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Infrared thermography for microclimate assessment in agroforestry systems

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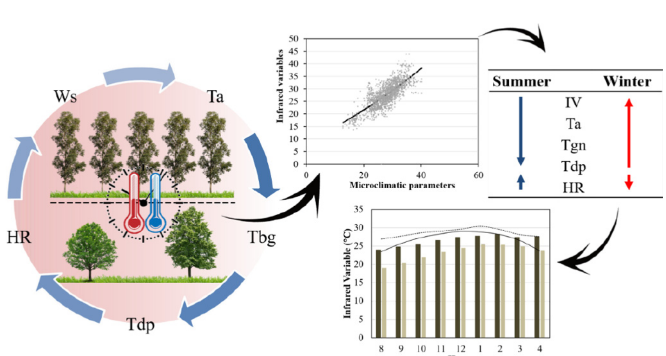
HIGHLIGHTS

- Tree canopies and pasture infrared radiation were studied in agroforestry systems.
- Leaf infrared radiation is capable to interfere on agroforestry microclimate.
- There is a temperature range with higher leaf infrared emission.
- Leaf infrared radiation emissions are similar among systems and higher in summer.
- Infrared thermography can be used as a tool for microclimate assessment.

GRAPHICAL ABSTRACT



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ABSTRACT

In agroforestry systems, trees modify climatic parameters over a given area and create a complex microclimate through interactions between topography, plant composition and organizational structure of trees. In this way, indicators such as surface temperature of tree canopy and pasture, monitored by infrared thermography, are important to monitor the thermal environment of animal production and pasture establishment. Goals of this study were (1) to evaluate temporal and local variations of temperature and humidity leaf surface of tree canopy and pasture in agroforestry systems by infrared remote sensing and, (2) to validate infrared thermography as a potential tool for assessment microclimate in agroforestry systems. The study was carried out between June 2015 and February 2016 in an experimental area located at 54°370′W, 20°270′S and 530 m altitude, in Brazil. Surface temperatures and humidity of tree canopy and pasture in two agroforestry systems with different densities and tree spatial arrangements were determined using infrared thermography. Air, black globe and dew point temperatures, relative humidity and wind speed were measured using digital thermo-hygrometers with datalogger. Moderate to strong associations have been identified between microclimate parameters and those monitored by means of thermography measurements ($0.45 \geq r \leq 0.78$), suggesting positive relationships and equally well explained by air temperature, black globe temperature and relative air humidity ($R^2 = 0.68 \geq R^2 \leq 0.98$). Variations in hourly averages of temperatures and humidity of pasture and tree canopy show similar patterns between seasons, with consistently higheraverages during summer and under full sun, indicating the existence of a

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thermal band with leaf temperatures above air temperature. Therefore, this work's findings support use of infrared thermography as a tool for microclimate assessment in agroforestry systems.

1. Introduction

Combination of climatic parameters at different scales creates peculiar local conditions that modify balance and flow of energy in the air layers above soil surface (Zellweger et al., 2019). These conditions are defined through variables such as above ground biomass, surface temperature and humidity, air temperature, relative humidity, solar radiation, evapotranspiration, wind speed and direction, precipitation etc. In general, these are large-scale climatic variations that, at least temporarily, dissociate from the atmospheric level (Bramer et al., 2018). In agroforestry systems, the combination and interaction of crops and grasses, shrubs and/or trees of multiple usages, respond to the thermal environment with a variety of processes and feedbacks, highly dynamic and correlated in space and time (Karvatte Jr et al., 2016; Oliveira et al., 2017).

In these systems, trees modify climatic parameters within a given area and create a favorable microclimate through a complex interaction between topography, plant composition and organizational structure of trees (Kim et al., 2016; Kovács et al., 2017). By intercepting direct solar radiation, trees reduce thermal radiation load that penetrating below the forest canopy, providing a cooling effect on the environment directly through evapotranspiration and shading (Renaud et al., 2011; Karvatte Jr et al., 2016; Maes et al., 2016). However, with forest fragmentation and formation of tree lines in different configurations, parts of the internal environment become more exposed to external climatic conditions making the forest microclimate unstable and vulnerable (Ewers and Banks-Leite, 2013).

In the tropic and subtropics, micrometeorological studies using climatic data collected inside these systems are important to understand thermal environment for animal production and pasture development (Karvatte Jr et al., 2016; Lopes et al., 2016; Oliveira et al., 2017; Giro et al., 2019; Pezzopane et al., 2019). In general, these studies use a series of analog sensors - thermo-hygrometers - that require high precision resistors and manual calibration to provide the desired accuracy, since these systems are non-linear (Srbinovska et al., 2015). Although efficient, data obtained by this equipment is limited in coverage, representing specific climatic conditions only at the exact observation site. Its spatial representation in a larger area is limited, since it is a high cost equipment, leading to poor sampling over the whole monitored area. Therefore, it is necessary to look for alternative ways for assessments with better representation.

Indicators such as surface temperature of tree canopy and pasture are highly variable, requiring observations in both high spatial and temporal resolution. These temperature variations result from physical and biological interactions affected by leaf morphology and albedo, tree canopy position, radiation, wind and stomatal response to the environment, directly influenced by season and regional climate (Gersony et al., 2016; Kim et al., 2016; Hammerle et al., 2017; Ngao et al., 2017). In this sense, infrared thermography can be used to describe in detail the patterns of leaf thermal variations and their relationship with environmental variables that characterize microclimate in agroforestry systems, extending traditional measurements to a spatial and temporal scale because, regardless of the application, all collected data are influenced by atmospheric conditions.

In recent years, infrared thermography has made an impressive contribution to the investigation of surface thermal behavior in a most varied areas of knowledge, driven mainly by high resolution in data collection, operational simplicity and increasing computational data storage capacities (Abreu-Harbich et al., 2015; Kovács et al., 2017; Giro et al., 2019; Pezzopane et al., 2019). In agriculture, forestry and forage thermal monitoring, it has been mainly used to examine status and regulation of stomatal conductance and its influence on water vapor and carbon dioxide exchanges, indicating strict relationships with climatic elements (Gersony et al., 2016; Kim et al., 2016; Hammerle et al., 2017; Ngao et al., 2017). However, to date, no study has been carried out to identify the influences of leaf infrared radiation emissions on the establishment of the microclimate below the forest canopy in agroforestry systems.

Our hypothesis is that (1) there are significant relationships between microclimatic variables and thermography measurements of tree canopy and pasture; and (2) temporal and local variations in leaf emissions of infrared radiation are capable of altering the microclimate below forest canopy in agroforestry systems. Goals of this study, therefore, were: (1) to evaluate temporal and local variations of temperature and humidity leaf surface of tree canopy and pasture in agroforestry systems using infrared remote sensing and, (2) to validate infrared thermography as a potential tool for monitoring microclimate in agroforestry systems.

