



## Black globe temperature from meteorological data and a bioclimatic analysis of the Brazilian Northeast for Saanen goats



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### ABSTRACT

The black globe temperature (BGT) is not a common measurement for weather station networks, despite having great relevance to bioclimatic studies. The aim of this study was to propose equations for estimating the BGT, using meteorological data for different time scales and a bioclimatic evaluation of the Brazilian Northeast for breeding Saanen dairy goats. The data used in elaborating the equations were collected between 1 November 2014 and 31 October 2017. Data for BGT, incident global solar radiation (SR), air temperature (AT), relative humidity (RH) and wind speed were handled on a daytime, night-time, daily and monthly scale. One half of the database was used to adjust the equations and the other half in the evaluation. The bioclimatic diagnosis of the Brazilian Northeast was carried out based on mean monthly values of the black globe temperature and humidity index (BGHI) estimated for the four seasons of the year. For the daytime scale, an equation based on AT ( $BGT = 1.3897 \cdot AT - 5.4421$ ,  $r^2 = 0.80$ ) and a multiplicative model combining the effects of AT and SR ( $BGT = [1.3897 \cdot AT - 5.4421] (0.0384 \cdot \ln(SR) + 0.7935)$ ,  $r^2 = 0.91$ ) were obtained. AT adjusted well for BGT on the night-time scale ( $BGT = 0.995 \cdot AT - 0.6964$ ,  $r^2 = 0.99$ ), daily scale ( $BGT = 1.1641 \cdot AT - 1.5941$ ,  $r^2 = 0.97$ ) and monthly scale ( $BGT = 1.1550 \cdot AT - 1.3498$ ,  $r^2 = 0.98$ ). The BGT can therefore be calculated from AT and/or SR for the daytime scale, and from AT only for the night-time, daily and monthly scales. In general, the west and centre-south of the state of Bahia offer the animals the most thermal comfort during each season of the year. In the state of Maranhão, heat stress occurs throughout the year, with the BGTI predominately in the range of 85–95. As such, strategies to combat heat stress should be encouraged to minimise the negative effects of climate on milk production in Saanen goats, and favour the milk-production chain in the northeast of Brazil.

### 1. Introduction

Thermal stress is caused by a combination of environmental factors that affect the physiological parameters of animal intake, reproduction, lactation and production (Zobel et al., 2015; Das et al., 2016; Ribeiro et al., 2016; Curtis et al., 2017; Sejian et al., 2018). Bioclimatic indices have been developed to express the comfort/discomfort of the environment to animals (Lemke and Kjellstrom, 2012; Hajizadeh et al., 2017), so that they can be used for improving agricultural planning and decision-making (Silva et al., 2008; da Silva et al., 2010; McManus et al., 2016; Pezzopane et al., 2019).

The black globe temperature index (BGTI) is a good example of an index applied to bioclimatic diagnosis, but which requires data of the black globe temperature (BGT) (Lemke and Kjellstrom, 2012; Pezzopane et al., 2019). The BGT is an indirect measurement of the radiant heat load of the environment obtained with a thermometer installed inside a hollow copper sphere painted matte black, 0.05 m thick and 0.15 m in diameter, that allows the thermal sensation of an animal to be inferred (Abreu et al., 2011; Hajizadeh et al., 2017).

The absence of black globe thermometers in the weather stations of the meteorological monitoring networks of public State and Federal institutions and private companies in Brazil makes it difficult to assess

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the bioclimatic risk of different regions. Developing equations for estimating the BGT from meteorological variables can be useful in calculating bioclimatic indices in different regions (Silva et al., 2008; da Silva et al., 2010; Dimiceli et al., 2012; Mendes et al., 2014). Besides, the black globe temperature sensor can be costly, making it difficult to install in many locations (Dimiceli et al., 2012). Even more-expressive results can be achieved with equations for different time scales, since the data supplied by the institutions varies greatly with regard to time (i.e. hourly, daily and monthly). The application of these equations in estimating the BGT is very important for evaluating daytime and night-time energy exchanges in the interface animal-environment, as well as assess most promising producing regions and species. In addition, it allows the level of environmental modification required for animal production to be defined, and measure production costs (Das et al., 2016; Curtis et al., 2017; Sejian et al., 2018).

One activity that is being increasingly exploited is dairy goat farming, due to the high nutritional value of the milk and its derivatives (Irano et al., 2012; Zambom et al., 2013). Although important, especially in the northeast of Brazil, its inclusion in agro-industry depends on the use of activities that alter the low yield of the animals in hot environments, i.e. bioclimatic analysis and the adoption of genetically more-productive species (Lôbo and Silva, 2005; Pequeno et al., 2017; Arnal et al., 2018). As Brazil is a tropical country, many native European animals from a temperate climate do not adapt well, i.e. Saanen goats, which specialise in milk production. Exotic breeds with good dairy performance are concentrated in the south and southeast of Brazil, and exploiting them in the northeast therefore depends on a bioclimatic diagnosis. Pequeno et al. (2017) developed a mathematical model based on maximum air temperature to estimate milk production during peak lactation of the animals, and mapped the areas most exposed to heat stress in the Brazilian Northeast. However, these authors did not consider the BGTI, the index that best represents the thermal environment of the animals.

In the Northeast of Brazil, the goat herd amounts to 9,092,724 head, composed of different races and aptitudes, meat and dairy, which results in a large discrepancy in the goat milk yield between the states of this region (IBGE, 2017). The wide diversity of climate (Alvares et al., 2014) and predominant adoption of an pastoral/extensive farming system causes heat stress in most of the animals (Silva et al., 2008; da Silva et al., 2010; Mendes et al., 2014), and good performance depends on bioclimatic assessments together with correct management. This type of action can boost local dairy farming, with added income for the population, and encourage producers to remain on the farm.

The aim of this study therefore, was to propose equations for estimating the BGT using meteorological data for different time scales (daytime, night-time, daily and monthly) and a bioclimatic evaluation of the Brazilian Northeast for breeding Saanen goats, with a view to guiding practices for improving animal welfare and enhancing the production of goat milk.

## 2. Material and methods

### 2.1. Estimating the BGT from meteorological data

The data used in elaborating and evaluating mathematical equations for estimating the BGT were collected between 1 November 2014 and 31 October 2017 (1096 days) from a micro-weather station installed in the district of Floresta (8.3°S, 38.5°W at 381 m), in the state of Pernambuco, Brazil. The micro-weather station of 4 m-high with coupled sensors (black globe thermometers, aspirated psychrometers, pyranometer and anemometer) was installed in the centre of an area of flat bare ground with no obstacles nearby, to avoid affecting the sensor readings. Each sensor was connected to a multiplexer (AM16/32B-ST-SW, Campbell Scientific, Logan, Utah, USA) and a data acquisition system (CR1000-ST-SW-NC, Campbell Scientific, Logan, Utah, USA), which registered data every 60 s, and stored the mean values at 10-min

intervals. Two globe thermometers were installed at the station (Type T copper-constantan thermocouple, Campbell Scientific, Logan, Utah, USA, inserted inside a black-painted copper globe of high absorptivity, diameter 150 mm, Testo, Inc., West Chester, PA, USA) at a height of 1.5 and 2.5 m above the ground to measure the BGT in °C. Two aspirated psychrometers, comprising copper-constantan thermocouples (type T, Campbell Scientific, Logan, Utah, USA), measured the dry-bulb temperature (DBT) (equal to the air temperature, AT) and the wet-bulb temperature (WBT), at the same height as the two globe thermometers, with readings output in °C. A pyranometer (CS 300 Pyranometer, Campbell Scientific, Logan, Utah, USA) at a height of 2.5 m was used to measure incident global solar radiation (SR), with output values in  $W m^{-2}$ . An anemometer (03002 R.M. Young Wind Sentry Set, Campbell Scientific, Logan, Utah, USA), placed at a height of 2 m, measured the wind speed in  $m s^{-1}$ .

