6B.3 WIND SPEED AND SOLAR RADIATION ADJUSTMENTS FOR THE TEMPERATURE-HUMIDITY INDEX[1]

Terry Mader*
University of Nebraska, Concord, Nebraska

Shane Davis
Koers-Turgeon Consulting Service, Inc., Salina, Kansas

John Gaughan
School of Animal Studies, University of Queensland, Gatton Campus, Gatton, Queensland, Australia

Tami Brown-Brandl
USDA-ARS US Meat Animal Research Center, Clay Center, NE 68933

1. ABSTRACT

Wind speed (WSPD, m/s) and solar radiation (RAD, kcal/m^2) are known to influence the magnitude of heat stress experienced by livestock. Data from three summer feedlot studies were utilized to determine WSPD and RAD adjustments to improve the temperature-humidity index (THI). Visual assessments of heat stress based on panting scores (0 = no panting, 4 = severe panting) were collected from 1400 to 1700 during the three summer studies. These data were combined into one data set and included approximately 2,000 observations. Temperature-humidity index averaged 77.9 ± 5.2 (range 62.49 to 86.1) at the time panting scores were assigned. A multiple regression equation (R^2 = 0.49) was developed using hourly values for THI, WSPD, and RAD to predict panting score of individual animals (panting score = -7.563 + (0.121 * THI) – (0.241 * WSPD) + (0.00095 * RAD)). The ratio of WSPD to THI and RAD to THI (-1.992 and 0.0079 for WSPD and RAD, respectively) represent the adjustments to the THI for WSPD and RAD. On the basis of these ratios and average 1400 to 1700 hourly data, the THI, adjusted for WSPD and RAD, equals [4.51 + THI – (1.992*WSPD) + (0.0079*RAD)]. Three separate cattle studies, comparable in size, type of cattle, and number of observations to the three original studies, were utilized to evaluate the relationship between the adjusted THI and panting score. Actual mean panting score, derived from individual observations, in these studies was 1.1 versus the predicted mean of 1.2. The mean R^2 between THI and mean panting score was 0.39, with correlation coefficients ranging between 0.47 and 0.87; while the mean R-square (R^2) between the adjusted THI and mean panting score was 0.50 with correlation coefficients ranging between 0.64 and 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. As real-time conditions change, immediate adjustments in THI can be taken into account while implementing management strategies to mitigate heat stress effects on livestock. Although knowledge of THI alone is beneficial in determining the potential for heat stress, adjustments for WSPD and RAD are essential to more accurately assess animal discomfort.

*Corresponding author address: Terry L. Mader, Univ. of Nebraska, Haskell Agricultural Laboratory, 57905 866 Road, Concord, NE 68728; e-mail: tmader@unlnotes.unl.edu.

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2. INTRODUCTION

Feedlot cattle finished in the summer months are often affected by periods of adverse climatic conditions (Hahn and Mader, 1997; Mader et al., 1999b; Hahn et al., 2001). 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(or) death (Mader et al., 1997a; Mader et al., 1999a; Hubbard et al., 1999). The ability of feedlot managers and consultants to assess climatic conditions and determine effects on cattle is of utmost importance, not only to ensure that the animal's welfare is maintained, but also to ensure animal performance and profitability (NRC, 1981; Mader, 1986; NRC, 1987). Performance is largely dependent on DMI which is influenced by climatic conditions (NRC, 1996). Under hot environmental conditions, DMI is a function of core body temperature (Hahn, 1995; Frank et al., 2001). Core body temperature is an excellent indicator of an animal's susceptibility to heat load, however, devices used to monitor core 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 degree of panting and/or respiration rate (Silanikove, 2000; Gaughan et al. 2000).

