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Photovoltaic panels as shading resources for livestock

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Based on our search, we believe that this is the first paper to evaluate the use of photovoltaic panels as shade resources for livestock. Photovoltaic panels can provide artificial shades to protect livestock against intense solar radiation while serving as a clean energy source, reducing CO_2 emission, and providing an additional source of income to farmers. These benefits foster sustainable livestock farming practices. In this study, we (1) determined livestock shade preference for photovoltaic panels and the classical 80%-blockage cloth material, and (2) quantified the reduction in radiant heat load provided by these shade structures. To determine the shade preference, the behavior of five Corriedale lambs and six Corriedale ewes were observed in a paddock with two shade structures (one with photovoltaic panels and another with an 80%-blockage cloth). The following behavioral activities were determined using the instantaneous scan sampling method each 10-min from 07:00 h to 17:00 h: grazing, ruminating, idling, lying, standing, under the sun, under the shade from photovoltaic panels, and under the shade from cloth. To correlate animal behavior with environmental conditions and to quantify the reduction in radiant heat load provided by these shade structures, the following meteorological variables were recorded: solar radiation (total and short-wave), air temperature, relative humidity, wind speed, and black-globe temperature (in the shades and in the sun). We observed that the animals spent less than 1% of their time under the shade from cloth compared to 38% under the shade from photovoltaic panels and 61% exposed to the sun. Sheep preference for shade projected by photovoltaic panels might be explained by the reduced radiant heat load (approximately lower by 40 W m^{-2}) compared to that from the cloth. When the intensity of solar radiation increased from 250 to 850 W m^{-2}, the time the animals spent outside the shades decreased from 96.7 ± 3.6% to 30.2 ± 6.3%, which was coupled with a similar increase in the time spent in the shade from photovoltaic panels (from 13.0 ± 3.3% to 69.3 ± 6.2%). For the same increase in solar radiation, the energy generated (integrated over 5-min) by the photovoltaic panels increased from 38.8 ± 5.9 to 197.9 ± 3.8 kWh. Over a period of one year, an electric energy of 5.19 MWh (monthly average of 432.33 kWh) was generated and 2.77 tons of CO_2 were not emitted to the atmosphere. In economic terms, the electric energy generated in one year was equivalent to a saving of $740.

1. Introduction

The expected increase in the population of the world to 9.7 billion in 2050 (Umer et al., 2019) and the simultaneous increase in wealth, which drives up the per-capita consumption of animal products (Alexandratos and Bruinsma, 2012; Popp et al., 2010), call for a dramatic increase in food production (25%–70% by 2050; Hunter et al., 2017). This food production increase must be followed by sustainable farming practices that improve animal comfort and welfare (Milan et al., 2018). One sustainable livestock farming practice that can improve comfort and welfare of livestock managed in open pasture or feedlots is to provide shades using photovoltaic panels.

Consumers are increasingly concerned about livestock comfort

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and welfare. Research showed that 69% of consumers believe that animal welfare is important and is perceived to result in safer, healthier, and higher quality food products (Grimshaw et al., 2014; Verbeke et al., 2010). To encourage animal comfort and welfare practices by companies and farmers, the Humane Farm Animal Care organization (certificating more than 160 companies and 5500 farms in the USA, Canada, Chile, Peru, and Brazil) developed the Certified Humane Raised & Handled Certification (HFAC). Among the requirements for this certification (HFAC, 2012, 2013, 2014a,b) is access to shade areas that can accommodate all animals simultaneously. Similarly, the Animal Welfare Committee of Australia with the Primary Industries Standing Committee (PISC) recommends the provision of shades for livestock exposed to heat stressful conditions (PISC, 2004).

One of the major issues for comfort and welfare of livestock managed in open pasture or feedlots is the intense heat load from solar radiation. In tropical regions, solar radiation may exceed 800 W m^{-2} (Maia et al., 2015; Da Silva et al., 2015), negatively impacting animal comfort, welfare, and production (e.g., weight gain or milk yield; Domingos et al., 2013; Tucker et al., 2015). For instance, in the USA, heat stress on livestock is responsible for an estimated $3 billion annual loss (Ferreira et al., 2016; Polsky and von Keyserlingk, 2017). To cope with heat stress, animals use physiological and behavioral responses. Physiological responses include panting and sweating (Domingos et al., 2013; Maia et al., 2015). Behavioral responses include standing up to increase the surface area for convective heat loss (Gebremedhin et al., 2011) and shade-seeking (Oliveira et al., 2014, 2019).

The benefits of shade have been widely studied for beef cattle (Averós et al., 2014; Brown-Brandl et al., 2017), and for dairy cows (Kamal et al., 2018; Oliveira et al., 2019) but little is known about shade preference by sheep (Cloete et al., 2000). For example, lactating Holstein cows in Brazil can spend approximately 80% of their time under shade from 100%-blockage cloth structures (Oliveira et al., 2019). Similar results were reported for Holstein cows in the USA (Schütz et al., 2009; Tucker et al., 2008) and for lactating Holstein-Friesian cows in Australia (Gaughan et al., 1998). In addition, Gebremedhin et al. (2011) reported a direct correlation (R^2 ~0.90) between the solar absorbing capacity of hair coat and percent of time heifers (Black Angus, white Charolais, tan-colored MARC I, and dark-red colored MARC III) spent in shade.

