



Infrared thermography reveals agroforestry systems mitigate soil thermal stress in coffee cultivation

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Abstract Soil temperature regulation plays a central role in sustaining coffee productivity under climate change, yet comparative evidence across contrasting land-use systems remains limited. This study used infrared thermography to characterize soil thermal regimes in four management systems: *Coffea canephora* monoculture, *Hevea brasiliensis* monoculture, coffee–rubber tree agroforestry, and native vegetation. A total of 160 thermal images were collected across five daytime intervals (11:00–16:00) under two surface conditions (with and without soil cover). Soil temperatures differed markedly among systems. The coffee monoculture exhibited the highest values, reaching 48.0 °C on exposed soil and 34.1 °C under cover, whereas native vegetation showed minimal thermal fluctuation ($\Delta T = 2.5$ °C). Temperatures in the agroforestry system closely resembled those in the rubber tree monoculture (24.2–36.8 °C on exposed soil) and provided 32 percent greater buffering of minimum temperatures compared with the coffee monoculture. Thermal amplitude was also

reduced in the agroforestry system (13.8 °C versus 20.3 °C), indicating enhanced microclimatic stability. Overall, the results demonstrate that integrating coffee with rubber trees substantially mitigates soil thermal stress while maintaining conditions compatible with productive cultivation. Infrared thermography proved to be an effective tool for high-resolution monitoring of soil temperature dynamics in perennial cropping systems.

Keywords Agroforestry systems · *Coffea canephora* · Thermal imaging · Soil temperature · Microclimate regulation · Climate-smart agriculture

Introduction

Coffee production faces significant challenges due to climate change, with both cultivated species, *Coffea arabica* and *Coffea canephora*, being vulnerable to temperature extremes, though *C. arabica* is considered particularly sensitive to thermal stress (DaMatta et al. 2018; Martins et al. 2020).. Studies have shown that temperatures above 35 °C during flowering and fruit development can severely reduce yields and bean quality (DaMatta et al. 2018; Martins et al. 2020). In this context, agroforestry systems (AFS) have emerged as a promising strategy to mitigate thermal stress, combining coffee cultivation with shade trees to buffer microclimatic conditions. For instance, rubber trees (*Hevea brasiliensis*) in AFS have been

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reported to reduce air temperature by up to 4.8 °C and increase relative humidity (Araújo et al. 2016), without compromising coffee productivity (Partelli et al. 2014). However, while the aerial microclimate benefits of AFS are well-documented, their effects on soil temperature, a critical factor for root development, water retention, microbial activity, and nutrient uptake, remain poorly understood.

Recent field observations have revealed that soil temperature fluctuations in coffee plantations can be even more extreme than air temperature variations, particularly in full-sun systems. During peak sunlight hours, bare soil surfaces in coffee monocultures have been recorded reaching temperatures exceeding 50 °C (Rosisca et al. 2022), while shaded systems maintain more stable thermal regimes. These extreme soil temperatures not only affect plant physiology but also alter soil fauna composition and organic matter decomposition rates (Santos et al. 2018a, b). The rubber tree's dense canopy and litter layer may provide particularly effective soil insulation, as demonstrated in other perennial crop systems (Rosisca et al. 2022), though this specific interaction has not been quantified for coffee-rubber tree agroforestry.

Most research on coffee AFS has focused on above-ground conditions, leaving a gap in knowledge regarding how different shade systems influence soil thermal dynamics. Traditional methods for measuring soil temperature, such as thermocouples, provide limited spatial resolution and may disturb the soil structure. Infrared thermography offers a non-invasive alternative, enabling high-resolution thermal mapping of soil surfaces (Lima et al. 2014). Yet, its application in coffee AFS, particularly in systems integrating rubber trees, has not been explored. This study addresses this gap by using infrared thermography to assess soil temperature variations in a *Coffea canephora* and *Hevea brasiliensis* AFS, comparing it with monoculture systems and native vegetation.

Our study tested the hypothesis that a conilon coffee-rubber tree agroforestry system would maintain lower soil temperatures (both under and above ground cover) compared to coffee monocultures, using infrared thermography as an innovative assessment tool. Specifically, we aimed to: (1) quantify soil temperature variations under different cover conditions in these agroforestry systems, and (2) compare these thermal patterns against both monoculture systems

(coffee and rubber tree) and native vegetation as a reference ecosystem.

Materials and methods

Study sites

The study was conducted in a municipality located on the southeastern coast of Brazil, within the Atlantic Forest biome. The study area is classified as Aw climate, characterized as tropical with dry winters, based on the Köppen system (Alvares et al. 2013). All sites had soils classified as Ferralsols (IUSS Working Group WRB 2015). According to the Brazilian soil classification system (Santos et al. 2018a, b), the soil was identified as a typical dystrophic YELLO-LATOSOL. The study areas were situated in proximity (Fig. 1), all located within the same soil group (sandy soils with > 800 g kg⁻¹ sand content and 24–27 g kg⁻¹ organic matter) and exhibiting similar slope characteristics.

Four different land management systems were assessed (Fig. 2): i) CC: monoculture system of conilon coffee (*Coffea canephora*), which was planted in 2006, with spacing of 2.6m×1.3m; ii) RT: monoculture system of rubber tree (*Hevea brasiliensis*), which was planted in 1982, with spacing of 7.8m×2.3m; iii) AS: agroforestry system of conilon coffee and rubber tree, which was composed of two rows of conilon coffee (2.6×1.3m planted in 2006) intercropped with two rows of rubber trees (7.8×2.3m, planted in 2007); and iv) NV: native vegetation, which was composed of the dense ombrophilous forest of the Atlantic Forest biome, and set as a reference for the agricultural areas in order to investigate how the temperature changes according to different land management systems.

