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A new heat load index for feedlot cattle[1]

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ABSTRACT: The ability to predict effects of extreme climatic variables on livestock is important in terms of welfare and performance. An index combining temperature and humidity (THI) has been used for over 4 decades to assess heat stress in cattle. However, the THI does not include important climatic variables such as solar load and wind speed (WS; m/s). Likewise, it does not include management factors (the effect of shade) or animal factors (genotype differences). Over 8 summers a total of 11,669 *Bos taurus* steers, 2,344 *Bos taurus* crossbred steers, 2,142 *Bos taurus* x *Bos indicus* steers, and 1,595 *Bos indicus* steers were used to develop and test a heat load index for feedlot cattle. A new heat load index (HLI) incorporating black globe temperature (BG; °C), relative humidity (RH; decimal form) and WS has been initially developed using panting score (PS) of 2,490 Angus steers. The HLI consists of 2 parts based on a BG temperature threshold of 25 °C: $HLI_{BG>25} = 8.62 + (0.38 \times RH) + (1.55 \times BG) - (0.5 \times WS) + [e^{(2.4 - WS)}]$, and $HLI_{BG<25} = 10.66 + (0.28 \times RH) + (1.3 \times BG) - WS$. Where e = the base of the natural logarithm. A threshold HLI above which cattle of different genotypes gain body heat was developed for 7 genotypes. The threshold for unshaded black *Bos taurus* steers is 86 and for unshaded *Bos indicus* (100%) the threshold is 96. Threshold adjustments were developed for factors such as coat color, health status, access to shade, drinking water temperature, and manure management. Upward and downward adjustment are possible; upward adjustments occur where cattle have access to shade (+3 to +7) and downward when cattle are sick (-5). A related measure, the accumulated heat load (AHL) model also was developed following the development of the HLI. The AHL is a measure of the animals heat load balance and is determined by the duration of exposure above the threshold HLI. The THI and THI-hours (hours above a THI threshold) were compared to HLI and AHL. The relationship between tympanic temperature and the average HLI and THI for the previous 24 h were ($R^2 = 0.67$; $P < 0.001$) and ($R^2 = 0.26$; $P < 0.001$)

respectively. The R^2 between HLI and panting score, and AHL and PS were positive ($P < 0.001$). The R^2 were 0.93 and 0.92 for HLI and AHL respectively. The R^2 for THI was 0.61 ($P < 0.001$), and for THI-hours $R^2 = 0.37$ ($P < 0.001$). The HLI and the AHL are successful in predicting panting score responses of different cattle genotypes during periods of high heat load.

Key words: bioclimatic index, beef cattle, feedlot, heat stress

INTRODUCTION

Occasional periods of excessive ambient heat impact growth performance and welfare of feedlot cattle. The temperature humidity index (THI; Thom, 1959) has been widely used as an indicator of thermal stress in livestock (Ingraham et al., 1974; Ibrahim et al., 1975; Hahn and Mader, 1997; Gaughan et al., 1999), and forms the basis of the Livestock Weather Safety Index (LCI, 1970). However THI has limitations as it does not account for solar radiation or wind speed (St-Pierre et al., 2003; Brown-Brandl et al., 2005a; Mader et al., 2006). Various THI have been developed using dry bulb temperature in combination with wet bulb temperature, relative humidity or dew point (Buffington et al., 1981; Baeta et al., 1987; Roseler et al., 1997). Recently wind and solar radiation adjustments based on changes in respiratory dynamics (Mader et al., 2006), and a respiration rate index using dry bulb temperature, relative humidity, wind speed, and solar radiation (Eigenberg et al., 2005) have been developed.

Current indices do not account for cumulative effects of heat load, and/or natural cooling. Cattle may accumulate heat during the day (body temperature rises) and dissipate the heat at night. If there is insufficient night cooling, cattle may enter the following day with an ‘accumulated’ heat load (Hahn and Mader, 1997). The THI-hours model was developed to account for the impact of intensity x duration on thermal status (Hahn and Mader, 1997). Similarly St-Pierre et al. (2003) developed models using combinations of maximum THI, daily duration of heat stress, and a heat load index. Neither model accounts for air movement or solar radiation. Therefore, the objectives of this study were to develop and validate a new heat load index for cattle based on respiratory dynamics and tympanic temperature. Heat load thresholds were also determined for different genotypes, and an accumulated heat load model was developed to predict the heat balance of cattle.

MATERIALS AND METHODS

Heat Load Index Development

The use of animals in this study was approved by The University of Queensland Animal Ethics Committee in accordance with the Queensland Animal Care and Protection Act and the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes.

