2008

A New Heat Load Index for Feedlot Cattle

J. B. Gaughan
*The University of Queensland, Gatton, Queensland, Australia*

Terry L. Mader
*University of Nebraska - Lincoln, tmader1@unl.edu*

S. M. Holt
*Hubbard Feeds Inc., PO Box 8500, Mankato, MN*

A. Lisle
*University of Queensland, Gatton, Queensland, Australia*

Follow this and additional works at: [http://digitalcommons.unl.edu/animalscifacpub](http://digitalcommons.unl.edu/animalscifacpub)

Part of the [Animal Sciences Commons](http://digitalcommons.unl.edu/animalscifacpub)


[http://digitalcommons.unl.edu/animalscifacpub/613](http://digitalcommons.unl.edu/animalscifacpub/613)

This Article is brought to you for free and open access by the Animal Science Department at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Faculty Papers and Publications in Animal Science by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.
A new heat load index for feedlot cattle

J. B. Gaughan,*2 T. L. Mader,† S. M. Holt,‡ and A. Lisle*

*The University of Queensland, Gatton, Queensland, Australia, 4343; †Haskell Agricultural Laboratory, University of Nebraska-Lincoln, 57905 866 Rd., Concord 68728; and ‡Hubbard Feeds Inc., PO Box 8500, Mankato, MN 56002-8500

ABSTRACT: The ability to predict the 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 more than 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 B. taurus crossbred steers, 2,142 B. taurus × Bos indicus steers, and 1,595 B. indicus steers were used to develop and test a heat load index (HLI) for feedlot cattle. A new HLI incorporating black globe (BG) temperature (°C), relative humidity (RH, decimal form), and WS was initially developed by using the panting score (PS) of 2,490 Angus steers. The HLI consists of 2 parts based on a BG temperature threshold of 25°C: HLIBG>25 = 8.62 + (0.38 × RH) + (1.55 × BG) − (0.5 × WS) + e^(2.4−WS), and HLIBG<25 = 10.66 + (0.28 × RH) + (1.3 × BG) − WS, where e is 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 B. taurus steers was 86, and for unshaded B. indicus (100%) the threshold was 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 adjustments are possible; upward adjustments occur when cattle have access to shade (+3 to +7) and downward adjustments occur when cattle are showing clinical signs of disease (−5). A related measure, the accumulated heat load (AHL) model, also was developed after the development of the HLI. The AHL is a measure of the animal’s 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 with the HLI and AHL. The relationships between tympanic temperature and the average HLI and THI for the previous 24 h were R² = 0.67, P < 0.001, and R² = 0.26, P < 0.001, respectively. The R² for the relationships between HLI or AHL and PS was positive (0.93 and 0.92 for HLI and AHL, respectively, P < 0.001). The R² for the relationship between THI and PS was 0.61 (P < 0.001), and for THI-hours was 0.37 (P < 0.001). The HLI and the AHL were successful in predicting PS 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 affect the 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 the THI forms the basis of the Livestock Weather Safety Index (Livestock Conservation Incorporated, 1970). However, the THI has limitations because it does not account for solar radiation or wind speed (St-Pierre et al., 2003; Brown-Brandl et al., 2005b; Mader et al., 2006). Various THI have been developed by using dry bulb temperature in combination with wet bulb temperature, relative humidity, or dew point (Buffington et al., 2003a).
an AHL model was developed to predict the heat balance
and validate a new HLI for cattle based on respiratory
dynamics and tympanic temperature. Heat load thresh-
olds were also determined for different genotypes, and
heat load index (HLI) (Hahn and Mader, 1997). Similarly, St-Pierre et al. (2003) developed models using combinations of the
maximum THI, daily duration of heat stress, and a
heat load index (HLI). Neither model accounts for air
movement or solar radiation.

Therefore, the objectives of this study were to develop
and validate a new HLI for cattle based on respiratory
dynamics and tympanic temperature. Heat load thresh-
olds were also determined for different genotypes, and
an AHL model was developed to predict the heat bal-
ance of cattle.

