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Environmental factors influencing heat stress in feedlot cattle[1,2]

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ABSTRACT: Data from 3 summer feedlot studies were utilized to determine the environmental factors that influence heat stress in cattle and also to determine wind speed (WSPD; $m\cdot s^{-1}$) and solar radiation (RAD; $W\cdot m^{-2}$) adjustments to the temperature-humidity index (THI). Visual assessments of heat stress, based on panting scores (0 = no panting to 4 = severe panting), were collected from 1400 to 1700. Mean daily WSPD, black globe temperature at 1500, and minimums for nighttime WSPD, nighttime black globe THI, and daily relative humidity were found to have the greatest influence on panting score from 1400 to 1700 ($R^2 = 0.61$). From hourly values for THI, WSPD, and RAD, panting score was determined to equal $-7.563 + (0.121 \times \text{THI}) - (0.241 \times \text{WSPD}) + (0.00082 \times \text{RAD})$ ($R^2 = 0.49$). Using the ratio of WSPD to THI and RAD to THI (−1.992 and 0.0068 for WSPD and RAD, respectively), adjustments to the THI were derived for WSPD and RAD. On the basis of these ratios and the average hourly data for 1400 to 1700, the THI, adjusted for WSPD and RAD, equals $[4.51 + \text{THI} - (1.992 \times \text{WSPD}) + (0.0068 \times \text{RAD})]$. Four separate cattle studies, comparable in size, type of cattle, and number of observations to the 3 original studies, were utilized to evaluate the accuracy of the THI equation adjusted for WSPD and RAD, and the relationship between the adjusted THI and panting score. Mean panting score derived from individual observations of black-hided cattle in these 4 studies were 1.22, 0.94, 1.32, and 2.00 vs. the predicted panting scores of 1.15, 1.17, 1.30, and 1.96, respectively. Correlations between THI and panting score in these studies ranged from r = 0.47 to 0.87. Correlations between the adjusted THI and mean panting score ranged from r = 0.64 to 0.80. These adjustments would be most appropriate to use, within a day, to predict THI during the afternoon hours using hourly data or current conditions. In addition to afternoon conditions, nighttime conditions, including minimum WSPD, minimum black globe THI, and minimum THI, were also found to influence heat stress experienced by cattle. Although knowledge of THI alone is beneficial in determining the potential for heat stress, WSPD and RAD adjustments to the THI more accurately assess animal discomfort.

Key words: bioclimatic index, cattle, environmental factor, feedlot, heat stress

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INTRODUCTION

Feedlot cattle finished in the summer months are often adversely affected by periods of hot climatic conditions (Hahn and Mader, 1997; Mader et al., 1999b). Summer conditions consisting of above normal ambient temperature, relative humidity, and solar radiation (**RAD**) coupled with low wind speed (**WSPD**) can increase animal heat load, resulting in reduced performance, decreased animal comfort, and death (Mader et al., 1997a, 1999a; Hubbard et al., 1999). Feedlot cattle performance is highly dependent on DMI, which is influenced by climatic conditions (NRC, 1981, 1987). Under hot environmental conditions, DMI is a function of core body temperature (Hahn, 1995).

Body temperature is an excellent indicator of an animal's susceptibility to heat load; however, devices used to monitor body temperature are not feasible for large numbers of animals in commercial settings (Mader et al., 2002; Davis et al., 2003; Mader, 2003). A viable alternative to using body temperature to assess animal heat load would be to monitor the degree of panting, respiration, or both (Gaughan et al., 2000; Silanikove, 2000).