2. Material and methods

2.1. Experimental area and period characterization

The study was conducted at the experimental station of the Brazilian Agricultural Research Corporation - Embrapa Beef Cattle, located in Campo Grande, state of Mato Grosso do Sul, Brazil (20°27′S, 54°37′W, average elevation: 530 m). Local climatic pattern is in the transition between warm temperate (CFA) and humid tropical (Aw), with precipitation and average annual temperature of 1560 mm and 23.0 °C (Köppen, 1948) respectively, with dry season from May to September, and rainy season from October to March.

The experimental area, with 12 ha, was established in 2008 with two agroforestry systems (AS-1 and AS-2) as a strategy to recover pastures by cultivating soy as an agricultural component, followed by Piatã grass (*Urochloa brizantha* cv. BRS Piatã), as a forage component, managed under a system of continuous stocking rate and variable number of animals. The AS-1 system was implemented with eucalyptus (*Eucalyptus grandis* and E. *urophylla*, clone H 13; reaching average height of 26 m during the experimental period), planted in simple line rows (22 m and 2 m; density of 227 trees.ha^{-1}), with a displacement of −20.41°S and − 54.71°W, in relation to the East-West axis. In the AS-2 system, trees native to the Brazilian Cerrado (*Dipteryx alata* Vogel and *Gochnatia polymorpha* Less), in undefined natural scattered arrangement and approximate density of 3 trees ha^{-1}. The experimental area was divided into eight paddocks (four per system) of 1.5 ha each (Fig. 1). Detailed information about the experimental area can be found in Karvatte Jr et al. (2016) and Oliveira et al. (2017).

The experimental period run from June 2015 to February 2016, covering one winter and one summer season. Readings were always carried out during four consecutive days for each month of the experiment, from 08:00 a.m. to 04:00 p.m. (GMT −04: 00, in hourly intervals), evaluating simultaneously one paddock of each system per day.

2.2. Thermographic records and infrared images

It was used a professional thermal camera (Testo®, model 875 2i) with a resolution of 360 × 240 (number of pixels: 76.800), a lens with a focal length of 7.5 mm (field of view of 32° and 23°; f/0.84) and emissivity equal to 0.97, according to Stabentheiner and Schmaranzer (1987). For image capture, fixed shooting spots were defined between

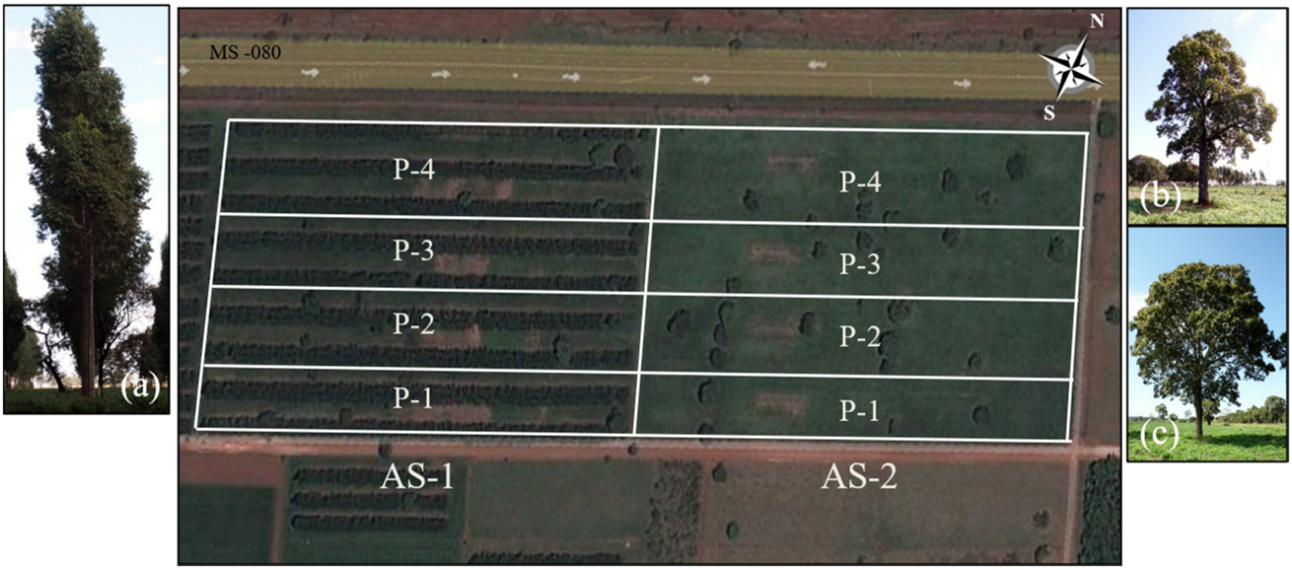

Fig. 1. Aerial image of the experimental area, considering agroforestry systems (AS-1 and AS-2) with *Eucalyptus grandis* and *urophylla*, clone H 13 (a), *Dipteryx alata* Vogel (b) and *Gochnatia polymorpha* Less (c) and four paddocks (P-1 to 4).

trees rows, in the AS-1 system, and in front of trees in the AS-2 system, approximately 10 m away from trees in both systems, covering the entire desired area and one more contrast area of the focal environment, according to the illustration below (Fig. 2). For the shootings, the camera was set eye height, in this case, approximately 1.75 m above soil level.

Thermal images obtained were analyzed through IRSoft® (Testo software), obtaining values of infrared temperature (°C) of leaf surface for tree canopies (Table 1). Under shade projection and under full sun, infrared temperature (°C) of leaf surface for pasture (Table 1) were obtained, as shown in Fig. 3. Considering that surfaces with a higher temperature present less humidity, the values of humidity by infrared (%), of the leaf surfaces of the tree canopies and of the pasture (Table 1), were obtained in the same locals previously indicated, from the differential of scales of thermal colors automatically converted by the equipment used (Fig. 3).

