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Spatial distribution of thermal variables, acoustics and lighting in compost dairy barn with climate control system

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Abstract. The main objective of this research was to evaluate the spatial distribution of the thermal variables, acoustics and lighting in climate controlled compost dairy barn. The experiment was conducted in October 2017, in a farm located in the west of Minas Gerais state, Brazil. For the study, the interior of the animal facility was divided into 120 meshes equidistant points, in which air temperature (t_{db}), relative humidity (RH), noise, illuminance, and air speed (V_{air}) were manually collected. The technique of geostatistics was used to evaluate the distribution and spatial dependence of variables. Spatial distribution maps showed the occurrence of high variability of attributes and content within the animal facility. Thermal environment variables showed alert situations throughout practically the entire facility. The noise and luminance levels were within the recommended values.

Key words: animal welfare, dairy cattle, geostatistics.

INTRODUCTION

In Brazil, extensive systems of milk production predominated for a long time, and it is still feasible for the producers to raise the animals in the fields (Bond et al., 2012). However, due to the introduction of animals genetically developed for temperate climate conditions to increase the productivity of the herds, problems related to the animal comfort are increased mainly due to the tropical climate of the country with the occurrence of elevated temperatures throughout the most of the year (Faria et al., 2008).

Confinement of animals emerged as a way to improve productivity, through the control of environmental conditions, associated with a good management of genetics, nutrition, reproduction and sanity. Intensive production systems, in which animals remain housed in functional facilities, have been used as a way to provide a comfortable environment, reducing stress and, consequently, increasing the welfare and productive capacity of the animal (Perissinotto et al., 2009).

The compost dairy barn (Compost Bedded Pack, CBP) consists of a large, open resting area. It is usually bedded with sawdust or dry fine wood shavings that are composted in place, along with manure, and mechanically stirred on a regular basis

(Barberg et al., 2007; Shane et al., 2010; Black et al., 2013). Virginia dairy farmers developed the CBP barn concept to improve cow comfort, increase cow longevity, reduce initial barn costs (Barberg et al., 2007), and potentially reduce the mastitis risks associated with the conventional deep bedding.

In the CBP, the ventilation system is responsible for the maintenance of a comfortable environment for the animals, for the removal of gases and heat, and for the drying of bedding material (Janni et al., 2007; Lobeck et al., 2011).

In CBP barns, different natural and mechanical ventilation systems can be used. In the case of mechanical ventilation, the main types of fans used are low volume and high speed (LVHS) and high volume and low speed (HVLS) (Leso et al., 2018). For farms with inadequate climatic conditions, where only fan use is not sufficient to ensure a comfortable environment for the animals, climate control systems are used (Nääs & Arcaro Júnior, 2001). In this case, the design and adaptation to the hot climate condition can allow the maintenance of the ideal temperature and air velocity, but relative humidity, ammonia and carbon dioxide concentration have to be well managed.

In the climate controlled systems, the monitoring and evaluation of the environment of the animal facilities can be useful to aid decision-making regarding adjustments and corrections of the systems (Sales et al., 2011). Among the models used for the evaluation of spatial variability, the geostatistical methods allow the understanding of the randomness of the data and the establishment of a spatial dependence function, making possible the interpretation of the results based on their spatial variability (Yamamoto & Landim, 2015).

The main objective of this research was to evaluate the spatial distribution of the thermal variables, acoustics, and lighting in compost dairy barn with a climate control system.

MATERIALS AND METHODS

Characterization of the animal facility

The study was carried out during the month of October, 2017, at a farm located in the West of Minas Gerais state, Brazil (latitude 20° 47' 30" S, longitude 45° 18' 52" W, and altitude 921 m), According to classification of Köppen, the climate is Cwa - humid temperate, with dry winter and hot, subtropical summer, and hottest month temperature above 22 °C (Sá Júnior et al., 2012).