The mean value of the DBT and WBT data from the two psychrometers, measured at 1.5 and 2.5 m, was used to estimate the relative humidity (RH,%) by means of Eq. (1) (Pereira et al., 2002).

$$e = (RH/eS) 100 \quad (1)$$

where: e – the current water vapor pressure in air, kPa; and, eS - saturation water vapor pressure in air, kPa.

The value for “e” was calculated with Eq. (2) (Pereira et al., 2002).

$$e = eSW - A Pa (DBT - WBT) \quad (2)$$

where: eSW - saturation water vapor pressure in air based on the WBT, kPa; A - psychrometric constant ( $8.0 \cdot 10^{-4} \text{ } ^\circ\text{C}^{-1}$ ); and, Pa - estimated atmospheric pressure based on the local altitude, kPa.

The values for “eS” and “eSU” were calculated using the mean values for DBT and WBT respectively (Pereira et al., 2002):

$$eS = \{ [0.6108 \exp(17.27 DBT)] / [DBT + 237.3] \} \quad (3)$$

$$eSU = \{ [0.6108 \exp(17.27 WBT)] / [WBT + 237.3] \} \quad (4)$$

The data for BGT, SR, AT, RH and WS of the 1096 days (157,824 values by variable) were processed every 10 min (separating them into daytime and night-time), daily (from all 144 data for each day, with average of BGT, AT, RH and WS values, and integration of the SR data) and monthly (mean value of all the daily data for each month). For the daily and monthly scales, the unit for each variable was expressed in °C,  $MJ m^{-2} day^{-1}$ , °C, % and  $m s^{-1}$  respectively.

Half of the database for each time scale, comprising alternate days or months, was used to establish linear and non-linear regressions between the BGT (dependent variable) and the meteorological elements SR, AT, RH and WS (independent variables). The regressions were carried out using the Sigmaplot v14 (Systat software, Inc., 2019). The significance of the equations and their respective coefficients were evaluated by Student's F-test and Student's t-test respectively, at a level of 5%, and the coefficient of determination ( $r^2$ ) was calculated. Based on  $r^2$ , the variables were then ordered as to their importance in explaining the BGT: 1st, 2nd, 3rd and 4th. The equations with higher values for  $r^2$  were used in elaborating a multiplicative model. This model comprised two equations, as per a structure described by Silva et al. (2007):

$$Y = f(a) f(b) \quad (5)$$

where: Y - dependent variable; f(a) - dependent function of x with linear or non-linear fluctuation; and f(b) - dependent function of x with linear or non-linear fluctuation;

In this step, f(a) was represented by the equation with the greatest  $r^2$  generated between the BGT and one of the independent variables (SR, AT, RH or WS), i.e. the first most important equation in explaining the BGT. This function f(a) was used in calculating the BGT (estimated black globe temperature, BGTe), and the ratio was then obtained from the actual observed values (observed black globe temperature, BGTo), giving BGTo/BGTe. This ratio is the residual unexplained by the first

independent variable. The BGT<sub>o</sub>/BGT<sub>e</sub> ratio was correlated with the second independent variable having the greatest  $r^2$ . In cases where insertion of the variable did not contribute expressively to the multiplicative model, the third followed by the fourth most important variable was used to form  $f(b)$ . This procedure was adopted to obtain the variable that explains the variation in BGT which was not explained by the first variable.

The generated equations and multiplicative model were evaluated from their application to the other half of the data set, with the results compared to the observed data by means of the mean bias error (MBE) and root mean square error (RMSE), as well as the statistical indices of precision (Pearson's correlation coefficient,  $r$ ), accuracy (Willmott agreement index) and confidence (coefficient of performance,  $c$ ) (Willmott, 1981, 1982; Camargo and Sentelhas, 1997). The MBE, obtained in °C, was used to measure the underestimation or overestimation of the BGT equations in the long term. In turn, the RMSE, in °C, gives the mean error in the short term. The closer to zero the MBE and RMSE, the lower the error in estimation by the equations. The coefficient “ $r$ ” indicates the degree of dispersion of the generated data in relation to the mean (straight), ranging from  $-1$  to  $+1$ , so that the closer to the extremes, the better the accuracy of the equation. The signs indicate whether the correlation is negative or positive. The “ $d$ ” index indicates the degree of accuracy, the closer to  $+1$ , the greater the accuracy, i.e. the estimated values are the same as the observed values. The “ $c$ ” index, as suggested by Camargo and Sentelhas (1997), calculated as the product of the values for “ $r$ ” and “ $d$ ”, was used to classify the performance of the equations in estimating the BGT. Student's t-test was also applied between the estimated and observed data for non-rejection of the hypothesis  $H_0$  ( $p \geq 0.05$ ), i.e. that the mean value between them did not differ.

## 2.2. Bioclimatic evaluation of the Brazilian Northeast for Saanen dairy goats

The evaluation was performed to ascertain the thermal comfort conditions of the Brazilian Northeast for breeding Saanen goats, which are animals specialised in dairy production. Monthly observed and monthly estimated historical data for maximum air temperature ( $T_X$ , °C) and minimum relative humidity ( $RH_N$ , %) (data for mid-afternoon) from 2102 stations (Fig. 1A) were used to calculate the maximum BGT and maximum BGTI (BGTI<sub>X</sub>) (Buffington et al., 1981):

$$BGTI_X = BGT + 0.36 T_{DP} + 41.5 \quad (6)$$

where:  $T_{DP}$  = dew point temperature, in °C.

The observed data were obtained from the Meteorological Database for Teaching and Research of the National Meteorological Institute ([www.inmet.gov.br](http://www.inmet.gov.br)) (74 weather stations), and the estimated data (2028 points), calculated from the models proposed by Medeiros et al. (2005) and Silva et al. (2007) for  $T_X$  and minimum relative humidity ( $RH_N$ ) respectively. Silva et al. (2007) state that, from the data for local longitude ( $\lambda$ , in degrees), moisture index ( $I_M$ , dimensionless) and mean monthly air temperature ( $T$ , °C), it is possible to estimate the mean relative humidity, as per Eq. (7).

$$RH = a \exp\{-\exp[-(I_M - b)/c]\} [d + e (T \lambda)] \quad (7)$$

where:  $a$ ,  $b$ ,  $c$ ,  $d$ ,  $e$  – coefficients of the equation.

However, in this study, in order to estimate the  $RH_N$ , the values for  $T$  were replaced by  $T_X$ . This procedure was adopted in order to obtain the best estimates and ensure more-accurate spatialization of the BGTI<sub>X</sub> data, since most of the stations used have no  $RH_N$  data. For the  $I_M$ , obtained by  $I_M = [(P/PET)-1].100$ , monthly values of precipitation ( $P$ ) and potential evapotranspiration ( $PET$ ) are necessary. The  $PET$  was calculated from the data for effective temperature ( $T_{EF}$ ) as described in Pereira et al. (2002):  $T_{EF} = 0.36 (3 T_X - T_N)$ , where  $T_N$  is the minimum monthly air temperature.  $T_{PO}$  was calculated by means of  $T_X$ , in “eS” (Eq. (3)) and by means of  $RH_N$ , used in quantifying “ $e$ ” by Eq. (1).

Therefore:

$$T_{PO} = \{[(237.3 \log(e/0.6108)]/[7.5 - \log(e/0.6108)]\} \quad (8)$$

The BGTI<sub>X</sub> values for the Brazilian Northeast were compared to the ideal range of BGTI values for Saanen dairy goats. This range was established from information on the critical air temperature for Saanen dairy goats quoted by Pequeno et al. (2017), and on RH for domestic animals quoted in Baêta and Souza (2010) and in Silva (2000).