In terms of soil cover, it is important to note the study was performed in early August, after an occurrence of intense litter deposition by rubber tree shedding. Likewise, in the areas with conilon coffee, there were crop residues from pruning, which were crushed and kept in the interrows.

Thermal images

Thermal data collection was performed using a FLIR T440 infrared camera (FLIR Systems, USA) with

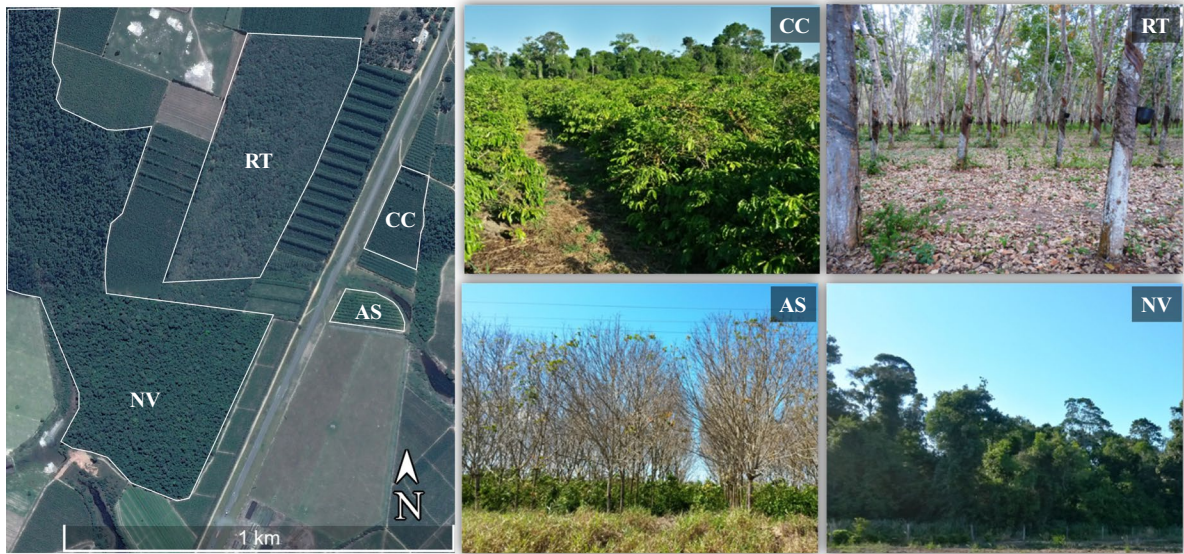


Fig. 1 Location of the study site. CC: monoculture of conilon coffee (18°56'28.6"S and 39°58'33.3"W); RT: monoculture of rubber tree (18°56'26.0"S and 39°58'45.5"W); ARC: agrofor-

estry system of conilon coffee and rubber tree (18°56'36.4"S and 39°58'36.2"W); NV: native vegetation (18°56'39.6"S and 39°58'49.9"W)

a resolution of 320×240 pixels, thermal sensitivity <0.045 °C, and ±2% measurement accuracy. For agricultural areas, we adopted standardized imaging protocols where coffee plants (*Coffea* spp.) were imaged at 0.5m distance from the trunk, while rubber trees (*Hevea brasiliensis*) were imaged at 1.0m distance, with all measurements taken in the interrow direction to maintain consistency. Native vegetation areas were sampled using randomized imaging points to capture natural thermal variability.

To evaluate the thermal regulation effects of different soil cover management systems, we implemented a paired sampling approach. At each predetermined sampling point, we first captured the baseline thermal image with existing soil cover intact. Immediately following this initial measurement, we carefully removed the surface cover while minimizing soil disturbance and captured a second thermal image under identical conditions (1m distance, same camera angle and settings). This before-after sampling design allowed for direct comparison of surface temperatures with versus without vegetative cover at each specific microsite. Figure 3 illustrates this experimental protocol, showing representative thermal images from both measurement conditions.

The images were taken during daytime at five intervals: from 11–12h, 12–13h, 13–14h, 14–15h and 15–16h, which were used as replications. Eight images were taken in each land management system (four over and four under the soil cover) for every interval. This led to a total of 160 images in this study, all of which were collected on a single day.

Image processing and data analysis

All thermal images were processed and analyzed using FLIR Tools software (version 5.13.18031.2002, FLIR Systems, USA). We applied histogram equalization for optimal color distribution and selected the 'rainbow' color palette to maximize thermal contrast visualization. Given the native resolution of 320×240 pixels per infrared image, each image contained 76,800 discrete temperature measurement points.

