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ORIGINAL PAPER

Infrared thermography for evaluation of the environmental thermal comfort for livestock

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Abstract

The objective of this study was to assess the use of infrared thermography as a microclimate-evaluating tool and an estimate of the thermal comfort provided by four types of tree to cattle under grazing conditions in the central region of Brazil. The experiment was conducted at the Embrapa Beef Cattle Company, in Campo Grande, MS, Brazil, from June to August 2015. Evaluations were carried out over four consecutive days, at 1-hour intervals, from 8:00 a.m. to 4:00 p.m. (local time; GMT −4:00). Infrared thermography images of tree crowns and soil surface underneath them from the shadow projection of four tree species native to the Brazilian cerrado (savannah-like) biome were obtained. The microclimate was assessed by estimation of thermal indices: temperature and humidity index, black globe, and radiation thermal load. The previous was calculated based on records of air temperature, dew point temperature, black globe temperature, air relative humidity, wind speed, and solar radiation. The geometrical settings of the trees were assessed for each tree component. Five thematic groups were formed based on multiple factor analysis that summarizes three synthetic analytical dimensions to explain the total variance among the studied elements and the existing correlations between groups. Positive linear correlations were found between thermography and the temperature measurements, thermal comfort indices, and radiation, suggesting that infrared thermography can be used as a tool for estimating and monitoring the microclimate and thermal comfort, presenting a potential use of measurement in agroforestry systems.

Keywords Ambience · Multiple factor analysis · Trees · Tropical conditions · Infrared · Microclimate

Introduction

The productive performance of cattle reared on pasture in tropical regions is highly dependent on the climatic conditions to which these animals are subjected, which include mainly high relative humidity, elevated air temperature, and intense solar radiation (Collier et al. 1982; Alves 2012). Ambient temperatures outside the adequate range for each cattle categories may lead to losses in production (Da Costa et al. 2015; Cattelam and Vale 2013) and reproduction (Costa et al. 2010).

In addition, trees together with pasture contribute significantly to carbon sequestration, improving the life cycle assessment (LCA) of beef production. In fact, some recent works propose that when assessed as LCA, the grass beef is neutral or negative in CO2 equivalents.

Different methodologies and tools of varying costs, precision, and usability are available for qualifying and quantifying the influence of trees on the thermal comfort of man and animals. The most common examples of such methods are those employing physiological indicators of thermal stress. However, they generate additional stress due to the handling of individuals, which may compromise results (Stewart et al. 2005). Several studies investigating heat flow in constructed environments through infrared thermography (IRT) have shown that this technique generates accurate and reliable data on the thermal condition of constructions and materials (Balaras and Argiriou 2002; Clark et al. 2003; Ocaña et al.

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2004; Barreira and de Freitas 2007; Albatici and Tonelli 2010; Fokaides et al. 2016). In this way, the use of IRT for assessing thermal comfort in constructed environments also proved its feasibility in the evaluation of rural environments.

Infrared thermography has also stood out as a tool for the evaluation of rural facilities and for drawing inferences about the thermal comfort of animals, since infrared cameras can indicate the thermal comfort of an animal based on a particular reference region of the body. In this regard, Andersen et al. (2008) determined that the ear temperature of pigs is an indicator of thermal comfort. Shao and Xin (2008) demonstrated the use of IRT in an automated monitoring system which classifies the thermal comfort state of pigs housed collectively in real time. Sevegnani et al. (2016) evaluated the thermoregulatory response of dairy buffaloes using IRT and concluded that high temperatures contribute directly to the increase in the skin surface temperature of animals. The authors also came to the conclusion that this measurement is a better indicator of thermal comfort than respiratory frequency, which is a physiological indicator whose measurement requires animal handling. De Moura et al. (2011) evaluated the thermoregulatory response of training horses and confirmed that IRT determined their body surface temperature accurately, allowing for inferences to be drawn about thermoregulation. Roberto et al. (2014), on the other hand, studied physiological responses and thermal gradients of goats in the Brazilian semiarid region using IRT and were able to measure how stressful the environment was. Those authors also observed that the afternoon period was the most critical to the animals, even under confinement conditions. The broad field of application of IRT tends to increase because it has been more accessible in recent years, in addition to being a non-invasive, easy-to-handle technique that provides immediate and accurate results (Roberto and De Souza 2014). Thus, in rural areas, although no study has yet been found, the use of IRT represents an innovation and will allow a better understanding of the effects of infrared radiation on environmental thermal comfort for beef cattle.