According to Pequeno et al. (2017), Saanen goats significantly reduce milk production during the period of maximum lactation when  $T_X$  is greater than 33 °C. In turn, Baêta and Souza (2010) and Silva (2000) state that the ideal RH for domestic animals is, on average, 75%. These data were applied in quantifying the BGTI with Eq. (6) and defining the critical value to be used in bioclimatic evaluations for breeding Saanen goats.

BGTI<sub>X</sub> maps for the Brazilian Northeast were prepared for the four seasons of the year (summer, January to March; autumn, April to June; winter, July to September; and spring, October to December) from the Quantum GIS, version 2.18.12. (QGIS, 2009). The data were spatialised using spatial modelling, as described by Alvares et al. (2013), submitting the BGTI<sub>X</sub>, latitude, longitude and altitude to multivariate non-linear regressions. In applying the multivariate equations, the digital elevation model (Shuttle Radar Topography Mission, 90 × 90 m) (Miranda, 2019) was used as an independent variable. Latitude and longitude maps were obtained by means of the trend method of spatialization, from which, together with the MDE, the BGTI<sub>X</sub> maps were generated.

## 3. Results

### 3.1. Equations for estimating the BGT from meteorological data

According to Table 1, there was a highly significant correlation ( $p < 0.0001$ ) between BGT and the meteorological elements, except for WS, which had no effect on BGT at any of the time scales under study; therefore, WS was not adopted in generating the multiplicative model. On the daytime scale, the correlation between BGT and the meteorological elements was significant for SR, RH and AT (Table 1). AT explained 80% of the variability in the BGT, followed by RH (65%) and SR (45%). As AT explained most of the variability in the BGT (80%), when the 20% residual not explained by AT (i.e. the BGT<sub>o</sub>/BGT<sub>e</sub> ratio) was correlated, first with RH and then with SR, the latter variable showed a higher value for  $r^2$  (Fig. 2), and was therefore used in generating the multiplicative model. The resulting multiplicative model was written as the product of the equation, BGT versus AT (Table 1), with the equation, BGT<sub>o</sub>/BGT<sub>e</sub> versus SR (Fig. 2B):

$$BGT = [(1.3897 AT - 5.4421) (0.0384 \ln(SR) + 0.7935)], \text{ with } r^2 = 0.91 \quad (9)$$

Combining AT and SR accounted for 91% of the variability in the BGT, which is greater than explained using AT only (80%).

According to Fig. 3, the linear equation as a function of AT only has a low long-term error (MBE = 0.02 °C), however in the short term, the mean error is 3.34 °C (RMSE) (Fig. 2A). The “ $r$ ” of 0.90 showed the high precision of the model, i.e. that 90% of the estimated data were very close to the mean. On the other hand, the “ $d$ ” index was 0.94, indicating optimal accuracy, i.e. 94% of the estimated data were very close to observed data. As such, according to the confidence index (“ $c$ ”), the performance of this equation was classified as “Very Good” and, based on Student's t-test at 5% significance ( $t = 0.16$ ), the estimated values did not differ from the observed values. For the multiplicative model (Eq. (9)), the performance was even better, with high precision ( $r = 0.95$ ) and accuracy ( $d = 0.98$ ), and low errors (MBE = 0.15 °C, RMSE = 2.38 °C), and was considered “Excellent” ( $c = 0.93$ ); Student's t-test was also significant ( $t = 0.43 > 0.05$ ).

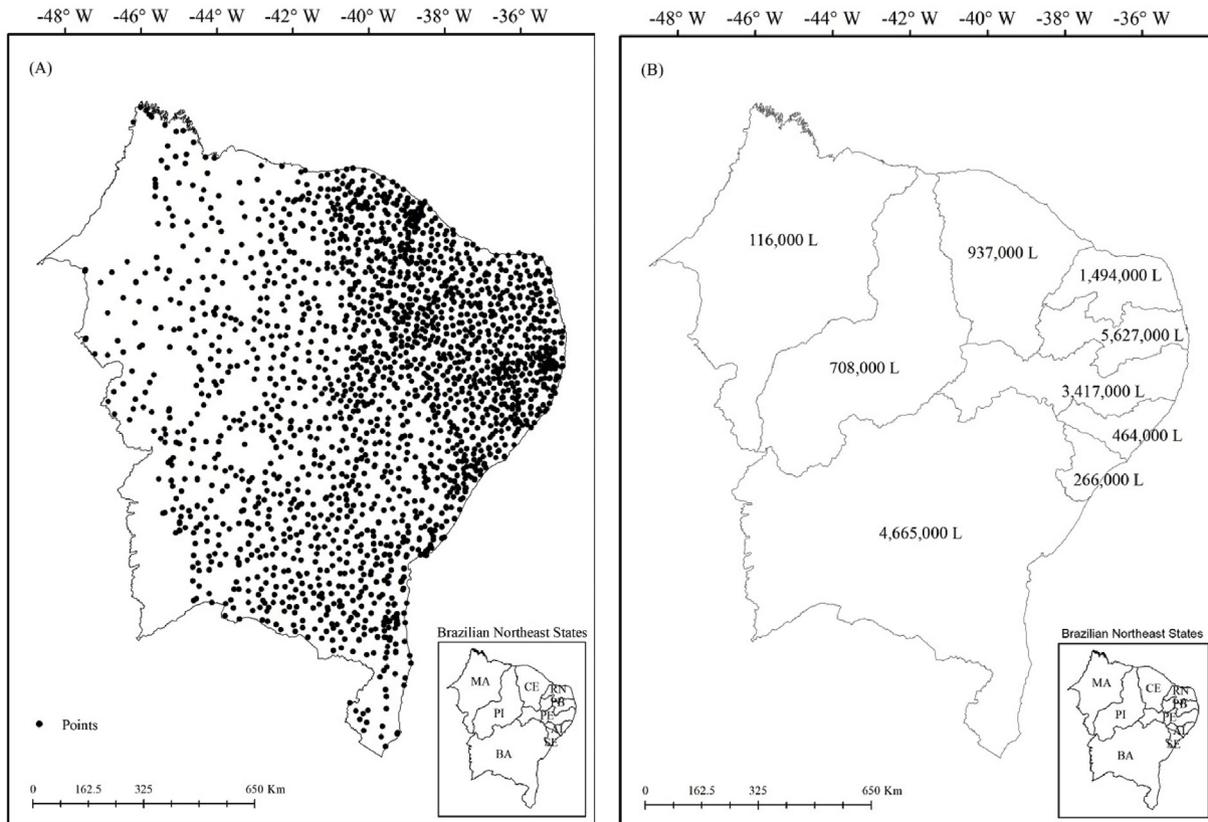


Fig. 1. (A) Location of the data points in the Brazilian Northeast. (B) Amount of goat milk, in litres, by state (IBGE, 2017). AL - Alagoas; BA - Bahia; CE - Ceará; PB - Paraíba; MA - Maranhão; PE - Pernambuco; PI - Piauí; RN - Rio Grande do Norte; SE - Sergipe.