2.3. Microclimatic records

We evaluated the microclimate parameters (Table 1) of air temperature (°C), dew point temperature (°C) and relative humidity (%) using digital thermo-hygrometers (THD) with datalogger (Instrutherm®, model HT-500; humidity 0.0 to 100.0% scale; 3% precision, and 0.1% resolution; and temperature − 40.0 to 70.0 °C scale; −20.0 to 50.0 °C precision, and 0.1 °C resolution), inserted in PVC tube micrometeorological shelters (with 0.15 m length, 0.40 m diameter, with 12 holes drilled around the tube), and black globe temperatures (°C) using THD, inserted into dim black plastic floats (PVC) with 0.15 m in diameter and painted in matte black. The wind speed ($m.s^{-1}$) was measured with a portable digital anemometer (Homis®, HMM 489; 0.4 to 30.0 $m.s^{-1}$ scale; >20.0 $m.s^{-1}$ precision; 0.1 $m.s^{-1}$ resolution) for 3 min with the devices' sensors facing the wind direction. The equipment was allocated in full sun (A) and in the projection of the shade of the trees (B), at two points corresponding to transects perpendicular to the rows of trees, 2.0 m away from the tree trunk and 1.5 m above the level of the ground, being horizontally displaced in the transect according to the hourly movement of the shadow projection (Fig. 1). More detailed information on the methodology can be found in Karvatte Jr et al. (2016).

2.4. Experimental design and statistical analysis

Experimental design was randomized blocks in a sub-subdivided plot scheme, where treatments were agroforestry systems (AS-1 and

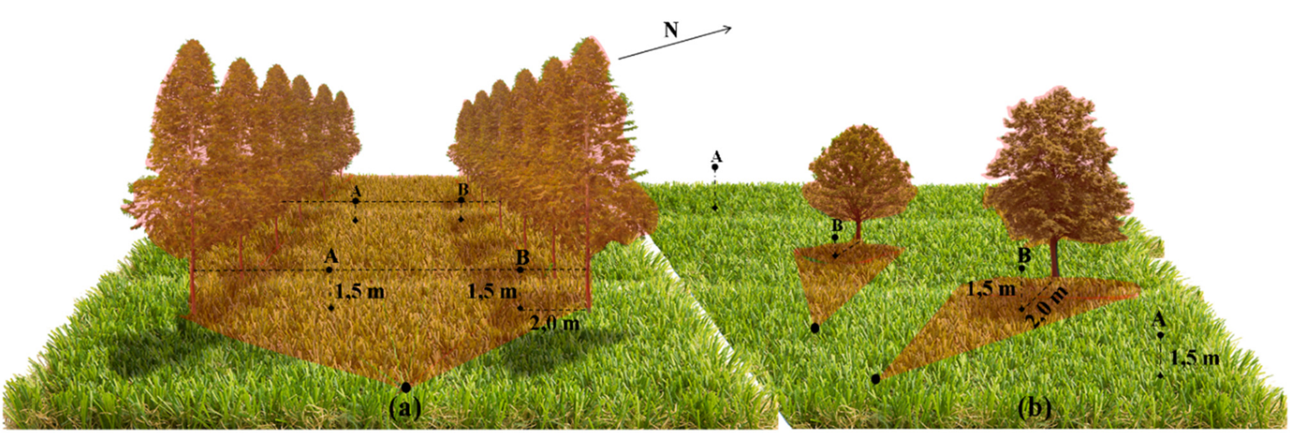

Fig. 2. Schematic representation of equipment allocation for thermographic images capture (red coloring) and microclimate records using thermo-hygrometers (dotted lines), under full sun (A) and under tree shade (B), and in agroforestry system with eucalyptus (AS-1; a) and native trees (AS-2; b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Description of variable abbreviations used in the study.

Variable	Unit of measure	Description
T_{Canopy}	°C	Canopy temperature
$T_{Pasture}$	°C	Pasture temperature
H_{Canopy}	%	Canopy humidity
$H_{Pasture}$	%	Pasture humidity
Ta	°C	Air temperature
Tdp	°C	Dew point temperature
Tbg	°C	Black globe temperature
RH	%	Relative humidity
Ws	$m.s^{-1}$	Wind speed

AS-2), sub-plot were seasons (winter and summer); sub-subplot were time of the day (08:00 a.m. to 04:00 p.m.) and the sub-sub-subplot were location (under full sun and under shade). Pearson (r) correlation was performed to identify and quantify linear relationships between infrared variables and microclimatic parameters. The correlation coefficients were defined according to the following classification: $|r| = 0.00$, null; $0.00 < |r| < 0.20$, very weak; $0.20 < |r| < 0.40$, weak; $0.40 < |r| < 0.60$, moderate; $0.60 < |r| < 0.80$, strong; $|r| > 0.80$, very strong; e $|r| = 1.00$, perfect. The regression analysis was performed using the SAS REG procedure, considering the model:

$$Y_{ijkl} = \alpha + S_i + E_j + L_k + H_l + \beta_1 X_{1ijkl} + \beta_2 X_{2ijkl} + \ldots + \beta_p X_{pijkl} + e_{ijkl}$$

where: Y_{ijkl} is the dependent variable in the umpteenth observation, performed in the i^{th} system, the j^{th} station, the local k^{th}, the lth hour; α is the intercept; S_i - effect of the system i^{th}; E_j - effect of the j^{th} season; L_k - local k^{th} effect; H_l - effect of l^{th} hour; B_m (m = 1, .., p) - partial regression coefficients of microclimate parameters (independent variable) whose measures are the X_{mijkl} values, corresponding to the Y_{ijkl} observation; and e_{ijkl} - random error.

Data were tested for normality using the UNIVARIATE procedure and analysis of variance by the SAS GLM procedure (version 9.2; SAS Inst., Inc., Cary, NC, USA). The mean values of temperature and humidity of pasture and tree canopies, based on infrared thermography, were separated for comparison by the Tukey test at $P \leq .05$ and the significant interactions adjusted by the LSMEANS procedure of the SAS, according to the following statistical model:

$$Y_{ijkl} = \mu + B_b + S_i + e_{bi} + E_j + SE_{ij} + e_{bij} + L_k + SL_{ik} + EL_{jk} + SEL_{ijk} + e_{bijk} + H_l + SH_{il} + EH_{jl} + LH_{kl} + SEH_{ijl} + SLH_{ikl} + ELH_{jkl} + e_{bijkl}$$

where: μ - constant; B_b - effect of the b^{th} block, b = 1, …, 4; S_i is the effect of the system i^{th} (i = AS-1 and AS-2); e_{bi} - error a; E_j - effect of the j^{th} season (j = water and drought); SE_{ij} - effect of the system and the j^{th} station; e_{bij} - error b; L_k - local k^{th} effect (k = sun and shadow); SL_{ik} - effect of the system on the local k^{th}; EL_{jk} - effect of the j^{th} station on the local k^{th}; SEL_{ijk} - effect of the interaction between the system, the station and the local k^{th}; e_{bijk} - error c; H_l - effect of the l^{th} hour (l = 8, …, 16); SH_{jl} - effect of the j^{th} system and lth hour; EH_{jl} - effect of the j^{th} season and the lth hour; LH_{kl} - effect of local l^{th} and H^{th} hour; SEH_{ijl} - effect of the interaction between the system, the station and the hour; SLH_{ikl} - effect of the interaction between the system, local k^{th} and l^{th} hour; ELH_{jkl} - effect of the interaction between j^{th} station, k^{th} location and l^{th} hour; and e_{bijkl} – residue.