MATERIALS AND METHODS

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.

HLI Development

Data from 13 feedlots were used in this study. Ten
of these data sets were obtained from Australia (9 com-
mercial feedlots and 1 research feedlot) and 3 were
obtained from research feedlots in the United States.
The data collection periods for the commercial Austra-
lian feedlots were January to March 2000, 2002, 2004,
2005, and 2006. Data collection for the research feedlots
occurred from January to February 2003 (Australia) and
from July to August 2002, 2004, and 2005 (United
States). These data were used to develop and evaluate
the HLI.

Cattle (n = 2,490) for the initial data collection period
(January to March 2000) were selected for consistency
in terms of genotype (black Angus), days on feed (100
d as of January 1), BCS (4+; based on the Australian
body condition score of 1 = lean to 5 = very fat), no
access to shade, and sex (steers); this was 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 Ger-
trudis (n= 1,039), Hereford (n= 1,011), Waygu (n =
894), Hereford × Angus (n = 704), Hereford × Brahman
(n = 608), European-cross (with unidentified Bos taurus;
n = 587), European-cross (with unidentified Bos indi-
cus; n = 429), Angus × Charolais (n = 298), Charolais
(n = 293), Santa Gertrudis × Charolais (n = 293), Short-
horn (n = 206), Droughtmaster (n = 192), Santa Gertrud-
is × Hereford (n = 191), Santa Gertrudis-cross (with
 unidentified B. indicus; n = 190), and Shorthorn × Here-
ford (n = 147), were used to evaluate the HLI. From
these, 7 genotypic categories were defined: B. taurus
(British), B. taurus (European), Waygu, and B. indicus
(25, 50, 75, or 100%). Factors considered in the develop-
ment 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,
watertrough space, shade design, and area under shade
were not standardized among feedlots.

The commercial feedlots ranged in capacity 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
of 720 cattle. Across all feedlots, stocking densities var-
ied from 12.5 to 22 m²/animal. In feedlots that provided
shade, the shaded areas varied from 1.1 to 5.3 m²/ani-
mal (at 1200). Shade materials used included shade
cloth (70 to 90% solar block) and steel (various combina-
tions 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 the front to the rear of a pen
at approximately 15-m intervals. Measures were made
at the beginning, approximately midway, and at the end
of the data collection period. Values were then aver-
aged. 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 by 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 (Ta, °C), solar
radiation (W/m²), wind speed (m/s), relative humidity
(%), and black globe (BG) temperature (°C) were re-
corded at 10-min intervals. Rainfall (mm) was also re-
corded. From 2000 to 2002, the THI was calculated for
each weather station by using the following equation:

\[
\text{THI} = (0.8 \times \text{ambient temperature}) + \left[\left(\frac{\text{relative humidity}}{100}\right) \times (\text{ambient temperature} - 14.4)\right] + 46.4
\]

(adapted from Thom, 1959). In addition, THI-hours
were calculated by using the method of Hahn and
Mader (1997). After 2002, in addition to THI and THI-
hours, the new HLI and AHL 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 day 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...
Table 1. Panting score, breathing condition, and the associated respiration rate

<table>
<thead>
<tr>
<th>Panting score</th>
<th>Breathing condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No panting.</td>
</tr>
<tr>
<td>1</td>
<td>Slight panting, mouth closed, no drool, easy to see chest movement.</td>
</tr>
<tr>
<td>2</td>
<td>Fast panting, drool present, no open mouth.</td>
</tr>
<tr>
<td>2.5</td>
<td>As for 2, but occasional open mouth panting, tongue not extended.</td>
</tr>
<tr>
<td>3</td>
<td>Open mouth and excessive drooling, neck extended, head held up.</td>
</tr>
<tr>
<td>3.5</td>
<td>As for 3 but with the tongue out slightly and occasionally fully extended for short periods.</td>
</tr>
<tr>
<td>4</td>
<td>Open mouth with tongue fully extended for prolonged periods with excessive drooling. Neck extended and head up.</td>
</tr>
<tr>
<td>4.5</td>
<td>As for 4 but head held down. Cattle “breathe” from the flank. Drooling may cease.</td>
</tr>
</tbody>
</table>