The objective of this study was to test the use of infrared thermography as a tool for evaluating the microclimate and for estimating the thermal comfort provided by tree species in pastures in the central region of Brazil.

Materials and methods

Experimental location and climatic classification

The project was conducted out at the Brazilian Agricultural Research Corporation (Embrapa), at the National Research Center for Livestock (CNPGC), located in Campo Grande, MS, Brazil (20° 27′ S, 54° 37′ W and 530 m). The evaluations were performed during four (4) consecutive days per month, in the months of June, July, and August (dry period), from 8:00 a.m. to 4:00 p.m. (local time, GMT − 04:00), at 1-hour intervals.

Evaluation period and evaluated components

The tree species used in this study (*Gochnatia polymorpha* [“cambará”], *Dipteryx alata* Vogel [“cumbaru”], *Qualea grandiflora* Mart. [“pau-terra”], and *Hymenaea stigonocarpa* Mart. Ex Hayne [“Jatobá-do-cerrado”]) were chosen for being native trees of the Brazilian *cerrado* (savannah-like) biome (Fig. 1). The chosen specimens displayed features representative of the species and were used to data collection. Four specimens of “cambará,” four specimens of “cumbaru,” one specimen of “pau-terra,” and one specimen of “jatobá-do-cerrado” were collected.

Infrared thermography

For each specimen evaluated, crown temperature (IRTcrown; °C), shaded soil surface temperature (IRTshade; °C), and soil surface temperature under full sun (IRTsurf; °C) were determined hourly using a Testo® 875i 2i thermal imager with emissivity regulated to 0.85 (according to Incropera and Dewitt (2003), as ideal for use in vegetation). The device was handled by the same evaluator, positioning it always at the level of the eyes and without the use of a tripod, perpendicularly to the evaluated focus, at a 90° angle. The images were captured at a distance of 10 m from the trees that allowed them to be fully framed the display of the equipment. Captured images were processed in IRSoft Testo software, where the “cold spot” and “hot spot” commands were used after the image was opened and selected to obtain the highest and lowest temperatures, respectively, in a delimited area of the image. These tools allow the user to choose how they will select the area of the image to be analyzed. The “free form” option was used to delimit the area of the image to obtain the tree’s crown and shadow data, whereas the “rectangle shape” option was applied for the unshadow soil. The same areas were used to obtain both the maximum and the minimum temperatures (Fig. 2).

Climate data collection

For comparison purposes, the air temperature (AT; °C), air relative humidity (RH; %), and dew point temperature (DPT; °C) were measured by digital thermohygrometers equipped with a data logger (Instrutherm® HT-500), inside perforated PVC pipes (Trumbo et al. 2012), as described in detail by Karvatte Junior et al. (2016). To measure the black globe temperature (BGT; °C), digital thermohygrometers with data loggers (Instrutherm® HT-

Species	Date of measurements
1. *Gochnatia polymorpha* (cambará)	06/11-06/12; 07/21-07/24; 08/18-2015/08/21
2. *Dipteryx alata* Vogel (cumbaru)	06/11-06/12; 07/21-07/24; 08/18-2015/08/21
3. *Qualea grandiflora* Mart. (pau-terra)	06/17; 06/23; 07/27-07/28; 08/24-2015/08/25
4. *Hymenaea stigonocarpa* Mart. ex Hayne (jatobá-do-cerrado)	06/17; 06/23; 07/27-07/28; 08/24-2015/08/25

