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Dynamic Response Indicators of Heat Stress in Shaded and Non-shaded Feedlot Cattle, Part 1: Analyses of Indicators

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Heat stress in feedlot cattle can cause decreases in feed intake and growth, and in extreme cases may result in death. Providing shade during hot weather has shown inconsistent results, reducing direct and indirect losses in some areas of the United States, but not in others. The objectives of this study were to evaluate the dynamic responses of feedlot cattle to environmental conditions with and without access to shade, and to determine the most appropriate physiological measurement for monitoring feedlot cattle during hot weather as a guide for improved management. Eight crossbred steers (initially weighing 294·7 ± 10·8 kg) were randomly assigned to one of eight individual pens, where one of two treatments were applied: shade access, or no-shade access. Respiration rate, daily feed intake, and core body temperature were collected, using automated systems during eight periods, for a total of 37 days. The data were analysed using four categories of daily maximum temperature humidity index (maximum I_{TH}) values (Normal for maximum $I_{TH} < 74$; alert for $74 \leqslant$ maximum $I_{TH} < 78$; Danger for $78 \leqslant$ maximum $I_{TH} < 84$; Emergency for maximum $I_{TH} \geqslant 84$). Shade was found to impact the physiological responses in all I_{TH} categories, with the largest impacts in the Danger and Emergency categories. Shade lowered respiration rate and core body temperature during the peak temperature hours of the day. It was concluded that respiration rate is the most appropriate indicator of thermal stress to monitor because it was consistently affected in all I_{TH} categories, it is easy to monitor without the need for costly equipment, and there is little or no lag associated with it.

1. Introduction

Hot weather affects animal bioenergetics, and has negative impact on animal performance and well-being. Reductions in feed intake, growth, and efficiency are commonly reported in heat-stressed cattle (Hahn, 1999). The impacts of heat load on these production parameters are quite varied, ranging from little to no effect in a brief exposure, to death of vulnerable animals during an extreme heat event (Hahn & Mader, 1997). An extreme event in July, 1995, caused the loss of approximately 3750 head of cattle in western Iowa; direct losses were estimated at US $2·8 million, and production losses at US $28 million (Busby & Loy, 1996). *Bos taurus* feedlot cattle are particularly vulnerable to heat stress as a result of the high-energy diet they are fed, and their inability to move into a more suitable environment (Blackshaw & Blackshaw, 1994). With the increased concern for global warming and animal welfare, along with the high number of cattle in feedlots, researchers and producers have increased their interest in methods to reduce thermal stress.

As absorbed solar radiation may exceed metabolic heat production by several times (Riemerschmid, 1943), the use of shade during hot weather has been of interest for many years. A simple shade can reduce the animals' radiant heat load by 30% or more (Bond *et al.*, 1967). Results from performance trials with shaded and unshaded feedlot cattle have shown inconsistent results. Garrett (1963) summarised results from several shade studies and concluded that feedlot cattle in areas with more than 750 h/yr of temperatures above 29·5 °C generally show a performance improvement, while gains of cattle in areas that receive 500–750 h/yr of temperatures above 29·5 °C are less conclusive. This lack of performance improvement from shade can be explained by the ability of cattle to acclimate and compensate for a short-term suppression in feed intake and growth resulting from a heat stress event (Hahn, 1982; Mader *et al.*, 1999).

While shades have not consistently shown a performance improvement, cattle with access to shade have consistently shown a reduction in core body temperature and respiration rate (Mitlöehner *et al.*, 2001; Valtorta *et al.*, 1997; Paul *et al.*, 1999). During times of high solar radiation, high temperature, and high humidity, a reduction of solar radiation may be a method of reducing heat stress (Blackshaw & Blackshaw, 1994), improving animal well-being, and preventing death in extreme cases.

2. Objectives

The objectives of this study were to evaluate the dynamic physiological responses of feedlot cattle (respiration rate, daily feed intake, feeding behaviour, and core body temperature) to different environmental conditions with and without access to shade, and to determine which physiological measurement was the most appropriate to monitor feedlot cattle under heat stress conditions.