Data from 13 feedlots were used in this study. Ten of these were obtained from Australia (9 commercial and 1 research feedlot), and 3 from research feedlots in the USA. The data collection periods for the commercial Australian feedlots were: January to March 2000, 2002, 2004, 2005, and 2006. The research feedlot data collection occurred between January to February 2003 (Australia), and July to August 2002, 2004, and 2005 (USA). These data were used to develop and evaluate the heat load index (HLI).

Cattle (n = 2,490) for the initial data collection period (January to March 2000) period were selected for consistency in terms of genotype (black Angus), days on feed (100 d as of 1 January), BCS (4+) (based on the Australian body condition score of 1 lean to 5 very fat), no access to shade and sex (steers). This is the 'reference' animal. The predominant breed across all feedlots for the post 2000 studies was Angus (n = 6,585). Sixteen additional genotypes: Brahman (n = 1,403), Santa Gertrudis (n = 1,039), Hereford (n = 1,011), Waygu (n = 894), Hereford x

Angus (n = 704), Hereford x Brahman (n = 608), European-cross (with unidentified *Bos taurus*) (n = 587), European-cross (with unidentified *Bos indicus*) (n = 429), Angus x Charolais (n = 298), Charolais (n = 293), Santa Gertrudis x Charolais (n = 293), Shorthorn (n = 206), Droughtmaster (n = 192), Santa Gertrudis x Hereford (n = 191), Santa Gertrudis-cross (with unidentified *Bos indicus*) (n = 190) and Shorthorn x Hereford (n = 147) were used to evaluate the HLI. From these 7 genotypic categories were defined: *Bos taurus* (British), *Bos taurus* (European), Waygu, *Bos indicus* (25%, 50%, 75% or 100%). Factors considered in the development of the heat load model included, genotype, coat color, health status, access to shade, area of shade, days on feed, manure management, and drinking water temperature. Pen size, stocking rate, feed bunk space, water trough space, shade design, and area under shade were not standardized between feedlots.

The commercial feedlots ranged in capacities from 9,000 to 50,000 cattle. The Australian research feedlot had a capacity of 200 cattle. Two of the US research feedlots had capacities of 325 cattle and 1 had a capacity 720 cattle. Across all feedlots, stocking density varied from 12.5 to 22-m^2/animal. In feedlots that provided shade, the shaded areas varied from 1.1 to 5.3 m^2/animal (at 1200). Shade materials used included shade cloth (70 to 90 % solar block out), and steel (various combinations of open spacing between solid and open areas to solid shade). The height of the shade structures ranged from 2 to 5.4 m. Manure depth (mm) was measured at 5 feedlots (20 pens; 4,000 cattle). This was done by taking 5 measures from front to rear of a pen at approximately 15 m intervals. Measures were made at the start, approximately mid way, and end of the data collection period. Values were then averaged. Drinking water temperature was measured at 3 feedlots (6 pens; 1,080 unshaded Angus steers) at approximately 1000, 1200, 1400, and 1600 on days when cattle were heat stressed. Water temperature was measured using a thermistor attached to a data logger (YSI 400, Mini-Mitter, Sun River, OR).

Automated weather stations were located at each feedlot. At each location air temperature (^{o}C; T_a), solar radiation (Watts/m), wind speed (m/s), relative humidity (%) and black globe temperature (BG) (^{o}C) were recorded at 10-min intervals. Rainfall (mm) was also recorded. From 2000 to 2002 the temperature humidity index (THI) was calculated for each weather station. The THI was calculated using the following equation THI = (0.8 x ambient temperature + [(relative humidity/100) × (ambient temperature – 14.4)] + 46.4] (adapted from Thom, 1959). In addition THI-hours were calculated using the method of Hahn and Mader (1997). After 2002, in addition to THI and THI-hours, the new HLI and accumulated heat load units were calculated (see below for details).

Within each commercial data set, the panting scores (Table 1) of cattle were recorded for 54 d. Cattle were assessed 3 times each d at approximately 0600, 1200, and 1600. Thus approximately 162 observations were made per animal. During periods of extreme weather, observations were made at 2-h intervals between 0600 and 1800. Panting score was the key physiological and behavioral factor used in development of the HLI, and in establishing the heat load thresholds. Mean panting score was calculated according to the following formula;

$$\text{Panting Score} = \frac{\sum_{i=0}^{4.5} N_i \times i}{\sum_{i=0}^{4.5} N_i \times i} \qquad \text{Eq. 1}$$

where N_i = the number of cattle observed at panting score i.