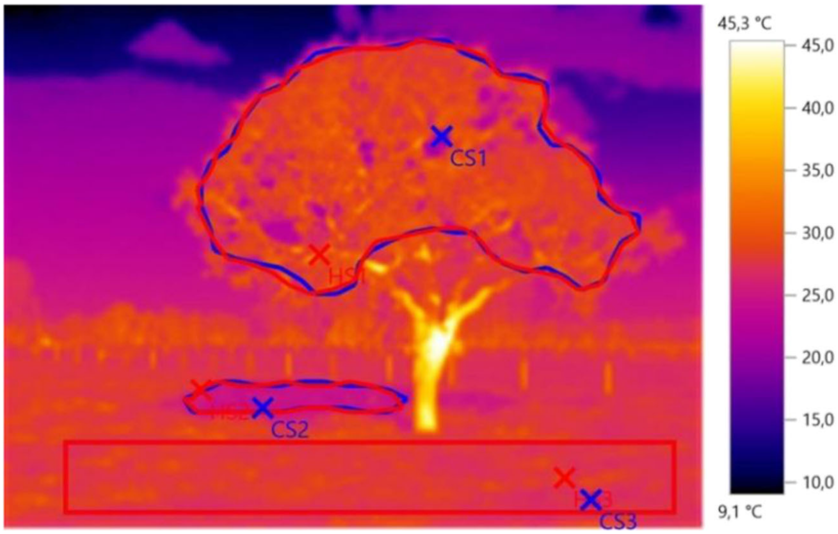
Fig. 1 Evaluation sites, species, and measurement dates

500) were inserted in adapted black globes (Souza et al. 2002). Wind speed (WS; m s^{-1}) was obtained by a portable digital anemometer (Homis® HMM 489), with sensors facing the wind direction. The devices were placed under the tree crowns, at 1.3 m above the soil, and displaced horizontally according to the shadow projection and zenith angle variation.

Thermal comfort indices

To characterize the thermal environment, the thermal comfort index was calculated for each evaluated time, area (shaded and sun-lighted), day, and month. The temperature and humidity index (THI) was determined according to Thom (1959), whereas the black globe temperature and humidity index

Fig. 2 Thermogram of the *Qualea grandiflora* Mart. specimen



(BGHI) was calculated following Buffington et al. (1981). Lastly, the radiation thermal load (RTL) was determined by following the methodology proposed by Esmay (1979).

Solar radiation

Photosynthetically active ration (μmol s^{-1} m^{-2}), total solar radiation (W m^{-2}), and luminosity (lux) were determined in four points: two in the shade and two in areas under full sun, according to the solar inclination. A spectroradiometer coupled to a data logger equipped with quantum (qt), pyranometer (pnm), and photometer (ptm) sensors (Li-Cor® Li-1400) was used. Sensors were kept parallel to the ground, leveled at 1.3 m, and positioned towards the sun.

Shadow measurements' predictions

The shadow measurements were determined by following the methodology proposed by Silva (2006), based on the geometric shape of the crown of each species. All studied species had a spherical or globose crown shape. Total height, trunk height, and crown length were measured with a digital clinometer (Haglof), while crown diameter was measured using a tape. These data were then used to calculate the following variables: shaded area (SA), shadow length (SL), and shadow distance in relation to the trunk (SD).

Statistical analysis

Multiple factor analysis (MFA) was applied for the simultaneous analysis of the environmental variables, and the procedures used for its modeling were carried out using the FactoMiner package in R software version 2.15.0. The data were categorized and divided into the following five thematic groups: (1) indices (THI, BGHI, and RTL); (2) temperature measurements (AT, BGT, and DPT); (3) radiation (qt, pnm, and ptm); (4) thermography (IRTsurf, IRTcrown, and IRTshade); and (5) shadow measurements (SA, SL, and SD). Data analysis was based on the incidence matrix of the variables, as depicted in Fig. 3. The assumptions for regression were fully attended, with normality (Shapiro-Wilk) tests, and the residues distribution.