The complete dataset from each image was exported to spreadsheet format (Microsoft Excel, Microsoft Corp.) for comprehensive statistical analysis. For every image, we calculated five key temperature parameters: (1) minimum temperature, representing the coldest detected point; (2) average temperature, indicating the mean thermal value across all pixels; (3) median temperature, showing

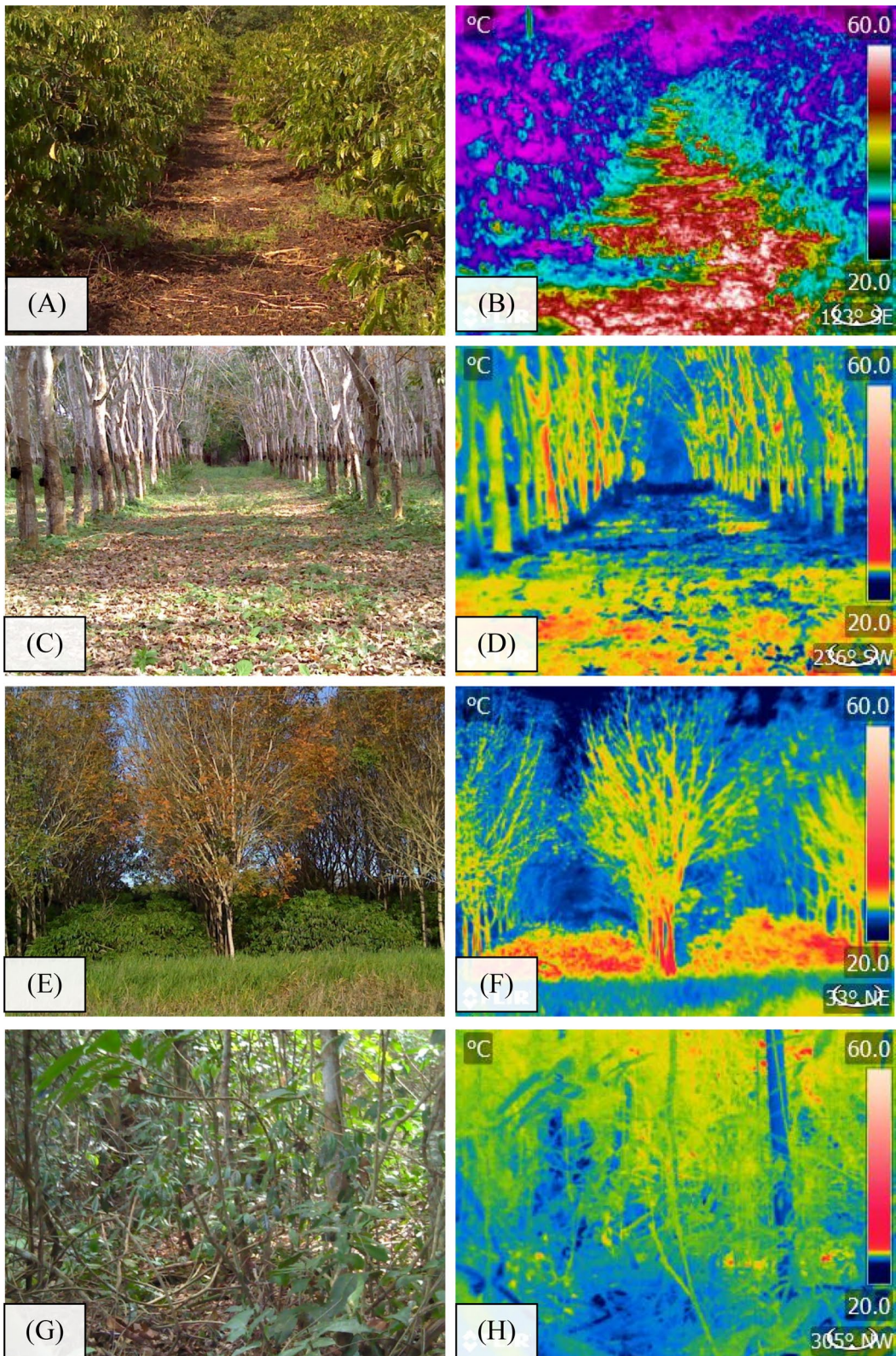


Fig. 2 Optical (A, C, E and G) and thermal (B, D, F and H) images of the study sites. A and B: monoculture system of conilon coffee, C and D: monoculture system of rubber tree, E and F: agroforestry system of conilon coffee and rubber tree, G and H: native vegetation

the central tendency; (4) modal temperature, identifying the most frequently occurring value; and (5) maximum temperature, revealing the hottest spot in each image. This multi-parameter approach provided a robust characterization of the thermal distribution patterns.

The statistical analysis employed non-parametric methods after confirming non-normal data distributions through Shapiro–Wilk tests ($W=0.87–0.92$, $p<0.001$ for all temperature parameters). We initially applied the Kruskal–Wallis test (Kruskal and Wallis 1952) to evaluate system-wide differences in all five temperature metrics (minimum, average, median, mode, maximum) across management systems (CC, RT, AS, NV) and cover conditions, adopting a conservative significance threshold ($p<0.01$) to account for multiple comparisons and minimize Type I errors. This omnibus approach allowed us to detect overall differences without requiring parametric assumptions about data distributions (Corder and Foreman 2014), making it particularly suitable for ecological data with inherent variability.

For significant Kruskal–Wallis results ($p<0.01$), we conducted Dunn’s post-hoc tests (Dunn 1964) with Bonferroni adjustment to identify specific pairwise differences while maintaining family-wise error control at $\alpha=0.05$. This non-parametric alternative to Tukey’s HSD is robust to unequal variances and sample sizes (Dinno 2015), implemented through the FSA package in R (Ogle et al. 2023). The results were visualized using letter-based groupings from the multcompView package (Graves et al. 2019). Additionally, we assessed thermal regulation capacity by analyzing absolute temperature differences ($\Delta T = \text{over} - \text{under}$) for each parameter, applying the same non-parametric framework (Kruskal–Wallis tests at $p<0.05$ with Dunn’s post-hoc where appropriate) to compare ΔT values across systems.