Additional data collected at the research feedlots was respiration rates (15-min intervals; Australian facility) and panting scores at 2-h intervals from 0600 to 1800. Tympanic temperatures were recorded from cattle (n = 90) at the US 720 capacity feedlot at 30-min intervals over three 6 d heat waves, from 80 cattle at the US 325 capacity feedlots at 30-min intervals and from 20 cattle at the Australian research feedlot at 15-min intervals on four 5 d heat waves. Tympanic temperature was measured using the procedure of Mader et al. (2002). The thermistors remained in the ear for a maximum of 7 d.

Development of Thresholds

Following development of the HLI a threshold value for the reference animal was developed. The HLI value at which body heat is readily dissipated to the environment is influenced by a number of factors. The major non climatic factors which influence heat dissipation were identified and HLI thresholds were determined for these factors. Data collected after the first study in 2000 were used to identify the major thresholds. The major thresholds were identified as genotype (*Bos taurus*, *Bos indicus* and crossbred cattle), coat color (black, red and white), health status, degree of acclimatization, access to shade, area of shade available, days on feed, depth of manure, and water trough temperature. The influence of previously mentioned factors on alleviating or contributing to heat load was assessed primarily on changes in mean panting score. Adjustments to the reference animal threshold (positive or negative) were made on the basis of ≥ 20 % of cattle in a pen having a panting score ≥ 1. This value was determined on the basis that the majority of reference cattle in a pen move from a panting score of 1 to 2 very quickly when more than 20% of the cattle in a pen have a panting score of 1.

Accumulated Heat Load Model Development

Following the development and validation of the HLI the accumulated heat load model (AHL) was developed. The AHL is a 2 dimensional function incorporating time and animal heat balance (the amount of time that the animal is exposed to a HLI above its threshold, the upper threshold). When this occurs, the animal is not dissipating sufficient body heat to the environment and therefore core body temperature increases above its normal range. Alternatively, if the HLI falls below the upper threshold, then the animal is able to dissipate body heat to the environment, and core body temperature will return to the normal range. The threshold value is genotype specific and is also affected by management factors such as access to shade and drinking water temperature. The upper threshold is defined as the HLI where ≥ 20 % of un-shaded cattle had a panting score > 1.

Statistical Analysis

Due to the uneven number of animals per pen within and across feedlots all observational data were converted from the actual observation number to the proportion of animals in the pen. For statistical analysis the percentages of cattle recorded for each panting score measure (within a feedlot, and then within a genotype across and within feedlots) were transformed to a normalized distribution using squared root-arcsine transformation.

The HLI was developed using regression analysis (PROC REG, RSREG) (SAS Inst., Inc., Cary, NC). The regression analysis was used to determine the relationship between mean panting score (2,490 cattle; 403,380 observations) and climatic parameters (ambient temperature, relative humidity, wind speed, solar radiation, and BG temperature). Solar radiation and ambient temperature were eliminated from the model by the backward elimination procedure.

Based on the statistical analysis of panting score (4,200 observations) and body temperature (3,148 observations) data of unshaded Angus steers (n = 190) at the research feedlots, the HLI was divided into 4 categories: (1) thermoneutral conditions, when the HLI is < 70.0; (2) warm conditions, when the HLI is 70.1 to 77.0; (3) hot conditions, when the HLI is 77.1 to 86.0; and, (4) very hot, when HLI is > 86.0. Accumulated heat load was divided into 5 categories: (1) thermoneutral conditions, when the AHL is < 1; (2) mild conditions, when the AHL is 1 to 10; (3) warm conditions, when the AHL is 10.1 to 20; (4) hot conditions when the AHL is 20.1 to 50; and, (5) very hot, when the AHL is > 50. These thresholds were identified by fitting polynomial equations using PROC REG. The thresholds identify marked upward or downward shifts in panting score and body temperature of unshaded Angus steers.

The panting score data from the post 2000 studies were analyzed using Chi-Square analysis, PROC CORR, PROC NLIN, PROC SORT, PROC MIXED, PROC REG and PROC GLM options of SAS. The models used were the effects of HLI, AHL, HLI category, AHL category, THI and THI-hours on panting scores (14,481 cattle; 1,563,948 observations). Pen effects were considered where the same genotype was in shaded and unshaded pens within a feedlot. Interactions between genotype, pen, time of day (0601 to 1200; 1201 to 1700; 1701 to 0600), HLI, AHL, THI and THI-hours were analyzed and the effect of those individual variables on panting scores were determined. Statistical models for mean panting score included genotype × feedlot × pen × HLI × time of day, genotype × feedlot × pen × AHL × time of day. The HLI × AHL category interactions on panting score was also investigated. Similar models were used for THI and THI-hours. Independent data sets comprising 1200 to 1800 observations were used to validate the HLI, AHL and the threshold values.