While high levels of solar radiation compromise animal comfort and welfare, clean and renewable electrical energy can be generated through photovoltaic cells (Hinrich et al., 2015), and reduce CO_2 emission from power generation plants. In addition, photovoltaic panels could be used to provide artificial shade for humans (Middel et al., 2016) or animals. Using photovoltaic panels to provide artificial shade for animals can lead to a “co-generation” of electrical energy and agricultural products. The possibility of such integrated systems has elicited the interest of policy makers and governmental agencies, such as the Brazilian Governmental Company for Research on Energy (EPE; responsible for future planning of energy consumption, demand, and generation). The EPE recently manifested an expectation in the innovation of “sustainable co-generation systems,” combining power generation plants (e.g., photovoltaic panels) and agricultural systems (EPE, 2018).

Sustainable co-generation systems using photovoltaic panels are suitable in several parts of the world (Hinrich et al., 2015). For instance, the American Solar Grazing Association (recently created) encourages scientists to quantify the benefits of integrating grazing livestock and solar farms, which can reduce land competition for renewable energy and agricultural production, increase crop biomass production, grasses for livestock, and offer cooler microclimates for animals (lower air temperature and thermal radiation, Adeh et al., 2018; Sobrosa Neto et al., 2018). Recently, American farmers (Dickrell, 2018) reported behavioral and productive benefits for animals under the shade from solar panels. Another strong motivation for the implementation of sustainable co-generation systems using photovoltaic panels is the continuous decrease of the price of photovoltaic panels (from US$ 3.90 per Wp in 2006 to US$ 0.39 per Wp in 2016; 5% expected annual price drop; Ferreira et al., 2018; Pereira et al., 2017) as well as the development of new technologies expected to increase the efficiency of energy conversion (from 18% to 45% using Single-Junction GaAs, Thin-Film Crystal; IRENA, 2017).

The objective of this study is to investigate the potential of co-generation systems using photovoltaic panels to generate electrical energy and to provide shade for sheep managed in paddock. This is the first study to present scientific data on photovoltaic panels as shading resources for livestock.

2. Material and methods

2.1. Animals and experimental design

Animal use and research protocol (Proc. 006062/19) was approved by the Institutional Animal Care and Use Committee of São Paulo State University. This experiment was conducted in the Animal Biometeorology Laboratory of the São Paulo State University (Latitude 21°15′ S Longitude 48°19’ W). Five Corriedale lambs (36.46 ± 1.17 kg body weight (BW), mean ± standard deviation (SD)) and six Corriedale ewes (64.62 ± 5.46 kg BW, mean ± SD) were monitored in April 2018, for five days (08:00 h to 17:00 h). The animals were kept in a paddock (area ±650 m^2), fed *Cinodon* grass, and water was provided *ad libitum*. Two types of shade structures were used in the study. The first one (Fig. 1; lower height: 3.0 m; inclination angle: 15°; width: 4.0 m; length: 5.0 m; area: 20 m^2; projected shade area: 19.3 m^2; share area per animal: 1.76 m^2 $animal^{-1}$) consisted of ten photovoltaic panels (1.0 m × 2.0 m; 335 Wp, peak efficiency of 16.72%, Canadian Solar model CS6U−335P, Guelph, ON; installed by Blue Sol, Blue Sol Energia Solar, Ribeirão Preto, SP). The second shade structure (height: 1.6 m; width: 3.05 m; length: 5.1 m; area: 15.56 m^2; projected shade area: 15.56 m^2; share area per animal: 1.3 m^2 $animal^{-1}$) consisted of shade cloth (80% of solar radiation blockage). Between 17:00 h and 08:00 h, animals were housed in a barn and fed a concentrated diet (corn meal, soybean meal, and mineral mixture).

2.2. Behavioral observations

Animal behavior was monitored by direct observation using the instantaneous scan sampling method at 10-min intervals (Martin and Bateson, 2007) from 08:00 h to 17:00 h by two observers. The inter-observer agreement was above 90% (Fonsêca et al., 2014). Animals were identified using black painted numbers on their left and right rumps. Animal behavior was recorded as L.P.A., where, L represents location (S: under the sun; P: under the shade from photovoltaic panels; C: under the shade from cloths), P represents posture (L: lying; S: standing), and A represents activity (G: grazing; R: ruminating; I: idling) (Fig. 2). Grazing was defined when the head of the sheep was pointing towards the ground and the sheep was searching for or ingesting grass; ruminating was defined as chewing movements without feed in the mouth, feed regurgitation, or both (Schütz et al., 2014); otherwise, idling was recorded. Lying was defined when the flank of the sheep was in direct contact with the ground; otherwise, standing was recorded. Under a shade was recorded when at least the head or one of the hooves of the sheep were within the shade projected by the artificial structure; otherwise, sun was recorded.

Fig. 1. Photo showing sheep under the shade from photovoltaic panels.