All analyses were conducted in RStudio (v4.5.1; R Core Team 2025) using the FSA package (Ogle et al. 2023) for Dunn’s test and ggplot2 (Wickham

2016) for visualization. The non-parametric framework was chosen to align with the data’s distributional properties and enhance robustness to field-based variability (Zar 2010).

Results

The thermal analysis revealed striking contrasts among management systems (Fig. 4). The conilon coffee monoculture (CC) exhibited the highest soil temperatures across all metrics, with peak values reaching 48.0 °C (surface) and 34.1 °C (sub-cover), significantly surpassing the other systems ($p<0.01$). The agroforestry system (AS) showed thermal behavior statistically equivalent to the rubber tree monoculture (RT), with temperature ranges of 24.2–36.8 °C (over cover) and 21.9–27.0 °C (under cover), suggesting similar microclimatic conditions.

Native vegetation (NV) maintained the most stable thermal regime, with all temperature parameters (minimum, average, median, mode, maximum) consistently 18–52 percent lower than CC. The temperature differential (ΔT) between covered and bare soil also revealed clear distinctions: CC showed a 9.5 °C average reduction under cover, AS and RT exhibited moderate reductions (7–8 °C), and NV displayed minimal variation (2.5 °C), indicating strong insulating efficiency of natural forest litter.

Overall, the results demonstrate that AS exhibits its thermal behavior similar to RT and significantly lower temperatures than CC. NV consistently presented the lowest thermal variation and the most stable soil temperature profile among all systems.

The temperature difference between upper and lower soil cover (ΔT) showed statistically significant variation among management systems (Fig. 5). For minimum temperature (Fig. 5A), CC showed the highest ΔT values while NV displayed the lowest, reflecting greater thermal stability in natural environments. Although RT and AS showed no statistical difference, AS exhibited higher ΔT values and greater thermal amplitude than RT. These results indicate that while agroforestry systems provide better thermal moderation than coffee monocultures, their minimum temperature regulation still underperforms compared to rubber tree monocultures and native vegetation.

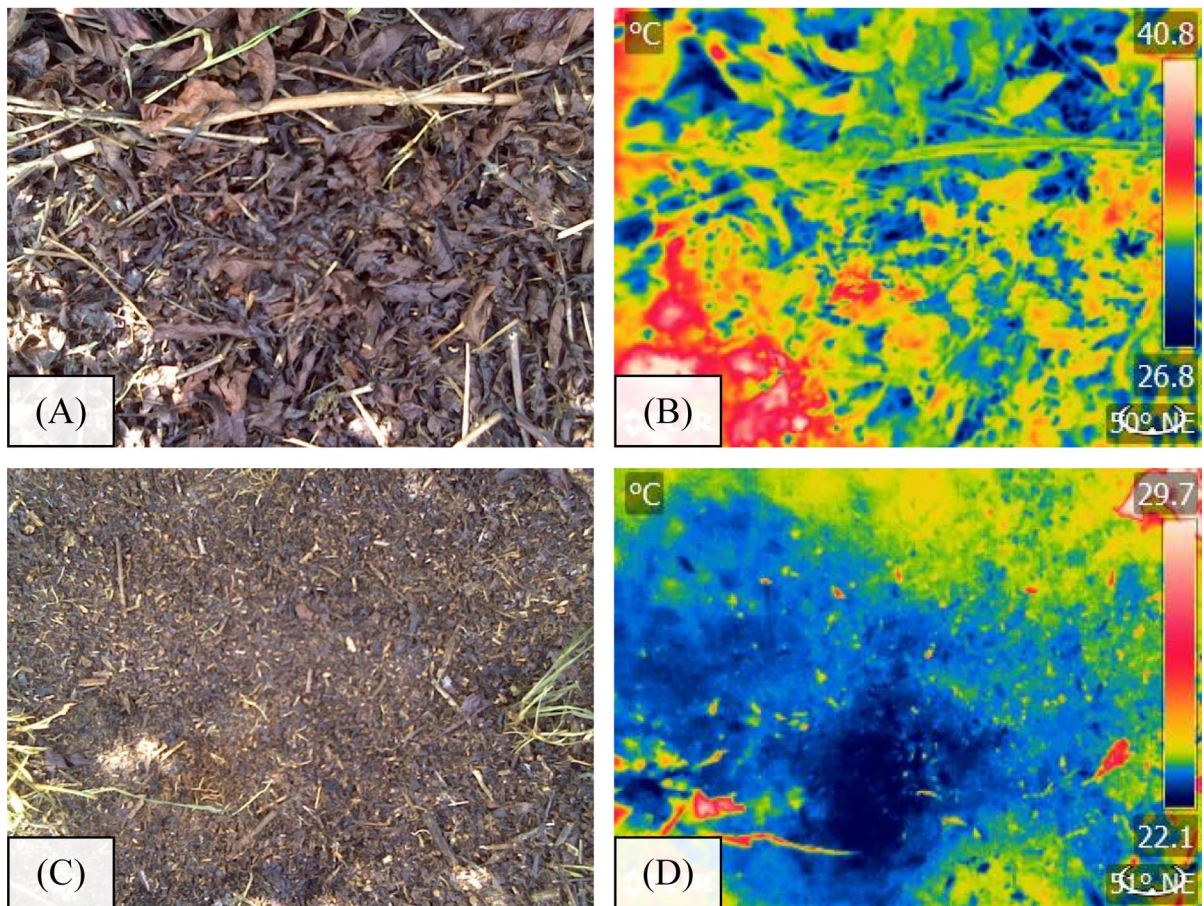


Fig. 3 Optical (A and C) and thermal (B and D) images of the study sites taken over (A and B) and under (C and D) soil cover