The Livestock Weather Safety Index (LCI, 1970) is commonly used as a benchmark to assign heat stress levels to normal, alert, danger and emergency categories. The Livestock Weather Safety Index quantitates environmental conditions using the temperature-humidity index (THI; Thom, 1959; NOAA, 1976) where THI = 0.8 * ambient temperature + ((relative humidity/100) * (ambient temperature - 14.3)) + 46.4. Although THI has been effectively used as a heat stress indicator, adjustment of the THI for WSPD and RAD should enhance usefulness. Solar radiation can greatly influence heat load, while 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.

3. PROCEDURE

Temperature-humidity index correction analysis. The database used for this analysis was derived from three 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 with the approval of the University of Nebraska-Lincoln Institutional Animal Care and Use Committee. Facility design has been previously reported by Mader et al. (1997a). Facilities are located at 42º 23' N latitude and 96º 57' W longitude, with a mean elevation of 445 m above sea level. Experiments 1 (72 head) and 2 (96 head) were conducted from June 23, 1999 to September 13, 1999 (82 days), while Exp. 3 (192 head) was conducted from June 8, 2000 to August 30, 2000 (83 days). Cattle utilized in these experiments were predominantly Angus and Angus crossbred steers. Panting scores were assigned to individual animals between 1400 and 1700 hour 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 two whole number scores. Only cattle from treatments within the three 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 more than 2,000 individual panting score assessments.

Table 1. Panting scores assigned to steers.

Score	Description
0	Normal respiration, ~60 or less breaths/min (bpm)
1	Slightly elevated respiration, ~ 60 to 90 bpm
2	Moderate panting and/or presence of drool or small amount of saliva, ~ 90 to 120 bpm
3	Heavy open-mouthed panting; saliva usually present, ~120 to 150 bpm
4	Severe open-mouthed panting accompanied by protruding tongue and excessive salivation; usually with neck extended forward

Climatic variables used for this analysis are shown in Table 2. Black globe-temperature-humidity index (BGTHI) was also calculated to characterize heat load (Buffington et al., 1981) by substituting black globe temperature (BG) for ambient temperature in the THI equation. The same relative humidity value was used in calculating black globe 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. Solar radiation 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. Regression analysis was used to determine the simplest model in which environmental variables best predicted panting score.

Table 2. Mean, maximum (Max), and minimum (Min) values for temperature, relative humidity, temperature-humidity index (THI), wind speed, and solar radiation at 1400 to 1700, and daily averages on the days panting scores were assigned.

Item	Mean ± SD	Max	Min
1400 to 1700			
Temperature, ºC			
Ambient (T_a)	28.9 ± 4.2	36.0	17.2
Blackglobe	36.8 ± 6.3	45.2	19.7
Relative humidity, %	60.2 ± 14.8	98.5	37.5
Wind speed, m/s	4.1 ± 1.8	8.4	1.0
Radiation, kcal/m^2/h	455.8 ± 215.9	836.0	15.1
THI[a]	77.9 ± 5.4	86.1	62.4
BGTHI[b]	88.7 ±8.0	105.1	69.2
Daily			
Temperature, ºC			
Ambient	24.4 ± 3.3	29.4	15.6
Blackglobe	27.8 ± 3.8	34.0	18.4
Relative humidity, %	75.4 ± 8.0	92.7	62.5
Wind speed, m/s	3.2 ±1.3	6.3	1.2
Radiation, kcal/m^2	5346 ± 1474	7464	1170
THI[b]	73.0 ± 5.0	80.4	59.7
BGTHI	78.8 ± 5.8	88.3	64.6

[a]Temperature-humidity index = $.8*T_a + ((RH/100)*(T_a-14.3)) + 46.4$.
[b]Black-globe temperature substituted for ambient temperature in THI equation.

The predictor models were used to predict panting score between 1400 and 1700 hours and were separated into three separate analyses. 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 BG. The third model (Model 3) consisted of only using THI, WSPD, and RAD between 1400 and 1700. In addition, a fourth model was constructed similar to Model 3 with the exception that daily averages were utilized for climate data only. Only the linear value for each variable was used in the final analyses. Preliminary analysis in which the square of each climatic characteristic was included in the model resulted in no improvement in the coefficient of determination (R^2).