The data were collected in a climate controlled compost dairy barn (CBP), equipped with a ventilation system in air-conditioned tunnel mode (negative pressure). This system had 22 exhaust fans (Equipaves®, model 53", diameter of 1.42 m, six propellers and power of 1.0 CV) installed in the southwestern face of the installation, and evaporative cooling of porous material type moistened through porous plate of pulp with dimensions 18.0 x 3.0 m, installed in the northeast face of the CBP barn. The system remained switched on whenever the temperature was above 21 °C, and its monitoring and actuation was performed by means of two sensors that were located inside the installation.

The CBP barn had a width of 23.0 m and a length of 180.0 m, eave height of 4.0 m, roof pitch of 15°, and cover in metallic tiles (thickness of 0.50 mm). The orientation of barn was northeast-southwest (Fig. 1). The floor of the feed alley was covered in concrete. The lateral closure was done by means of plastic curtains of blue colour with

3.5 m of height. Throughout the barn, baffle curtains were installed, starting at 2.5 m in height, spaced every 12 m and used to direct the air towards the bedding. The lighting of the CBP barn was realized by means of 90 tubular fluorescent lamps with power of 36 W, installed equally spaced. The surrounding vegetation was composed of *Eucalyptus* trees.

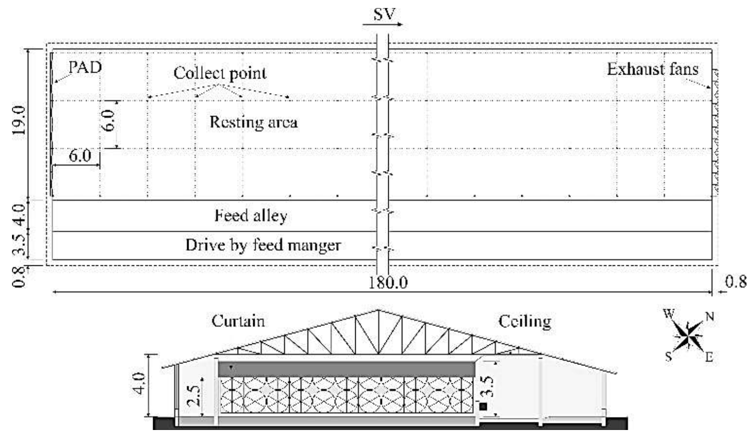

Figure 1. Schematic representation of the CBP barn with collection points and cross section.
* SV – sense of ventilation; PAD – evaporative cooling plate. Dimensions in meters (m).

Inside of CBP barn 325 Holstein cows (305 lactating and 20 pre-calving) were housed. The lactating cows were distributed in 5 groups divided according to the order of production of the animals. Larger animals were housed in lots 1 and 2, located near the evaporative cooling plate (PAD). The milk production per cow was 28 kg day^{-1}.

The CBP barn had a total area of 4,770 m^2, where 3,420 m^2 were resting area (wood sawdust with depth of 0.4 m). The stirring was performed twice a day at milking times (7:00 a.m. and 2:00 p.m.) by means of a rototiller with cultivator, coupled to a small tractor.

Data collection

The resting area of the CBP barn was divided into a rectangular grid containing 120 equidistant points (6 x 6 m), arranged according to the constructive characteristics of the barn (Fig. 1, a). The data collection was performed between 12:00 to 16:00 h.

The environmental variables were collected near the geometric centres of the animals (1.5 m height). A portable digital thermo-higro-decibel-lux meter was used to collect air temperature (t_{bs}), relative humidity (RH) and noise level (Instrutherm®, model THDL-400, with accuracy of ± 3.5%). The air velocity was measured by means of a hot wire anemometer (Instrutherm®, model TAFR-190, with accuracy of ± 0.1 m s^{-1}).

For the evaluation of the thermal comfort inside the CBP, the Temperature and Humidity Index (THI) was used, according to the model proposed by Buffington et al. (1983):

$$THI = 0.8 \cdot t_{bs} + RH \cdot \left(\frac{t_{bs} - 14.3}{100} \right) + 46.3 \qquad (1)$$

where t_{bs} is dry-bulb air temperature (°C); *RH* is the relative humidity (%).