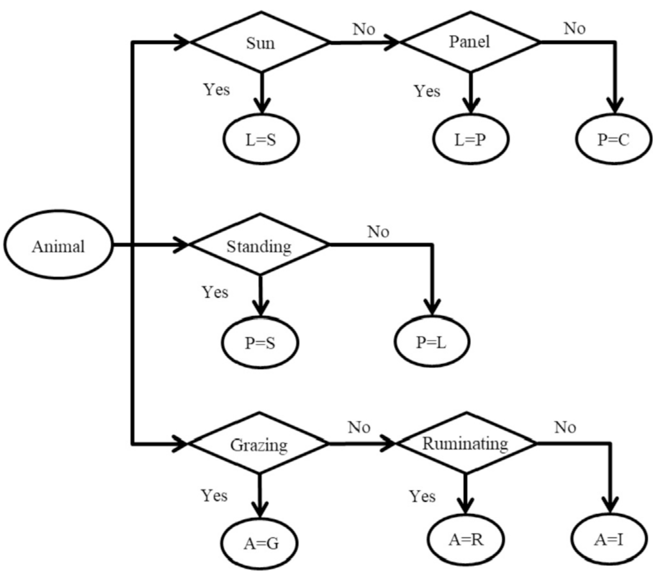

Fig. 2. Flowchart of animal behavior recording.

2.3. Meteorological data

Meteorological data were recorded every minute using a portable weather station (WS-18 model 110, Nova Lynk, Auburn, CA, USA) placed within ~1 m of the paddock. The recorded meteorological data were solar irradiance (R_S, W m^{-2}; CMP-22, Kipp and Zonen, Delft, Netherlands; spectral range = 0.3–3.6 μm), ultraviolet solar irradiance (U_V, W m^{-2}; spectral range = 0.28–0.4 μm), air temperature (T_A, °C; accuracy ± 0.1 °C), black-globe temperature (T_G, °C; accuracy ± 0.1 °C), relative humidity (R_H, %; accuracy ± 3%), and wind speed (W_S, m s^{-1}; accuracy ± 0.44, m s^{-1}). To avoid animal interference with the recording instruments, after the behavioral experiment, T_G under the shades projected by the structures, underneath and outside the structure, were recorded every minute for six days from 07:00 h to 17:00 h (Hobo Data Logger, Onset Computer Corporation, Bourne, MA; accuracy ± 0.1 °C). The thermal comfort provided by the shading structures was estimated using the Radiant Heat Load (RHL, W m^{-2}; DaSilva and Maia, 2013).

2.4. Electricity generation and CO_2 savings estimation

Electricity generated by the photovoltaic panels for the period between April/2018 and March/2019 was recorded every 5 min by the frequency inverter (Fronius 3kWp). The amount of CO_2 not emitted to the atmosphere because of electricity generated by the photovoltaic panels was calculated using the 2018 daily Brazilian CO_2 emission factor for electric energy generation (hydroelectric, wind, photovoltaic, and thermal; MCTIC, 2018).

2.5. Statistical analyses

The experimental data were analyzed using generalized least squares with the general linear model procedure (PROC GLM) of the Statistical Analysis System (SAS Institute, 1999), according to Littell et al. (2006). The behavioral classes used in the statistical analysis were SSG, SSI, PSR, PLR, PSI and PLI (represented >98% of the observations). The generalized linear model used to describe the behavioral observations (expressed in percentage, with a logarithmic transformation) is expressed as

$$Y_{ijkLm} = \mu + C_i + A_j(C_i) + D_k + D_kA_j(C_i) + R_L + (CR)_{iL} + e_{ijkLm} \quad (1)$$

where, Y_{ijkLm} is the mth observation of the behavioral activity; C_i is the fixed effect of the ith age group (i = lambs or ewes); $A_j(C_i)$ is the random effect of the jth animal within the ith age group (if i = lambs, then j = 1,…,5; if i = ewes, then j = 6,…,11); D_k is the random effect of the kth day of observation (k = 1,…,5); $D_kA_j(C_i)$ is the interaction between the random effect of the kth day of observation within the random effect of the jth animal within the ith age group; R_L = fixed effect of the L^{th} class of solar radiation (<200; $200 \leq R_S < 300$; $300 \leq R_S < 400$; $400 \leq R_S < 500$; $500 \leq R_S < 600$; $600 \leq R_S < 700$; $700 \leq R_S < 800$ and $R_S \geq 800$ W m^{-2}); e_{ijkLm} is the residual term, assumed to be independent and identically distributed (iid) over N(0, σ); μ is the overall mean; N(*a*, *b*) represents a normal distribution with mean *a* and standard deviation *b*.

The probability of the choice of shade (cloth, panel, or exposed to the sun) was analyzed using a machine learning algorithm: multinomial logistic generalized additive model (GAM; Wood et al., 2016; Wood, 2017). GAM was used to model the equations defined below:

$$h_{panel} = \alpha + f_1(R_S)_{lamb} + f_2(R_S)_{ewe} + \alpha_{lamb} + N(0, \sigma_{lamb}) + N(0, \sigma_{ewe}) \quad (2)$$

$$h_{sun} = \beta + f_3(R_S)_{lamb} + f_4(R_S)_{ewe} + \beta_{lamb} + N(0, \gamma_{lamb}) + N(0, \gamma_{ewe}) \quad (3)$$

$$p_{cloth} = \frac{1}{1 + \exp\left(h_{panel}\right) + \exp(h_{sun})} \quad (4)$$

$$p_{panel} = \frac{\exp\left(h_{panel}\right)}{1 + \exp\left(h_{panel}\right) + \exp(h_{sun})} \quad (5)$$

$$p_{sun} = \frac{\exp(h_{sun})}{1 + \exp\left(h_{panel}\right) + \exp(h_{sun})} \quad (6)$$

where, h_{panel} and h_{sun} represent link functions (transform probabilities of categories, bounded between 0 and 1, to unbounded values from -∞ to +∞); α and β represent intercepts (value of the function when all other variables are zero); $f_1(R_S)_{lamb}$ and $f_3(R_S)_{lamb}$ represent smooth functions (functions that do not change values drastically, i.e., low derivative values) for lambs; $f_2(R_S)_{ewe}$ and $f_4(R_S)_{ewe}$ represent smooth functions for ewes; α_{lamb} and β_{lamb} represent additive effects for lambs; σ_{lamb} and γ_{lamb} represent the standard deviation of the random effect of the lambs; σ_{ewe} and γ_{ewe} represent the standard deviation of the random effect of the ewes; p_{cloth}, p_{panel}, and p_{sun} represent the probability of animals at the shade from cloth, solar panels, or exposed to the sun, respectively. Input solar radiation in the model was averaged over a 10 min window.