1Modified from Mader et al. (2006).

and 1800. Panting score was the key physiological and behavioral factor used in the development of the HLI and in establishing the heat load thresholds. Mean panting score was calculated according to the following formula:

\[
panting \text{ score} = \frac{\sum_{i=0}^{4.5} N_i \times i}{\sum_{i=0}^{4.5} N_i}, \tag{1}
\]

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

Additional data collected at the research feedlots were respiration rates (15-min intervals; Australian facility) and panting scores at 2-h intervals from 0600 to 1800. Tympnic 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. Tympnic temperature was measured by using the procedure of Mader et al. (2002). The thermistors remained in the ear for a maximum of 7 d.

**Development of Thresholds**

After development of the HLI, a threshold value for the reference animal was developed. The HLI value at which body heat is readily dissipated into the environment is influenced by a number of factors. The major nonclimatic factors that 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 (\( B. taurus, B. indicus, \) 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 \( \geq 20\% \) of the cattle in a pen having a panting score of \( \geq 1 \). This value was determined on the basis of the majority of reference cattle in a pen moving from a panting score of 1 to 2 very quickly when more than \( 20\% \) of the cattle in a pen had a panting score of 1.

**AHL Model Development**

Following the development and validation of the HLI, the AHL model was developed. The AHL is a 2-dimensional function incorporating time and animal heat balance (the amount of time the animal is exposed to an HLI above its threshold, the upper threshold). When this occurs, the animal is not dissipating sufficient body heat into 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 into 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 was defined as the HLI, where \( \geq 20\% \) of unshaded cattle had a panting score of \( \geq 1 \).

**Statistical Analysis**

Because of 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 by using a square root-arcsine transformation.

The HLI was developed by 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 conditions, 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 conditions, when the AHL is >50. These thresholds were identified by fitting polynomial equations by using PROC REG. The thresholds identified 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 by using \( \chi^2 \) analysis and the PROC CORR, PROC NLIN, PROC SORT, PROC MIXED, PROC REG, and PROC GLM options of SAS. The models were used for the effects of HLI, AHL, HLI category, AHL category, THI, and THI-hours on panting scores were determined. Statistical models for mean panting score included genotype \( x \) feedlot \( x \) time of day and genotype \( x \) feedlot \( x \) time of day and genotype \( x \) feedlot \( x \) time of day and genotype \( x \) feedlot \( x \) time of day. The HLI \( x \) AHL category interactions on panting score was also investigated. Similar models were used for THI and THI-hours. Independent data sets comprising the 1,200 to 1,800 observations were used to validate the HLI, AHL, and threshold values.

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

\[
Y = B_0 + B_1 \sin(2\pi \times h/24) + B_2 \cos(2\pi \times h/24), \quad [2]
\]

where \( h = \) time in hours.

A fraction of a day \( (h/24) \) was multiplied by \( 2\pi \), which translated 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:

\[
Y = B_0 + B_1 \sin(2\pi \times h/24) + B_2 \cos(2\pi \times h/24) + B_3 \sin(4\pi \times h/24) + B_4 \cos(4\pi \times h/24), \quad [3]
\]

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**

**HLI**

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 \( \geq 20\% \) of the cattle. Two multiple regression models were developed by using the panting score data from unshaded Angus steers \( (n = 2,490) \). The first model (equation [4]) was a nonlinear regression model, which was applied when BG temperature was greater than 25°C. The second linear model (equation [5]) was applied when BG temperature was less than 25°C. Both models were developed by using relative humidity (in decimal form), BG temperature, and wind speed. All parameters were significant \( (P < 0.001) \).