The adjusted R^2 selection method was used for the first two models. Plots of adjusted R^2 versus the number of parameters in the model were used to determine the point at which 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 less than one unit with the addition of an additional parameter. Model 3 consisted of the environmental variables of THI, WSPD, and RAD at the time panting score observations were made, while Model 4 utilized daily averages of THI, WSPD, and RAD to predict panting score between 1400 and 1700. The goal of the later model was to develop correction factors for WSPD and RAD on THI based on data collected within a given day (Model 3) vs predicting a future animal response based on daily averages (Model 4).

THI correction validation. Three separate experiments were utilized to validate THI equations with RAD and WSPD corrections. Two of these experiments (Trials 1 and 2) were conducted at the University of Nebraska Haskell Agricultural Laboratory (HAL) facilities, near Concord. The third experiment (Brown-Brandl et al., 2003) was conducted at the USDA-ARS Meat Animal Research Center, Clay Center, NE, approximately 250 km SSW of HAL. Experiments 1 and 2 utilized 108 (mean weight = 450 ± 27 kg) and 96 (mean weight = 462 ± 34 kg) heifers, respectively. In Exp. 3, Angus (mean weight = 421 ± 8 kg), MARC III crossbred (Pinzgauer, Red Poll, Hereford, Angus; mean weight = 407 ± 8 kg), Gelbvieh (mean weight 462 ± 8 kg), and Charolais (mean weight 465 ± 8 kg) heifers were utilized. Coat color for the MARC III, Gelbvieh, and Charolais cattle and dark red, tan, and white, respectively. Cattle in these experiments were fed high energy finishing diets comparable to those fed in experiments utilized in developing the THI correction equation.

A preliminary model was tested which consisted of temperature and relative humidity as separate components in the regression model. This resulted in no improvement in adjusted R^2 (0.47), thus THI was used instead of individual values of ambient temperature and relative humidity. The ratio of WSPD and RAD parameter estimates to the THI parameter estimate were used to determine THI adjustments for WSPD and RAD.

4. RESULTS AND DISCUSSION

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, while relative humidity averaged 60.2 14.8%. This resulted in average THI being 77.9 5.4 units. The Livestock Weather Safety Index 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 score was determined on the animals represented all categories of the Livestock Weather Safety Index. In addition, measurements of hourly WSPD and RAD also comprised a wide range of values (1.0 to 8.4 m/s and 15.1 to 836.0 kcal/m^2/h, respectively). Daily average climatic conditions were very comparable to those reported previously by Mader et al. (1999a). Inferences made regarding application of this model must remain within the bounds of the ranges of environmental variables measured.

Regression equations to predict panting score or prevalence of heat stress, using various climatic conditions, are shown in Table 3. In Models 1 (with BG data) and 2 (without BG data), panting score was found to be dependent on mean daily WSPD. However, with BG values included in the model, BG at 1500 were the only afternoon parameter found to influence panting score between 1400 and 1700 h, Black globe temperatures and related measures are used because they are 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 vs 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 related effects on livestock would be indicative of the time it takes for heat gain from the environment and metabolism to overload heat dissipation mechanisms in feedlot cattle fed high energy diets.