Tympanic temperature data (3,148 observations) where analyzed using Fourier frequencies. Each 30 min time point represents a proportion of a complete cycle. The linear regression model (PROC REG) used was as follows:

$$Y = B_0 + B_1 \sin(2\pi \times h / 24) + B_2 \cos(2\pi \times h / 24) \qquad \text{Eq. 2}$$

where h = time in hours.

A fraction of a d (h / 24) is multiplied by 2π, which translates the time into radians. Having both sine and cosine components allows the cycle to shift left or right as required. The intercept B_0 estimates the average temperature around which the cycle oscillates.

When Fourier frequencies are fitted, the model becomes:

$$Y = B_0 + B_1 \sin(2\pi \times h / 24) + B_2 \cos(2\pi \times h / 24) + B_3 \sin(4\pi \times h / 24) + B_4 \cos(4\pi \times h / 24) \qquad \text{Eq. 3}$$

This equation adjusts the diurnal cycle by making the oscillations in tympanic temperature less symmetric.

The parameter associated with HLI in the regression models is thus the elevation in tympanic temperature for each 'unit' of heat load. An increase of 10 in the HLI should result in an increase of 0.3 °C in tympanic temperature.

RESULTS

Heat Load Index

Analysis of the panting score data determined that there was a BG temperature threshold (25 °C) above which panting score increased from 0 to 1 by ≥ 20% of the cattle. Two multiple regression models were developed using the panting score data from unshaded Angus steers (n = 2,490). The first model (Eq. 4) was a non-linear regression model which was applied when black globe temperature was greater than 25 °C. The second linear model (Eq. 5) applies when black globe temperature is less than 25 °C. Both models were developed using relative humidity (in decimal form), BG temperature and wind speed. All parameters were significant ($P < 0.001$).

$$HLI_{BG>25} = 8.62 + (0.38 \times \text{relative humidity}) + (1.55 \times \text{BG temperature}) - (0.5 \times\text{x wind speed}) + [e^{(2.4 - \text{wind speed})}] \qquad \text{Eq. 4}$$

$$HLI_{BG<25} = 10.66 + (0.28 \times \text{relative humidity}) + (1.3 \times \text{BG}) - \text{wind speed} \qquad \text{Eq. 5}$$

Where e = the base of the natural logarithm (approximate value of e = 2.71828)

Accumulated Heat Load

For the reference animal the upper threshold at which the animal "accumulates" heat was established at HLI = 86 and the lower threshold was 77. For a Brahman the upper threshold was defined as HLI = 96 (Table 2). Over a 24-h period the AHL may be increasing or may be decreasing. However the AHL value does not fall below zero. A zero value indicates that the animal is in thermal balance. The following equation was used to calculate the AHL;

$$\text{IF}\ (HLI_{ACC} < HLI_{\text{Lower Threshold}},\ (HLI_{ACC} - HLI_{\text{Lower Threshold}})/M,\ \text{IF}\ (HLI_{ACC} > HLI_{\text{Upper Threshold}},\ (HLI_{ACC} - HLI_{\text{Upper Threshold}})/M,\ 0)) \qquad \text{Eq. 6}$$

Where HLI_{ACC} = the actual HLI value at a point in time; $HLI_{\text{Lower Threshold}}$ = the HLI threshold below which cattle in a particular class will dissipate heat e.g. 77 for the reference animal; $HLI_{\text{Upper Threshold}}$ = the HLI threshold above which cattle in a particular class will gain heat e.g. 86 for the reference animal; and M = measures per h i.e. how often HLI data is collected per h. If every 10 min then M = 6.

Development of Threshold Adjustments

The critical HLI threshold value of 86 was determined based on panting score observations (n = 4,200) of unshaded Angus steers. However, the HLI value at which body heat is dissipated to the environment is influenced by a number of factors including but not limited to genotype, coat color, health status, degree of acclimatization and access to shade. The influence of the previously mentioned factors on alleviating or contributing to heat load was assessed primarily on changes in mean panting score. Adjustments (either positive or negative) were made on the basis of ≥ 20 % of cattle in a pen having a panting score > 1. Adjustments to the reference threshold were made and new thresholds for the different management strategies and genotypes observed were developed (Table 2). A positive value indicates that the threshold has been increased, and a negative value indicates that the threshold has been reduced. For example, the HLI threshold for purebred *Bos indicus* is 96 (86 + 10). The threshold for these animals may be greater than 96 however there is not sufficient data where HLI > 95.