The Livestock Weather Safety Index (**LWSI**; LCI, 1970) is a benchmark commonly used to assign heat stress levels to normal, alert, danger, and emergency categories. The LWSI quantitates environmental conditions using the temperature-humidity index (**THI**)

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Table 1. Panting scores assigned to steers

Score	Description
0	Normal respiration
1	Elevated respiration
2	Moderate panting and/or presence of drool or small amount of saliva
3	Heavy open-mouthed panting; saliva usually present
4	Severe open-mouthed panting accompanied by protruding tongue and excessive salivation; usually with neck extended forward

Table 2. Temperature, relative humidity, temperature-humidity index (THI), wind speed, and solar radiation at 1400 to 1700 and daily averages for the days on which the panting scores were assigned in the model development experiments (Exp. 1, 2, and 3)

Item	Mean ± SD	Maximum	Minimum
1400 through 1700			
Temperature, °C			
Ambient	28.9 ± 4.2	36.0	17.2
Black globe	36.8 ± 6.3	45.2	19.7
Relative humidity, %	60.2 ± 14.8	98.5	37.5
Wind speed, $m \cdot s^{-1}$	4.1 ± 1.8	8.4	1.0
Radiation, $W \cdot m^{-2}$	530.0 ± 250.9	971.7	17.6
THI[1]	77.9 ± 5.4	86.1	62.4
BGTHI[2]	88.7 ± 8.0	105.1	69.2
Daily			
Temperature, °C			
Ambient	24.4 ± 3.3	29.4	15.6
Black globe	27.8 ± 3.8	34.0	18.4
Relative humidity, %	75.4 ± 8.0	92.7	62.5
Wind speed, $m \cdot s^{-1}$	3.2 ± 1.3	6.3	1.2
Radiation, $W \cdot m^{-2}$	258.9 ± 71.4	361.5	56.7
THI[1]	73.0 ± 5.0	80.4	59.7
BGTHI[2]	78.8 ± 5.8	88.3	64.6

[1] Temperature-humidity index (THI) = 0.8 × ambient temperature + [(% relative humidity ÷ 100) × (ambient temperature − 14.4)] + 46.4.

[2] Black-globe temperature substituted for ambient temperature in the THI equation.

based on temperature and humidity only (Thom, 1959; NOAA, 1976). Although THI has been effectively used as an indicator of heat stress, adjustment of the THI for WSPD and RAD should enhance its usefulness. Solar radiation can greatly influence heat load, whereas changes in WSPD result in altered convective cooling. Both RAD and WSPD alter the ability of the animal to maintain thermal balance (Brosh et al., 1998; Mader, 2003). Therefore, the objectives of this study were to identify environmental variables that correspond to a visual assessment of heat stress (i.e., panting) and determine adjustments to the THI for WSPD and RAD.

MATERIALS AND METHODS

Model Development and THI Analysis

The database used for this analysis was derived from 3 previously reported experiments involving management strategies designed to reduce the effect of heat stress on summertime feedlot performance of cattle (Davis et al., 2003). Experiments were conducted at the University of Nebraska Haskell Agricultural Laboratory. Facility design has been previously reported by Mader et al. (1997a). Facilities are located at 42° 23′ N latitude and 96° 57′ W longitude; mean elevation is 445 m above sea level.

Experiments 1 (n = 72) and 2 (n = 96) were conducted from June 23, 1999 to September 13, 1999 (82 d), whereas Exp. 3 (n = 192) was conducted from June 8, 2000 to August 30, 2000 (83 d). Cattle utilized in these experiments were predominantly Angus and Angus crossbred steers. Panting scores were assigned to individual animals between 1400 and 1700 by visual observation using the scoring system presented in Table 1. Half scores were also used if the panting score of the animal appeared to be between 2 whole number scores. Only cattle from treatments within the 3 experiments that were provided feed ad libitum and had no cooling management strategy imposed were included in the final database. The combination of these observation times resulted in >2,000 individual panting score assessments, which were derived from approximately 12 d of observations within each experiment.

Environmental variables used for this analysis are shown in Table 2. Black globe THI (**BGTHI**) was also calculated to characterize heat load (Buffington et al., 1981) by substituting black globe (**BG**) temperature for ambient temperature in the THI equation {THI = [0.8 × ambient temperature] + [(% relative humidity ÷ 100) × (ambient temperature − 14.4)] + 46.4}. The same relative humidity value was used in calculating BG humidity index as was used for THI. All variables, except RAD, were collected continuously and compiled hourly using a weather station located in the center of the feedlot facility. In addition, daytime and nighttime mean, minimum, and maximum values and the square of all variables were included in the analysis. Daily and hourly RAD was obtained from the High Plains Climate Center automated weather station located 0.6 km west and 1.5 km north of the feedlot facilities. The units of RAD are $W \cdot m^{-2}$, which represents heat flux density, also known as irradiance (http://physics.nist.gov/Pubs/SP330/sp330.pdf). Regression analysis was used to determine the simplest model in which environmental variables best predicted the actual panting score.