For dairy cattle, the limits of THI that characterize a situation of comfort or discomfort are not fully agreed among the scientific community. In general, the limits proposed by Thom (1959) and Hubbard et al. (1999) for dairy cattle are: THI < 74 - thermal comfort condition; $74 \leq$ THI < 79 - an alert condition for producers; $79 \leq$ THI < 84 - a hazard condition, and safety measures must be taken to prevent disastrous losses, especially for confined herds; and, THI > 84 - emergency situation, and urgent steps must be taken to avoid loss of staff. However, THI values above 72 represent a stress condition for Holstein cows, which may lead to reduced productivity (Johnson, 1980).

Geostatistics analysis

In order to verify the spatial behaviour of the variables within the CBP barn, as well as to predict their levels in non-sampled locations and the occurrence of spatial dependence, the geostatistical technique was used. The analyses were performed using the R (Development Core Team, 2016) software, through the geoR library (Ribeiro Junior & Diggle, 2001). The evaluation of the spatial dependence of the variables inside the CBP facilities was made through semivariogram adjustments. For the estimation of the semivariogram we used the estimator of Matheron (1962):

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \left[Z(X_i) - Z(X_i + h)\right]^2 \tag{2}$$

where $N(h)$ corresponds to the number of experimental pairs of observations $Z(X_i)$and $Z(X_i + h)$, separated by a distance h.

The coefficients of the theoretical model for semivariogram, called nugget effect - C_0, plateau - $C_0 + C_1$, and reach - a, were obtained from a mathematical model for the calculated values of Bachmaier & Backers (2008).

The degree of spatial dependence (GDE) was determined by the ratio between the nugget effect (C_0) and the threshold ($C_0 + C_1$), multiplying by 100. Dependency analysis was performed using Cambardella et al. (1994). According to this classification, a strong spatial dependence is considered for the semivariograms that have nugget effect of less than 25% of the plateau, a moderate spatial dependence for the semivariograms that have a nugget effect between 25% and 75% of the plateau and a weak spatial dependence for the semivariograms that present nugget effect greater than 75% of the plateau.

Due to the small grouping of data, the Restricted Maximum Likelihood Estimation (REML) method was used, as suggested by Marchant & Lark (2007). The model tested for the adjustment of the experimental semivariogram was the Spherical, a model widely used in geostatistics and that returns good results.

In order to make maps of the spatial distribution of the levels of variables within the CBP barn, the ordinary data kriging technique was used. From the interpolated data, response surface maps were generated, using the ArqGIS® software, version 10.1.

The descriptive statistics were used to determine the fraction of area occupied by the intervals of each of the analysed variables and to better characterize the spatial distribution of the variables inside the climate controlled CBP barn.

RESULTS AND DISCUSSION

The estimated models and parameters of experimental semivariograms adjusted for the variables and THI, acoustic and lighting environment within the evaluated facility are reported in Table 1. The experimental semivariograms were adjusted by the spherical model. According to Isaaks & Srivastana (1989), from a value of the distance between points, there is no more spatial dependence and the variance of the difference between pairs of samples becomes invariant.

Table 1. Estimated models and parameters of experimental semivariograms adjusted for the variables and THI, acoustic and lighting environment within the evaluated facility

Variable	Method	Model	C_0	C_1	C_0+C_1	*a*	GDE	Classification
t_{bs}	REML	Spherical	0.08	1.62	1.69	96.90	4.45	Strong
RH	REML	Spherical	9.91	38.78	48.69	104.71	20.35	Strong
THI	REML	Spherical	0.31	1.88	2.19	100.16	13.96	Strong
V_{air}	REML	Spherical	0.15	0.28	0.43	22.45	34.85	Moderate
Noise	REML	Spherical	6.09	26.02	32.11	112.27	18.96	Strong
Illuminance	REML	Spherical	46.08	29.54	75.62	21.61	60.94	Moderate

*C_0 – nugget effect; C_1 – contribution; C_0 + C_1 – threshold; a – reach; GDE – degree of spatial dependence; t_{bs} – dry-bulb air temperature; RH – air relative humidity; THI – temperature-humidity index; and V_{air} – air velocity.