Results

Average temperature, relative humidity, and precipitation in the evaluated period were 24.05 °C, 76%, and 39.6 mm (June); 24.95 °C, 81%, and 83.2 mm (July); and 28.25 °C, 51%, and 8.4 mm (August).

Multiple factor analysis identified associations between the observed variables, establishing common factors between them, which facilitates the interpretation of data. The thematic groups formed contributed to isolating three distinct analytical dimensions that elucidate the results. Together, these three analytical dimensions explain 72.37% of the total observed variance (Fig. 4).

The variables corresponding to the comfort indices (THI, BGHI, and RTL) as well as AT and BGT were correlated with thermography, and all contribute largely to dimension 1, which accounted for 42.44% of the explained variance. Dimension 2, in turn, concerns the geometrical settings of the shadows projected (SA, SD, and SL) by the evaluated trees as a function of the thermal and radiation variables, corresponding to 16.67% of the variance. Lastly, dimension 3 was mostly discriminated by DPT, which is opposed to the dimensions explained by the shadow measurements, specifically SL and SD, establishing a negative association of $r \cong -1.0$ and explaining 13.26% of the variance.

In dimension 1, there was a strong, positive association between the variables that compose the thematic groups of THI, BGHI, RTL, AT, BGT, qt, pnm, ptm, IRTshade, and IRTsurf, which were positioned near the *X* axis of dimension 1, in the graph. These variables had a high, positive, and linear association with the dimension and with each other, as seen by the acute angles formed between them. Therefore, decreases or increases in any of these variables will affect the others.

In dimension 2, the shadow measurements formed acute angles with each other, indicating a positive relationship between them. The variable shadow length (SL) had the highest weight in dimension 2, as it was farthest from the point of

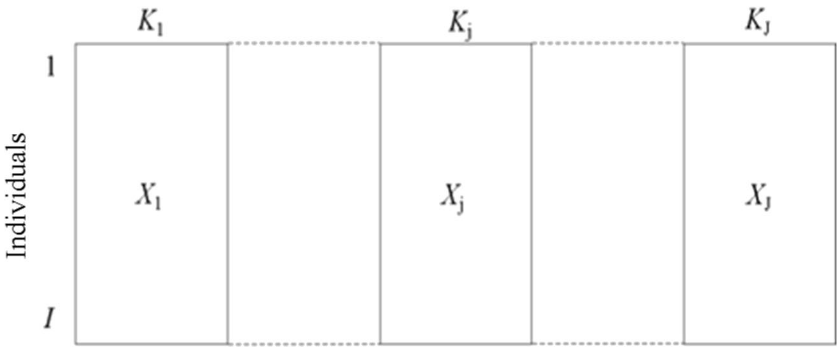


Fig. 3 MFA conceptual model, where X = values of observations of the I_n individuals for each K_{nm} variable within the K_m subsets; I = all I_n individuals; and K = all the variable K_n within the K_m subsets. Source: adapted from Escofier and Pagès (2008)