The predictor models were used to predict panting score between 1400 and 1700 and were as follows. The first full model (Model 1) consisted of utilizing all environmental variables including those with BG. The second full model (Model 2) consisted of all environmental factors except those containing BG data. Only the linear value for each variable was used in the final analyses for Models 1 and 2. Preliminary analysis in which the square of each environmental variable was included in the model resulted in no improvement in the coefficient of determination (R^2). The third model (Model 3) consisted of only using hourly data for THI, WSPD, and

RAD between 1400 and 1700. In addition, a fourth model was constructed similar to Model 3 with the exception that only daily THI, WSPD, and RAD averages were utilized. The goal of the latter model was to develop adjustment factors for WSPD and RAD to THI based on data collected within a given day (Model 3) vs. predicting a future response based on daily averages (Model 4).

The adjusted R^2 selection method of SAS (SAS Inst., Inc., Cary, NC) was used for the first 2 models. Plots of adjusted R^2 vs. the number of parameters in the model were used to determine the point at which the adjusted R^2 reached a plateau, and additional parameters were deemed not to make improvements in the predictive model. This occurred when the changes in R^2 were <0.01 units with the addition of an additional parameter. Simple regression techniques were utilized for Models 3 and 4. For all models, the relative contribution of each variable to the model was determined using PROC Reg and the STB option of SAS to predict the panting score between 1400 and 1700. From the equation for predicting panting score, the ratios of the WSPD and RAD parameter estimate to the THI parameter estimate were used to determine the adjustments for WSPD and RAD in the THI equation. The equation was further enhanced by multiplying the respective ratio by the difference between the actual WSPD or RAD and the average WSPD or RAD, respectively. Thus, adjustments were based on average environmental conditions that approximated the conditions associated with the development of the original LWSI (LCI, 1970).

THI Model Adjustment Validation

Independent of the model development experiments (Exp. 1 through 3), 4 additional experiments (Exp. 4 through 7) were utilized to validate the THI equations with RAD and WSPD adjustments. Three of these experiments (Exp. 4, 5, and 7) were conducted at the University of Nebraska Haskell Agricultural Laboratory facilities, near Concord. Experiment 6 (Brown-Brandl et al., 2005) was conducted at the USDA-ARS Meat Animal Research Center (**MARC**), Clay Center, NE, approximately 250 km SSW of the University of Nebraska Haskell Agricultural Laboratory.

Experiments 4 and 5 utilized 108 (mean BW = 450 ± 27 kg) and 96 (mean BW = 462 ± 34 kg) heifers, respectively. In Exp. 6, Angus (mean BW = 421 ± 8 kg), MARC III crossbred (Pinzgauer, Red Poll, Hereford, Angus; mean BW = 407 ± 8 kg), Gelbvieh (mean BW 462 ± 8 kg), and Charolais (mean BW = 465 ± 8 kg) heifers were utilized. Thirty-two animals were utilized within each breed. Coat colors for the MARC III, Gelbvieh, and Charolais cattle were dark red, tan, and white, respectively. Experiment 7 utilized 164 mixed breed (mean BW = 457 ± 41 kg) steers that were black-hided (Angus crossbred), red-hided (Gelbvieh or Red Angus crossbred), or white-hided (Charolais or crossbred).

Cattle in these experiments were fed high-energy finishing diets comparable with those fed in experiments utilized in developing the THI adjustment equations. All experiments conducted at the University of Nebraska were conducted with the approval of the University of Nebraska-Lincoln Institutional Animal Care and Use Committee. The experiment conducted at MARC was conducted in accordance with the U.S. MARC Animal Care Guidelines and the *Guide for the Care and Use of Agricultural Animals in Agricultural Research and Teaching* (FASS, 1999).