According to Ferraz et al. (2017a), the nugget effect (C_0) is an important parameter of the semivariogram, since it indicates the unexplained variability. The importance of this parameter is related to the discontinuity check of the semivariograms for distances less than the shortest distance between the collection points, being this discontinuity caused by errors during collection and analysis, local variations, among others, and it is not possible to perform the quantification of each of these components.

The individual quantification of the nugget effect was performed according to the classification suggested by Cambardella et al. (1994). For the variables that compose the thermal environment (t_{bs}, RH, THI and V_{air}), the highest value of C_0 was verified for RH, which presented a value equal to 9.91. However, when the contribution of this one at the level was analysed, it was verified that it was less than 25%, being classified as a strong spatial dependence, in the same way as for t_{bs} and THI. The same condition was not verified for the V_{air} attribute, which, despite having a low C_0 value, was higher than 25% of the plateau, indicating the occurrence of moderate spatial dependence.

The noise variable presented initial variability at 6.06, but its contribution at the level was less than 25%, characterizing a strong spatial dependence. The same condition was not observed for the illuminance, which presented quite high C_0 and with contribution higher than 25% of the plateau, classifying its dependence as moderate.

The determination of the spatial dependence limit was performed from the scope assessment (*a*), which indicates how far a variable is influenced by space. These values, related to semivariograms, are of considerable importance in determining the limit of spatial dependence (Ferraz et al., 2017b).

Samples separated by smaller distances are correlated with one another, allowing interpolations to be performed for smaller spacing than sampling. In this case, if *a* is less than the smallest sample spacing, the semivariogram is constant and equal to any value, the absence of spatial dependence, and the spatial distribution is completely random, and the geostatistical methods must not be applied (Vieira, 2000).

For all attributes evaluated, the value of *a* was higher than the smaller distance between sampling points, allowing the application of geostatistics techniques in a satisfactory way. The lowest range values *a* were verified for the variables illuminance (21.61 m) and air velocity (22.45 m), which still presented values above the shortest distance between samplings (6.0 m).

All variables evaluated in this study presented different spatial dependence ranges, from lower values, such as 21.61 m, to quite high values, such as 104.71 m. From this information, it can be inferred that it is possible to use larger distances between sampling points. This distance is variable according to the attribute of interest. It is also worth noting that for variables with values *a* closely related to each other, such as t_{bs}, RH and THI, it is possible to use the same sampling mesh.

The results obtained infer that the variables and indexes evaluated did not have a random distribution in the space, since they presented strong or moderate spatial dependence and the superior one to the smaller distance between points sampled, indicating that it is appropriate to apply the geostatistical technique. The occurrence of spatial dependence allows to perform data interpolation using the ordinary kriging technique and to make spatial distribution maps. These maps give important information (Fig. 2), such as the location and magnitude of the areas with the highest and lowest levels of the variables and index evaluated, allowing the precise management of the required interventions (Ferraz et al., 2017b).

The t_{bs} varied throughout the CBP barn (Fig. 2, a), presenting values between 23 and 29 °C. The greatest variation was observed in the region between the evaporative cooling plate (PAD) and the central part of the barn, where there was initially a decrease of t_{bs}, followed by its increase. In general, t_{bs} tends to have lower levels in the area close to the PAD, due to the system for climate control. However, the predominance of remarkably high t_{bs} values was observed, due to the bad side seal related to the presence of a gate located in the entrance of the feed alley, which was damaged, remaining partially open. The infiltration of air (sealing faults) through the sides and parts damaged in this gate, as well as its opening, cause leaks of cooled air and the entrance of outside warm air. This can be the reason for the increase of t_{bs} in this region. Except for this particular condition present near the PAD of the CBP barn, an increase of t_{bs} with the distance of the cooling device was observed, with emphasis on the occurrence of higher levels and greater uniformity in the region near the exhaust fans.