The shade preference prediction (cloth, solar panel, or sun) from this model can be determined as the shade preference with the maximum predicted probability. The accuracy of the model in predicting shade preference was assessed using sensitivity, specificity, precision, and accuracy. Sensitivity was calculated as the number of shade preference correctly predicted divided by the total number of observations of the same shade preference. Specificity was calculated as the number of other shade preferences correctly predicted divided by the total number of observations of these shade preferences. Precision was calculated as the number of shade preference correctly predicted divided by the total number of predictions for the same shade preference. Accuracy was calculated as the number of correctly predicted shade preferences divided by the number of observations.

To study the relationship between power output and solar radiation, the power output by the photovoltaic panels was analyzed using the following model:

$$P = \alpha + f(R_s) + N(0, \sigma) \quad (7)$$

where, P represents the power output (W); α represents the intercept; $f(R_S)$ represents a smooth function; σ_{day} is the standard deviation of the random effect of the day; σ is the standard deviation of the residues.

The effect of the shades in the RHL was analyzed using the following model:

$$RHL = \alpha_{i,j} + f_{i,j}(\text{time}) + N(0, \sigma_d) + N(0, \sigma_{j,d}) + N(0, \sigma_{i,j,d}) + N(0, \sigma) \quad (8)$$

$$corr\ (\varepsilon_m, \varepsilon_n) = \varphi^{\ s} \quad (9)$$

where, $\alpha_{i,j}$ represents the intercept for location i (underneath or outside the structure) and structure j (panel or cloth); $f_{i,j}(time)$ represents a smooth function for location i and structure j; σ_d is the standard deviation of the random effect of the day d; $\sigma_{j,d}$ is the standard deviation of the random effect of the structure j within the day d; $\sigma_{i,j,d}$ is the standard deviation of the random effect of the location i within the structure j within the day d; σ is the standard deviation of the residues; $cor(\varepsilon_m, \varepsilon_n)$ represents the correlation between residues of the observations m and n within the location i within the structure j within the day d; s is the time interval between observations m and n (≥0); φ is the correlation coefficient (≥0). Equation (9) represents the continuous time autoregressive model of order 1 (Pinheiro and Bates, 2000). Statistical difference between the smooth functions was determined using the method from Rose et al. (2012) with the inclusion of fixed effects.

Equations (2)–(9) were modelled in R (R Core Team, 2018) using the mgcv package (Wood, 2011) and adding a penalty in the null space of the smooth functions (Marra and Wood, 2011). Statistical significance of the terms was analyzed using the chi-square test and terms not statistically significant were removed from the model. Expected values and the simultaneous 95% Bayesian credible intervals (similar to a 95% confidence intervals) were obtained through simulating 10,000 draws from the Bayesian posterior probability density of the model, as described by Simpson (2016). The expected value was obtained through averaging the draws and the 95% Bayesian credible intervals were obtained from the quantiles of the draws.

3. Results and discussion

The mean measured values for solar irradiance (R_S), ultraviolet solar irradiance (U_V), air temperature (T_A), relative humidity (R_H), and wind speed (W_S) were 501.9 ± 47.4 W m^{-2}, 23.7 ± 1.8 W m^{-2}, 28.1 ± 0.54 °C, 39.2 ± 2.9% and 0.33 ± 0.15 m s^{-1}, respectively. Fig. 3 shows that R_S and U_V have similar trends, with values above 700 W m^{-2} for R_s and 30 W m^{-2} for U_V between 10:00 h to 14:00 h, respectively. The peak values were >800 W m^{-2} for R_s and 35 W m^{-2} for U_V and occurred at around 12:00 h. R_S and U_V were generally higher in the morning than in the afternoon, likely because of the existence of larger number of clouds in the afternoon. From 11:00 h to 17:00 h, T_A was above 29 °C and R_H was below 40%. W_S was very low throughout the day (<0.5 m s^{-1}), with moderate increase of W_S to 0.7 m s^{-1} between 09:00 h and 12:00 h (convection heat loss was calculated to be approximately 10 W m^{-2}; Maia et al., 2015). High values of R_S and T_A and low values of W_S are typical in tropical areas. This environmental condition cause heat stress in livestock (de Melo Costa et al., 2018a; Maia et al., 2015) and compromise animal comfort and welfare (Kamal et al., 2018). For these environmental conditions, the Humane Farm Animal Care organization requires shades for the animals (HFAC, 2012, 2013, 2014a,b).