\[
\begin{align*}
\text{HLI}_{\text{BG}>25} &= 8.62 + (0.38 \times \text{relative humidity}) \\
&\quad + (1.55 \times \text{BG temperature}) - (0.5 \times \text{wind speed}) \quad [4] \\
&\quad + [e^{2.4 - \text{wind speed}}], \\
\text{HLI}_{\text{BG}<25} &= 10.66 + (0.28 \times \text{relative humidity}) \quad [5] \\
&\quad + (1.3 \times \text{BG}) - \text{wind speed},
\end{align*}
\]

where \( e = \) the base of the natural logarithm (approximate value of \( e = 2.71828 \)).

**AHL**

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:

\[
\begin{align*}
\text{If } [\text{HLI}_{\text{ACC}} < \text{HLI}_{\text{Lower Threshold}}], \\
&\quad (\text{HLI}_{\text{ACC}} - \text{HLI}_{\text{Lower Threshold}})/M, \quad [6] \\
\text{If } [\text{HLI}_{\text{ACC}} > \text{HLI}_{\text{Upper Threshold}}], \\
&\quad (\text{HLI}_{\text{ACC}} - \text{HLI}_{\text{Upper Threshold}})/M, 0,
\end{align*}
\]

where \( \text{HLI}_{\text{ACC}} = \) the actual HLI value at a point in time; \( \text{HLI}_{\text{Lower Threshold}} = \) the HLI threshold below which cattle in a particular class will dissipate heat (e.g., 77 for the
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 of the reference steer1

<table>
<thead>
<tr>
<th>Item</th>
<th>Cattle2 used to determine the specific threshold, n</th>
<th>Relative effect on upper HLI threshold of the reference steer (HLI = 86)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genotype</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Bos taurus</em> (British)</td>
<td>9,075</td>
<td>03</td>
</tr>
<tr>
<td><em>B. taurus</em> (European)</td>
<td>429</td>
<td>+3 (i.e., 86 + 3)</td>
</tr>
<tr>
<td>Waygu</td>
<td>894</td>
<td>+4</td>
</tr>
<tr>
<td><em>Bos indicus</em> (25%)</td>
<td>451</td>
<td>+4</td>
</tr>
<tr>
<td><em>B. indicus</em> (50%)</td>
<td>1,345</td>
<td>+7</td>
</tr>
<tr>
<td><em>B. indicus</em> (75%)</td>
<td>1,039</td>
<td>+8</td>
</tr>
<tr>
<td><em>B. indicus</em> (100%)</td>
<td>666</td>
<td>+10</td>
</tr>
<tr>
<td>Coat color</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black</td>
<td>2,859</td>
<td>0</td>
</tr>
<tr>
<td>Red</td>
<td>1,158</td>
<td>+1</td>
</tr>
<tr>
<td>White</td>
<td>293</td>
<td>+3</td>
</tr>
<tr>
<td>Health status</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Healthy</td>
<td>15,623</td>
<td>0</td>
</tr>
<tr>
<td>Showing clinical signs of disease or recovering</td>
<td>1,987</td>
<td>−5</td>
</tr>
<tr>
<td>Acclimatization</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acclimated</td>
<td>6,200</td>
<td>0</td>
</tr>
<tr>
<td>Not acclimated</td>
<td>2,920</td>
<td>−5</td>
</tr>
<tr>
<td>Shade4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No shade</td>
<td>3,467</td>
<td>0</td>
</tr>
<tr>
<td>Shade, m2/animal &gt;1.5 to 2</td>
<td>1,336</td>
<td>+3</td>
</tr>
<tr>
<td>2.0 to 3</td>
<td>6,473</td>
<td>+5</td>
</tr>
<tr>
<td>3.0</td>
<td>4,761</td>
<td>+7</td>
</tr>
<tr>
<td>Days on feed5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to 80</td>
<td>2,672</td>
<td>+2</td>
</tr>
<tr>
<td>80 to 130</td>
<td>8,385</td>
<td>0</td>
</tr>
<tr>
<td>130+</td>
<td>1,239</td>
<td>−3</td>
</tr>
<tr>
<td>Manure management,6 maximum depth of manure pack, mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>3,224</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>704</td>
<td>−4</td>
</tr>
<tr>
<td>200</td>
<td>220</td>
<td>−8</td>
</tr>
<tr>
<td>Drinking water temperature,7 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 to 20</td>
<td>224</td>
<td>+1</td>
</tr>
<tr>
<td>21 to 30</td>
<td>2,035</td>
<td>0</td>
</tr>
<tr>
<td>31 to 35</td>
<td>399</td>
<td>−1</td>
</tr>
<tr>
<td>&gt;35</td>
<td>201</td>
<td>−2</td>
</tr>
</tbody>
</table>