3. Results

3.1. Relationship between infrared variables and microclimatic parameters

Strong associations were found between T_{Canopy} with Ta ($r = 0.72$) and Tbg ($r = 0.62$) and moderate with Tdp ($r = 0.46$). $T_{Pasture}$ also showed strong associations with Ta ($r = 0.78$) and Tbg ($r = 0.77$) and a moderate and negative association with RH ($r = -0.45$). Strong association was found between H_{Canopy} with RH ($r = 0.70$), moderate association with Tdp ($r = 0.45$) and weak and negative associations with Ws ($r = -0.22$); Ta ($r = -0.33$) and Tbg ($r = -0.32$). Likewise, $H_{Pasture}$ showed a strong association with RH ($r = 0.73$), moderate with Tdp ($r = 0.47$) and weak and negative associations with Ws ($r = -0.25$), Ta ($r = -0.35$) and Tbg ($r = -0.39$) (Table 2).

Partial regression coefficients and respective standard deviations of quadratic functions of infrared variables (IV) for measuring microclimate in agroforestry systems in the tropics are presented in Table 3. Regression models proposed between IV and microclimatic parameters, for temperature evaluation, showed that the variations in T_{Canopy} presented a positive relationship and equally well explained by Ta and Tg ($R^2 = 0.88$ and 0.68, $n = 1727$), while a negative and little explained

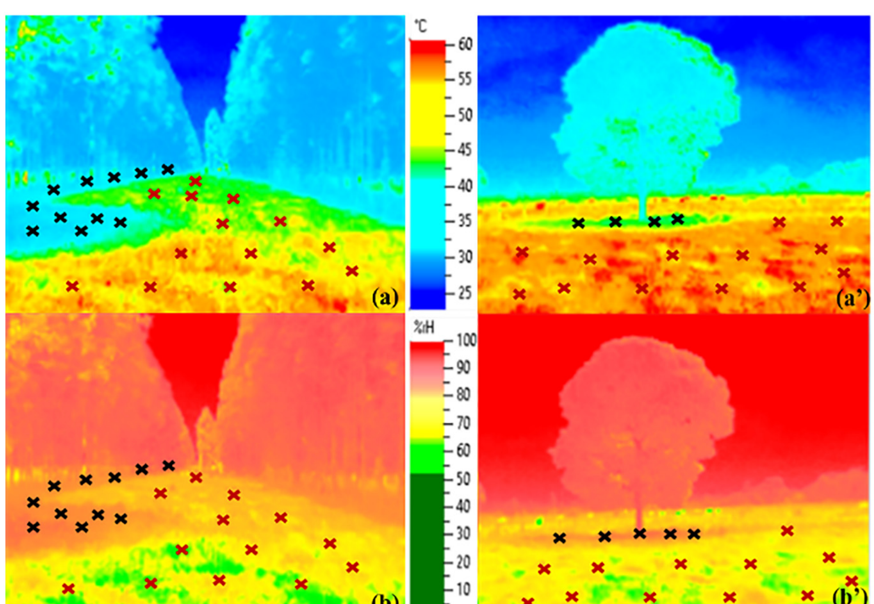

Fig. 3. Examples of infrared images for temperature (a and a') and humidity (b and b'), of the evaluated systems. "x" represents the locations selected for evaluation of the infrared variables (red for full sun and black for shade). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Pearson correlation coefficients (r) and *P*-value (*P*) between infrared variables and microclimatic parameters in tropical agroforestry systems.

Infrared Variable		Wind Speed	Air temperature	Relative Humidity	Dew point temperature	Black globe temperature
Canopy temperature	r	−0.04	0.72	−0.19	0.46	0.62
	P	*0.0885*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*
Pasture temperature	r	0.08	0.78	−0.45	0.21	0.77
	P	*0.0005*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*
Canopy humidity	r	−0.22	−0.33	0.69	0.45	−0.32
	P	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*
Pasture humidity	r	−0.25	−0.35	0.73	0.47	−0.39
	P	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*

relationship was observed in relation to Ws and RH ($R^2 = 0.005$ and 0.007, $n = 1727$). A positive and well-explained relationship was observed, respectively, between $T_{Pasture}$ with Ta and Tg ($R^2 = 0.95$ and 0.92, n = 1727) (Fig. 4.a-d). However, a negative and poorly explained relationship was observed, respectively, in relation to the RH and Tdp parameters ($R^2 = 0.35$ and 0.35, $n = 1727$) (Fig. 4.a'-d').

The regression models proposed for IV and microclimatic parameters, for moisture assessment, showed that the variations in H_{Canopy} and $H_{Pasture}$ also presented a positive relationship and equally well explained by RH ($R^2 = 0.99$ and 0.95, $n = 1727$), but with respect negative and little explained by Ta ($R^2 = 0.24$ and 0.23, n = 1727), for both thermographic variables respectively (Fig. 5.a-b '). $H_{Pasture}$ also presented a negative and poorly explained relationship in relation to the variables Tbg ($R^2 = 0.28$, n = 1727) and Ws ($R^2 = 0.12$, n = 1727) and positive and moderate in relation to Tdp ($R^2 = 0.39$, n = 1727) (Fig. 5.c-e).

3.2. Infrared variables interactions

Significant differences were found for IV as a function of experimental conditions ($P < 0.001$, $n = 1727$; Table 4). Significant interactions between seasons vs. systems show superior variations of T_{Canopy} and $T_{Pasture}$ detected during the summer in both systems (AS-1 and AS-2). Also, in this season, in the AS-1 system (with eucalyptus) the highest averages of H_{Canopy} and $H_{Pasture}$ were found. Significant interactions between seasons and locations ($P < 0.0001$, $n = 1727$) show higher T_{Canopy} and H_{Canopy} detected during the summer, with upper $H_{Pasture}$ and lower $T_{Pasture}$ detected in the shade, not differing between seasons for the location in full sun. Significant interactions between systems vs. locations ($P < 0.0157$, n = 1727) do not show significant differences for T_{Canopy} and H_{Canopy}, however, higher averages of $T_{Pasture}$ were found in full sun, in both systems, and higher $H_{Pasture}$ in the shade of the AS-1 system.