Relationships Between Mean Panting Score, HLI, and AHL

Effects of HLI category on the panting scores of 6 genotypes are presented in Table 3. Both HLI and AHL had an effect ($P < 0.001$) on MPS. The R^2 were high at 0.93 and 0.92 for HLI and AHL, respectively. The R^2 for THI was 0.6 ($P < 0.001$), and 0.37 ($P < 0.001$) for THI-hours. The HLI x AHL interactions were a good predictor but only slightly better than HLI on its own ($P < 0.001$; $R^2 = 0.92$) of panting score (all genotypes) when pen within feedlot and feedlot location were considered. The effect of the HLI x AHL on Angus and Brahman steers are presented in Figures 1 and 2 respectively.

The Brahman cattle were less affected than Angus by the HLI and AHL encountered (Figure 2), nevertheless they were not immune to extreme conditions. Increased panting scores were observed when AHL exceed 10 and HLI was greater than 86. However, the percentage of Brahman with a panting score of 0 was higher ($P < 0.05$) when compared to Angus exposed to similar climatic conditions.

Tympanic Temperature

The relationship between tympanic temperature and the average HLI for the previous 24 h was moderate ($R^2 = 0.67$; $P < 0.001$), and was considerably better than the relationship between tympanic temperature and THI ($R^2 = 0.26$; $P < 0.001$). A linear model was developed for tympanic temperature using time and the average HLI over the previous 24 h (Eq.7).

$$TT = 37.12 - 0.45 \times \sin T + 0.09 \times \cos T + 0.13 \times \sin^2 T - \cos^2 T \times 0.02 + 0.03 \times HLI_{24} \qquad \text{Eq. 7}$$

where TT = tympanic temperature; T = hour of the day in half hour increments (1300 = 13, 1330 = 13.5, 0100 = 1); and HLI_{24} = the average HLI over the previous 24 h.

DISCUSSION

High heat load in feedlot cattle is a result of local climatic conditions and animal factors which lead to an increase in body heat content beyond the animals' normal physiological range and its ability to cope. By using a combination of observed local climatic conditions and animal responses to the climate (panting scores) feedlot management will be able to implement strategies to reduce the impact of severe hot weather conditions.

Development of a thermal stress index for cattle should be based on biological factors (Nienaber et al., 1999; Hahn et al., 2003). The need for a large data set to develop and test an index necessitates that the biological parameter used must be easy to measure and be a good indicator of heat load. Behavioral changes are reliable indicators of heat load status. Feedlot location, feedlot layout and pen microclimate influence the behavior of cattle (Castaneda et al., 2004). However, measuring climatic conditions within pens is difficult, and not practical under most conditions. Therefore location of a weather station at a feedlot needs to be representative of the average climatic conditions to which cattle are exposed. Changes in DMI when cattle are exposed to hot conditions have been well documented (NRC, 1981; Roseler et al., 1997; Holt et al., 2004). However on its own DMI is not a good indicator of heat load status. Body temperature and respiration rate are reliable indicators of heat load but are difficult to measure under field conditions (Hahn et el., 1997; Gaughan et al., 2000; Gaughan et al., 2002; Brown-Brandl et al., 2005b) especially where large numbers of animals are involved. An alternative method is the use of panting scores (Mader et al., 2001). Panting scores have been used to evaluate the heat load status of feedlot cattle under commercial and research conditions, and are a reliable indicator of heat load status (Mader et al., 2001, 2006; Davis et al., 2001; Gaughan et al., 2002; Gaughan, 2004; Brown-Brandl et al., 2006). In the current study panting scores served as the basis for the development of the HLI.

There are temperature thresholds above which respiration rate and panting score increase. The thresholds are somewhat genotype specific. Threshold values are defined as the climatic values, in this case HLI values which trigger a response (Hahn et al., 1992; St-Pierre et al., 2003). In the present study a threshold of 25 ^{o}C (black globe temperature) was determined for increasing respiration rates. A lower value (21 ^{o}C; dry bulb temperature) was reported by Brown-Brandl et al. (2006). Similar threshold values for respiration rate have been reported by Hahn et al. (1997) (21 ^{o}C; dry bulb temperature) and Eigenberg et al. (2005) with a threshold range of 25 to 30 ^{o}C (dry bulb temperature).