For average temperature (Fig. 5B), no statistical differences occurred among agricultural systems (CC, RT, AS), indicating similar daily mean temperatures across treatments. However, NV showed significantly lower ΔT values, demonstrating superior soil thermal regulation efficiency, likely due to denser, continuous vegetation cover.

Regarding median (Fig. 5C) and modal temperatures (Fig. 5D), similar patterns emerged: agricultural systems showed no differences, while NV consistently displayed the lowest ΔT values. This reinforces native vegetation's role in maintaining more stable and homogeneous thermal conditions throughout the day.

For maximum temperature (Fig. 5E), CC showed the highest ΔT values while NV maintained the lowest. AS displayed intermediate values without significant differences from monocultures. These data

indicate that while agroforestry systems do not significantly reduce maximum temperatures compared to monocultures, they play a crucial role in mitigating minimum temperatures, promoting greater overall thermal stability.

Analysis of temperature differences between covered and bare soil (ΔT) across different land-use systems revealed distinct thermal regulation patterns, with the agroforestry system (AFS) exhibiting behavior closer to native vegetation (NV) compared to monocultures. The AFS showed ΔT values more similar to NV, particularly for minimum (Fig. 5A) and median temperatures (Fig. 5C), indicating greater thermal stability in this agroecological arrangement relative to monocultures.

For minimum temperature, the AFS showed a significant reduction in ΔT compared to coffee monoculture (CM), though it remained statistically