For the other time scales, AT was the only variable adopted in explaining the BGT, and it was not necessary to generate a multiplicative model to include a new explanatory variable. On the night-time scale, the AT explained 99% of the variation in BGT ( $BGT = 0.995 AT - 0.6964$ ,  $r^2 = 0.99$ , Table 1). From Fig. 3C, the low errors ( $MBE = -0.02\text{ }^\circ\text{C}$  and  $RMSE = 0.44\text{ }^\circ\text{C}$ ) and the “Excellent” performance ( $c = 0.99$ ) can be seen, with the estimated values not differing from the observed values ( $t = 0.88 > 0.05$ ). On the daily scale, AT explained 97% of the fluctuation in BGT data ( $BGT = 1.1641 AT -$

$1.5941$ ,  $r^2 = 0.97$ , Table 1). The long-term ( $MBE = 0.0\text{ }^\circ\text{C}$ ) and short-term ( $RMSE = 0.6\text{ }^\circ\text{C}$ ) errors were greatly reduced (Fig. 4A). The “r” of 0.98 indicated the high precision, and the “d” of 0.99, the optimal accuracy of this equation. Performance, therefore, was classified as “Excellent”, and the t-test showed that there was no difference between the estimated and observed data ( $t = 0.23 > 0.05$ ). On the monthly scale, AT explains 98% of the variability in BGT ( $BGT = 1.1550 AT - 1.3498$ ). The long-term ( $MBE = 0.01\text{ }^\circ\text{C}$ ) and short-term ( $RMSE = 0.30\text{ }^\circ\text{C}$ ) estimation errors were even lower when compared to the other time scales,

Table 1

Descriptive statistics and regression between the black globe temperature ( $Y = BGT, \text{ }^\circ\text{C}$ , dependent variable) and meteorological elements ( $X$ , independent variables) at different time scales (daytime, night-time, daily and monthly). Logarithmic equation  $Y = a.\ln(X) + b$ ; and Linear equation  $Y = a(X) + b$ .

Time scale	aBGT ( $^\circ\text{C}$ )	X	Unit	Minimum	$\mu$	Maximum	Equation	r <sup>2</sup>	p	n
Daytime (SR > 0)	12.0–55.2	WS	$\text{m s}^{-1}$	0.0	2.0	6.9	ns	–	> 0.05	35436
Daytime (SR > 0)		SR	$\text{W m}^{-2}$	0.1	427	1233	$BGT = 2.8646.\ln(X) + 20.4247$	0.45	< 0.0001	35436
Daytime (SR > 0)		RH	%	19.4	58.1	100.0	$BGT = -0.3416.(X) + 55.5556$	0.65	< 0.0001	35436
Daytime (SR > 0)		AT	$^\circ\text{C}$	12.7	29.6	40.6	$BGT = 1.3897.(X) - 5.4421$	0.80	< 0.0001	35436
Night-time (SR < 0)	12.0–47.9	WS	$\text{m s}^{-1}$	0.0	1.2	5.9	ns	> 0.05	30861	
Night-time (SR < 0)		RH	%	27.3	75.4	100.0	$BGT = -0.1764.(X) + 37.1534$	0.61	< 0.0001	30861
Night-time (SR < 0)		AT	$^\circ\text{C}$	12.8	24.7	37.1	$BGT = 0.9950.(X) - 0.6964$	0.99	< 0.0001	30861
Daily	21.8–36.4	WS	$\text{m s}^{-1}$	0.5	1.6	3.0	ns	> 0.05	461	
Daily		SR	$\text{MJ m}^{-2} \text{ day}^{-1}$	3.1	19.7	27.1	$BGT = 0.4618.(X) + 21.1379$	0.47	< 0.0001	461
Daily		RH	%	43.4	65.9	89.9	$BGT = -0.1935.(X) + 42.9984$	0.46	< 0.0001	461
Daily		AT	$^\circ\text{C}$	20.4	27.3	32.9	$BGT = 1.1641.(X) - 1.5941$	0.97	< 0.0001	461
Monthly	23.4–33.9	WS	$\text{m s}^{-1}$	1.0	1.6	2.6	ns	> 0.05	30	
Monthly		SR	$\text{MJ m}^{-2} \text{ day}^{-1}$	13.4	19.7	24.0	$BGT = 0.7331.(X) + 15.7701$	0.63	< 0.0001	30
Monthly		RH	%	54.2	66.2	80.5	$BGT = -0.2152.(X) + 44.4487$	0.43	< 0.0001	30
Monthly		AT	$^\circ\text{C}$	22.1	27.3	30.3	$BGT = 1.1550.(X) - 1.3498$	0.98	< 0.0001	30

SR - incident global solar radiation, RH - relative humidity, AT - air temperature, WS = wind speed,  $r^2$  = coefficient of determination.

aBGT - variation in the values of the black globe temperature.

$\mu$  - mean.

n - number of observations.

ns - no significant.

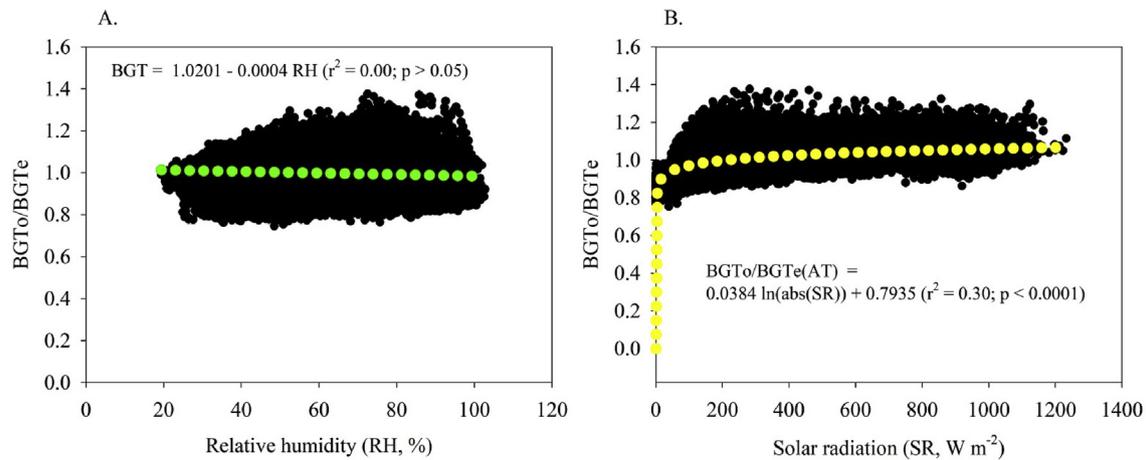


Fig. 2. Correlation of the residual TGNo/TGNe not explained by air temperature (AT) (A) with relative humidity and (B) with incident global solar radiation.

with high precision ( $r = 0.98$ ) and accuracy ( $d = 1.00$ ), and a performance considered “Excellent” (Fig. 4B). According to Student’s t-test, the estimated values again did not differ from the observed data ( $t = 0.42 > 0.05$ ).

### 3.2. Bioclimatic evaluation of the Brazilian Northeast for Saanen dairy goats

In the Northeast of Brazil, the BGTI varies between 75 and 95 (Fig. 5). The largest range of territory with ideal thermal conditions ( $BGTI < 85$ ) for breeding Saanen dairy goats occurs during the summer and autumn (Fig. 5A and B), when maximum air temperatures are high ( $\sim 31^\circ\text{C}$ ), but lower than found at the end of winter (September) and during the spring. During the winter and spring (Fig. 5C and D), areas with a  $BGTI < 85$  are reduced, predominating in the state of Bahia and in the high-altitude areas of the other states. In general, the west and centre-south of the state of Bahia offer the animals the most thermal comfort during each season of the year. In Maranhão, heat stress occurs throughout the year, with the BGTI predominately in the range of 85–95.

## 4. Discussion

### 4.1. Estimating the BGT from meteorological data

The climate is a major factor in animal farming, especially in tropical and subtropical regions. Furthermore, the climate defines the level of modification of the breeding environment, management,

performance, animal health, and production costs (Das et al., 2016; Ribeiro et al., 2016; Curtis et al., 2017). Therefore, bioclimatic evaluation should always be included in planning by the producer. In this analysis it is essential to compare the climate conditions of the area with the requirements of the animals. In bioclimatic assessments, indices of thermal comfort/discomfort are used; the BGTI is a good example, however, it requires BGT data. The absence of black globe thermometers in weather stations makes bioclimatic evaluation difficult in the various regions (Dimiceli et al., 2012).