According to Nääs (1989), the air temperature range characterized as a thermal comfort situation for lactating cows is between 4.0 and 24.0 °C and may be restricted to the limits of 7.0 to 21.0 °C, depending on RH and solar radiation. According to Huber (1990), the zone of thermoneutrality for lactating Holstein cows is between 4.0 and 26.0 °C.

Considering the temperature range recommended by Huber (1990), it is verified that t_{bs} inside the CBP barn was above the upper critical temperature limit indicated for lactating Holstein cows, with the most critical conditions in areas close to PAD and the entrance of the feed alley.

A high spatial variability of RH inside the climate controlled CBP barn was observed (Fig. 2, b), with an amplitude of variation equal to 35%. Areas with the highest RH were observed near the PAD, where the levels were predominantly greater than 65%.

It is also worth noting the occurrence of regions with higher RH in the feeding alley. A trend towards lower RH values (> 60% RH) along the entire north-west face of the facility was observed, due to faults in the lateral closure provided by the plastic curtains, as well as the presence of the openings of the gates for access to the lots, necessary for the management of the animals.

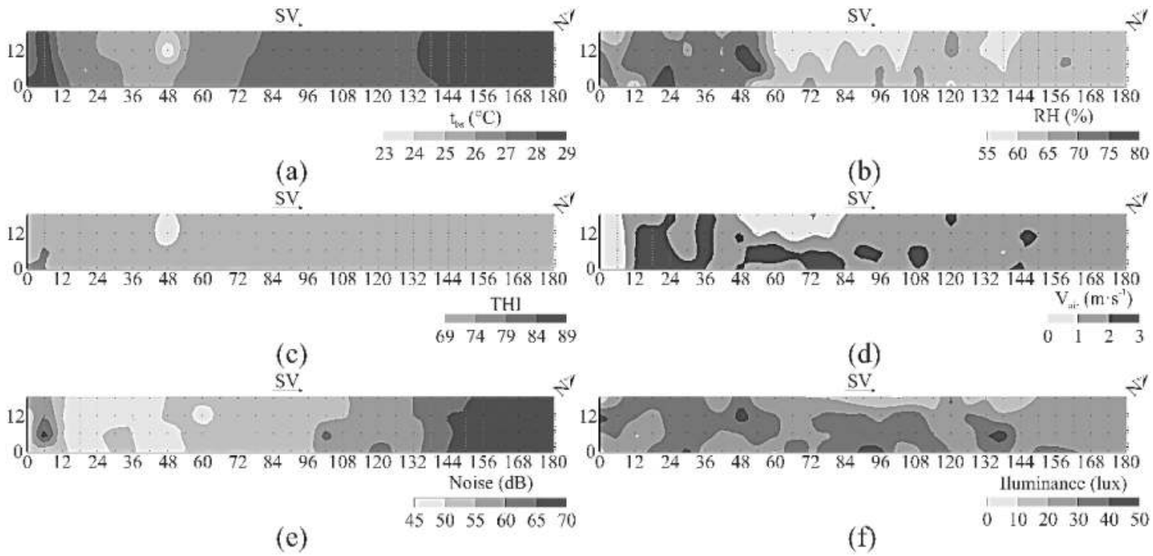

Figure 2. Spatial distribution of the variables: (a) dry bulb air temperature (t_{bs}); (b) relative humidity (RH); (c) Temperature and Humidity Index (THI); (d) air velocity (V_{air}); (e) noise levels and (f) illuminance.

According to Nääs & Arcaro Jr. (2001), the RH value of 70% is considered as the upper limit for cooling an environment for animals through the use of water. Above this value, the heat exchanges between the animals and the environment are impaired, and the animals may suffer from heat stress. Notably in the region close to the PAD, values of RH were close to or even above this limit, indicating that, despite the climate control system, the animals could be exposed to heat stress, not being able to exchange heat with the environment in the form of latent heat.

The THI presented uniform distribution throughout the CBP barn, with the predominance of the condition characterized as alert to the producer (Fig. 2, c). In a small region close to the PAD and the feed alley, the occurrence of a condition characterized as a hazard was observed, due to the combination of the high t_{bs} and RH values verified for this region. The results show that the THI inside the facility is above the required values for lactating Holstein cows, which should be less than 72 (Johnson, 1980).