In each validation experiment, panting scores were obtained for each animal between 1400 and 1700 for an average of 16 d per experiment and primarily on those days in which warmer than normal and/or hot conditions (THI predicted to be >69) were anticipated to exist. However, in Exp 5, data were obtained on 1 d during which the THI was <69. Also, in Exp 7, data were utilized only if average panting score exceeded 1.5. A score of 1.5 is comparable with first-phase panting and the point at which heat stress mitigation should be considered (NRC, 1981; Mader et al., 2002). Pearson correlation coefficients between actual THI and actual panting score and between adjusted THI and actual panting score were obtained using the PROC CORR procedure of SAS. Paired *t*-test was used to compare mean actual panting scores and predicted panting scores.

RESULTS

Mean, maximum, and minimum values for THI, WSPD, and RAD for the days that panting scores were assigned are presented in Table 2. Hourly temperature during the panting score assessment period (1400 to 1700) averaged 28.9 ± 4.2°C, whereas relative humidity averaged 60.2 ± 14.8%. This resulted in an average THI of 77.9 ± 5.4 units. The LWSI classifications for heat stress are as follows: normal, ≤74; alert, 74 < THI < 79; danger, 79 ≤ THI < 84; and emergency, THI ≥84. The range of THI for the days in which panting scores were determined represented all categories of the LWSI. In addition, measurements of hourly WSPD and RAD between 1400 and 1700 also comprised a wide range of conditions (1.0 to 8.4 $m \cdot s^{-1}$ and 17.6 to 971.7 $W \cdot m^{-2}$, respectively). Daily average climatic conditions were comparable with those reported previously by Mader et al. (1999a).

Regression equations to predict panting score and prevalence of heat stress, using various environmental conditions, are shown in Table 3. In both Models 1 (with BG data) and 2 (without BG data), panting score was found to be dependent on and negatively correlated with mean daily WSPD. For each 1-$m \cdot s^{-1}$ increase in mean daily WSPD, panting score declined 0.24 units in Model 1 and declined 0.38 units in Model 2. In Model 1, BG temperature at 1500 and minimum daily relative humidity, which are both daytime environmental factors, exhibited positive relationships with panting score,

Table 3. Partial regression coefficients ± SE for models assessing environmental factors influencing the panting score of feedlot cattle[1]

Variable	Model 1 (All environmental factors included; $R^2 = 0.61$)	Model 2 (All black globe data excluded; $R^2 = 0.56$)
Intercept	−6.178 ± 0.226	−9.38 ± 0.46
Mean daily wind speed (WSPD), $m \cdot s^{-1}$	−0.241 ± 0.022	−0.380 ± 0.015
Minimum nighttime THI[2]	—	0.046 ± 0.005
Mean hourly THI[3]	—	0.084 ± 0.005
Mean hourly solar radiation,[3] $W \cdot m^{-2}$	—	0.00076 ± 0.00007
Maximum daily relative humidity, %	—	0.021 ± 0.004
Minimum nighttime WSPD, $m \cdot s^{-1}$	−0.174 ± 0.023	—
Minimum nighttime BGTHI[4]	0.074 ± 0.004	—
Black globe temperature at 1500, °C	0.083 ± 0.004	—
Minimum daily relative humidity, %	0.012 ± 0.002	—

[1] *P*-values for all variables <0.01.

[2] Temperature humidity index (THI) = 0.8 × ambient temperature + [(% relative humidity ÷ 100) × (ambient temperature − 14.4)] + 46.4.

[3] Values obtained between 1400 and 1700.

[4] Black globe THI (BGTHI) = black globe temperature substituted for ambient temperature in the THI equation.

whereas the nighttime factors, minimum nighttime WSPD and minimum nighttime BGTHI, exhibited negative and positive relationships, respectively, with panting score. Minimum nighttime BGTHI and BG temperature at 1500 were the 2 factors contributing the most to the overall R^2 with partial R^2 of 0.20 and 0.29, respectively.