Cattle adjust physiologically, behaviorally, and immunologically to minimize the adverse effects of thermal stress (Johnson, 1987; Hahn, 1999). Factors such as nutrition (Hahn et al., 1990; Hahn and Nienaber, 1993; Mader et al., 1999b; Mader et al., 2001; Gaughan et al., 2004; Holt et al., 2004), health status (Morrow-Tesch and Hahn 1994; Brown-Brandl et al. 2006), BCS (Brown-Brandl et al., 2006), genotype/phenotype (Hammond et al., 1996, Hammond et al., 1998; Gaughan et al., 1999; Brown-Brandl et al., 2006), magnitude of exposure (Hahn and Mader, 1997), and housing (Mader et al., 1999a; Mitlöhner et al., 2001) affect the responses of cattle when faced with a thermal challenge. Development of a predictive model which takes into account all the factors that are likely to affect heat tolerance is difficult (Nienaber et al., 1999). The HLI model can explain 93 % of the variation in panting score and is a good predictor of the thermal status of various genotypes. As expected British breeds (Angus and Hereford) had lower heat tolerance than Brahman and Waygu (Table 3). The percentage of cattle with a panting score of 0 decreased (more cattle had elevated panting scores) as the HLI categories moved through each stage from thermoneutral to very hot, except for Brahman and Waygu where the percentage did not decrease until the very hot conditions were encountered. These data show that there are differences between genotypes, and therefore a single value to predict or measure the impact of heat stress is not valid.

The existing indicis (THI) use a 1 dimensional approach, the thermal situation at a point in time (intensity only). They do not take into account the effect of exposure (duration) to adverse thermal conditions. Furthermore there is no genotype distinction, so it is assumed that all cattle respond the same. As such THI may under or overestimate the effect of an adverse heat event especially if night time conditions are not considered. Nighttime recovery (or a lack of) is an important element when assessing heat load status of cattle (Hahn and Mader, 1997). If nighttime conditions are not considered the heat load status of cattle may be under estimated. If the day following a heat event is cool then underestimation is not critical. However, if the following day is hot (HLI > threshold) then cattle may enter the day with a carry over heat load and may be susceptible to heat stress at lower HLI values than expected. In addition, Hahn et al. (1997) and Gaughan et al. (2000) reported that respiration rate may lag dry bulb temperature by up to 3 h when cattle are housed in climate chambers. A lag of 1 h for cattle housed in a feedlot was reported by Brown-Brandl et al. (2005b). It is clear that current ambient conditions may not have an immediate impact on the animal.

On a daily basis cattle may be subjected to a HLI greater than 86 and yet have an AHL less then 1. In addition cattle may be exposed to a HLI less than 70 but have an AHL greater than 50. In both cases panting score will be elevated for *Bos taurus* cattle (Figure 1). Cattle observed in the afternoon of a hot day continue to have elevated panting scores even if HLI has decreased below the threshold, especially where they have considerable accumulated heat. This comes about because the cattle have not had sufficient time to off load the excessive heat gained during the day.

In conclusion, development of a dynamic thermal index will improve animal management during periods of adverse weather. The AHL model takes into account the magnitude of exposure (intensity x duration), genotype/phenotype, coat color, degree of acclimatization and access to shade. The AHL index can be adjusted (by feedlot management) by using thresholds based on animal responses to observed conditions. Adjustments can be made on a pen by pen basis if required (newly arrived cattle verses 150-d on feed cattle). An on-site weather station will improve the accuracy of the HLI and AHL for a particular site.

The HLI and AHL have been incorporated into a web based heat load model (www.katestone.com.au) which allows feedlot managers to input their location, cattle type, days on feed, health status, and heat alleviation strategies such as shade and manure management. Based on these inputs a heat risk assessment is calculated. The model uses historical weather data for the specified locations. However potential risk can also be calculated using current weather conditions. A 6-d forecast is also provided. The model is dynamic and, as results from future studies involving both beef and dairy cattle, and feed back from users are obtained adjustments will be made.

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Table 1. Panting score, breathing condition and associated respiration rate

Panting Score	Breathing Condition
0	No panting.
1	Slight panting, mouth closed, no drool, easy to see chest movement.
2	Fast panting, drool present, no open mouth.
2.5	As for 2, but occasional open mouth panting, tongue not extended.
3	Open mouth and excessive drooling, neck extended, head held up.
3.5	As for 3 but with tongue out slightly and occasionally fully extended for short periods.
4	Open mouth with tongue fully extended for prolonged periods with excessive drooling. Neck extended and head up.
4.5	As for 4 but head held down. Cattle “breath” from flank. Drooling may cease.

(Modified from Mader et al., 2006).

Table 2. Animal (genotype, coat color, health status, acclimatization) and management (access to shade, days on feed, manure management and drinking water temperature) adjustments (+ and -) to the heat load index (HLI) threshold (86) of the reference steer (healthy unshaded Angus, 100 days on feed).