The air velocity (V_{air}) presented considerable spatial variability inside the CBP barn, with values ranging from 1.0 to 3.0 m s^{-1}, and lower values (< 1.0 m s^{-1}) observed at the locations farthest from the exhaust fans and near the sides of the CBP barn (Fig. 2, d). Since the exhaust fans are the direct source of elevation of the V_{air} within the CBP barn, it is expected that the highest levels of such an attribute can be observed close to the face on which such equipment is installed. The results indicated that the regions with the highest values of V_{air} did not occur in the area near the exhaust fans, but in areas located between the central part of the facility and the PAD, notably near the feed alley

(Fig. 2, d). It can be inferred that its occurrence is due to the formation of preferred paths for the air currents inside the facility, as well as the occurrence of infiltrations of air through the side curtains. The difficult explanation of spatial distribution for this attribute is due to its high spatial and temporal variability, since it can change of magnitude and direction abruptly (Faria et al., 2008).

The noise levels presented considerable spatial variability within the CBP barn (Fig. 2, e), with values ranging from 45 to 70 dB. The results evidenced the increase of the noise levels as it approached the exhaust fans, the highest values being observed in the area immediately next to the face where they were located, allowing to infer that their occurrence is due to the characteristic noise caused by the rotation of the exhaust fans. A small area with higher noise near the PAD (> dB) was also observed, due to the noise caused by the passage of air through the PAD and other external sources.

The results of intensity of illumination showed the occurrence of variation of distribution inside CBP barn, which presented amplitude of variation equal to 50 lux (Fig. 2, f). The illuminance was greater than 20 lux throughout the CBP barn, being less than that value only in the region of the northwest face of the facility. Since the lamps were uniformly arranged inside the facility, a uniform spatial distribution of the illuminance was expected. However, the presence of air deflecting curtains throughout the installation in some cases may act as obstacles to the passage of light and cause lower levels in some places. Also the faults in the lateral closing system, allowing the entrance of solar rays and elevation of the intensity of illumination, can be responsible of the irregular light distribution in the barn.

The spatial distribution maps do not provide detailed numerical information about the area occupied by each class of attributes or indexes. Frequency distribution graphs were generated in order to allow the best characterization of the CBP barn. Fig. 3 shows the frequency distribution graphs of the all variable evaluated in this study.

The t_{bs} was higher than the recommended upper critical limit for lactating cows (26 °C) in 85.6% of the resting area, characterizing a condition of thermal discomfort by heat (Fig. 3, a).

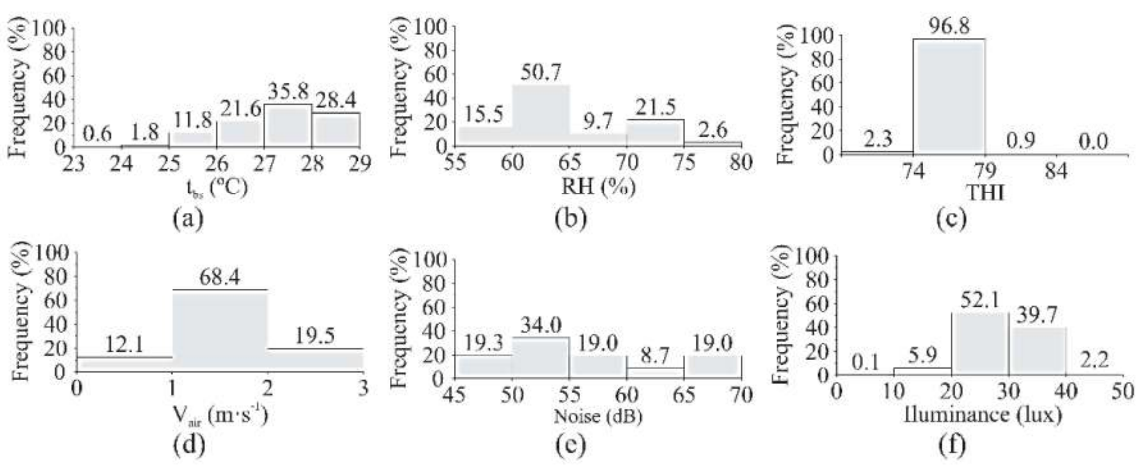

Figure 3. Frequency distribution of the variables: (a) dry bulb air temperature (t_{bs}); (b) relative humidity (RH); (c) Temperature-Humidity Index (THI); (d) air velocity (V_{air}); (e) noise levels; (f) illuminance.

