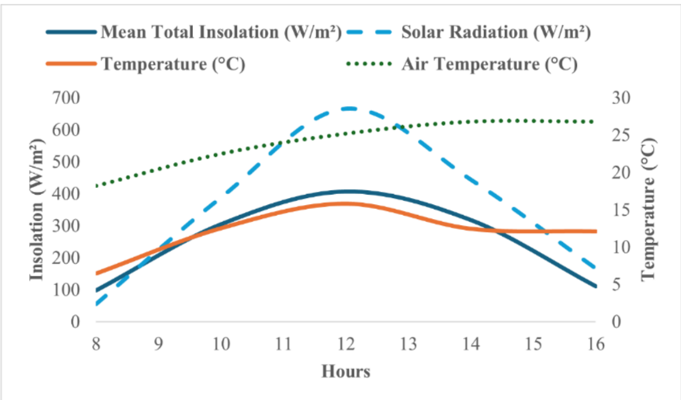

Figure 2. Variation in air temperature, surface temperature, solar radiation and average insolation throughout the evaluation day.

However, regardless of the time of day analyzed, the influence of diffuse insolation remains greater than the other types. Diffuse insolation refers to solar radiation that is "absorbed, scattered or reflected by water vapor, sand particles or pollution as it passes through the atmosphere" (Adefarati & Bansal, 2019). Unlike direct insolation, diffuse insolation can penetrate the plant canopy (Ryu et al., 2019) and has a high rate of blue wavelength radiation (Urban et al., 2012), which promotes photosynthesis in shaded leaves. So, despite being correlated with an increase in temperature, this type of radiation also favors photosynthesis in the understory of the AFS.

At 8 a.m. in all the locations analyzed, the plants had optimum temperature conditions, according to the index used. Over time, the pasture area suffered the most stress, with minimum index values (equal to zero) between the hours of 12 am and 2 pm. Despite the shade provided by the rows of banana trees, this area showed stress levels at midday. Although a reduction in the index was also observed, the tree areas of the system remained less stressed than the other areas evaluated, except at 10 a.m. (see Table 1). With the change in the position of the sun, the region with trees shows higher TCI values after noon, thus indicating less stress. This behavior is only achieved by the region between the trees at 4 p.m.

Regarding times, the differences between the average values of the index show that for pasture and the area between trees there is no statistical difference between the values calculated at 8 a.m. and 4 p.m. However, for all locations, the lowest index values occur at midday, indicating that this time of day is critical for plant development. The behavior of the TCI index is consistent with the temperature variation in the areas evaluated, as indicated in Table 2.

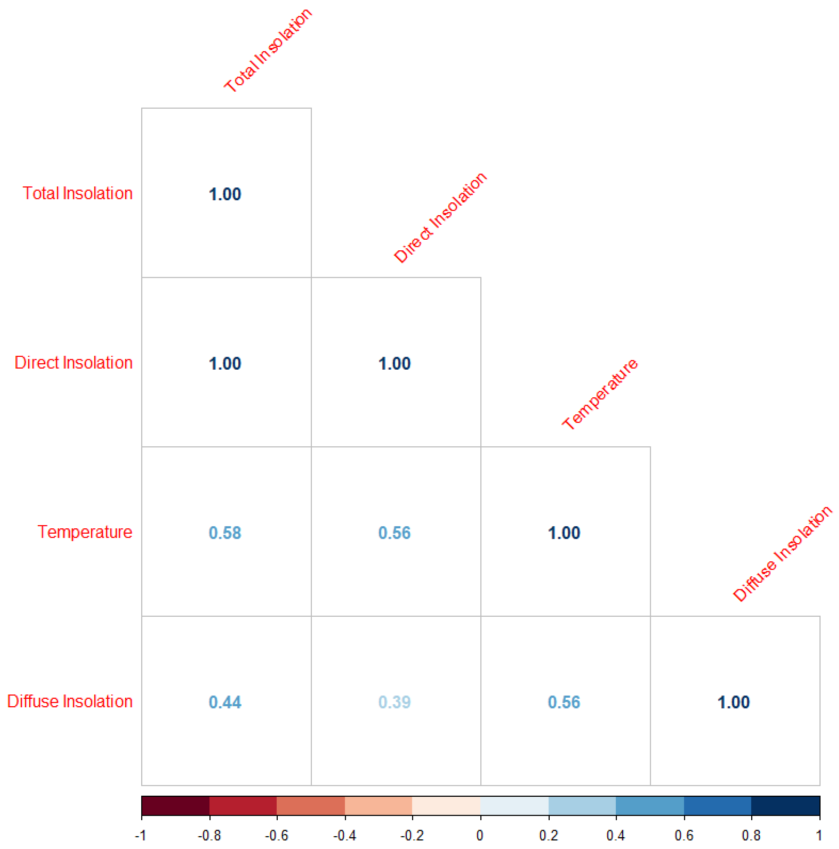

Figure 3. Correlation between temperature, total insolation, direct and diffuse insolation at 2pm.