Therefore, in the present study, equations for estimating the BGT were first obtained by means of meteorological data for different time scales (daytime, night-time, daily and monthly). The BGT showed a correlation with all the possible variables, with the exception of wind speed. This variable affects the injection or removal of heat to/from the environment, but its contribution was low when compared to the other variables (global solar radiation, temperature and relative humidity). The correlation between the BGT and SR fit a logarithmic equation, while the other equations were linear (Table 1). The positive signs of the angular coefficient of the equations (“a”) show that an increase in one variable increases the values of the BGT. Only the correlation between BGT and RH generated a negative “a” coefficient. A similar result was noted by Hajizadeh et al. (2017).

For all time scales, the most important variable was air temperature (AT), as noted by Lemke and Kjellstrom (2012) and Hajizadeh et al. (2017); however, these authors also found correlation of the BGT with solar radiation and wind speed. In the present study, global solar radiation (SR) gained importance on the daytime scale. When  $SR > 0$ , two equations can be used to estimate the BGT, a simple linear equation

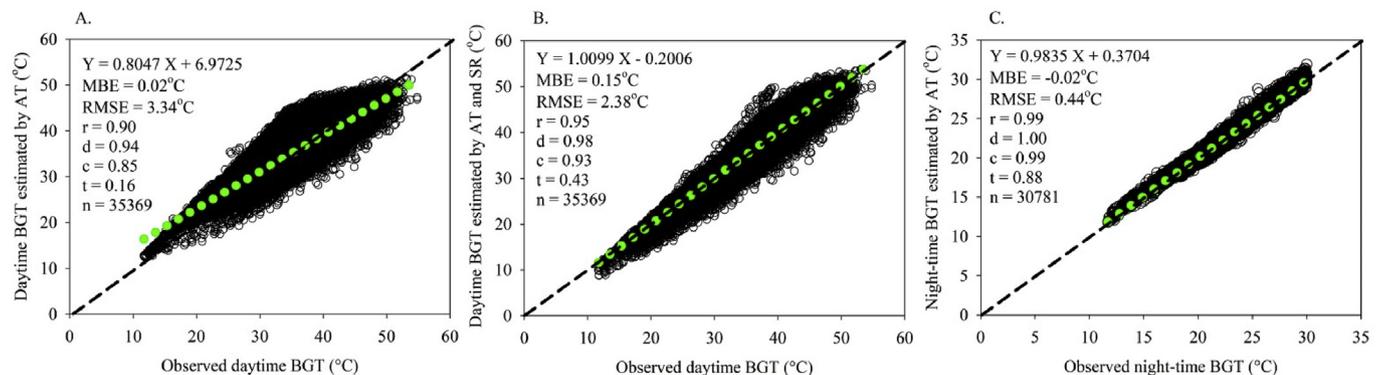


Fig. 3. Evaluation of the performance of the equation for estimating the daytime black globe temperature (BGT) (A) based only on air temperature (AT), (B) of the multiplicative model combining daytime air temperature and incident global solar radiation (SR), and (C) of the equation for estimating the night-time black globe temperature based on the night-time temperature.

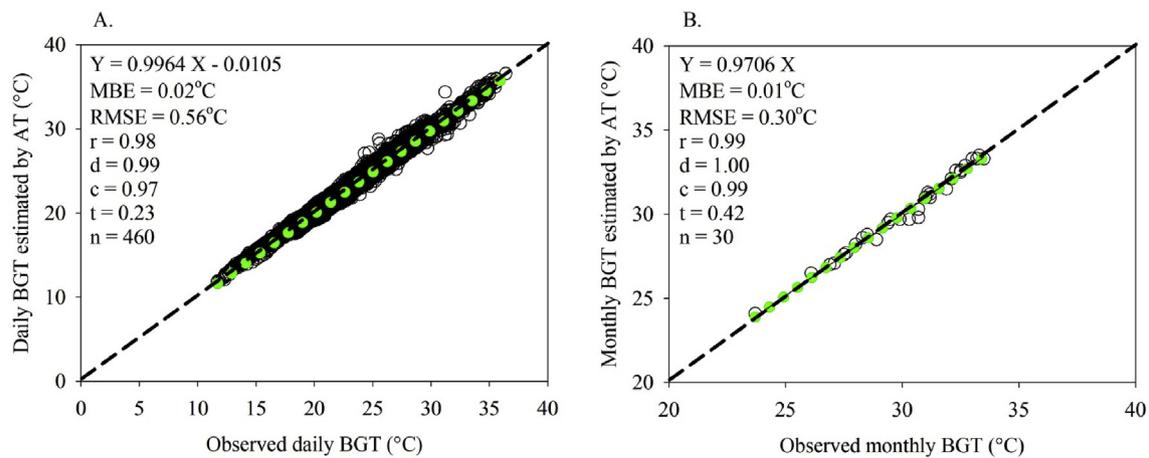


Fig. 4. Evaluation of the performance of the equation for estimating the black globe temperature (BGT) (A) daily and (B) monthly based on mean air temperature (AT).

based on AT only ( $BGT = 1.3897 AT - 5.4421$ ,  $r^2 = 0.80$ , Table 1) and the other resulting from the product of two equations, generating the multiplicative model, which combines the effect of AT and SR (Eq. (9)). This result shows that, depending on applicability, estimating the BGT from AT alone may be acceptable. However, for better estimates on a daytime scale, the multiplicative model is a good choice. These results corroborate those presented by Turco et al. (2008), who combined the effects of AT and SR on the BGT in a multiplicative model ( $BGT = [1360 AT - 2.358] (0.075 \ln(SR) + 0.562)$ ), and found that these variables explained 87.7% of the variability in the BGT. Hajizadeh et al. (2017) propose a multiple linear equation as a function of three variables ( $BGT = 0.01498 SR + 1.184 AT - 0.0789 RH - 2.739$ ). The good BGT estimate from the meteorological data is of extreme importance for improving zootechnical planning and decision-making (Silva et al., 2008; da Silva et al., 2010).

For the night-time scale, AT explained 99% of the variation in BGT, so it should be the only variable used to estimate the BGT ( $BGT = 0.995 AT - 0.6964$ ,  $r^2 = 0.99$ , Table 1), it not being necessary to generate a multiplicative model to include a new variable. After the regression analysis, AT was also the variable that most explained the fluctuation in BGT data on the daily scale ( $BGT = 1.1641 AT - 1.5941$ ,  $r^2 = 0.97$ , Table 1). Good results for this time scale were also quoted by Abreu et al. (2011), when relating the BGT and AT measured inside and outside poultry sheds. From the result obtained here, it was found that the daily AT explained 97% of the variability in the BGT, so it was not necessary to generate a multiplicative model to include another variable. The same procedure was adopted for the monthly scale, since AT was again the variable that explained most of the variability in the BGT (98%) ( $BGT = 1.1550 AT - 1.3498$ ).