3. Materials and methods

Eight crossbred steers (1/4 Angus, 1/4 Hereford, 1/4 Pinzgauer, 1/4 Red Poll) initially weighing 294·7 ± 10·8 kg were randomly assigned to one of eight individual concrete-surfaced pens where one of two treatments was applied (Shade or No-shade). The pens were located at the US Meat Animal Research Center near Clay Center, Nebraska; they had a north/south orientation and were connected to the south side of a 122 m long building (*Fig. 1*). Animal access to the building was prevented. The pens were 3·6 m by 12 m, with a 3·6 m space between pens. Shade treatment pens were equipped with free-standing shade structures made of 0·3 mm thick polyvinyl 100% shade cloth, and were 3·6 m by 6 m by 3 m high at the peak, 2·4 m high on the east side, and 1·8 m high on the west side. These shade structures were designed such that steers had access to shade from mid-morning (10:00 h Central Daylight Time [CDT)]) to early evening (19:00 h CDT). The shade structures covered approximately 50% of the pen area. Data were collected during eight periods during the summer of 2001. The collection periods were a combination of pre-selected periods and periods selected based on weather predictions. The steers were moved to a new pen and changed treatments at the end of each period.

Respiration rate, core body temperature, and feeder weights were continuously recorded during each of the eight treatment periods. Respiration rate was obtained using respiration rate monitors, which consisted of a respiration rate sensor, and a data logger/micro-computer. The output signal from the respiration rate sensor was recorded on the data logger/micro-computer for 1 min every 15 min at 10 Hz (Eigenberg *et al.*, 2000). These data were then post-processed using software developed in-house (Eigenberg *et al.*, 2000).

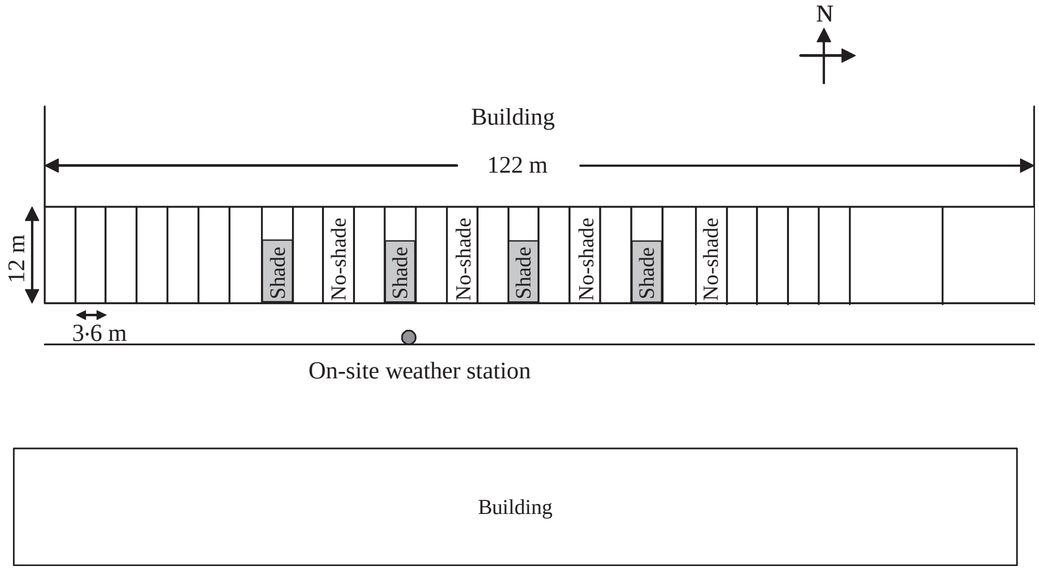

Fig. 1. Detail of experimental site; eight, 12 by 3·6 m pens were used, four equipped with a 3·6 m by 6 m by 3 m high shade structure; both the feed and the waterer were placed under the shade

Core body temperature was measured using a telemetry system manufactured by HQ, Inc (West Palmetto, FL , USA), consisting of an implantable transmitter and a CorTemp™ data logger. Twenty-eight days prior to the initiation of the experiment, a licensed veterinarian implanted a transmitter in the abdominal cavity of each steer (Brown-Brandl *et al*., 2003). Data were logged at a frequency of one reading/minute.