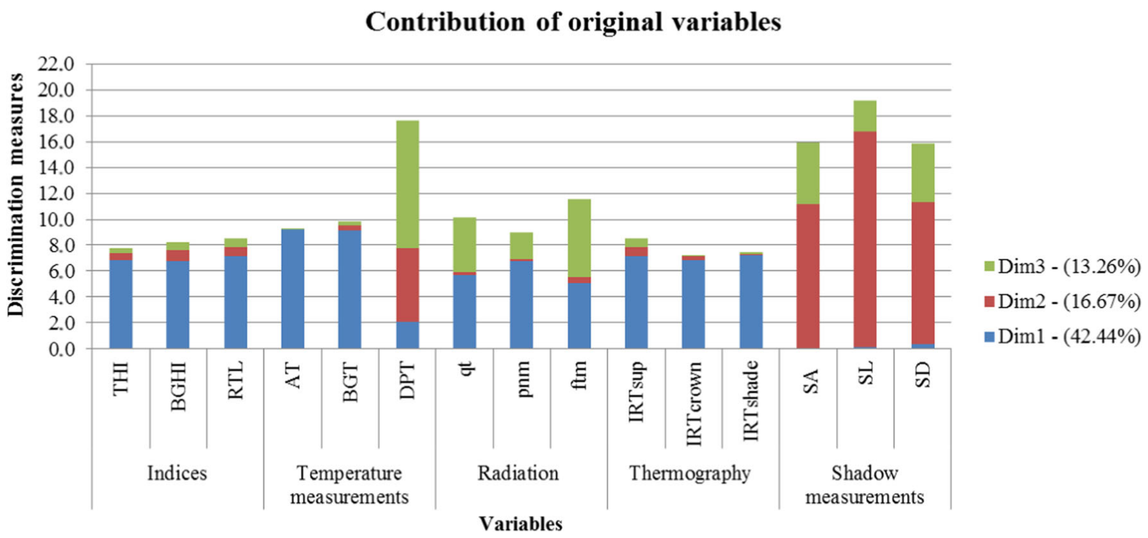


Fig. 4 Contribution of original variables, within each thematic group, for the formation of explanatory dimensions 1, 2, and 3. Temperature and humidity index (THI), black globe temperature and humidity index (BGHI), radiation thermal load (RTL), air temperature (AT), black globe temperature (BGT), dew point temperature (DPT), quantum (qt), pyranometer (pnm), photometer (ptm), infrared thermography of soil surface in the sun (IRTsurf), infrared thermography of crown (IRTcrown), infrared thermography of shaded soil (IRTshade), shaded area (SA), shadow length (SL), and shadow distance in relation to the trunk (SD)

origin in the image, i.e., alterations in SL will considerably affect the shadow distance in relation to the trunk (SD) and the shaded area (SA). The variables plotted onto the axis of ordinates behave independently of the variables present on the axis of abscissas, since there is no association between them. Dew point temperature, in turn, behaved independently of the other variables, showing no association with them in dimensions 1 and 2.

In dimension 3 (Fig. 6), DPT was inversely proportional to the shadow measurements (SA, SD, and SL), with which it had a negative association of $r \cong -1.0$. Thus, as DPT increases, there is a reduction in the tree shadow measurements. Figure 5 reinforces the non-association of DPT with dimension 1. The variables SD, SL, and SA are positively correlated with each other and behave independently in relation to dimension 1.

In Fig. 6, the grouped variables being positioned on the right side of the graph indicate a direct and positive correlation between them. The shadows' measurements, in turn, which quantifies the shading provided by the trees, are associated