Table 3. Partial regression coefficients ± SE for models assessing environmental factors affecting panting score of feedlot steers*

	Model 1 (All environmental factors included; R^2 = 0.61)	Model 2 (All blackglobe data excluded; R^2 = 0.56)
Intercept	-6.178±0.226	-9.38±0.46
Mean daily wind speed (WSPD), m/s	-0.241±0.022	-0.380±0.015
Minimum nighttime THI[a]	--	0.046 ±0.005
Mean hourly THI[a]	--	0.084 ±0.005
Mean hourly solar radiation, kcal/m^2	--	0.00088±0.00008
Maximum daily relative humidity, %	--	0.021 ±0.004
Minimum nighttime WSPD, m/s	-0.174±0.023	---
Minimum nighttime BGTHI[b]	0.074±0.004	--
1500 blackglobe temperature, ºC	0.083±0.004	--
Minimum daily relative humidity, %	0.012±0.002	--

*P-values for all statistics < 0.0001.
[a]Temperature-humidity index = 0.8 ambient temperature + (% relative humidity/100)*(ambient temperature – 14.3) + 46.3.
[b]Blackglobe THI (BGTHI) = blackglobe temperature substituted for ambient temperature in THI equation.

The 1500 BG temperature and minimum daily relative humidity were the only daytime climatic conditions that impacted panting score for Model 1. The remaining climatic factors, after average WSPD, were all minimum nighttime climatic values. These were minimum nighttime WSPD and BGTHI. The ability of cattle to cool down at night appears to be important for minimizing overall heat load and maintenance of normal behavior and feeding activity. Thus, nighttime cooling conditions appear to be just as important as daytime heat load in determining heat stress dynamics in feedlot cattle.

With the exclusion of BG data, minimum nighttime THI was found to influence panting score, in addition to mean hourly THI and mean hourly RAD between 1400 and 1700 (Model 2). As opposed to the minimum daily relative humidity with BG data included, 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. These models clearly show the influence of temperature and relative humidity, through THI on panting score. However, WSPD and RAD are also factors that influence heat gain or loss in cattle.

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 being replaced by this 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 only hold true as long as ambient temperatures are below body temperatures. Additionally, Arkin et al. (1991) showed that thermal conductivity of the boundary layer of air adjacent to the fur increases linearly with wind velocity even though the increased ability of the animal to dissipate heat has been suggested to reach a maximum when WSPD approaches 2 m/s (NRC, 1981). For the models developed in this study, benefits of WSPD above 2 m/s were apparent, since no quadratic or curvilinear response to WSPD was found.

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) + (0.00095 * RAD) between 1400 and 1700. The ratio of WSPD to THI and RAD to THI (-1.992 and 0.0079 for WSPD and RAD, respectively) represent the adjustments to the THI for WSPD and RAD. For instance, for each 1 m/s increase in WSPD, THI can be reduced 1.99 units to reflect the effects of WSPD on panting. For each 100 kcal/m^2 decrease in RAD, THI can be reduced 0.79 units.

A significant impact of RAD on panting score, particularly for the equation using the hourly data, is not surprising given the benefit shade structures have in reducing heat stress in cattle (Mader et al., 1997b; Brosh et al., 1998; Mitlohner et al., 2001). Solar radiation can contribute 1000 W/m^2 to the overall heat load of the animal (Walsberg, 1992). This amount of RAD can be further exacerbated by the hair color of the animal. In these studies, approximately 75% of the steers were black-haired. Arp et al. (1983) found that black-haired steers in commercial feedlots had body surface temperatures as much as 21 ^oC greater than white-haired contemporaries. Relative absorptivity and emissivity differs considerably between black-haired and white-haired contemporaries (Robertshaw, 1985; Cena and Monteith, 1975). Thus, large numbers of black-haired steers in the current data set may have allowed for a more drastic effect of RAD. Nevertheless, substitution of average 1400 to 1700 hour values for WSPD and RAD (Table 3) into the regression equation and solving the equation to determine the THI value at which panting score equals 1 (100% of steers elevated respiration rate) results in THI equal to 75.4. This value is consistent with the Livestock Weather Safety Index threshold value of 75 to signify an “alert” environmental situation. Lemerle and Goddard (1986) reported that respiration begins to increase when THI exceeds 73.