Variations between the hours of the day on temperature and humidity of the pasture and tree canopies show similar patterns between seasons, however, consistently higher during summer (Fig. 6). Significant interactions between seasons vs. times ($P < 0.001$, n = 1727) show maximum T_{Canopy} (average variation of 27.6 ± 0.6 °C for season and average difference of 2.7 ± 0.4 °C between stations) and minimum $H_{Pasture}$ and H_{Canopy} (average variation of 55.0 ± 1.4 pp. and 62.5 ± 1.3 pp. for season and average difference of 15.5 ± 2.3 pp. and 12.9 ± 1.6 pp. between seasons, respectively) recorded in the summer, between 11:00 and 14:00 for $T_{Pasture}$, similar average values were observed between seasons, between 11:00 and 14:00 (average variation of 29.4 ± 0.8 °C, n = 1727). However, between 8:00–10:00 and 15:00–16:00, $T_{Pasture}$ averages were higher during summer (average variation of 0.0 to 3.6 °C between seasons, n = 1727). Still at this season, $T_{Pasture}$ greater than Ta were recorded between 11:00 and 14:00.

Table 3
Partial regression coefficients and their respective standard deviations of linear functions between infrared variables and microclimatic parameters.

Variable	B	Standard deviation	*P*-value
Canopy Temperature			
Intercept	0.46762	0.63891	0.4643
Wind speed	−0.18266	0.03608	<0.0001
Air temperature	0.91501	0.03324	<0.0001
Relative Humidity	0.05495	0.00401	<0.0001
Black globe temperature	−0.13579	0.02599	<0.0001
Pasture Temperature			
Intercept	−5.85294	1.69828	0.0006
Air temperature	0.9926	0.07632	<0.0001
Relative humidity	0.13429	0.01823	<0.0001
Dew point temperature	−0.51969	0.06821	<0.0001
Black globe temperature	0.24628	0.0291	<0.0001
Canopy Humidity			
Intercept	8.15911	3.08372	0.0082
Air temperature	0.29222	0.07946	0.0002
Relative humidity	0.67512	0.01916	<0.0001
Pasture Humidity			
Intercept	−20.1297	7.6897	0.0089
Wind speed	−0.46575	0.18051	0.01
Air temperature	2.21953	0.34334	<0.0001
Relative humidity	0.91737	0.08227	<0.0001
Dew point temperature	−0.67023	0.30688	0.0291
Black globe temperature	−1.13732	0.13093	<0.0001

B – partial regression coefficient.

4. Discussion

Several studies have shown relationship between microclimatic parameters and thermal status of canopies in forests and pastures (Baluja et al., 2012; Meier and Scherer, 2012; Abreu-Harbich et al., 2015; Maes et al., 2016). Neglecting these interactions leads to substantial errors in microclimate measurements, due to temperature differences established between earth's surface and the air masses that overlap below tree canopies (Hammerle et al., 2017). In fact, the correlations found in this study reveal the existence of positive relationships between IV and microclimatic parameters, demonstrating that the increase in T_{Canopy} and $T_{Pasture}$ follow the increase in Ta, Tbg and Tdp, while the increase in RH promotes the decrease in T_{Canopy} and $T_{Pasture}$, as well as increases in H_{Canopy} and $H_{Pasture}$. The relationship between IV and microclimatic parameters was expected, because infrared temperature is a measure related to radiation of long waves emitted by the surfaces of tree canopies (Kim et al., 2016). For many years, micrometeorological studies using conventional assessment methods (thermo-hygrometers) associated this measure with Tbg (Navarini et al., 2009; Baliscei et al., 2013; Karvatte Jr et al., 2016; Oliveira et al., 2017; Giro et al., 2019). As this microclimate parameter represents the interaction between combined effects of solar radiation, air temperature and wind speed (Kelly and Bond, 1971), the higher the temperature, the greater the thermal load imposed on the environment and, thus, the greater the intensity of emitted infrared radiation. As a consequence, lower levels of leaf moisture and relative humidity are detected due to the lower concentration of water vapor (greater water vapor pressure deficit) in the atmosphere (Leuzinger et al., 2010; Kim et al., 2016).

Regression analysis shows that Ta, Tbg and RH explained most of the variations in IV. Thus, we can suggest that these are the main microclimatic parameters that control the dynamics of temperature and humidity of the pasture and tree canopies in the evaluated agroforestry