1A healthy, unshaded Angus at 100 d on feed.
2Not all cattle were assessed within each threshold trait. For example, coat color was assessed only in *B. taurus* cattle, manure management was assessed at 5 feedlots, and drinking water temperature was assessed on 3 feedlots.
3The values for the reference steer are presented as 0 (i.e., no change from the threshold of 86).
4For shade that provides 70% blockout (includes shade cloth and also steel structures with gaps in the roof). Unshaded *B. indicus* cattle >25% were not included.
5Not all cattle were assessed for this trait. Waygu cattle were excluded from 130+ d.
6Mean depth over 54 d.
7Only unshaded Angus cattle were assessed for this trait.

reference animal); HLIUpper 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 hour (i.e., how often HLI data are collected per hour). 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 into 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 based 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 of ≥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,
Table 3. Panting scores (%) for 6 genotypes when the heat load index (HLI) was categorized as thermoneutral (TNC), warm, hot, or very hot

<table>
<thead>
<tr>
<th>Genotype</th>
<th>HLI 1,2</th>
<th>Panting score3</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>≥3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angus, shade (n = 4,210)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TNC</td>
<td>92.96a</td>
<td>6.65a</td>
<td>0.36a</td>
<td>0.03</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm</td>
<td>83.31a</td>
<td>13.66a</td>
<td>2.89a</td>
<td>0.14a</td>
<td>&lt;0.01</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Hot</td>
<td>74.92a</td>
<td>23.41a</td>
<td>1.61a</td>
<td>0.06a</td>
<td>0a</td>
<td>0a</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Very hot</td>
<td>43.91a</td>
<td>37.77a</td>
<td>14.46a</td>
<td>3.12a</td>
<td>0.68a</td>
<td>0.06a</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angus, no shade (n = 2,859)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TNC</td>
<td>89.41a</td>
<td>10.11a</td>
<td>0.48a</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm</td>
<td>55.11c</td>
<td>32.68c</td>
<td>11.21a</td>
<td>1.0a</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Hot</td>
<td>47.62c</td>
<td>11.16c</td>
<td>21.22a</td>
<td>13.22b</td>
<td>3.00b</td>
<td>3.78b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very hot</td>
<td>33.91a</td>
<td>28.00b</td>
<td>19.09a</td>
<td>16.00b</td>
<td>1.00a</td>
<td>2.00b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brahman, shade (n = 657)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TNC</td>
<td>100.00b</td>
<td>0b</td>
<td>0b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm</td>
<td>99.99b</td>
<td>0.01b</td>
<td>0b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Hot</td>
<td>99.12b</td>
<td>0.88b</td>
<td>0b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Very hot</td>
<td>99.09d</td>
<td>0.91d</td>
<td>0b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Brahman, no shade (n = 746)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TNC</td>
<td>99.84b</td>
<td>0.16b</td>
<td>0b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Warm</td>
<td>99.60b</td>
<td>0.40b</td>
<td>0b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Hot</td>
<td>99.12b</td>
<td>0.88b</td>
<td>0b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Very hot</td>
<td>97.87c</td>
<td>3.58c</td>
<td>8.68c</td>
<td>2.07a</td>
<td>0.34</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brahman × Hereford, shade (n = 608)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TNC</td>
<td>100.00b</td>
<td>0b</td>
<td>0b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Warm</td>
<td>100.00b</td>
<td>0b</td>
<td>0b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Hot</td>
<td>99.81b</td>
<td>0.19b</td>
<td>0b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Very hot</td>
<td>96.39d</td>
<td>3.61d</td>
<td>0d</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Brahman × Hereford, no shade (n = 704)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TNC</td>
<td>89.52a</td>
<td>10.37a</td>
<td>0.08b</td>
<td>0.03</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Warm</td>
<td>78.52d</td>
<td>21.34a</td>
<td>0.14c</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Hot</td>
<td>60.03d</td>
<td>39.84c</td>
<td>0.13c</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Very hot</td>
<td>35.30a</td>
<td>53.58c</td>
<td>8.68c</td>
<td>2.07a</td>
<td>0.34</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waygu, shade (n = 894)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TNC</td>
<td>98.90b</td>
<td>1.1b</td>
<td>0b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Warm</td>
<td>100.00b</td>
<td>0b</td>
<td>0b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Hot</td>
<td>97.87b</td>
<td>2.13b</td>
<td>0b</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Very hot</td>
<td>94.12d</td>
<td>5.88d</td>
<td>0d</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