With the exclusion of BG data (Model 2), minimum nighttime THI, mean hourly THI and RAD between 1400 and 1700, maximum daily relative humidity, and mean daily WSPD were found to influence panting score between 1400 and 1700. This model clearly shows the influence of temperature and relative humidity through THI on panting score. However, WSPD and RAD are also factors that influenced heat balance in cattle. Nevertheless, for this model, mean hourly THI and mean daily WSPD were the 2 factors that contributed the most to the overall R^2 with partial R^2 of 0.21 and 0.25, respectively.

The parameter estimates for the effects of THI, WSPD, and RAD on panting score of cattle are presented in Table 4. The regression equation developed using hourly values predicts panting score to be equal to −7.563 + (0.121 × THI) − (0.241 × WSPD) + (0.00082 × RAD) between 1400 and 1700. The ratios of WSPD to THI and RAD to THI (−1.992 and 0.0068 for WSPD and RAD, respectively) represent the adjustments to the THI for WSPD and RAD. For instance, for each 1-$m \cdot s^{-1}$ increase in WSPD, THI can be reduced 1.99 units to reflect the effects of WSPD on panting. For each 100-$W \cdot m^{-2}$ decrease in RAD, THI can be reduced 0.68 units. As expected in both models, THI was the variable contributing the most to the R^2; WSPD was the next greatest contributor, and RAD contributed least.

Table 4. Partial regression coefficients ± SE for the equations predicting panting score from the temperature-humidity index (THI), wind speed, and solar radiation between 1400 to 1700 using environmental data between 1400 and 1700 ($R^2 = 0.49$) and using average daily conditions ($R^2 = 0.53$)

Variable	Model 3 (1400 to 1700)	Model 4 (Daily)
Intercept	−7.563 ± 0.273	−7.538 ± 0.270
THI[1]	0.121 ± 0.003	0.134 ± 0.004
Wind speed, $m \cdot s^{-1}$	−0.241 ± 0.11	−0.412 ± 0.015
Solar radiation, $W \cdot m^{-2}$	0.00082 ± 0.00007	0.00153 ± 0.0002

[1] THI = 0.8 × ambient temperature + [(% relative humidity ÷ 100) × (ambient temperature − 14.4)] + 46.4.

On the basis of the ratios of WSPD and RAD to THI and average climatic conditions, the adjusted THI derived from hourly conditions within a day is equal to THI − [1.992 × (WSPD − 4.07)] + [0.0068 × (RAD − 530)], which reduces to 4.51 + THI − (1.992 × WSPD) + (0.0068 × RAD). The adjusted daily THI, based on average daily climatic conditions, is equal to 6.80 + THI − (3.075 × WSPD) + (0.0114 × RAD).

Environmental conditions associated with the experiments that were utilized for validating the adjustments to the THI for WSPD and RAD are shown in Table 5. The range in temperatures (21.2 to 38.9°C), relative humidity (23.5 to 91.2), WSPD (1.0 to 6.2 m/s), and RAD (65.9 to 1,030.4 $W \cdot m^{-2}$) were comparable with those observed in the model development experiments and other studies (Mader et al., 1999a). The mean (78.2) and range (62.1 to 85.1) in THI from 1400 to 1700 of the 4 validation experiments (Exp. 4 through 7) were close to the mean (77.9) and range (62.4 to 86.1) in THI of the model development experiments (Exp. 1 through 3).

Actual mean and predicted panting scores using regression equations of THI adjusted for WSPD and RAD based on hourly (1400 to 1700) data are shown in Table 6. In Exp. 4, the predicted panting score (1.15) was close to observed mean panting score (1.22). Correlation

Table 5. Environmental conditions from 1400 through 1700 for the days on which the panting scores were assigned in the 4 temperature-humidity index (THI) model validation experiments