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

Variable	1400 to 1700	Daily
Intercept	-7.563 ± 0.273	-7.538 ± 0.270
THI[a]	0.121 ± 0.003	0.134 ± 0.004
Wind speed, m/s	-0.241 ± 0.11	-0.412 ± 0.015
Solar radiation[b]	0.00095 ± 0.00008	0.000074 ± 0.00001

[a]THI = 0.8 x ambient temperature + (% relative humidity/100) * (ambient temperature – 14.3)) + 46.4.
[b]For 1400 to 1700 h, units are kcal/m^2/h, while for daily conditions coefficient would be for total daily radiation and units would be kcal/m^2.

On the basis of the ratios of WSPD and RAD to THI and average climatic conditions found during the period data were obtained, the adjusted THI derived from hourly conditions within a day, is equal to 4.51 + THI – (1.992 * WSPD) + (0.0079 * RAD). The adjusted daily THI, based on average daily climatic conditions is equal to 6.81 + THI – (3.075 * WSPD) + (0.00055 * RAD). The equation based on daily averages would most likely be used to predict THI for a future event using daily averages where the 1400 to 1700 hourly equation would be used for a current or “real-time” situation. Validation regression equations of THI adjusted for WSPD and RAD based on hourly (1400 to 1700) data are shown in Table 5. In Exp. 1, predicted panting score (1.15) was very close to observed mean panting score (1.22) with the correlation coefficients between observed mean panting score and actual THI and between observed panting score and adjusted THI were identical (r = 0.67). In Exp. 2, the new THI equation over predicted 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 were excellent at 0.8 or greater.

In Exp. 3, predicted panting score (1.30) was very close to 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. The correlation between actual panting score and the adjusted THI were all greater for non-Charolais cattle than the correlation between panting score and the actual THI. These data indicate that the THI equation adjusted for WSPD and RAD is very suitable for non-Charolais cattle.

Table 5. Correlation between actual THI and mean panting score and adjusted THI and mean panting score for various experiments and breeds of cattle.

	Mean panting score ± SD	Predicted panting score ± SD	Correlation	
			Actual THI	Adj THI
Exp. 1				
Angus crossbred	1.22 ± 0.55	1.15 ± 0.65	0.67	0.67
Exp. 2				
Angus crossbred	0.94 ± 0.42	1.17 ± 0.51	0.87	0.80
Exp. 3				
Angus	1.32 ± 0.89	1.30 ± 0.71	0.52	0.64
MARC III[a]	1.19 ± 0.95	1.30 ± 0.71	0.47	0.69
Gelbvieh	0.82 ± 0.77	1.30 ± 0.71	0.48	0.64
Charolais	0.73 ± 0.73	1.30 ± 0.71	0.54	0.53

[a]Crossbred cattle composed of Pinzgauer, Red Poll, Hereford, and Angus genotypes.

Since the initial experiments were conducted with mostly black cattle, the equation developed would have the best application for dark colored cattle. Also, over 75% of feedlot deaths due to 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.

In conclusion, when using hourly data, within a day, adjustments to the THI can be made by reducing the THI by 1.99 units for each 1 m/s increase in WSPD and by increasing THI 0.79 units for each 100 kcal/m^2 increase in RAD. In addition, close monitoring of weather variables is essential in determining the potential for environmental stress related complications in livestock operations (Mader and Davis, 2002). The Livestock Weather Safety Index has long been used as an indicator for potential heat stress related losses, however its applicability should be enhanced using adjustment to the THI for RAD and WSPD.

5. IMPLICATIONS

The most dominant environmental factors that influence visual signs of heat stress are not always the current environmental conditions. Instead, many nighttime climatic conditions including minimum THI and WSPD and maximum relative humidity, which often occurs at night, are important factors which influence heat stress experienced by cattle. While such relationships are more useful in predicting visual assessments of heat stress, they are not readily accessible by most livestock producers. Temperature-humidity index is easily obtainable when visual assessments of heat stress are being made. However, adjustments for WSPD and RAD are necessary to determine effective THI values.

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