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

1Heat load index (HLI) \( BG > 25 = 8.62 + (0.38 \times RH) + (1.55 \times BG) - (0.5 \times WS) + e^{2.4 - WS}; HLIBG < 25 = 10.66 + (0.28 \times RH) + (1.3 \times BG) - WS.\)

2TNC, HLI < 70; warm, HLI > 70 < 77; hot, HLI > 77 < 86; very hot, HLI > 86.

3Cattle with a panting score >1 were considered to be stressed.

and a negative value indicates that the threshold has been reduced. For example, the HLI threshold for pure-bred \( B. indicus \) is 96 (86 + 10). The threshold for these animals may be greater than 96; however, there were not sufficient data where HLI > 95.

**Relationships Among Mean Panting Score, HLI, and AHL**

Effects of the 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 mean panting score. 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 was 0.37 (P < 0.001) for THI-hours. The HLI x AHL interactions were a good predictor (P < 0.001; \( R^2 = 0.92 \)) of panting score (all genotypes) when pen within feedlot and feedlot location were considered. The effects of the HLI x AHL on Angus and Brahman steers are presented in Figure 1.

The Brahman cattle were less affected than Angus by the HLI and AHL encountered (Figure 1). Nevertheless, they were not immune to extreme conditions. Increased panting scores were observed when the AHL exceeded 10 and the HLI was greater than 86. However, the percentage of Brahman with a panting score of 0 was higher (P < 0.05) when compared with 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 by using time and the average HLI over the previous 24 h (equation [7]):

\[ TT = 37.12 - 0.45 \times \sin T + 0.09 \times \cos T + 0.13 \times \sin^2 T - \cos^2 T \times 0.02 + 0.03 \times HLI_{24} \]  

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 that lead to an increase in body heat content beyond the animal’s 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 managers 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 (Castañeda et al., 2004). However, measuring climatic conditions within pens is difficult and is not practical under most conditions. Therefore, the 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 are 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 al., 1997; Gaughan et al., 2000; Gaughan et al., 2002; Brown-Brandl et al., 2005a), 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, 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, that trigger a response (Hahn et al., 1992; St-Pierre et al., 2003). In the current study, a threshold of 25°C (BG temperature) was determined for increasing respiration rates. A lower value (21°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°C; dry bulb temperature) and Eigenberg et al. (2005) with a threshold range of 25 to 30°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., 1999a; 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
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 × duration), the genotype or phenotype, coat color, the 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 vs. cattle at 150 d on feed). 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) that 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 by 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 feedback from users are obtained, adjustments will be made.

**LITERATURE CITED**