	Environmental variable[1]				
Item	Temperature, °C	Relative humidity, %	Windspeed, $m \cdot s^{-1}$	Solar radiation, $W \cdot m^{-2}$	THI[1]
Exp. 4					
Mean	27.6 ± 3.9	62.6 ± 10.3	3.9 ± 1.5	432.5 ± 211.4	76.7 ± 4.6
Minimum	23.2	52.1	1.8	98.6	70.8
Maximum	33.9	85.0	6.2	630.7	84.2
Exp. 5					
Mean	30.2 ± 4.8	44.3 ± 15.5	4.1 ± 1.6	481.3 ± 152.6	77.1 ± 5.5
Minimum	21.2	25.3	1.0	65.9	62.1
Maximum	34.5	91.2	5.8	662.4	81.0
Exp. 6					
Mean	31.6 ± 3.9	45.1 ± 11.5	5.8 ± 2.4	881.5 ± 161.7	78.7 ± 3.7
Minimum	22.2	23.5	2.1	437.6	69.4
Maximum	38.9	78.0	12.6	1,030.4	85.1
Exp. 7					
Mean	29.4 ± 2.0	67.4 ± 6.8	2.5 ± 1.1	534.7 ± 142.7	80.1 ± 3.0
Minimum	26.8	50.3	1.5	136.0	76.1
Maximum	31.8	72.1	4.2	634.5	83.2

[1] THI = 0.8 × ambient temperature + [(% relative humidity ÷ 100) × (ambient temperature − 14.4)] + 46.4.

coefficients between observed mean panting score and actual THI and between observed panting score and adjusted THI were identical (r = 0.67). In Exp. 5, the new THI equation overpredicted the panting score. Also, the correlation between panting score and the adjusted THI was slightly lower than the correlation between panting score and the actual THI, although correlation in both cases was excellent at ≥0.8.

In Exp. 6, the predicted panting score (1.30) was close to the actual (1.32) panting score for Angus cattle. However, as coat color went from black to red to tan to white, actual panting score declined, which would be expected. For nonCharolais cattle, the correlations between actual panting score and the adjusted THI were all greater than the correlations between panting score and actual THI. These data indicate that the THI equation adjusted for WSPD and RAD is most suitable for nonCharolais cattle, although differences ($P < 0.05$) existed between the actual mean panting score and the predicted panting score for cattle that were not purebred Angus.

In Exp. 7, the predicted panting score (2.00) was close to the actual panting score (1.96) for black-hided cattle, but the predicted panting scores were 0.41 and 0.74 units greater ($P < 0.05$) than the actual panting scores for red- and white-hided cattle, respectively. The THI equation adjusted for WSPD and RAD had a greater correlation to the mean panting score than did THI for all cattle color types, although the correlation was very low (0.37) for red-hided cattle and similar to the correlation (0.33) between the actual THI and the mean panting score. However, for white-hided cattle, even though the predicted panting score was lower than actual, the correlation between the adjusted THI and the panting score was very high (0.83).

Adjustments in THI, based on varying levels in WSPD and RAD between 1400 and 1700, are illustrated in Table 7. At elevated WSPD (10 $m \cdot s^{-1}$), THI values can be reduced by >10 units compared with the case in

Table 6. Comparison of the mean panting score (PS) to the predicted PS and correlations between the mean PS and actual temperature-humidity index (THI[1]) and between the mean PS and adjusted THI in the 4 THI model validation experiments

			Correlation	
Item	Mean PS ± SD	Predicted PS ± SD	Actual THI	Adjusted THI
Exp. 4				
Angus crossbred	1.22 ± 0.55	1.15 ± 0.65	0.67	0.67
Exp. 5				
Angus crossbred[2]	0.94 ± 0.42	1.17 ± 0.51	0.87	0.80
Exp. 6				
Angus	1.32 ± 0.89	1.30 ± 0.71	0.52	0.64
MARC III[3]	1.19 ± 0.95	1.30 ± 0.71	0.47	0.69
Gelbvieh[2]	0.82 ± 0.77	1.30 ± 0.71	0.48	0.64
Charolais[2]	0.73 ± 0.73	1.30 ± 0.71	0.54	0.53
Exp. 7				
Black-hided	2.00 ± 0.39	1.96 ± 0.34	0.47	0.67
Red-hided[2]	1.55 ± 0.65	1.96 ± 0.34	0.33	0.37
White-hided[2]	1.22 ± 0.97	1.96 ± 0.34	0.23	0.83

[1] THI = 0.8 × ambient temperature + [(% relative humidity ÷ 100) × (ambient temperature − 14.4)] + 46.4.