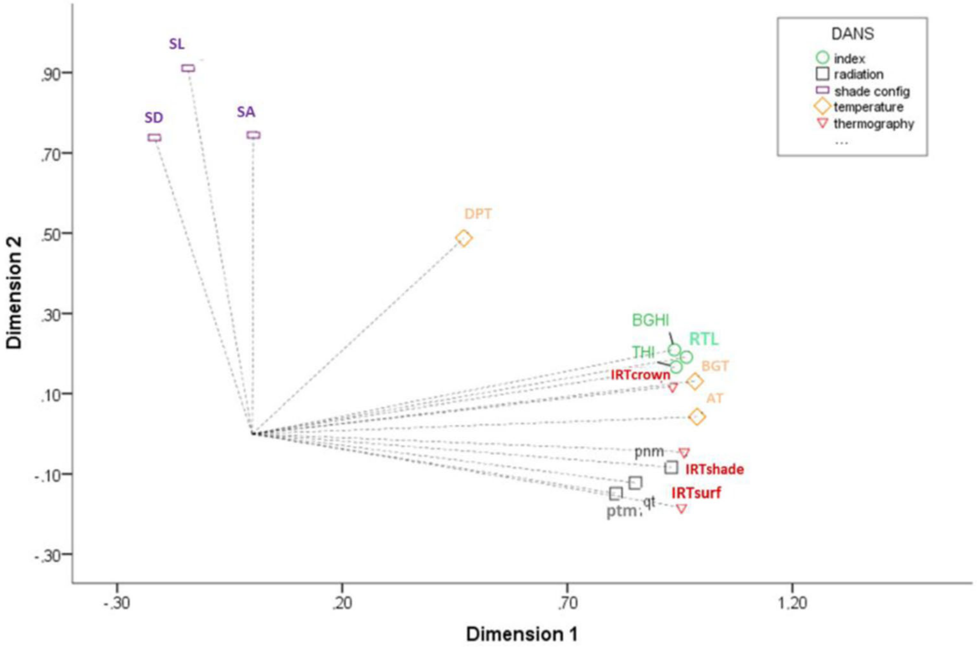


Fig. 5 Plotting of the variables onto the factorial plane according to the thematic groups for the orthogonal dimensions and their interactions. Temperature and humidity index (THI), black globe temperature and humidity index (BGHI), radiation thermal load (RTL), air temperature (AT), black globe temperature (BGT), dew point temperature (DPT), quantum (qt), pyranometer (pnm), photometer (ptm), infrared thermography of soil surface in the sun (IRTsurf), infrared thermography of crown (IRTcrown), infrared thermography of shaded soil (IRTshade), shaded area (SA), shadow length (SL), and shadow distance in relation to the trunk (SD)