The RH was higher than the recommended upper limit for cooling cows with water (70% RH) in 24.1% of the area, making the dissipation of heat in a latent form difficult. In this area the animals were exposed to heat stress conditions (Fig. 3, b).

According to Fig. 3, c, only 2.2% of the total resting area of the facility presented thermal conditions of adequate comfort ($THI < 74$); in 96.8%, the environmental attributes indicated the occurrence of alert condition ($74 \leq THI < 79$) and in 0.9% a hazard condition ($79 \leq THI < 84$). The results show that despite the use of the climate control system, in almost the whole area of the barn the environmental conditions were not adequate to the thermal needs of the animals. These results showed that the performance of the animals may be affected by the heat stress and, therefore, measures must be taken to make the environment adequate to the physiological needs of the animals, in order to avoid losses that can go from production drops to death of animals.

The results corroborate with those described by Faria et al. (2008), which, studying the spatial variability of the microclimate in a free-stall with forced ventilation associated with a nebulization system, found values of t_{bs}, RH and THI above the ideal condition comfort.

The V_{air} was between 1.0 and 2.0 m s^{-1} in 68.4% of the resting area, being higher than 2.0 m s^{-1} in 19.5% (Fig. 3d). In general, maintenance of V_{air} at levels of 1.8 m s^{-1} should be ensured in order to allow drying of the bed, removal of gases and favouring the temperature changes between the animal and the environment (Black et al., 2013). Thus, the exhaust fans system used was satisfactory in promoting the increase of the V_{air}, since it guaranteed its maintenance at levels higher than 1.0 m s^{-1} in 87.9% of the resting area.

Fig. 3, e shows that the frequency distribution of noise levels was approximately uniform, given the occurrence of values close to 20% for most classes. It should be noted that in 72.3% of the CBP barn area, noise levels were between 40 and 60 dB, indicating a condition of tranquillity, according to the scale proposed by Bistafa (2006).

The illuminance levels was between 20 and 40 lux, which occupied 91.8% of the CBP barn area, while only 6.0% of the area was below 20 lux (Fig. 3, f).

According to Dahl & Petitclerc (2003), dairy production can be increased by using a daily period of 16 to 18 hours with intensity of 200 lux, regardless of the adopted production system. Considering the value proposed by the authors, the results presented in Fig. 3, f show that the light intensity inside the installation was lower than the recommendations. According to the recommendation of minimum intensity suggested by Harmon & Peterson (2011) and the University of Wisconsin-Madison's Guide to Good Agricultural Practices for Energy Efficiency in Agriculture (Wisconsin Focus on Energy, 2016) for livestock facilities of 20 to 30lux, in general the luminous intensity delivered is in compliance with the recommended minimum values for housed lactating cows.

CONCLUSIONS

The spatial dependence of the variables of the thermal, acoustic and lighting environment was verified by means of the geostatistics technique, with strong spatial dependence predominating.

The spatial distribution maps showed the occurrence of high variability of attributes and indexes within a compost dairy barn (CBP) provided with a climate control system.

The thermal variables, air temperature and relative humidity presented high spatial variability, but their combination returned values of temperature and humidity index (THI) characterized as alert situation throughout practically the entire facility. Also the levels of noise and illuminance had considerable variability, presenting values between 45 and 70 dB, and 10 and 50 lux, respectively.

The geostatistics technique was able to assist the decision making regarding the definition of the pattern of air flow based on exhaust fans for air exchange and air cooling in the CBP barn.

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