The results from the analyze of variance showed that the animals spent less than 1% of their time under the shade projected from cloth (independently of level of solar irradiance), 38% of their time to that from photovoltaic panels, and 61.2% of their time exposed to the sun (Fig. 4). Oliveira et al. (2019) reported that, for a similar intensity of solar radiation, Holstein cows stayed ~50% of the time in a shade from 100% blockage cloth. The intensity of solar radiance (not air temperature, which increased continually throughout the day; Figs. 3 and 5) seemed to be the major factor leading to the shade-seeking behavior of the sheep (Fig. 4; a similar observation was reported for Holstein cows; Oliveira et al., 2019). However, the guidelines by the Humane Farm Animal Care (HFAC, 2014a,b; 2012) accounted for air temperature alone ("If daytime summer temperatures are consistently above 29.4 °C, shade, fans, misting/fogging systems or other cooling equipment must be provided to animals (dairy cow and young dairy beef)"). Our observations, together with previous observations (Gebremedhin et al.,

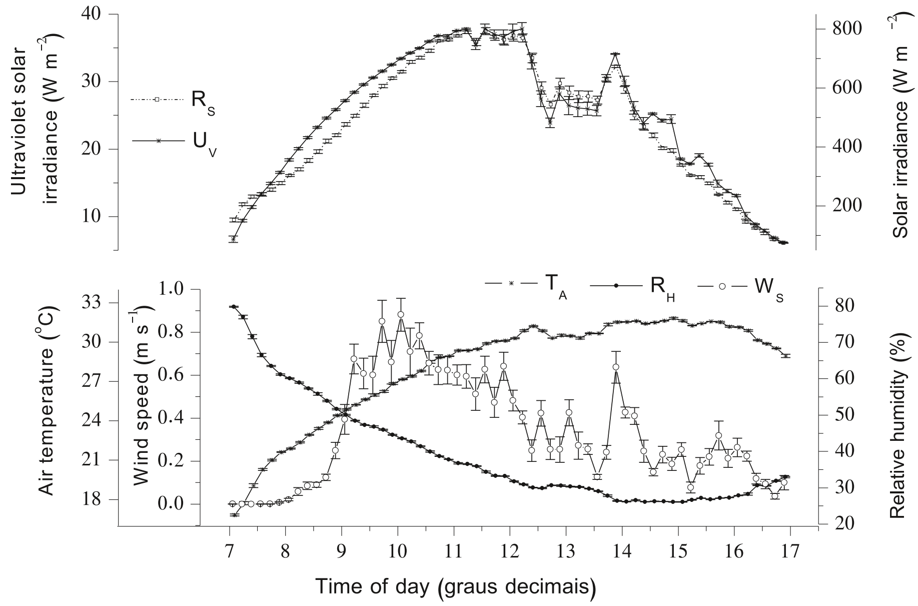

Fig. 3. Means (±SEM) of air temperature (T_A, °C), relative air humidity (R_H, %), solar radiation (R_S, W m^{-2}, spectral range = 0.3–3.6 μm), ultraviolet solar irradiance (U_V, W m^{-2}, spectral range = 0.28–0.4 μm), and wind speed (W_S, m s^{-1}).

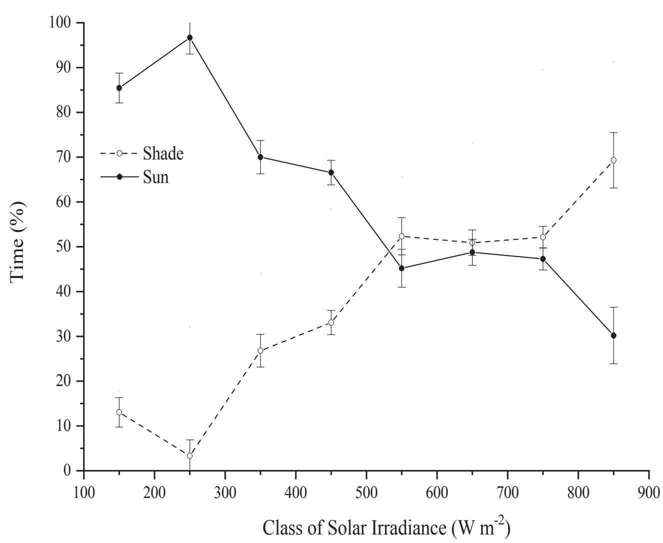

Fig. 4. Least square means (±SEM) of the time animals spent in the shade or under the sun (%) for different levels of solar radiation.

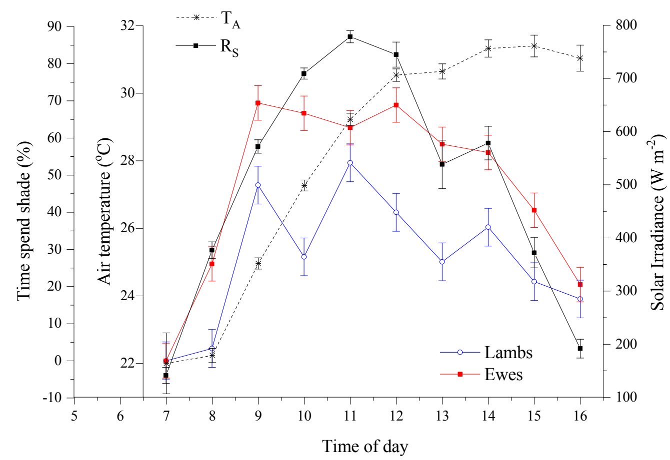

Fig. 5. Least square mean (±SEM) of air temperature (T_A, °C), solar radiation (R_S, W m^{-2}; spectral range = 0.3–3.6 μm) and time lambs and ewes spent in the photovoltaic panel shade (%) by lambs and ewe.