Item	Number of cattle[1] used to determine the specific threshold	Relative effect on upper HLI threshold of the reference steer (HLI = 86)
Genotype:		
Bos taurus (British)	9,075	0[2]
Bos taurus (European)	429	+ 3 (i.e. 86 + 3)
Waygu	894	+ 4
Bos indicus (25%)	451	+ 4
Bos indicus (50%)	1,345	+ 7
Bos indicus (75%)	1,039	+ 8
Bos indicus (100%)	666	+ 10
Coat Color:		
Black	2,859	0
Red	1,158	+ 1
White	293	+ 3
Health Status:		
Healthy	15,623	0
Sick/recovering	1,987	- 5
Acclimatization:		
Acclimated	6,200	0
Not acclimated	2,920	- 5
Shade:[3]		
No Shade	3,467	0
Shade (>1.5 – 2 m^2/animal)	1,336	+ 3
Shade (>2.0 – 3 m^2/animal)	6,473	+ 5
Shade (>3.0 m^2/animal)	4,761	+ 7
Days on Feed:[4]		
0 – 80 d	2,672	+ 2
80 – 130 d	8,385	0
130 + d	1,239	- 3
Manure Management:[5]		
Max. depth of manure pack = 50 mm	3,224	0
Max. depth of manure pack = 100 mm	704	- 4
Max. depth of manure pack = 200 mm	220	- 8
Drinking Water Temperature:[6]		
15 to 20 °C	224	+ 1
21 to 30 °C	2,035	0
31 to 35 °C	399	- 1
>35 °C	201	- 2

[1]Not all cattle have been assessed within each threshold trait. For example, coat color was only assessed in *Bos taurus* cattle, manure management at 5 feedlots and drinking water temperature was assessed on 3 feedlots.

[2] The values for the reference steer are presented as 0 i.e. no change from the threshold of 86.
[3] For shade that provides 70% block out (includes shade cloth and also steel structures with gaps in the roof). Unshaded *Bos indicus* cattle > 25 % not included.
[4]Not all cattle were assessed for this trait. Waygu cattle excluded from 130 + d.
[5] Mean depth over 54 d.
[6] Only unshaded Angus cattle were assessed for this trait.

Table 3. Panting scores (%) for 6 genotypes when HLI is categorised as thermonuetral (TNC), warm, hot or very hot

		Panting Scores[2]					
Genotype	HLI[1]	0	1	2	2.5	3	≥ 3.5
Angus	TNC	92.96[a]	6.65[a]	0.36[a]	0.03	0	0
(shade)	Warm	83.31[a]	13.66[a]	2.89[a]	0.14[a]	< 0.01	0
(n = 4,210)	Hot	74.92[a]	23.41[a]	1.61[a]	0.06[a]	0[a]	0[a]
	Very Hot	43.91[a]	37.77[a]	14.46[a]	3.12[a]	0.68[a]	0.06[a]
Angus	TNC	89.41[a]	10.11[a]	0.48[a]	0	0	0
(no shade)	Warm	55.11[c]	32.68[c]	11.21[a]	1.0[a]	0	0
(n = 2,859)	Hot	47.62[c]	11.16[c]	21.22[a]	13.22[b]	3.00[b]	3.78[b]
	Very Hot	33.91[a]	28.00[b]	19.09[a]	16.00[b]	1.00[a]	2.00[b]
Brahman	TNC	100.00[b]	0[b]	0[b]	0	0	0
(shade)	Warm	99.99[b]	0.01[b]	0[b]	0	0	0
(n = 657)	Hot	99.42[b]	0.58[b]	0[b]	0	0	0
	Very Hot	99.09[d]	0.91[d]	0[b]	0[b]	0	0
Brahman	TNC	99.84[b]	0.16[b]	0[b]	0	0	0
(no shade)	Warm	99.60[b]	0.40[b]	0[b]	0	0	0
(n = 746)	Hot	99.12[b]	0.88[b]	0[b]	0	0	0
	Very Hot	79.69[b]	19.55[b]	0.64[b]	0.09[b]	0.03	0
Hereford	TNC	88.55[a]	11.44[a]	0.01[b]	0	0	0
(shade)	Warm	49.37[c]	44.22[c]	6.13[a]	0.28	0	0
(n = 612)	Hot	42.06[c]	43.31[c]	13.68[b]	0.82[a]	0.14	0
	Very Hot	19.47[c]	54.31[c]	23.21[c]	2.69[a]	0.32	0
Brahman x	TNC	100.00[b]	0[b]	0[b]	0	0	0
Hereford	Warm	100.00[b]	0[d]	0[b]	0	0	0
(no shade)	Hot	99.81[b]	0.19[b]	0[b]	0	0	0
(n = 608)	Very Hot	96.39[d]	3.61[d]	0[d]	0[b]	0	0
Angus x	TNC	89.52[a]	10.37[a]	0.08[b]	0.03	0	0
Hereford	Warm	78.52[d]	21.34[a]	0.14[c]	0	0	0
(shade)	Hot	60.03[d]	39.84[c]	0.13[c]	0	0	0
(n = 704)	Very Hot	35.30[a]	53.58[c]	8.68[e]	2.07[a]	0.34	0.03
Waygu	TNC	98.90[b]	1.1[b]	0[b]	0	0	0
(shade)	Warm	100.00[b]	0[d]	0[b]	0	0	0
(n = 894)	Hot	97.87[b]	2.13[d]	0[b]	0	0	0
	Very Hot	94.12[d]	5.88[d]	0[d]	0[c]	0	0