[2] Mean PS and predicted PS differ ($P < 0.05$) based on paired *t*-test. For Exp. 4 and 5, the SE of the difference was 0.05 and 0.03, respectively. For Exp. 6 and 7, the pooled SE of the difference was 0.04 and 0.10, respectively.

[3] Crossbred cattle were composed of Pinzgauer, Red Poll, Hereford, and Angus genotypes. MARC = U.S. Meat Animal Research Center (Clay Center, NE).

Table 7. Temperature-humidity index (THI[1]) values between 1400 and 1700 adjusted for windspeed (WSPD) and solar radiation (RAD)

	THI								
	70			75			80		
RAD, W·m^{-2}	0 m·s^{-1} [2]	5 m·s^{-1}	10 m·s^{-1}	0 m·s^{-1}	5 m·s^{-1}	10 m·s^{-1}	0 m·s^{-1}	5 m·s^{-1}	10 m·s^{-1}
	Adjusted THI[3]								
250	76.21	66.25	56.29	81.21	71.25	61.29	86.21	76.25	66.29
500	77.91	67.95	57.99	82.91	72.95	62.99	87.91	77.95	67.99
750	79.61	69.65	59.69	84.91	74.65	64.69	89.61	79.65	69.69
1,000	81.31	71.35	61.39	86.31	76.35	66.39	91.31	81.35	71.39

[1] THI = 0.8 × ambient temperature + [(% relative humidity ÷ 100) × (ambient temperature – 14.4)] + 46.4.

[2] WSPD measurement.

[3] Adjusted THI = THI + 4.51 – (1.992 × WSPD) + (0.0068 × RAD).

which no adjustments were made, whereas elevated RAD (1,000 W·m^{-2}) can increase THI by approximately 5 units compared with low RAD (250 W·m^{-2}).

DISCUSSION

A greater R^2 (0.61 vs. 0.56) was found when BG data were included in models that were used to assess factors that influence panting score. However, BG temperature at 1500 was the only afternoon parameter found to influence panting score between 1400 and 1700. Black globe temperatures and related measures were used because they were known to partially account for a large number of climatic factors, including WSPD and RAD (Buffington et al., 1981). In these studies, average ambient temperature was the greatest at 1500 compared with any other time during the day; however, panting score was the greatest at 1700. A 2-h lag between prevalence of hot climatic conditions and observable effects on livestock would be indicative of the time it takes for heat gain from the environment (and metabolism) to exceed heat dissipation mechanisms in feedlot cattle fed high-energy diets.

Interestingly, in Model 1, 2 nighttime factors, minimum nighttime WSPD and BGTHI, were found to influence panting score. Low WSPD would lessen an animal's ability to dissipate heat at night, whereas low BGTHI values would enhance heat loss at night. Although the partial R^2 for minimum nighttime WSPD was <0.20, during heat episodes, typical nighttime temperatures and relative humidities are above normal, which limits transfer of heat from the animal to the environment. Evaporative cooling, through air movement, then becomes a primary mechanism by which the animal dissipates heat gained. The ability of cattle to cool (dissipate heat) at night appears to be important for minimizing overall heat load and contributing to the maintenance of normal behavior and feeding activity. As opposed to the minimum daily relative humidity that was found in models that included BG data (Model 2), when BG data were not included, panting score was found to be dependent on maximum daily relative humidity, which typically occurs at night shortly before dawn. The association of panting score with relative humidity likely occurs as a result of the decreased ability of the animal to fully utilize evaporative heat exchange processes. McLean (1963) found a strong negative relationship between total evaporative heat loss and relative humidity. Low nighttime WSPD (Model 1) and high nighttime relative humidity (Model 2) would both limit evaporative heat loss.