2011; Oliveira et al., 2019), indicate that level of solar radiance should be considered in conjunction with air temperature. Future research should consider the effects of solar radiation as a thermal environmental trigger for shade-seeking behavior (Da Silva et al., 2015; Mitchell et al., 2018) as well as other factors such as social hierarchy and interaction, phenotype adaptation, and maturity.

Sheep were thermally comfortable under the shade from photovoltaic panels because most of them were lying down, a behavior known to indicate thermal comfort (Gebremedhin et al., 2011). Sheep spent ~90% of the observed time doing the following activities: (1) exposed to the sun, standing and grazing (SSG), (2) under the shade from photovoltaic panels, lying and ruminating (PLR), and (3) under the shade from photovoltaic panels, lying and idling (PLI). SSG decreased ($p < 0.05$) from 83.61 ± 3.62% to 26.91 ± 6.29% when R_S increased from 250 to 850 W m^{-2} (Fig. 5) whereas PLR and PLI increased from 0.61 ± 2.36% to 22.5 ± 3.88% and 0.27 ± 2.94 to 40.73 ± 3.42%, respectively. PLR was not significantly different ($p > 0.05$) between lambs and ewes but ewes had higher PLI than lambs ($p < 0.05$). The time spent in the shade projected from cloth was negligible.

Lambs spent more time in the sun than ewes (Fig. 6), which can be explained by the lower grazing efficiency of lambs. Lambs have lower bite strength and compensate by grazing for longer periods of time ($p < 0.05$; Fig. 5; Vallentine, 2001). Lambs spent 69.3% of their time exposed to the sun vs. 28.7% for ewes. At high levels of R_S (between 09:00 to 14:00 h, which peaked at 800 W m^{-2}), lambs spent ~40% of their time in the shade while ewes spent ~60% (Fig. 6).

The statistical model developed to predict shade preference explained 15% of the deviance. Table 1 shows the confusion matrix, sensitivity, specificity, precision, and accuracy of the model. Except for predicting shade preference for cloth, which had a low number

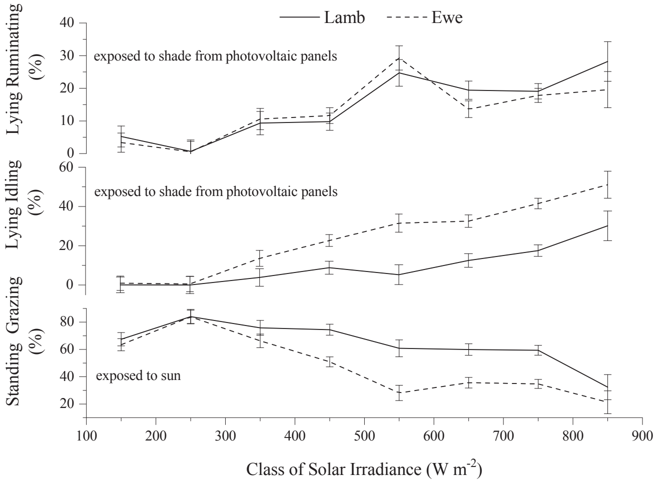

Fig. 6. Least square means (±SEM) of time of animal activities (%).

of observations, performance metrics were satisfactory. For example, shade preference predictions were ~70% accurate.

Figs. 7 and 8 show the estimated and observed probabilities, respectively, of shade preference. Both Figures show similar trends, which validates the statistical model. The preference for shade from photovoltaic panels increased with increasing solar radiation while no practical preference was observed for the shade from cloth. In addition, the lower bound of the confidence interval for the probability of preferring shade from solar panels was consistently higher than that of the upper bound of the confidence interval for the probability of preferring shade from cloth (Fig. 7). This shows that animals preferred shade from solar panels over cloth unconditionally on the intensity of the solar irradiance. The advantage of making inference using machine learning models (Fig. 7) over ranges of observed data (Fig. 8) is twofold. First, inference is based on continuous values of R_S (rather than on discrete ranges), thus allowing for precise inference over values of R_S. Second, inference includes measures of uncertainty (credible intervals), which cannot be obtained from observed data alone. This shows the advantage of using modern machine learning techniques, such as multinomial GAM models, to precisely analyze large datasets (Milan et al., 2018, 2019).

The shade preference reflected the differences in the thermal comfort provided by the shade structures (Fig. 9). The thermal comfort was assessed using the radiant heat load (RHL), which was ~40 W m^{-2} lower in the shade underneath the photovoltaic panels than in the shade underneath the cloth. Previous studies reported a similar conclusion on shade-preference of dairy cows (Schütz et al., 2009; Tucker et al., 2008).

As expected, Fig. 10a shows that when R_S increased the power output from the photovoltaic panels also increased. The GAM model for power output explains 67.2% of the deviance. The estimated efficiency of the photovoltaic panels was 17.96 ± 0.19% (mean ± SEM), close to the designed peak efficiency of 16.72%. Fig. 10b shows the electrical energy generated by the photovoltaic panels and the amount of CO_2 not emitted to the atmosphere. During one year, the artificial shading structure using photovoltaic panels generated 5.19 MWh and reduced the emission of 2.77 ton-CO_2 to the atmosphere. Assuming the price of electricity is 0.1424

Table 1
Confusion matrices and performance metrics (sensitivity, specificity, precision, and accuracy) of the statistical model developed to predict shade preference. Results shown for lambs, ewes, and both animals.