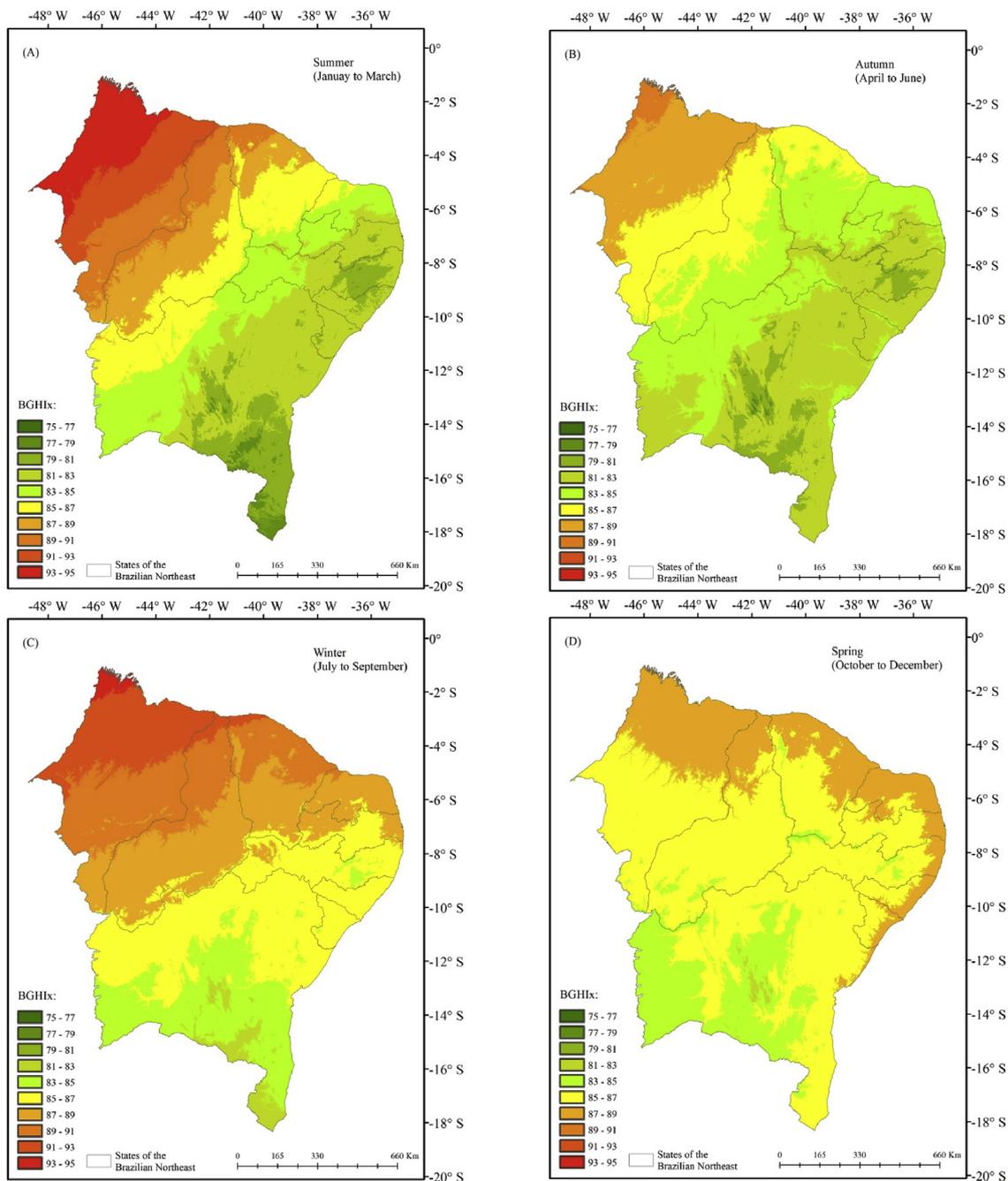
Though the data have been collected from a single meteorological station, the equations for estimating the BGT can be applied to other regions with different climate conditions. This application is possible because of the wide values range collected in this study (Table 1) and linear and constant response characteristic of BGT replicated by the models based AT and SR (Fig. 3B) or only AT (Fig. 4A and B), which allows the trend extrapolation. Other works showed this linear and constant response of BGT to different meteorological variables, especially air temperature (Lemke and Kjellstrom, 2012; Hajizadeh et al., 2017).

#### 4.2. Bioclimatic evaluation of the Brazilian Northeast for Saanen dairy goats

Bioclimatic evaluation allows the species most adapted to a specific climate condition to be identified and, therefore, the most promising livestock activity to be recommended (Turco et al., 2006; Silva et al.,

2008; Mendes et al., 2014). However, for a good result it is important to use indicators that unify the effects of the climate factors (Wang et al., 2018), since these are directly related to the physiological and behavioural responses of the animals (Neves et al., 2009; McManus et al., 2016). Because of the diversity of data cited in the literature on the condition of thermal comfort/discomfort of the Saanen breed, in the present study, a critical value for BGTI was defined, to be used in the bioclimatic evaluation of various regions for breeding the animals. Combining the values for maximum temperature and relative humidity cited by Baêta and Souza (2010), Pequeno et al. (2017) and Silva (2000) resulted in a critical limit for the BGTI of 85. Above this value, the reduction in milk production by these goats is considered quite pronounced, so that good animal performance is impaired; modifying the zootechnical structure and adjusting the management can significantly affect production costs. A BGTI of 85 is within the mean range of values normally found during the afternoon (82.50 in the shade and 91.30 in full sun, a mean of 86.90) in the Brazilian semi-arid region, according to studies carried out to evaluate the adaptation of Saanen goats in this region [Roberto et al. (2010): 87 in the shade and 94 in full sun; Silva et al. (2010): 82 in the shade and 94 in full sun; Silva et al. (2011): 81 in the shade and 91 in full sun; and Silva et al. (2014): 80 in the shade and 87 in full sun].

In the northeast of Brazil, Bahia offers the best thermal environment for breeding Saanen dairy goats, with the west and centre-south of the state being most important. Although the largest herd of goats (with different breeds and aptitudes, dairy and meat) is located in the north of the state, where there are higher values for air temperature and lower values for relative humidity, favourable conditions can be seen during the first six months of the year, i.e. during the summer and autumn. During the other months (winter and spring), the BGTI is slightly higher (from 85 to 87) than the critical limit. This same seasonality in the thermal condition of the environment was found for Alagoas, Sergipe, Pernambuco and a large part of the states of Rio Grande do Norte, Ceará and Piauí, where the lowest heat stress is found during the summer and autumn. The rainy period in the region is included in these two seasons, which continues until July along the coastal areas. The high amount of cloud reduces the incidence of solar radiation, lowering the temperature, which combined with higher values for relative humidity (~75%) promotes thermal comfort. During the second half of the year, part of winter and the whole of spring, the low cloud cover, high incidence of radiation and smaller rainfall events increase the BGTI, making the environment uncomfortable for the animals. The state of Maranhão has the worst thermal conditions for raising Saanen dairy animals. During 2017, the state had the lowest production of goat milk among the states of the Brazilian Northeast (IBGE, 2017) (Fig. 1B). For breeding dairy cows, Turco et al. (2006) cite appropriate conditions for the state of



**Fig. 5.** Bioclimatic evaluation of the Brazilian Northeast for breeding Saanen dairy goats. (A) BGHI<sub>x</sub> for spring (October to December); (B) BGHI<sub>x</sub> for summer (January to March); (C) BGHI<sub>x</sub> for autumn (April to June); and, (D) BGHI<sub>x</sub> for winter (July to September). Critical BGHI<sub>x</sub> for the race equal to 85.

Bahia during the coldest months only (June to August). [Silva et al. \(2008\)](#) report that during the hottest months (December to February), 81% of the territory of Pernambuco has conditions that are stressful to dairy cattle. Whereas, [Mendes et al. \(2014\)](#), in a bioclimatic study for breeding Dorper sheep in the state, found that throughout the year, the area of Agreste has the best climate conditions compared to the coastal, forest and semi-arid regions.