Feed and water were available on an *ad libitum* basis, with fresh feed provided before 9:00 CDT. In the shade treatment, both the feed and the water were placed under the shade structure. Water was provided using an automatic waterer. Feed intake and feeding behaviour were monitored using a load cell (Model 1250, Tedea-Huntleigh International Ltd., Israel) placed under the feedbox. Signal processing was provided by a Daytonic signal conditioning system (Model 9170; Daytronic Corporation, Dayton, OH, USA). The output voltage was then recorded on a Pace Pocket Logger (Model XR 440-M; Pace Scientific Inc., Mooresville, NC, USA) every one minute.

Four video cameras recorded animal location in the shade treatments. Videotapes were analysed after the completion of the experiment; animal position (under the shade structure or in the open) was recorded every 15 min between 10:00 and 19:00 h.

Weather data were collected from an automated weather data centre located 2·5 km north of the pens (South Central Station of the Automated Weather Data Network [AWDN], operated by the High Plains Regional Climate Center Central Weather Station). This data included dry-bulb temperature t_{db} in °C, dew-point temperature t_{dp} in °C, wind speed in m/s, and solar radiation in W/m^2. Weather conditions at the AWDN were recorded on a 15 min basis. On-site weather data were collected for the last four of eight data collection periods and data were collected every 15 min by a Davis Instruments weather station (Model Vantage PRO; Hayward, CA, USA). On-site data were used for analyses when available.

For the analyses, dynamic data were reduced to 15 min averages. Values of the temperature humidity index I_{TH} were determined for every time interval by using

$$I_{TH} = t_{db} + 0{\cdot}36 \times t_{dp} + 41{\cdot}2 \qquad (1)$$

The data was then categorised into four groups (Normal, Alert, Danger, and Emergency) using daily maximum temperature humidity index (THI-Thom, 1959; LCI, 1970). The Normal category was defined as maximum daily I_{TH} below 74. The Alert category had a maximum daily I_{TH} greater than or equal to 74, and less than 78. The Danger category had a maximum daily I_{TH} greater than or equal to 78, and less than 84. The Emergency category had a maximum daily I_{TH} equal to or above 84. Dynamic data for each category were analysed using the general linear model procedure (SAS, 2000) for effects of animal, treatment, period, hour of the day, and the interaction of treatment and hour of the day. Least-squares means were used to discern differences between treatments at each hour.

Daily average data were analysed using the general linear model procedure (SAS, 2000) for the effects of animal, treatment, category, and the interaction of treatment and category. Daily average data included average respiration rate, average core body temperature, feed intake, and feed behaviour data. Feed behaviour data were derived from feeder weights recorded every 1 min, and included total eating duration, number of meals, average meal size, average meal duration, and rate of eating. Significant differences were determined when the values for the probability P were less than 0·05, except in the case of feeding behaviour values, then probabilities of less than 0·1 were used.

The time an animal spent in the shade between the hours of 10:00 and 19:00 h was converted to a percentage on a daily basis. The percentages were analysed using the general linear model procedure (SAS, 2000) for the effects of animal and category.

Correlations of core body temperature and respiration rate with dry-bulb temperature and solar radiation with different offset times (at 15 min intervals) were used to determine the lags associated with the physiological parameters to the environmental factors. Lags were determined by maximising the values for the coefficient of determination R^2 for positive slope equations. Correlations were preformed using the SLOPE and RSQ functions in Microsoft Excel®. Lags for each heat stress category were determined using average physiological responses (averaged over all animals).