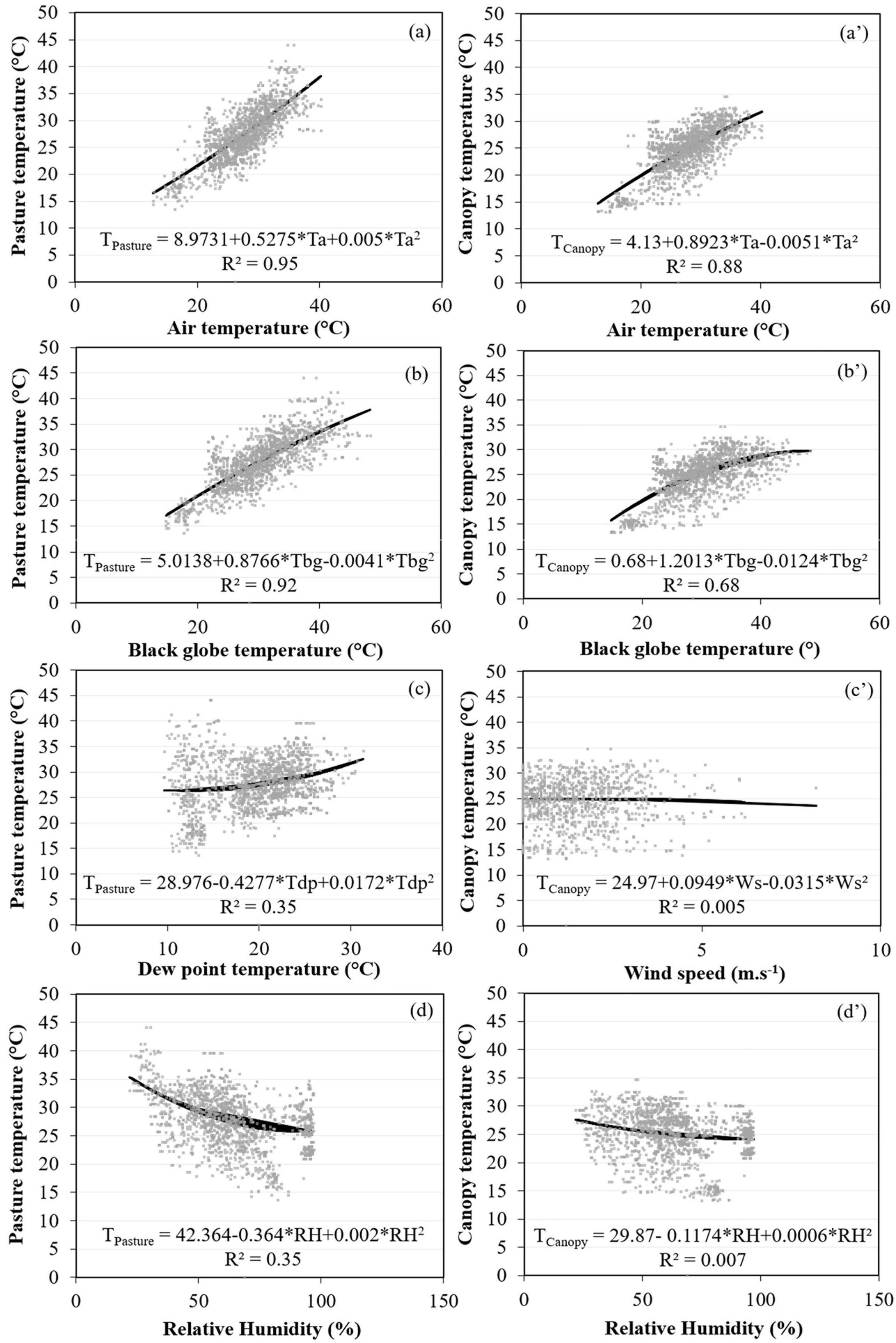

Fig. 4. Pasture temperature ($T_{Pasture}$; a-d) and tree canopy temperature (T_{Canopy}; a'-d') as a function of microclimatic parameters averages for microclimate monitoring in agroforestry systems. Ta – air temperature (°C); Tgn – Black globe temperature (°C); Tdp – dew point temperature (°C); Ws – Wind speed ($m.s^{-1}$); RH – relative humidity (%).

systems, corroborating with results obtained by Kim et al. (2016) who suggest that air temperature, water vapor and long-wave radiation are the first climatic factors that control the dynamics of canopy infrared radiation emissions, and thus, the microclimate in a rainforest of Pinus (*Pinus ponderosa* Dougl. Ex P. Laws), Oregon. Although the parameters evaluated in this study showed the same variation patterns, T_{Canopy}

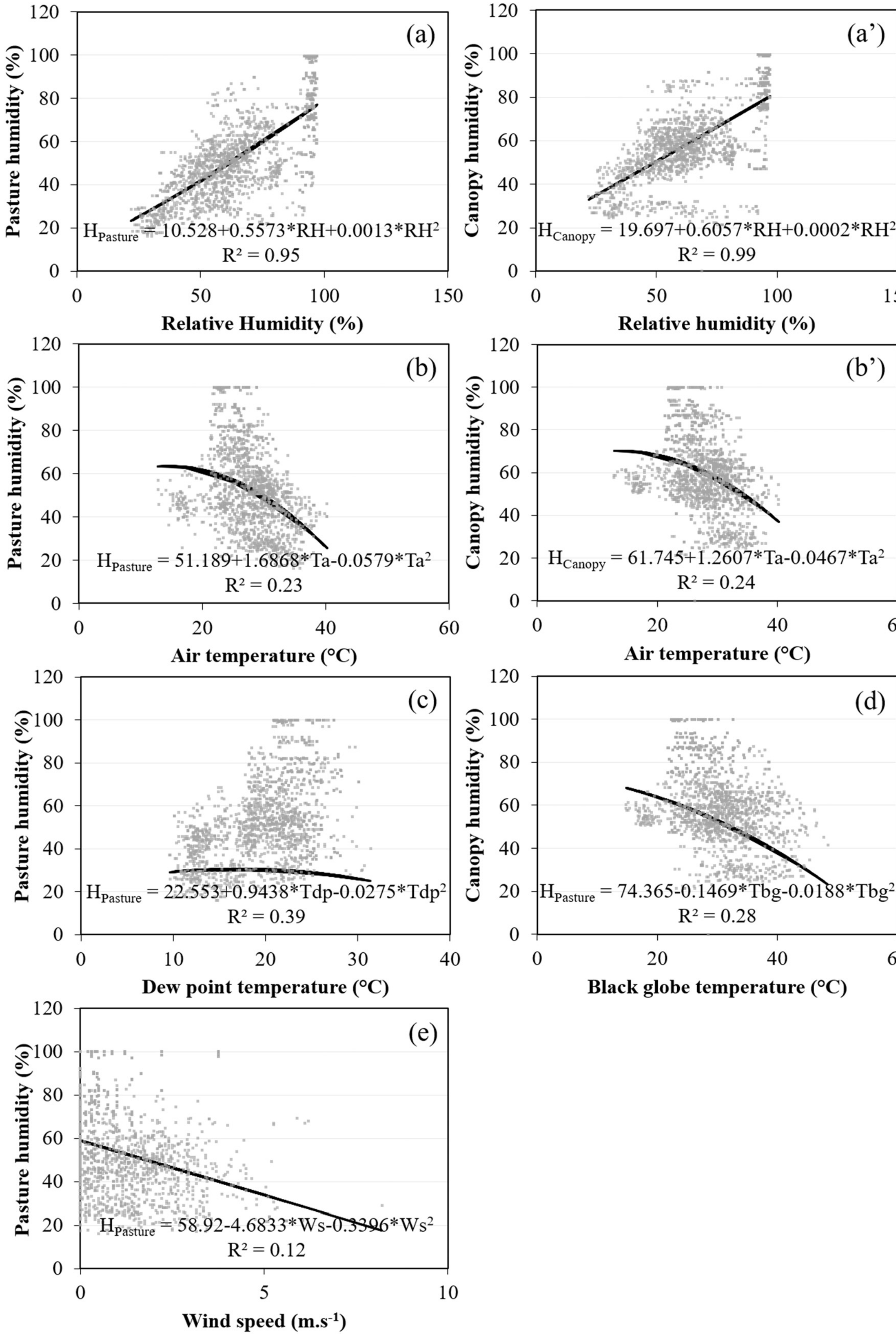

Fig. 5. Pasture humidity ($H_{Pasture}$; a-d) and canopy humidity (H_{Canopy}; a'-b') as a function of microclimatic parameters averages for microclimate monitoring in agroforestry systems. RH – relative humidity (%); Ta – air temperature (°C); Tdp – dew point temperature (°C); Tgn – Black globe temperature (°C); Ws – Wind speed ($m.s^{-1}$).