The negative relationship between WSPD and panting score in both models illustrates the ability of the animals to utilize convective heat exchange. Increased air movement over the body surface results in a disruption of the layer of air near the skin surface. Disruption of this airspace allows for the removal of warm air as it is replaced by cooler air. Body heat of the animal is then transferred to the cool air and removed via continuous air movement (Robertshaw, 1985), although this would likely only be true as long as ambient temperatures are below body temperatures. If ambient temperature exceeds body temperature, effects of WSPD are uncertain. When relative humidity is low, then WSPD effects could still be positive, however, under conditions in which relative humidity is high and evaporative cooling is limited, elevated WSPD could raise body temperature at a rate faster than that which would normally occur. Nevertheless, as long as animal temperature remains greater than the environmental temperature, then as the animal and environmental temperature gradient decreases, nighttime WSPD becomes more crucial to the cooling process. Additionally, Arkin et al. (1991) showed that thermal conductivity of the boundary layer of air adjacent to the fur increased linearly with wind velocity even though the increased ability of the animal to dissipate heat reached a maximum when WSPD approached 2 m·s^{-1} (NRC, 1981). For the models developed in this study, benefits of WSPD >2 m·s^{-1} were apparent, as no quadratic or curvilinear response to WSPD was found.

Models 3 and 4 provide adjustments to the THI for WSPD and RAD. The 1400 to 1700 hourly equation (Model 3) would be used for a current or "real-time" situation. The equation based on daily averages (Model 4) would most likely be used to predict THI for a future event using daily averages. The limited impact of RAD on panting score, particularly for the equation using the hourly data, was surprising given the benefit shade structures have in reducing heat stress in cattle (Mader et al., 1997b; Brosh et al., 1998; Mitlöhner et al., 2001). Solar radiation contributes significantly to overall heat load of the animal (Walsberg, 1992). This is particularly evident in black-hided cattle. Arp et al. (1983) found that black-haired steers in commercial feedlots had body surface temperatures as much as 21°C greater than white-haired contemporaries in part bcause of the relative absorptivity and emissivity differences between black-haired and white-haired contemporaries (Robertshaw, 1985). In the data set from the current experiments, the correlation between RAD and THI ranged between 0.24 and 0.42; whereas the correlation between WSPD and THI ranged between 0.05 and 0.17. Even though RAD did not contribute to heat load, a portion of its influence was attributed to temperature, whereas WSPD was influenced very little by temperature.

Because the initial experiments were conducted with mostly black cattle, the equation developed would logically have the best application for dark-colored cattle. Also, >75% of feedlot deaths caused by heat stress are dark-coated cattle (Busby and Loy, 1996). The THI equation with WSPD and RAD adjustments would be most useful for assessing conditions detrimental to dark-coated cattle. Also, basic guidelines have been provided to feedlot operations for managing cattle exposed to heat stress (Mader et al., 2000). A THI between 70 and 74 is an indication to producers that they need to be aware that the potential for heat stress in livestock exists. In the LWSI, THI values ≤ 74 are classified as alert, $74 < \text{THI} < 79$ as danger, and $79 \leq \text{THI} < 84$ as emergency. In addition, when THI values are >70 by 0800, it is recommended that feedlot operators begin or prepare to initiate heat stress management strategies prior to cattle becoming exposed to the excessive heat load (Mader et al., 2000). The advantage of using a THI equation that is adjusted for hourly WSPD and RAD is that heat stress mitigation strategies can be modified, depending on cloud cover and WSPD. The THI equation adjusted for daily WSPD and RAD has potential for use in predicting future heat stress levels associated with changing weather patterns or climatic conditions.

In conclusion, the LWSI has long been used as an indicator for potential heat stress-related losses in cattle. Because the LWSI is based on THI, within a day, adjustments to THI can be made by reducing the THI by 2 units for each $1\text{-m}\cdot\text{s}^{-1}$ increase in WSPD and by increasing THI 0.68 units for each $100\text{-W}\cdot\text{m}^{-2}$ increase in RAD. Close monitoring of weather variables is essential in determining the potential for environmental stress-related complications in livestock operations. Adjustments to the THI for RAD and WSPD would be useful for assessing current environmental stress levels, implementing heat stress mitigation strategies, and predicting the potential for stress to occur in the future.

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