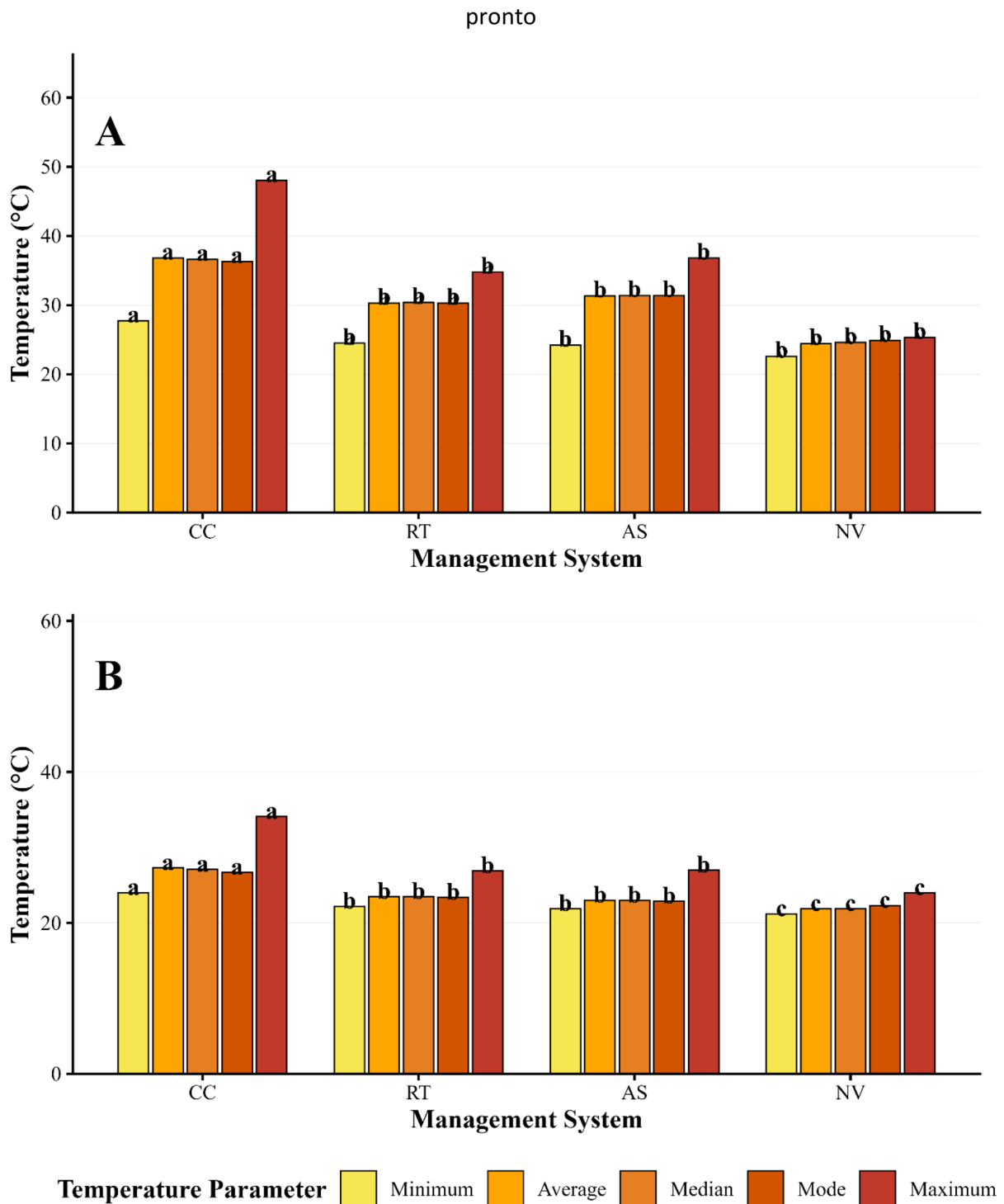
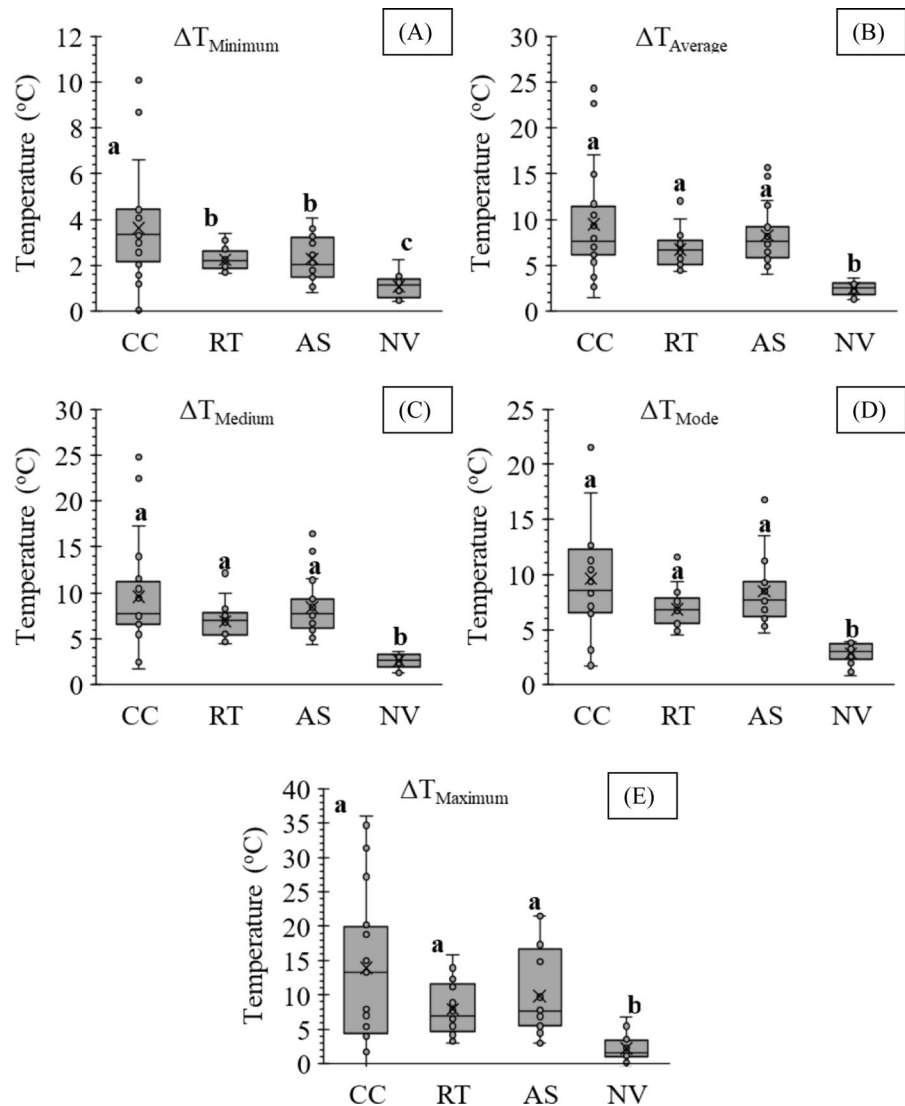


Fig. 4 Temperature variation under different management systems: **A** above soil cover and **B** below soil cover. The evaluated parameters (minimum, average, median, mode, and maximum; °C) are represented by colored bars. Different letters indicate significant differences between management systems for each

parameter (Kruskal–Wallis test, $p < 0.01$). Systems evaluated: CC=conilon coffee monoculture; RT=rubber tree monoculture; AS=coffee-rubber tree agroforestry system; NV= native vegetation

Fig. 5 Difference between the temperature over and under soil cover (ΔT) for **A** the minimum, **B** average, **C** medium, **D** mode, and **E** maximum temperature in different management systems. CC: monoculture of conilon coffee, RT: monoculture of rubber tree, AS: agroforestry system of conilon coffee and rubber tree, NV: native vegetation. Means followed by different letters in each bar are significantly different to each other according to the Kruskal–Wallis test ($p < 0.05$)



higher than NV. This result highlights that the presence of shade trees in the AFS, such as rubber trees, mitigates soil heat loss during the night, approximating thermal behavior to that observed in natural ecosystems.

Discussion

The similarity between AS and RT corroborates findings by Araújo et al. (2016), who reported reductions of up to 4.8°C in microclimate under rubber tree shade. This pattern suggests that rubber trees exert a dominant influence on thermal regulation, mitigating

extremes such as those observed in CC, where surface temperatures reached 48.0°C . The stability observed in NV ($\Delta T = 2.5^{\circ}\text{C}$) reinforces the protective role of natural vegetation cover, consistent with Blaser et al. (2018), who highlighted the climate-adaptation capacity of intermediate-shade agroforests (30–50 percent).