		Observed											
		Lambs				Ewes				Both			
		Cloth	Panel	Sun	Total	Cloth	Panel	Sun	Total	Cloth	Panel	Sun	Total
Predicted	Cloth	0	0	0	0	0	0	0	0	0	0	0	0
	Panel	0	56	37	93	3	616	344	963	3	672	381	1056
	Sun	2	351	1025	1378	6	220	611	840	8	571	1636	2215
Total		2	407	1062	1471	9	836	955	1800	11	1243	2017	3271
Sensitivity (%)		0	13.76	96.52	–	0	73.68	63.98	–	0	54.06	81.11	–
Specificity (%)		73.59	96.33	15.86	–	68.51	63.38	72.90	–	70.80	80.67	53.59	–
Precision (%)		0	60.22	74.38	–	0	63.97	72.74	–	0	63.64	73.86	–
Accuracy (%)		–	–	–	73.49	–	–	–	68.17	–	–	–	70.56

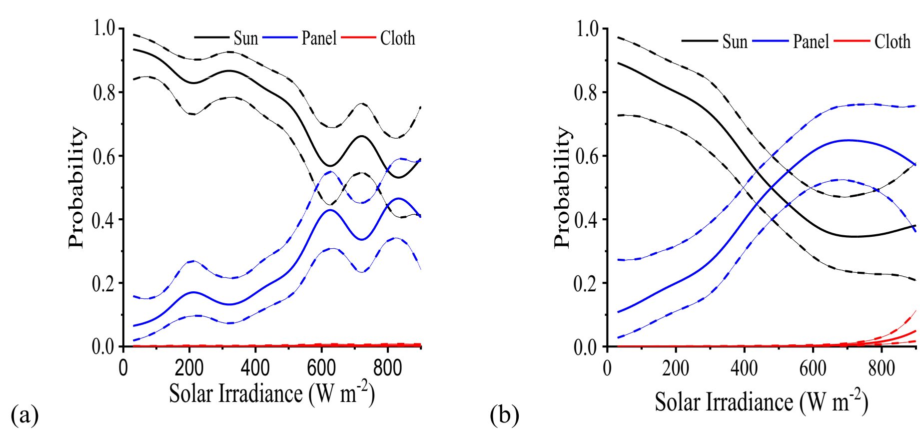

Fig. 7. Estimated probabilities for lambs (a) and ewes (b) under the shade from cloth (Cloth) or solar panels (Panel) or exposed to the sun (Sun). Continuous lines represent expected values. Broken lines represent simultaneous 95% Bayesian credible intervals.

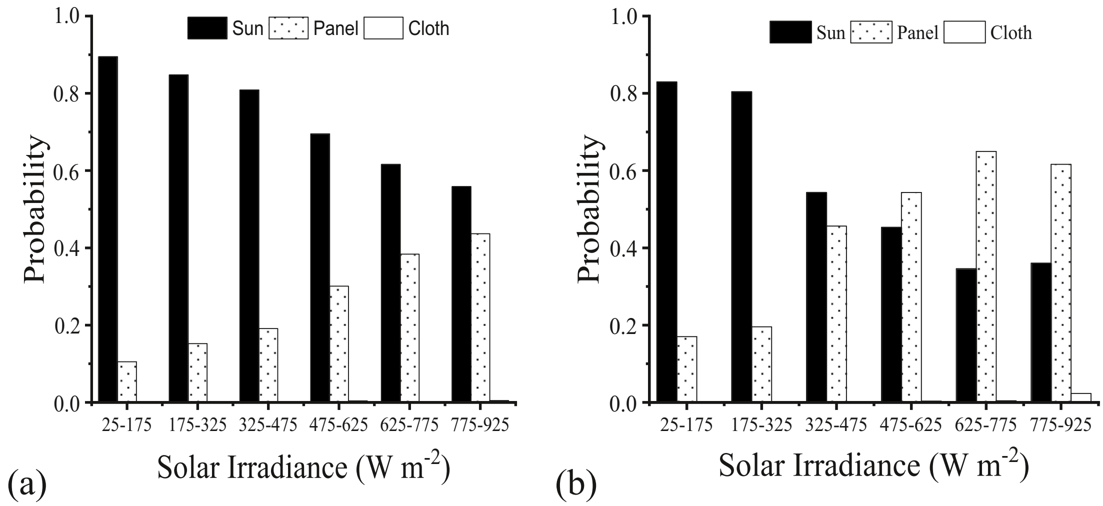

Fig. 8. Observed probabilities for lambs (a) and ewes (b) under the shade from cloth (Cloth) or solar panels (Panel) or exposed to the sun (Sun). There were used 250 observations in each range of solar irradiance in average. The ranges for solar radiation were inclusive for the lower bound and exclusive for the upper bound.