4. Results

A total of 37 days of data were used in the analyses. Of those, four were categorised in Normal, six in Alert, 13 in Danger, and 14 in Emergency range. Categories of individual experimental days are shown in *Fig. 2*. Average hourly weather data for the four categories are shown in *Fig. 3*. The ambient dry-bulb temperature, and the dew-point temperature, and I_{TH} for the four categories had good separation (*Figs 2 and 3* and Table 1). Although wind speed was significantly different between all categories except Normal and Alert, the average numeric differences were only slight (Normal, 2·9 m/s; Alert, 2·9 m/s; Danger, 3·5 m/s; Emergency, 2·6 m/s). The average solar radiation was slightly less in the Normal category (Normal, 249·3 W/m^2)

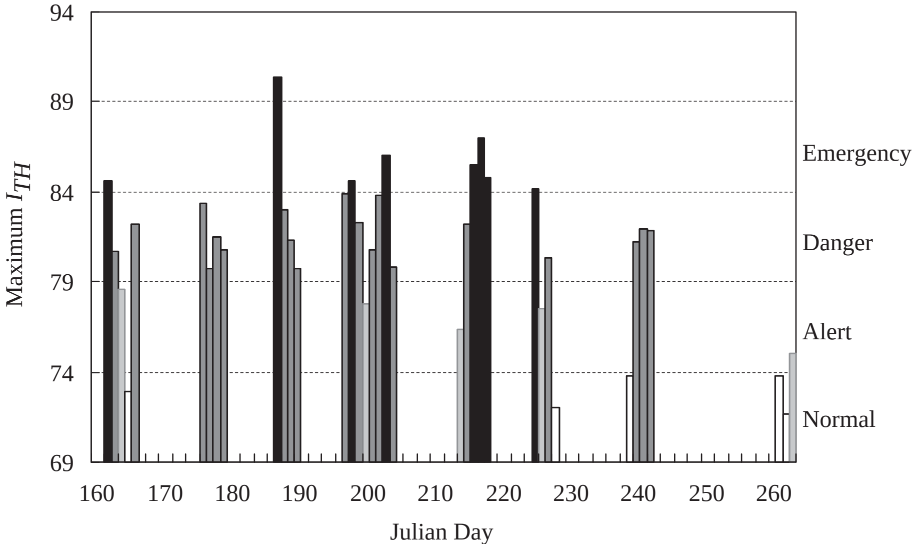

Fig. 2. Using four categories of heat stress based on daily maximum temperature humidity index (maximum I_{TH}), categories were assigned to each experimental day: Normal, maximum $I_{TH} < 74$; Alert, $74 \leqslant$ maximum $I_{TH} < 78$; Danger, $78 \leqslant$ maximum $I_{TH} < 84$; Emergency, maximum $I_{TH} \geqslant 84$

than in Alert (Alert, 281·8 W/m^2, not significant), Danger, or Emergency categories (Danger, 303·1 W/m^2; Emergency, 301·5 W/m^2; $P<0{\cdot}01$).

4.1. *Shade use*

Due to equipment failure, the second, sixth, seventh, and eighth periods were not videotaped. To help balance data, all days that were inadvertently videotaped were added to the analyses (day 191, Alert; day 192, Normal; day 220, Danger; day 221, Normal). A total of 23 days were analysed: Normal, 3; Alert, 3; Danger, 8; Emergency, 9. There was no significant difference in percentage of time cattle spent under shade in the lowest three categories (Normal, 80·8 ± 5·6%; Alert, 83·5 ± 5·2%; Danger 83·6 ± 3·3%) (Table 2). However, cattle exposed to the Emergency category spent significantly more time in the shade than in any other category (Emergency, 96·4 ± 3·3%; $P<0{\cdot}05$).

4.2. *Respiration rate*

The mean daily respiration rate was significantly affected by animal, treatment, category, ($P<0{\cdot}05$), and tended to have a significant treatment by category interaction effect ($P=0{\cdot}11$). Cattle in the Shade treatment had slower increase in mean daily respiration rate through the categories than cattle in the No-shade treatment (Table 2). Differences between the treatments were significant at the Danger and Emergency levels, with the Shade treatment having a lower mean daily respiration rate.

Upon analyses of the dynamic data patterns, treatment differences began to emerge. It appeared that under normal conditions animals in the Shade treatment had only a slight impact on respiration rate [significant effects of animal, period, hour of the day, and the interaction of treatment and hour of the day ($P<0{\cdot}05$)], while in all other categories the Shade treatment had a larger impact [significant effects of animal, period, treatment, hour of the day, and the interaction of treatment and hour of the day ($P<0{\cdot}05$)].