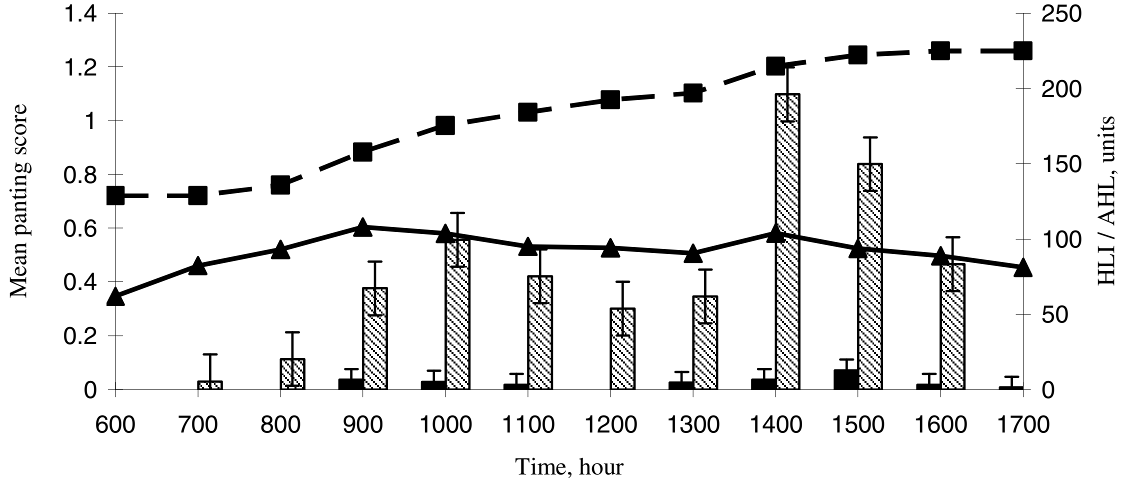
Means in a column (within HLI category, e.g. HOT only compared to HOT) with the same superscript are not significantly different ($P > 0.05$). Where significant all P-values < 0.01. If no superscripts are shown there was insufficient data to undertake analysis.

[1]$HLI_{BG>25} = 8.62 + (0.38 \times RH) + (1.55 \times BG) - (0.5 \times WS) + [e^{(2.4 - WS)}]$; $HLI_{BG<25} = 10.66 + (0.28 \times RH) + (1.3 \times BG) - WS$.

[2]Cattle with a panting score > 1 are considered to be stressed.

[3]TNC, HLI < 70; Warm, HLI > 70 < 77; Hot, HLI > 77 < 86; Very Hot, HLI > 86.

Figure 1. The mean hourly panting score of un-shaded Angus (stripped bars) and un-shaded Brahman steers (solid bars) and the mean hourly heat load index (▲, HLI[1]) and accumulated heat load (■, AHL[2]) between 0600 and 1700 on a day classified as very hot (HLI > 86; AHL > 50). [1]$HLI_{BG>25} = 8.62 + (0.38 \times RH) + (1.55 \times BG) - (0.5 \times WS) + [e^{(2.4 - WS)}]$; $HLI_{BG<25} = 10.66 + (0.28 \times RH) + (1.3 \times BG) - WS$. [2] The AHL is a 2 dimensional function incorporating time and animal heat balance i.e. the amount of time that the animal is exposed to a HLI above a threshold (i.e. the threshold for an un-shaded Angus is 86).


Mean panting score
1.4
1.2
1
0.8
0.6
0.4
0.2
0
HLI / AHL, units
250
200
150
100
50
0
600 700 800 900 1000 1100 1200 1300 1400 1500 1600 1700
Time, hour