Under conditions of heat stress, the level of production and the quality of the animals' milk decrease ([Zobel et al., 2015](#); [Ramón et al., 2016](#)). According to [Das et al. \(2016\)](#), the sensitivity of the dairy animal increases as its production level rises because of increased metabolic heat. In exotic breeds, the loss of yield is more intense, since the genes of these animals are less able to adapt to hot climates. The high temperature negatively affects the hypothalamus, and food intake is

therefore reduced ([Hill and Wall, 2017](#); [Sejian et al., 2018](#)); in addition, the high temperatures influence reproduction, due to changes in cellular function and in various organs of the reproductive system ([Das et al., 2016](#); [Pantoja et al., 2017](#)). [Sejian et al. \(2018\)](#) recommend four groups of strategies to combat heat stress in livestock: management of the facilities; nutritional, genetic and reproductive changes; and animal health and management.

In the face of moderate stress conditions (BGTI from 85 to 87), altering the environment by such practices as a more regular and balanced water and food supply, and adopting simple artificial or natural shade, can reduce the inappropriate effects of heat ([Ben Salem and Smith, 2008](#); [Sejian et al., 2018](#)). Good nutritional management allows the animals to remain in homeostasis or prevents nutritional deficiencies caused by heat stress ([Das et al., 2016](#)). In turn, [Pezzopane](#)

et al. (2019) report that, when properly arranged, shading in a silvopastoral system decreases the radiant heat load on the animal by 22%. However, under more severe and persistent heat stress (BGTI in the range of 87–95), more intense practices for physically changing the environment should be adopted, for example, the installation of air conditioning systems (i.e. an evaporative cooling system with water in the form of droplets, mist or spray, natural or forced air movement and cooling tanks) (Das et al., 2016). The use of a choice of floor-coverings also improves the thermal quality of the facility, quickly changing the microclimate and animal behaviour, encouraging the animal to experience different environmental conditions over time (Sutherland et al., 2017). By crossing more-productive exotic species with native species, it is also possible to obtain races that are less sensitive to heat stress (Ben Salem and Smith, 2008; Das et al., 2016; Sejian et al., 2018).

## 5. Conclusions

The proposal of equations for estimating the black globe temperature (BGT) on different time scales (daytime, night-time, daily and monthly) was advanced in this study for application in meteorological databases and the identification of suitable climate zones in the Northeast of Brazil for breeding Saanen dairy goats. On a daytime scale, the BGT can be calculated from a simple linear equation and air temperature (AT) data, but for even better results, combining the AT data with solar radiation (SR) data by means of a multiplicative model is even more recommended. To calculate the BGT on night-time, daily and monthly scales, it is enough to apply AT data, again with simple linear equations. In the bioclimatic evaluation of the Brazilian Northeast for breeding Saanen dairy goats, a critical limit of 85 was established for the black globe temperature index (BGTI). In general, the west and centre-south of the state of Bahia offer the animals the most thermal comfort during each season of the year. Alagoas, Paraíba, Pernambuco, Piauí, Rio Grande do Norte and Sergipe have suitable thermal conditions during the summer and autumn. In the state of Maranhão heat stress occurs throughout the year, with the BGTI predominately in the range of 85–95. As such, strategies to combat heat stress should be encouraged to reduce the negative effects of climate on milk production in Saanen goats, and favour the production chain in the northeast of Brazil.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jtherbio.2019.102408>.

## References

Abreu, P.G. de, Abreu, V.M.N., Franciscon, L., et al., 2011. Estimativa da temperatura de globo negro a partir da temperatura do bulbo seco. *Eng. na Agric* 19, 557–563.

Alvares, C.A., Staple, J.L., Sentelhas, P.C., de Moraes Gonçalves, J.L., 2013. Modeling monthly mean air temperature for Brazil. *Theor. Appl. Climatol.* 113, 407–427. <https://doi.org/10.1007/s00704-012-0796-6>.

Alvares, C.A., Staple, J.L., Sentelhas, P.C., Gonçalves, J.L. de M., 2014. Köppen's climate classification map for Brazil. *Meteorol. Z.* 22, 711–728. <https://doi.org/10.1127/0941-2948/2013/0507>.

Arnal, M., Robert-Granié, C., Larroque, H., 2018. Diversity of dairy goat lactation curves in France. *J. Dairy Sci.* 101, 11040–11051. <https://doi.org/10.3168/jds.2018-14980>.

Baêta, F.C., Souza, C.F., 2010. *Ambiência Em Edificações Rurais - Conforto Animal*, 2.ed. UFV, Viçosa, MG.

Ben Salem, H., Smith, T., 2008. Feeding strategies to increase small ruminant production in dry environments. *Small Rumin. Res.* 77, 174–194. <https://doi.org/10.1016/j.smallrumres.2008.03.008>.

Buffington, D.E., Collazo-Arocho, A., Canton, G.H., et al., 1981. Black globe humidity index (BGHI) as comfort equation for dairy cows. *Trans. ASAE (Am. Soc. Agric. Eng.)* 24, 711–714. <https://doi.org/10.13031/2013.34325>.

Camargo, A.P., Sentelhas, P.C., 1997. Avaliação do desempenho de diferentes métodos de estimativas da evapotranspiração potencial no Estado de São Paulo, Brasil. *Rev. Bras. Agrometeorol.* 5, 89–97. <https://doi.org/10.1590/S1415-43662007000600006>.

Curtis, A.K., Scharf, B., Eichen, P.A., Spiers, D.E., 2017. Relationships between ambient conditions, thermal status, and feed intake of cattle during summer heat stress with access to shade. *J. Therm. Biol.* 63, 104–111. <https://doi.org/10.1016/j.jtherbio.2016.11.015>.

da Silva, T.G.F., de Moura, M.S.B., Sá, I.L.S., et al., 2010. Cenários de mudanças climáticas e seus impactos na produção leiteira em estados nordestinos. *Rev. Bras. Eng. Agrícola Ambient.* 14, 863–870.

Das, R., Sailo, L., Verma, N., et al., 2016. Impact of heat stress on health and performance of dairy animals: a review. *Vet. World* 9, 260–268. <https://doi.org/10.14202/vetworld.2016.260-268>.

Dimiceli, V.E., Piltz, S.F., Amburn, S.A., 2012. Black globe temperature estimate for the WBGT index. *AIP Conf. Proc.* 170, 323–334. [https://doi.org/10.1007/978-94-007-4786-9\\_26](https://doi.org/10.1007/978-94-007-4786-9_26).

Hajizadeh, R., Farhang Dehghan, S., Golbabaee, F., et al., 2017. Offering a model for estimating black globe temperature according to meteorological measurements. *Meteorol. Appl.* 24, 303–307. <https://doi.org/10.1002/met.1631>.

Hill, D.L., Wall, E., 2017. Weather influences feed intake and feed efficiency in a temperate climate. *J. Dairy Sci.* 100, 2240–2257. <https://doi.org/10.3168/jds.2016-11047>.

IBGE, 2017. Produção e Venda de leite de cabra no ano. In: Censo Agropecuário, . <https://sidra.ibge.gov.br/tabela/963>, Accessed date: 19 November 2017.

Irano, N., Bignardi, A.B., Rey, F.S.B., et al., 2012. Parâmetros genéticos para a produção de leite em caprinos das raças Saanen e Alpina. *Rev. Cienc. Agron.* 43, 376–381.

Lemke, B., Kjellstrom, T., 2012. Calculating workplace WBGT from meteorological data: a tool for climate change assessment. *Ind. Health* 50, 267–278. <https://doi.org/10.2486/indhealth.ms1352>.

Lôbo, R.N.B., Silva, F.L.R., 2005. Parâmetros genéticos para características de interesse econômico em cabras das raças Saanen e Anglo-nubiana. *Rev. Cienc. Agron.* 36, 104–110.