Figure 4 illustrates the difference in respiration rate patterns between Shade and No-shade treatments in all categories. In the Normal category, animals with access to shade had lower respiration rate between 12:00 and 18:00 h (average for Shade, 69·8 breaths/min; average for No-shade, 79·5 breaths/min); the maximum difference (maximum respiration rate in the Shade—maximum respiration rate in the No-shade) was 11·9 breaths/min. In the Alert category, animals in the Shade treatment had lower respiration rate between 10:00 and 18:00 h (Shade, 80 breaths/min; No-shade, 94 breaths/min; maximum difference was 19·9 breaths/min), but had higher respiration at night (04:00 and 05:00), and again in midmorning (09:00 h) (Shade, 64·8 breaths/min; No-shade, 57·7 breaths/min). Under Danger conditions, shade was beneficial for animals between 10:00 and 19:00 h (Shade, 85·0 breaths/min; No-shade, 100·6 breaths/min; maximum difference was 20·7 breaths/min), but had no effect the remainder of the day. The response in the Emergency category was similar to the

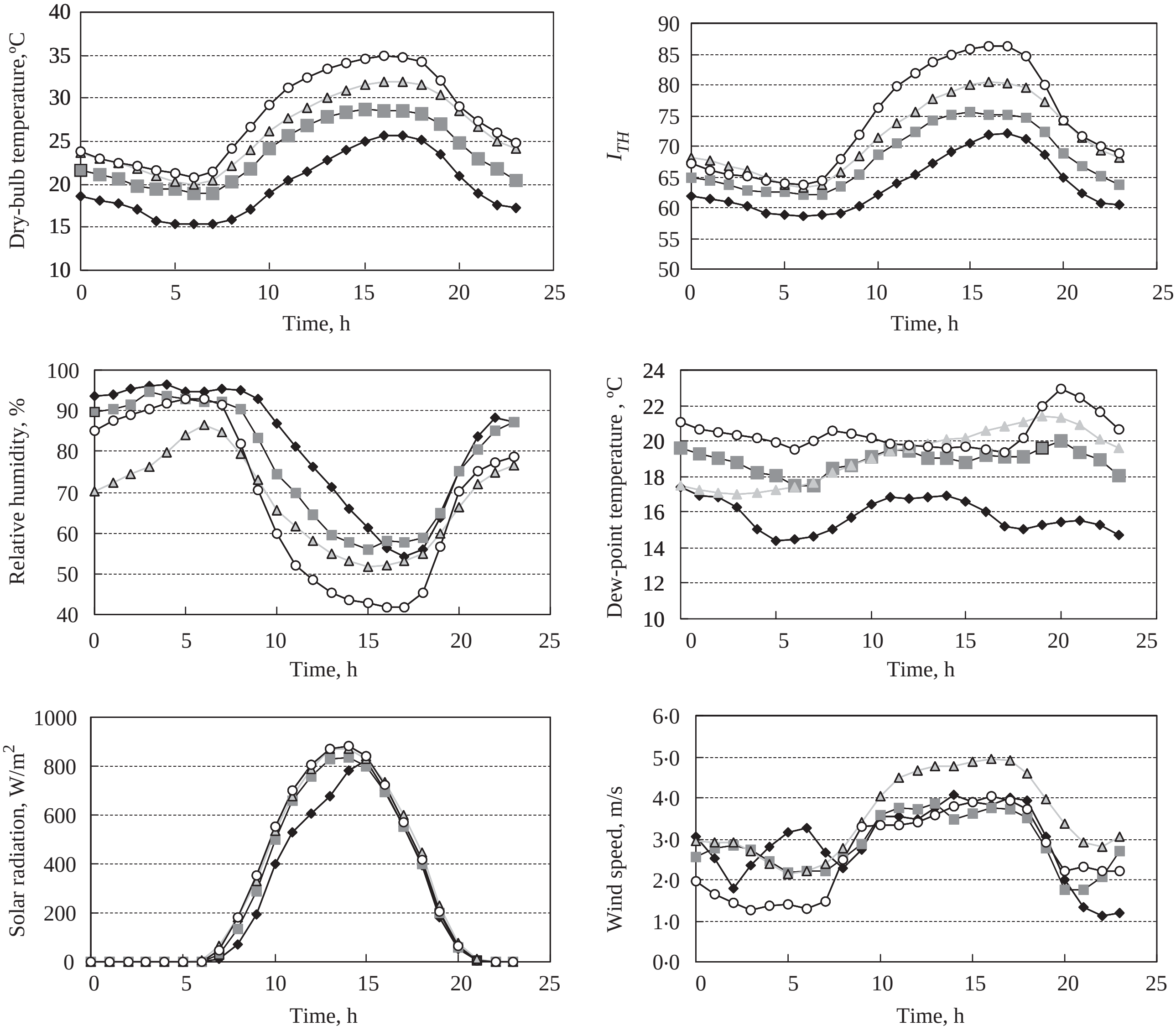

Fig. 3. Average hourly weather data and temperature humidity index for each of the four heat stress categories based on maximum daily temperature humidity index (maximum I_{TH}): (-◆-) Normal, maximum $I_{TH}<74$; (-■-) Alert, $74\leqslant$ maximum $I_{TH}<78$; (-△-) Danger, $78<$ maximum $I_{TH}<84$; (-○-) Emergency, maximum $I_{TH}\geqslant 84$

Danger category, with beneficial effects observed for the hours of 10:00–18:00, 20:00 h (Shade, 91·0 breaths/min; No-shade, 114·6 breaths/min; maximum difference was 31·0 breaths/min).