The pronounced 9.5°C reduction under cover in CC reveals the vulnerability of full-sun systems, aligning with Cassamo et al. (2023), who demonstrated greater thermal resilience in agroforestry systems under climate change scenarios. Although AS reduces thermal extremes, its higher variation compared to NV indicates that agroforestry systems

do not fully replicate natural ecosystem microclimates. This gap underscores the importance of optimizing shading intensity, as suggested by Piato et al. (2020), who identified physiological and productive benefits for robusta coffee under moderate shade (41–65 percent), while noting potential sensory quality trade-offs. Therefore, the adoption of AS requires careful management to balance thermal protection and productivity, ensuring that shading levels enhance microclimatic stability without compromising coffee quality or yield.

The reduction in nocturnal thermal amplitude is particularly relevant for *Coffea canephora*, a species known to be sensitive to thermal stress, especially during critical phenological stages such as flowering and fruiting (Partelli et al. 2014; DaMatta et al. 2018). This sensitivity is corroborated by Oliosi et al. (2016), who observed that Conilon coffee under Australian cedar (*Toona ciliata*) shade not only exhibited lower diurnal thermal variation (ΔT up to 3.5 °C) but also enhanced vegetative growth (a 47 percent increase in leaf area), underscoring the physiological benefits of thermal stability. High temperatures can significantly impair vegetative development and productivity in this species, with more pronounced impacts under full-sun conditions (Rodrigues et al. 2016; Covre et al. 2018).

Bezerra et al. (2024) further support this relationship by demonstrating that Conilon coffee in agroforestry systems with Brazil nut (*Bertholletia excelsa*) and teak (*Tectona grandis*) (up to 222 trees/ha) maintained an average yield of 88.6 bags/ha, with no significant reduction compared to full-sun cultivation, suggesting that moderate shading can alleviate stress without compromising production. As evidenced by Martins et al. (2020), *C. canephora* has well-defined thermal limits for optimal metabolism, and abrupt temperature fluctuations, particularly during the night, can disrupt essential physiological processes such as photosynthesis and photoassimilate translocation (DaMatta et al. 2018).

Regarding median temperature, the proximity between AFS and NV values reinforces the potential of agroforestry systems to mimic ecological attributes of native vegetation, promoting more balanced microclimatic conditions favorable to coffee physiological development. This thermal regulation capacity aligns with findings by Lopes et al. (2024), who observed in mature arabica coffee AFS a microclimatic stability

comparable to full-sun systems during winter, emphasizing the role of trees in maintaining homogeneous thermal conditions. For mean, mode, and maximum temperatures (Fig. 3B, D, and E), although the AFS did not match NV, it exhibited intermediate behavior, distinctly different from coffee monoculture. This moderation of extremes is critical for *C. canephora*, as demonstrated by Oliosi et al. (2016), where even under intensive shading (47 percent irradiance reduction), coffee productivity was not compromised, indicating that mitigating thermal peaks should be prioritized.

The thermal regulation provided by agroforestry systems carries particularly relevant implications for *Coffea arabica*, a species considered even more sensitive to temperature extremes than *C. canephora*. Elevated soil temperatures in full-sun systems not only impose direct physiological stress but also compromise soil water storage capacity, a variable closely associated with vegetative growth and yield stability in arabica coffee (Parada-Molina et al. 2025). This relationship is especially critical during phenologically sensitive stages: water deficit during the pre-flowering period has been shown to directly determine the percentage of flower bud opening in *C. arabica*, with insufficiently uniform flowering leading to uneven fruit ripening and reduced harvesting efficiency (Ronchi et al. 2020). Given that agroforestry systems moderated soil thermal amplitude and approached native vegetation conditions in several parameters observed in the present study, their adoption in arabica-producing regions could simultaneously buffer thermal stress and help maintain more favorable soil water conditions during critical phenological windows, representing a dual adaptation benefit under projected climate change scenarios.

From an agroecological perspective, the partial similarity between AFS and NV in thermal regulation underscores the importance of agroforestry systems as a strategy for ecological transition. The integration of tree species with agricultural crops not only enhances productivity and economic diversification, as observed by Bezerra et al. (2024), but also provides environmental benefits such as natural shading, increased soil organic matter, and more stable daily thermal ranges. These findings align with Lopes et al. (2024), who highlighted the ability of mature AFS to balance ecosystem services (e.g., carbon

sequestration) and agricultural production, even under seasonal climatic conditions.

These results corroborate previous studies identifying AFS as resilient systems against climatic variability, mitigating thermal and water stress in tropical environments (Schroth et al. 2001; Abigaba et al. 2024). The viability of these systems is supported by empirical evidence: Oliosi et al. (2016) showed that shading by Australian cedar did not affect coffee yield (70.9–91.15 bags/ha), while Bezerra et al. (2024) confirmed that species like teak and Brazil nut can be integrated with coffee without yield losses. While native vegetation remains the gold standard for ecological excellence, AFS represent a viable and efficient alternative to reconcile agricultural production with environmental conservation, particularly in Conilon coffee-growing regions vulnerable to climate change. Selecting slow-growing, low-competition tree species (e.g., Brazil nut) and moderate densities (≤ 222 trees/ha), as proposed by Bezerra et al. (2024), is recommended to ensure a balance between favorable microclimate and productive sustainability.