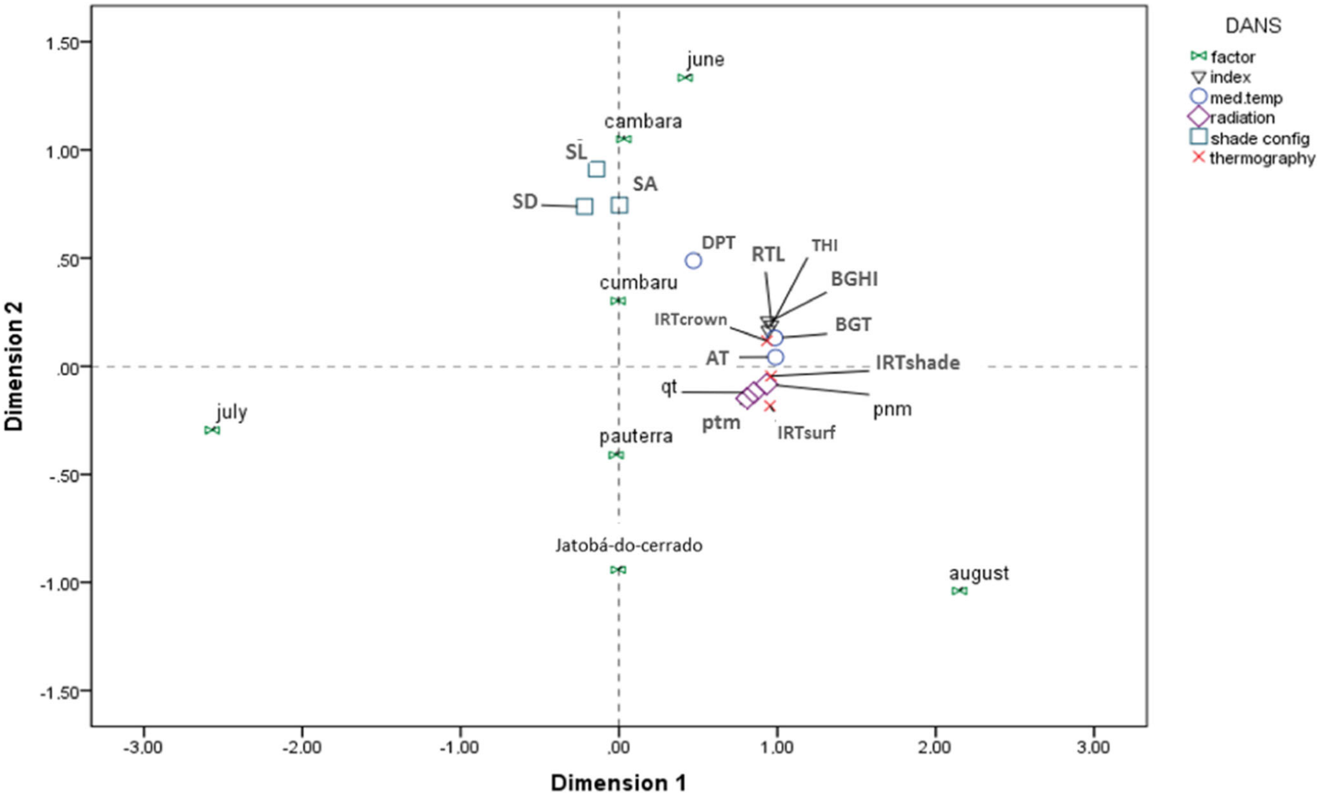


Fig. 6 Bidirectional contribution of the variables that make up the thematic groups for the formation of dimensions 1 and 2, and the interactions between them. Temperature and humidity index (THI), black globe temperature and humidity index (BGHI), radiation thermal load (RTL), air temperature (AT), black globe temperature (BGT), dew point temperature (DPT), quantum (qt), pyranometer (pnm), photometer (ptm), infrared thermography of soil surface in the sun (IRTsurf), infrared thermography of crown (IRTcrown), infrared thermography of shaded soil (IRTshade), shaded area (SA), shadow length (SL), shadow distance in relation to the trunk (SD), months (June, July, and August), and species (cambará, cumbaru, pau-terra and jatobá-do-cerrado)

with the elements June, "cambará," and "cumbaru" and exhibited an inversely proportional relationship with the elements July, August, "pau-terra," and "jatobá-do-cerrado."

As shown in Table 1, there was a positive linear correlation between the thematic groups ($p < 0.05$). A high degree of association was observed between the infrared-thermography variables and the variables of thematic-group thermal comfort indices, temperature measurements, and radiation.

Given the obtained correlations, linear regression analyses were carried out and positive linear regression equations were obtained ($p < 0.05$) between infrared thermography and the variables RTL, BGHI, THI, and AT. Our results demonstrate that it is possible to use IRT measurements to infer about the thermal conditions for livestock under different tree species in the Brazilian grasslands.

Discussion

The three dimensions in which the variance was explained summarize the meaning of the set of variables associated with them as well as establish linear associations between those and the original variables (Lebart et al. 2000). The positive linear correlation observed between thermography and the variables of the thematic groups: temperature, indices, and radiation, in dimension 1 (Table 1), and the equations defined by the regressions (Table 2) indicate that IRT can be used to evaluate the correlated variables. Catena and Catena (2008) demonstrated the efficiency of using IRT in the thermal evaluation of tree species, highlighting the fact that it is a totally nondestructive and easy method.

The high positive and direct correlation between the variables of the thematic groups thermal comfort indices,

Table 1 Matrix of correlations between the thematic groups of the studied variables: comfort indices (CI); temperature measurements (TM); radiation (RAD); infrared thermography (IRT); shadow measurements (SM)

	CI	TM	RAD	IRT	SM
CI	1.00	–	–	–	–
TM	0.87	1.00	–	–	–
RAD	0.59	0.59	1.00	–	–
IRT	0.78	0.85	0.77	1.00	–
SM	0.01	0.01	0.01	0.02	1.00

Table 2 Linear regression equations between infrared thermography of soil surface under full sun (IRTsurf), infrared thermography of crown (IRTcrown), and infrared thermography of shaded soil (IRTshade) and radiation thermal load (RTL), black globe temperature and humidity index (BGHI), temperature and humidity index (THI), and air temperature (AT)