McManus, C., Dallago, B.S.L., Lehugeur, C., et al., 2016. Patterns of heat tolerance in different sheep breeds in Brazil. *Small Rumin. Res.* 144, 290–299. <https://doi.org/10.1016/j.smallrumres.2016.10.004>.

Medeiros, S.D.S., Cecilio, R.A., Júnior, J.C.F.D.M., et al., 2005. Estimativa e espacialização da temperatura máxima na Região Nordeste do Brasil. *Rev. Bras. Eng. Agrícola Ambient.* 9, 247–255.

Mendes, A.M. de P., Azevedo, M. de, Lopes, P.M.O., Moura, G.B. de A., 2014. Zoneamento bioclimático para a raça ovina Dorper no Estado de Pernambuco. *Pesqui. Agropecu. Bras.* 49, 986–993. <https://doi.org/10.1590/S0100-204X2014001200009>.

Miranda E., E., 2019. In: Miranda E.E. (Ed.), *Embrapa Monitoramento por Satélite*, 2005, Campinas. <http://www.relevobr.cnpem.embrapa.br>, Accessed date: 15 January 2019.

Neves, M.L.M.W., De Azevedo, M., Da Costa, L.A.B., et al., 2009. Níveis críticos do Índice de Conforto Térmico para ovinos da raça Santa Inês criados a pasto no agreste do Estado de Pernambuco. *Acta Sci. Anim. Sci.* 31, 167–175. <https://doi.org/10.4025/actascianimsci.v31i2.3766>.

Pantoja, M.H. de A., Esteves, S.N., Jacinto, M.A.C., et al., 2017. Thermoregulation of male sheep of indigenous or exotic breeds in a tropical environment. *J. Therm. Biol.* 69, 302–310. <https://doi.org/10.1016/j.jtherbio.2017.09.002>.

Pequeno, I.D., Turco, S.H.N., da Silva, T.G.F., Facó, O., 2017. Dairy production of 'saanen' goats based on meteorological variables and future climate scenarios. *J. Braz. Assoc. Agric.* 37, 226–235. <https://doi.org/10.1590/1809-4430-Eng.Agric.v37n2p226-235/2017>.

Pereira, A.R., Angelocci, L.R., Sentelhas, P.C., 2002. *Agrometeorologia: Fundamentos e Aplicações Práticas*. Agropecuária, Guaiabá.

Pezzopane, J.R.M., Nicodemo, M.L.F., Bosi, C., et al., 2019. Animal thermal comfort indexes in silvopastoral systems with different tree arrangements. *J. Therm. Biol.* 79, 103–111. <https://doi.org/10.1016/j.jtherbio.2018.12.015>.

QGIS Development Team, 2009. QGIS Geographic Information System. Open Source Geospatial Foundation Project. <http://qgis.osgeo.org>.

Ramón, M., Díaz, C., Pérez-Guzman, M.D., Carabaño, M.J., 2016. Effect of exposure to adverse climatic conditions on production in Manchega dairy sheep. *J. Dairy Sci.* 99, 5764–5779. <https://doi.org/10.3168/jds.2016-10909>.

Ribeiro, N.L., Costa, R.G., Pimenta Filho, E.C., et al., 2016. Adaptive profile of Garfagnina goat breed assessed through physiological, haematological, biochemical and hormonal parameters. *Small Rumin. Res.* 144, 236–241. <https://doi.org/10.1016/j.smallrumres.2016.10.001>.

Roberto, J.V.B., Souza, B.B., Silva, A.L.N., et al., 2010. Parâmetros hematológicos de caprinos de corte submetidos a diferentes níveis de suplementação no semi-árido paraibano. *Rev. Caatinga* 23, 127–132.

Sejian, V., Bhatta, R., Gaughan, J.B., et al., 2018. Review: adaptation of animals to heat stress. *Animal* 12, S431–S444. <https://doi.org/10.1017/S1751731118001945>.

Silva, R.G., 2000. *Introdução à bioclimatologia animal*. Nobel, São Paulo.

Silva, TGF da, Zolnier, S., Moura, M.S.B., Sedyama, G.C., 2007. Estimativa e espacialização da umidade relativa do ar para os estados de Alagoas, Bahia e Sergipe. *Rev. Bras. Agrometeorol.* 15, 1–9.

Silva, TGF da, Turco, S.H.N., Zolnier, S., et al., 2008. Variação regional do declínio na produção de leite durante o verão no estado de pernambuco. *Eng. na Agric* 16, 109–123.

Silva, EMN da, Souza, B.B. de, Sousa, O.B. de, et al., 2010. Avaliação da adaptabilidade de caprinos ao semiárido através de parâmetros fisiológicos e estruturas do tegumento.

- Rev Caatinga 23, 142–148.
- Silva, C.M.B.D.A., Souza, B.B. de, Brandão, P.D.A., et al., 2011. Efeito das condições climáticas do semiárido sobre o comportamento fisiológico de caprinos mestiços F1 Saanen x Boer. *Rev Caatinga* 24, 195–199.
- Silva, E.M.N., Souza, B.B., Silva, G.A., et al., 2014. Avaliação da Adaptabilidade de Caprinos Leiteiros no Semiárido Brasileiro com Auxílio da Termografia Infravermelha. *J. Anim. Behav. Biometeorol.* 2, 95–101. <https://doi.org/10.14269/2318-1265/jabb.v2n3p95-101>.
- Sutherland, M.A., Lowe, G.L., Watson, T.J., et al., 2017. Dairy goats prefer to use different flooring types to perform different behaviours. *Appl. Anim. Behav. Sci.* 197, 24–31. <https://doi.org/10.1016/j.applanim.2017.09.004>.
- SYSTAT SOFTWARE Inc, 2019. Sigmaplot for windows, version 14. Available at: <https://systatsoftware.com/>.
- Turco, S.H.N., SILVA, T.G., SANTOS, L.F.D.O.S., et al., 2006. Zoneamento bioclimático para vacas leiteiras no estado da Bahia. *Eng. Agrícola* 26, 20–27. <https://doi.org/10.1007/s13398-014-0173-7.2>.
- Turco, S.H.N., Silva, T.G.F. da, Oliveira, G.M. de, et al., 2008. Estimating black globe temperature based on meteorological data. In: *Livestock Environments, Proceedings of the Eighth ASABE International Livestock Environment Symposium*. St. Joseph, MI, USA. ASABE, Foz do Iguaçu, Brasil, pp. 783–788.
- Wang, X., Bjerg, B.S., Choi, C.Y., et al., 2018. A review and quantitative assessment of cattle-related thermal indices. *J. Therm. Biol.* 77, 24–37. <https://doi.org/10.1016/j.jtherbio.2018.08.005>.
- Willmott, C.J., 1981. On the validation of models. *Phys. Geogr.* 2 (2), 184–194. <https://doi.org/10.1080/02723646.1981.10642213>.
- Willmott, C.J., 1982. Some comments on the evaluation of model performance. *Bull. Am. Meteorol. Soc.* 63, 1309–1313. [https://doi.org/10.1175/1520-0477\(1982\)063<1309:SCOTEO>2.0.CO;2](https://doi.org/10.1175/1520-0477(1982)063<1309:SCOTEO>2.0.CO;2).
- Zambom, M.A., Alcalde, C.R., Martins, E.N., et al., 2013. Produção, composição do leite e variação do custo e da receita de produção de leite de cabras Saanen recebendo rações com casca de soja em substituição ao milho1. *Semin. Agrar.* 34, 1313–1326. <https://doi.org/10.5433/1679-0359.2013v34n3p1313>.
- Zobel, G., Weary, D.M., Leslie, K.E., von Keyserlingk, M.A.G., 2015. Invited review: cessation of lactation: effects on animal welfare. *J. Dairy Sci.* 98, 8263–8277. <https://doi.org/10.3168/jds.2015-9617>.