From a practical management perspective, these findings carry direct implications for coffee producers facing increasing thermal stress. The integration of rubber trees at moderate densities, as demonstrated in the present study, represents an accessible adaptation measure that does not require radical changes to existing production systems. Producers operating in full-sun conilon coffee systems could progressively introduce shade trees in the interrows, prioritizing species with dense canopies and significant litter production, such as *Hevea brasiliensis*, to maximize soil thermal buffering. While this study focused on *Coffea canephora*, the thermal stress thresholds documented for *Coffea arabica* suggest that similar benefits could be expected in arabica-producing regions, where soil temperatures exceeding 30 °C during critical phenological stages have been associated with impaired root function and reduced yield stability (DaMatta et al. 2018). In the broader context of climate adaptation, agroforestry systems should therefore be considered not merely as productivity tools, but as infrastructure for agricultural resilience, capable of moderating soil thermal extremes, preserving soil biological activity, and extending the viable cultivation range of coffee species under projected warming scenarios.

In this context, the analysis of soil thermal patterns across different production systems reveals

implications beyond agronomy, establishing critical interfaces with the Sustainable Development Goals (SDGs) (United Nations 2015). The microclimatic regulation provided by AFS constitutes a strategic axis for convergence between soil science, public policy, and global sustainability targets. This intersection manifests in three key dimensions: (i) production, through optimization of essential edaphic processes; (ii) ecology, via biodiversity conservation in anthropized landscapes; and (iii) climate, by mitigating thermal variability impacts. These dimensions reveal the potential of AFS as catalysts for resilient agricultural models, particularly relevant for sensitive crops like coffee in tropical regions.

The capacity of AFS to modulate soil temperature has direct implications for multiple sustainability dimensions. Agronomically, thermal moderation favors critical edaphic processes, supporting agricultural productivity (SDG 2—Zero Hunger). Ecologically, the approximation of AFS microclimatic conditions to native vegetation suggests potential for maintaining soil biodiversity (SDG 15—Life on Land). Climatically, reduced diurnal thermal amplitudes represent a passive adaptation mechanism to climate change (SDG 13—Climate Action), enhancing agroecosystem resilience under increasing thermal variability. These synergies position AFS as key systems for transitioning to climate-smart agricultural models.

Despite the relevance of the findings, some limitations of this study should be acknowledged. First, the assessment was restricted to soil surface temperature, without incorporating complementary variables such as soil moisture, microbial activity, or organic matter dynamics, which interact closely with thermal conditions and would strengthen the mechanistic interpretation of the results. Second, data collection was conducted on a single day in early August, during the dry season, which limits the generalizability of the findings across seasons and climatic conditions. Third, the study was carried out at a single location within a specific soil type and climate classification, and caution is therefore warranted when extrapolating the results to other coffee-growing regions. Finally, although the agroforestry system approached native vegetation in some thermal parameters, it did not fully replicate natural ecosystem conditions, indicating that further optimization of shading density and tree species composition may be needed to maximize

microclimatic benefits. These limitations point to clear directions for future research, including multi-season monitoring, the incorporation of additional soil variables, and the evaluation of diverse agroforestry configurations across contrasting environments.

The global coffee sector faces increasing threats from climate change (DaMatta et al. 2012). In this context, agroforestry systems have been identified as a promising alternative to mitigate such impacts (Araújo et al. 2016, 2015; Oliosi et al. 2016; Pezzopane et al. 2011). The results of this study reinforce that Conilon coffee agroforestry systems, particularly those integrating rubber trees, significantly contribute to milder soil temperatures compared to monocultures, supporting their viability as a climate-resilient production strategy.

Conclusions

The coffee–rubber tree agroforestry system effectively moderated soil thermal conditions, reducing average temperatures by 14.9% and peak temperatures by 23.3% compared to conilon coffee monoculture, while also decreasing daily thermal amplitude by 26.3%. These results position agroforestry as a meaningful climate adaptation strategy for *Coffea canephora* cultivation, particularly given the species' sensitivity to thermal stress during critical phenological stages such as flowering and fruiting.

The dominant influence of rubber trees on thermal regulation was evident, as the agroforestry system closely mirrored conditions observed in rubber tree monoculture. This suggests that the strategic integration of *Hevea brasiliensis* into coffee systems can deliver substantial microclimatic benefits without requiring a complete transition away from productive agriculture. Native vegetation, however, remained the benchmark for thermal stability, indicating that agroforestry systems, while effective, do not fully replicate natural ecosystem conditions, a limitation that should guide future management decisions regarding shading density and tree species selection.

Infrared thermography proved to be an efficient and accessible tool for high-resolution soil temperature monitoring, yielding results of straightforward interpretation that could be applied directly in field management contexts. Future research should extend

this approach across seasons, incorporate complementary soil variables such as moisture content and microbial activity, and evaluate its applicability in other agroforestry configurations and coffee-growing regions facing increasing thermal stress under climate change.

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Author contribution G.P.V.: Data curation; Formal analysis; Project administration; Writing—original draft. G.O.: Data curation; Project administration; Visualization. D.H.G.J.: Writing—review and editing. F.L.P.: Conceptualization; Methodology; Supervision; Validation; Resources; Project administration; Funding acquisition; Interpretation of results; Writing—review and editing; Corresponding author responsibilities. All authors reviewed and approved the final manuscript.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interests The authors declare no competing interests.

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