Overall, it appears that shade access reduced respiration rate during portions of the day in all weather categories. Regardless of weather category, the shaded cattle's respiration rate followed non-shaded cattle's respiration rate until approximately 11:00 h, at which time shaded cattle's response flattened out, while non-shaded cattle's respiration rate continued to rise. This large impact of shade on respiration rate has been previously documented (Blackshaw & Blackshaw, 1994; Brown-Brandl *et al.*, 2001; Mitlöehner *et al.*, 2001; Mitlöehner *et al.*, 2002).

Respiration rate of non-shaded cattle peaked before dry-bulb temperature in every heat stress category. The lag analysis indicated that average respiration rate preceded dry-bulb temperature by just under 1 h, ranging between 0·75 and 1·25 h, and did not follow a trend (Table 2). Hahn *et al.* (1997) reported that respiration rate lagged dry-bulb temperature by 0–3 h for feeder cattle exposed to hot cyclic conditions in an environmental chamber. Gaughan *et al.* (2000) reported a similar lag of about 2 h. These discrepancies in lags are most likely a result of experimental conditions (cattle in

Table 1
Daily average weather conditions and standard errors reported for each of the four heat stress categories

Parameter	*Heat stress category*^{1}			
	Normal	*Alert*	*Danger*	*Emergency*
Number of days	4	6	13	14
N	384	576	1248	1344
Ambient dry-bulb temp, °C	19·7 ± 0·22^{a}	23·6 ± 0·18^{b}	26·0 ± 0·12^{c}	27·7 ± 0·12^{d}
Dew-point temp., °C	15·8 ± 0·17^{a}	18·9 ± 0·14^{b}	19·1 ± 0·09^{b}	20·4 ± 0·09^{c}
Relative humidity, %	81·5 ± 0·84^{a}	77·5 ± 0·69^{b}	68·1 ± 0·47^{c}	68·8 ± 0·45^{c}
Wind speed, m/s	2·9 ± 0·08^{a}	2·9 ± 0·07^{a}	3·5 ± 0·05^{b}	2·6 ± 0·02^{c}
Solar radiation, W/m^2	249·3 ± 16·7^{a}	281·8 ± 13·6^{ab}	303·1 ± 9·2^{b}	301·5 ± 8·9^{b}
Temperature–humidity index	63·7 ± 0·3^{a}	68·0 ± 0·3^{b}	71·5 ± 0·2^{c}	73·9 ± 0·2

N, number of observations

[a,b,c,d] Columns with differing superscripts are significantly different, probability $P < 0{\cdot}01$.