Factor	Prediction	R^2	Equations	MSE[n]	*p* value
IRTsurf	RTL	0.724	$y = 318.843 + 7.13^*$ IRTsurf	0.91	< 0.0001
	BGHI	0.660	$y = 50.964 + 0.926^*$ IRTsurf	0.14	< 0.0001
	THI	0.709	$y = 52.\ 101 + 0.791^*$ IRTsurf	0.11	< 0.0001
	AT	0.898	$y = 1.228 + 0.869^*$ IRTsurf	0.06	< 0.0001
IRTcrown	RTL	0.855	$y = 294.040 + 9.644^*$ IRTcrown	0.83	< 0.0001
	BGHI	0.706	$y = 49.163 + 1.195^*$ IRTcrown	0.16	< 0.0001
	THI	0.716	$y = 51.221 + 0.994^*$ IRTcrown	0.13	< 0.0001
	AT	0.926	$y = 0.002 + 1.103^*$ IRTcrown	0.07	< 0.0001
IRTshade	RTL	0.796	$y = 307.531 + 8.799^*$ IRTshade	0.92	< 0.0001
	BGHI	0.676	$y = 50.454 + 1.105^*$ IRTshade	0.16	< 0.0001
	THI	0.704	$y = 52.005 + 0.931^*$ IRTshade	0.13	< 0.0001
	AT	0.956	$y = 0.244 + 1.057^*$ IRTshade	0.05	< 0.0001

[n] Mean standard error

radiation, black globe temperature, and air temperature reveals that increments in any of these variables also represent an increase in the others. The results herein presented indicate the non-association of DPT with the variables that form the thematic groups: thermal comfort indices, radiation, shadow measurements, whereas it seems to be similar to those found by Paim et al. (2012) for BGT and AT (Fig. 5), in an evaluation of IRT and its relationship with the thermal comfort of animals in a production system. Like in the present study, Thompson and Marvin (2005) demonstrated that it is possible to obtain precise data in the identification of thermal variations in the landscape through thermographic images of the open environment. However, the present study went further by revealing the type of correlation among the studied variables and the potential use of infrared radiation to estimate the values of RTL, THI, and BGHI, in addition to AT, only by capturing the infrared radiations. Based on the equations presented in Table 2, it is possible to predict the thermal conditions by using IRT with considerably less labor when compared with the study by Karvatte Junior et al. (2016) who evaluated the influence of the presence of tree species in production systems in Central-West Brazil, from July to September 2013, and found climatic conditions similar to those of the present study. Additionally, those authors observed a direct association between thermal comfort indices, TA, BGT, and radiation, and that variations in AT and BGT throughout the study significantly influenced RTL.

The shadow measurements showed to be independent ($p > 0.05$) of the variables of the thematic groups temperature measurements, thermal comfort indices, radiation, and thermography. This can be explained by the fact that the shadow effect on the microclimate of the shaded region does depend not only on the shaded area but also on the amount of shade generated, which in turn varies according to the densification and color of leaves, number of branches, among other traits inherent to tree species.

Dew point temperature was inversely proportional to the distance between the tree trunk and the shadow line and to the shadow length (Fig. 5). These last variables indicate the distance of the shadow from the trees throughout the day; In other words, greater shadow projections are obtained at times of lower solar elevation. Thus, the results obtained in this study show that larger shadow projections are accompanied by lower DPT. Previous research suggests that DPT is a microclimate variable directly influenced by temperature and relative humidity; however, the density and spatial arrangements of trees used in a pasture production system can provide significant microclimate modifications even within 50 m away from trees (Pereira et al. 2002; Abreu and Labaki 2010; Karvatte Junior et al. 2016; de Oliveira et al. 2017).

Conclusions

Infrared thermography was positively and directly correlated with the variables radiation, temperature, and thermal comfort indices. It is, therefore, a tool that allows for predicting and monitoring these climatic variables in a fast, easy, and non-invasive manner.

The present results suggest that infrared thermography should be used in the thermal evaluation of rural environments.

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