Table 4
Values of infrared variables as a function of interactions between systems, seasons and locations in tropical agroforestry systems.

Infrared Variable	AS-1		AS-2		*P*-value
	Summer	Winter	Summer	Winter	
T_{Canopy} (°C)	26.4[a]	23.4[b]	26.7[a]	23.0[b]	<0.0001
$T_{Pasture}$ (°C)	28.5[a]	26.7[b]	28.1[a]	26.9[b]	<0.0001
H_{Canopy} (%)	68.1[a]	52.9[c]	63.5[b]	54.5[c]	0.0133
$H_{Pasture}$ (%)	62.3[a]	45.2[c]	57.7[b]	43.5[c]	0.0294
Infrared Variable	**Summer**		**Winter**		***P*-value**
	Full sun	Shade	Full sun	Shade	
T_{Canopy} (°C)	26.6[a]	–	23.4[b]	–	<0.0001
$T_{Pasture}$ (°C)	29.4[a]	27.1[b]	29.0[a]	24.6[c]	<0.0001
H_{Canopy} (%)	52.9[a]	–	46,3[b]	–	<0.0001
$H_{Pasture}$ (%)	56.7[b]	63.3[a]	39.7[d]	49.0[c]	<0.0001
Infrared Variable	**AS-1**		**AS-2**		***P*-Value**
	Full sun	Shade	Full sun	Shade	
T_{Canopy} (°C)	25.1	–	24.9	–	<0.0001
$T_{Pasture}$ (°C)	29.3[a]	28.5[b]	29.1[a]	25.9[b]	<0.0001
H_{Canopy} (%)	60.1	–	58.9	–	0.0358
$H_{Pasture}$ (%)	50.2[c]	57.4[a]	46.2[d]	54.9[b]	0.0157

Averages in the same line followed by letters differ statistically at $P < 0.05$. AS-1 – agroforestry system with eucalyptus; AS-2 – agroforestry system with native trees; T_{Canopy} – Canopy temperature; $T_{Pasture}$ – Pasture temperature; H_{Canopy} – Canopy humidity; $H_{Pasture}$ – Pasture humidity.

were higher than Ta and Tbg between the thermal range of 12 °C and 18 °C. Likewise, higher emissions of $T_{Pasture}$ were recorded between 12 and 27 °C of Ta and between 12 and 23 °C of Tbg. These results confirm the importance of using IV in microclimate assessments when presenting a temperature range where the infrared radiation emissions from the tree canopy and pasture can add to increase in thermal load of the adjacent environment. According to Abreu-Harbich et al. (2015), trees tend to maintain the temperature under the canopy equal to or less than the temperature of the surrounding air, as long as they are properly hydrated, even under high incidence of solar radiation. However, Pezzopane et al. (2015) suggest that sunlight passing through treetops in agroforestry systems is riched in infrared, creating a heat storage that can heat up the environment due to the emission of a portion of the accumulated thermal radiation (Konarska et al., 2014; Dangel et al., 2015).

Studies suggest that the photosynthetic rate and stomatal conductance influence the thermal balance of the tree canopy surfaces as a consequence of the decrease in leaf transpiration and increase of absorbed thermal energy, being able to change drastically in small distances and to overcome the air temperature when it is above 35 °C (Martinazzo et al., 2012; Bailey et al., 2016; Ngao et al., 2017). Upon reaching 40 °C of leaf temperature, photosynthesis is inhibited and the accumulated thermal surplus is irradiated to the environment (infrared emission), which can affect the surrounding microclimate and even the temperature of the adjacent soil surface (Costa and Marenco, 2007; Li et al., 2013; Panigada et al., 2014; Dejorge et al., 2015; Hammerle et al., 2017). This information contradicts results found in this study, which suggests the need for Ta and Tbg ranges above 35 °C in order for T_{Canopy} and $T_{Pasture}$ to reach 40 °C.

The relationships between T_{Canopy} and Tbg, show that when reaching 29 °C of leaf temperature, T_{Canopy} tends to reduce, suggesting changes in leaf metabolism with an increase in stomatal conductance and less emission of thermal energy in the environment below the forest canopy (Martinazzo et al., 2012), corroborating with other studies that demonstrate the effectiveness of agroforestry systems in providing