Table 1. Mean TCI values in the different analysis areas.

Area	**TCI Value**				
	8 am	10 am	12 pm	14 pm	16 pm
Trees	100 *a	30.15 Bb	9.85 Ac	25.24 Abc	35.24 Ab
Between the trees	100 *a	25.42 Bb	0 Bc	10.58 Bbc	31.45 ABab
Pasture	100 *a	9.94 Bb	0 Bbc	0.35 Bbc	16.64 Cab
Shaded Pasture	100 *a	58.29 Ab	7.76 ABcd	3.18 Bd	20.48 BCc

Identical capital letters in columns and identical lowercase letters in rows indicate that there is no difference between the means. Tukey test with 5% significance. * No statistical difference determined by ANOVA.

Table 2. Mean Temperature values in the different analysis areas.

Area	**Temperature Value**									
	8 am	SD (%)	10 am	SD (%)	12 pm	SD (%)	14 pm	SD (%)	16 pm	SD
Trees	12,7	12.31	21.7	9.91	25.2	11.63	22.2	8.93	21.0	5.85
Between the trees	12.5	7.72	23.9	25.38	31.4	15.26	24.2	5.85	21.4	8.25
Pasture	11.5	5.81	27.1	19.65	40.5	10.73	26.4	6	23.2	3
Shaded Pasture	9.5	3.97	18.2	14.36	27.6	18.27	25.9	6.38	22.8	2.31

SD = standard deviation.

For all the areas, the maximum surface temperature is attained at midday. During this period, the surface temperatures of the tree line, the space between them, the pasture, and the shaded pasture are 25.23, 31.41, 40.56, and 27.68 °C, respectively. On the other hand, insolation had greater differences of 143.76, 191.34, 693.85 and 88.24 W m-², respectively for the same areas. The exposure of the grassland subjects to greater insolation is directly proportional to the increase in surface temperature.

D'Acunha et al. (2024) observed that areas with management systems (pasture and agriculture) have a lower transpiration rate than areas of natural vegetation. Both grassland and trees can reduce the surface temperature compared to a site with exposed soil, but the temperature reduction is greater in areas with the presence of trees (Armson et al., 2012). Kim et al. (2024) observed that the presence of trees led to a reduction in air temperature by approximately 1.5°C, while certain types of grass exhibited a decrease of 0.8°C. This discrepancy in temperature reduction can be attributed to the shaded environment provided by trees, as well as their higher rates of evapotranspiration compared to grass. The observed decline in air temperature also resulted in a corresponding decrease in the surface temperature of the area under analysis. This effect was found to be more pronounced due to the shading of the ground by the trees, as confirmed by the reduced insolation levels in these areas.

The TCI value changes according to the type of soil cover, with Ren et al. (2023) observing that exposed soil has lower values of this index. In addition, TCI values below 40 indicate that the plant is subject to extreme values of surface temperature, which means stress and less ability to carry out its physiological functions (Kogan, 1997). Thus, the results obtained here show that all the areas analyzed were (at different times) under great thermal stress. This occurrence is most intense at midday, which coincides with the time of greatest solar radiation. These results show that, for the system analyzed, the inclusion of a greater number of tree components, in different strata, can help to reduce temperatures and reduce the plants' thermal stress.

On the date the analysis was performed, the temperature was above the average of the last ten years, which also contributed to greater stress on the plants. However, the occurrence of heat waves and periods with above-average temperatures will become more frequent with climate change. This instability of climate events directly impacts the development of crops and can have serious consequences on productivity, and consequently on economic and social conditions in view of the increased demand for food (Alves and Putti, 2022). For South America, Feron et al. (2019) point out that days tend to be hotter than the mid-century average. In addition, these authors observed that days of extreme heat were more than double what was observed in the last decade. Therefore, the results we observed in our work show that thermal stress on plants throughout the day tends to increase. Therefore, management techniques and adoption of practices, such as the inclusion of trees in production systems, tend to be more necessary to reduce plant stress in production areas.

Conclusions

The methodology outlined, which involved measuring surface temperature using a UAV and simulating insolation, proved to be effective. Consequently, the data observed in this manner exhibited a comparable trend to the data obtained from a meteorological station (with an increase in insolation throughout the day and the temperature following this behavior). The TCI index, calculated from the temperature data, exhibited a decline with rising temperatures throughout the day. The findings indicated that areas encompassing trees and shaded pasture exhibited lower values and periods of stress. This finding suggests that the incorporation of a tree component within the production area may serve to mitigate the stress induced by elevated temperatures. Consequently, this methodology has the potential to facilitate the management of agroforestry systems by providing insights into the optimal timing and intensity of pruning, as well as identifying areas that are particularly vulnerable to stress. It is imperative that future studies be conducted to substantiate the methodology and assess analogous regions during disparate seasonal periods.

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