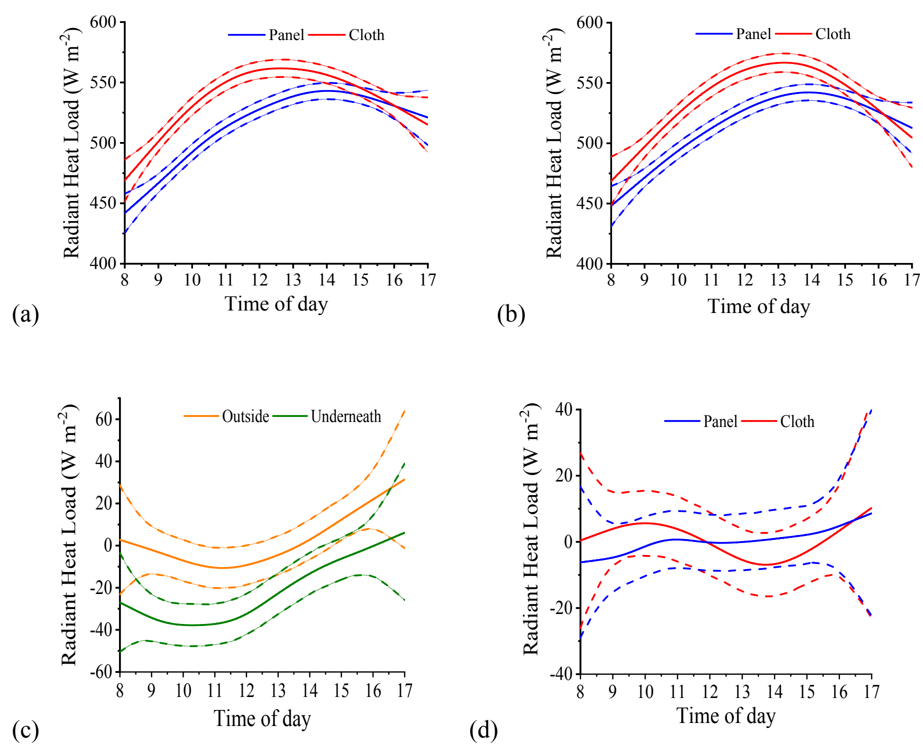

Fig. 9. Radiant heat load measured in the shade projected underneath the shade structure (a) or outside (b). Difference between radiant heat load in the shade projected by photovoltaic panels and cloth (c), and between underneath and outside (d). Broken lines represent simultaneous 95% Bayesian credible intervals.

US$/kWh, this shade structure saved US$ 740 per year. The total cost was US$ 6400.00.

Future research could also evaluate the reduction in heat-stress by photovoltaic panels based on measuring physiological data (we inferred heat-stress based on the RHL index, Fig. 9). Such data could demonstrate the correlation between heat-stress physiological responses and the shade-seeking behavior. In addition, future research could consider the combination of natural shade structures (e.g., tree canopy) and artificial shade structures from photovoltaic panels to determine the benefits for animal welfare and comfort as well as the environmental and economic aspects of both systems.

4. Conclusion

Shade under photovoltaic panels was compared to shade under cloth that has 80% blockage of solar radiation based on time spent under the shade by sheep and ewes. The animals spent more than 70% of their time under the shade from photovoltaic panels when solar radiation was wqual or greater than 800W m^{-2}. In addition to providing shade, the use of photovoltaic panels provide a viable resource for generating electrical energy and favoravle for reducing CO_2 emissions to the atmosphere. An electric power of 5.19 MWh was produced and CO_2 emission of 2.77 tons was reduced in a period of one year. In economic terms, this is equivalent to $740

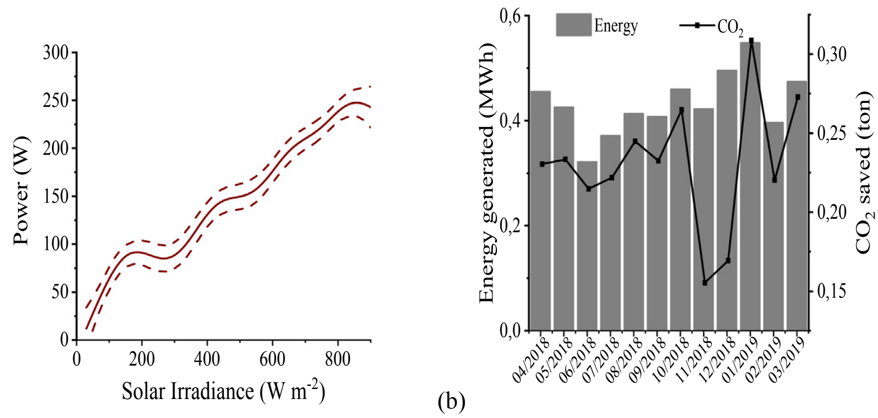

Fig. 10. Power output vs. intensity of solar radiation (a). Monthly energy generated by the photovoltaic panels (bars) and amount of CO_2 (points) not emitted to the atmosphere (b). Broken lines represent simultaneous 95% Bayesian credible intervals.

(US) saving per year. The shade provided by photovoltaic panels satisfied the requirements established by the welfare standards (e.g. HFAC).

Declaration of competing interestCOI

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Alex Sandro Campos Maia: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing - original draft, Writing - review & editing. **Eric de Andrade Culhari:** Data curation, Investigation, Methodology, Resources, Writing - original draft, Writing - review & editing. **Vinícius de França Carvalho Fonsêca:** Methodology, Writing - review & editing, Visualization. **Hugo Fernando Maia Milan:** Methodology, Software, Formal analysis, Writing - review & editing, Visualization. **Kifle G Gebremedhin:** Writing - review & editing, Visualization, Supervision.

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