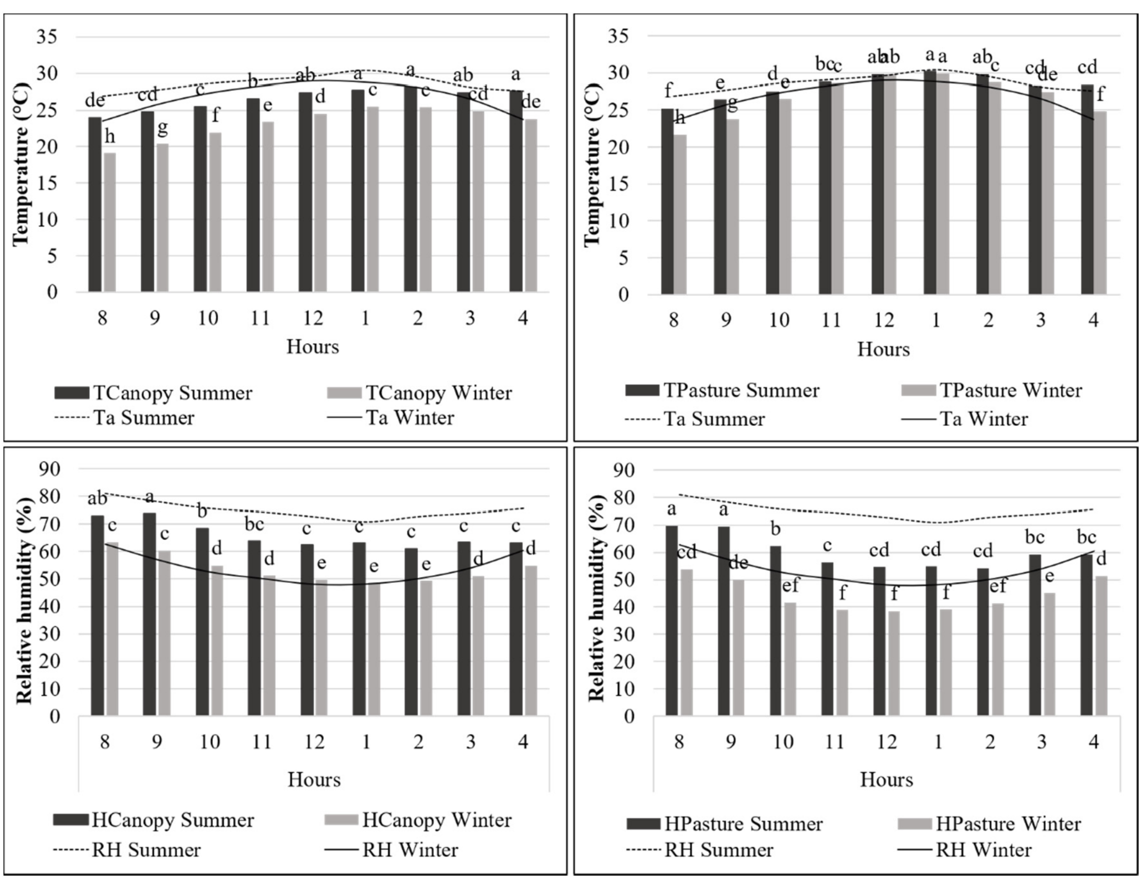

Fig. 6. Diurnal evolution of infrared variables and related microclimatic parameters during winter and summer. Different letters above the upper error bars indicate a significant difference ($P \leq 0.05$) for infrared variables during winter and summer.

microclimate changes (Karvatte Jr et al., 2016; Giro et al., 2019; Oliveira et al., 2019; Pezzopane et al., 2019). Despite these results contribution for new studies in the area, mainly regarding plant physiology in agroforestry systems, the temperature ranges with the highest emission of infrared radiation previously mentioned should not be disregarded, because, when related to animal thermal comfort, microclimate changes imposed can result in substantial yield losses due to the energy cost imposed for thermal equilibrium (Mader et al., 2010).

The Ws is directly influenced by the organizational structure and composition of forests. Studies show that higher density of trees reduces air circulation and creates conditions for greater humidity and less radiation input and output (Karvatte Jr et al., 2016; Oliveira et al., 2017). Thus, water vapor concentrations below the forest canopy can be changed and, depending on the temperature and relative humidity conditions, the dew point temperature will also be changed (Karvatte Jr et al., 2016; Kim et al., 2016). In this sense, it is difficult to generalize the relationships between IV, Ws and Tdp found in this study, however, we believe that systematic tree rows in the AS-1 system probably behaved as physical barriers for the entry and circulation of the winds inside, contrary to the AS-2 system, in which dispersion of trees favored free air circulation, establishing different flows of thermal energy between the systems and lesser associations with IV.

Interactions found confirm the hypothesis of this study and show the differences in IV that represent the interface responsible for the spatio-temporal patterns of dissipation of daytime and seasonal pulses of solar energy that reach Earth's surface. In both systems assessed, during summer T_{Canopy} and $T_{Pasture}$ were, respectively, from 3.0 to 3.7 °C and from 1.2 to 1.8 °C higher than the temperatures obtained in winter, possibly due to increase on solar radiation during summer, which can reach up to 1000 $W.m^{-2}$, according to Silva (2006). However, the forest canopy was effective in regulating emissions of infrared radiation in both seasons, avoiding heating extremes by reducing 2.3 °C of $T_{Pasture}$ in the shade during summer and 3.2 °C during winter. Consequently, reductions of 0.8 °C in $T_{Pasture}$ were obtained in the shade under AS-1 and 3.2 °C in the shade under AS-2. When related to RH, greater H_{Canopy} (4.6%) and $H_{Pasture}$ (4.6%) were found during the summer, due to higher rainfall compared to winter. However, with lower temperatures recorded under shade, an increase of 6.6% of $H_{Pasture}$ was obtained during summer and 9.3% during winter. Thus, $H_{Pasture}$ was 7.2% greater in the shade of the AS-1 and 8.7% in the AS-2.

Hourly fluctuations were accompanied by radiative heating, possibly due to solar elevation, and cooling during the early hours of the day and late afternoon (Pezzopane et al., 2015; Hammerle et al., 2017), while variations between seasons may be due to microclimatic conditions, such as rain, winds, more or less radiation during the whole experimental period, leading to a decrease in emissions of infrared radiation from pasture and tree canopies during winter. Results show temperatures, based on IV, above 29.0 °C and humidity below 40%. Between 10:00 a.m. and 02:00 p.m., $T_{Pasture}$ was 0.2 to 1.1 °C higher than Ta, confirming the hypothesis that infrared radiation emissions, within a thermal range, contribute to heating the adjacent environment, and promote lower levels of $H_{Pasture}$ and H_{Canopy}. Therefore, fluctuations of T_{Canopy} and $T_{Pasture}$ represent tree canopy responses to changes in microclimate and environmental conditions in tropical agroforestry systems and are negatively related to the content of RH, H_{Canopy} and $H_{Pasture}$, supporting other findings, like the increase in temperatures (higher radiation by infrared emission - T_{Canopy} and $T_{Pasture}$) and consequent decrease in relative humidity (lower evapotranspiration - H_{Canopy} and $H_{Pasture}$), which occur in response to times of higher incidence of solar radiation (Karvatte Jr et al., 2016; Giro et al., 2019; Pezzopane et al., 2019).

5. Conclusion

Progressive increases in T_{Canopy} and $T_{Pasture}$ promoted increase in air temperature and black globe temperature, while higher relative humidity led to a decrease in $T_{Pasture}$ and T_{Canopy}, and increases in $H_{Pasture}$ and H_{Canopy}, demonstrating the existence of positive relationships between IV and microclimatic parameters. Temporal and local variations of infrared radiation detected inside the systems indicated existence of a leaf temperature range where infrared radiation emissions exceed air and black globe temperatures, suggesting that infrared radiation emissions from trees canopy and pasture contribute to the increase in thermal load and influence the establishment of microclimate below the forest canopy. The differences between seasons showed higher IV during summer, however, the presence of trees in these systems leads to less $T_{Pasture}$ in the shade. In conclusion, infrared thermography is capable of identifying temporal and local thermal variations in agroforestry systems and, thus, can be used as a tool for microclimate assessments.

CRediT authorship contribution statement

Nivaldo Karvatte Junior: Conceptualization, Data curation, Formal analysis, Resources, Investigation, Methodology, Validation, Writing - original draft, Writing - review & editing, Visualization. **Eliane Sayuri Miyagi:** Supervision. **Caroline Carvalho de Oliveira:** Data curation, Formal analysis, Writing - review & editing. **Camilla Diniz Barreto:** Investigation. **Ariadne Pegoraro Mastelaro:** Investigation. **Davi José Bungenstab:** Writing - review & editing. **Fabiana Villa Alves:** Conceptualization, Formal analysis, Resources, Investigation, Methodology, Project administration, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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