[1] Heat stress categories assigned based on maximum daily temperature humidity index (maximum I_{TH}): Normal, maximum $I_{TH} < 74$; Alert, $74 \leqslant$ maximum $I_{TH} < 78$; Danger, $78 \leqslant$ maximum $I_{TH} < 84$; Emergency, maximum $I_{TH} \geqslant 84$.

Table 2
Daily average responses and standard errors reported for each of the four heat stress categories

	Heat stress category‡			
	Normal	*Alert*	*Danger*	*Emergency*
Feed intake, kg*				
Shade	11·3 ± 0·9^{a1}	14·2 ± 0·6^{b}	13·8 ± 0·4^{b}	12·5 ± 0·4^{a1}
No-shade	13·6 ± 0·9^{a2}	13·6 ± 0·6^{a}	13·6 ± 0·4^{a}	11·3 ± 0·4^{b2}
Total duration, min*				
Shade	177 ± 15^{ab}	192 ± 11^{a}	202 ± 7^{a}	167 ± 7^{b1}
No-shade	192 ± 15^{a}	195 ± 10^{a}	208 ± 7^{a}	150 ± 7^{b2}
Number of meals*				
Shade	12·7 ± 1·1^{a}	14·7 ± 0·8^{ab}	15·0 ± 0·6^{b}	13·7 ± 0·5^{ab}
No-shade	13·5 ± 1·1^{ab}	14·6 ± 0·8^{a}	15·2 ± 0·6^{a}	12·8 ± 0·5^{b}
Average meal size, g*				
Shade	898 ± 67	1009 ± 49	946 ± 34	930 ± 32
No-shade	1034 ± 67^{a}	970 ± 48^{ab}	947 ± 34^{ab}	910 ± 32^{b}
Average duration, min*				
Shade	13·8 ± 0·8^{ab}	13·5 ± 0·5^{ab}	13·8 ± 0·4^{a}	12·6 ± 0·4^{b}
No-shade	14·1 ± 0·8^{a}	13·6 ± 0·5^{a}	14·2 ± 0·4^{a}	12·2 ± 0·4^{b}
Rate of eating, g/min*				
Shade	65·2 ± 3·3^{ac}	74·1 ± 2·4^{b}	66·1 ± 1·7^{c}	72·4 ± 1·6^{b}
No-shade	73·6 ± 3·3^{a}	69·0 ± 2·4^{a}	63·4 ± 1·7^{b}	71·2 ± 1·6^{a}
Average respiration rate, breaths/min†				
Shade	66·9 ± 3·7^{a}	69·6 ± 3·0^{ab}	74·2 ± 2·0^{b1}	82·3 ± 1·8^{c1}
No-shade	65·2 ± 3·4^{a}	73·7 ± 2·9^{b}	79·4 ± 1·8^{c2}	93·4 ± 1·9^{d2}
Average core body temperature, °C†				
Shade	38·0 ± 0·16^{a}	38·2 ± 0·14^{ac}	38·4 ± 0·08^{b}	38·3 ± 0·8^{bc}
No-shade	38·3 ± 0·15^{a}	38·3 ± 0·12^{a}	38·6 ± 0·08^{b}	38·42 ± 0·8^{ab}
Percent of time spent in shade, %†				
Shade	80·7 ± 5·5^{a}	83·5 ± 5·2^{a}	83·6 ± 3·3^{a}	96·4 ± 3·3^{b}
No-shade	N/A**			

[a,b,c,d] Columns with differing superscripts are significantly different.

[1,2] Rows with differing superscripts are significantly different.

[*] Significant differences at probability $P < 0{\cdot}1$ level.

[†] Significant differences at probability $P < 0{\cdot}05$ level.

[**] N/A, not applicable.

[‡] Heat stress categories assigned based on maximum daily temperature humidity index (maximum I_{TH}): Normal, maximum $I_{TH} < 74$; Alert, $74 \leqslant$ maximum $I_{TH} < 78$; Danger, $78 \leqslant$ maximum $I_{TH} < 84$; Emergency, maximum $I_{TH} \geqslant 84$.

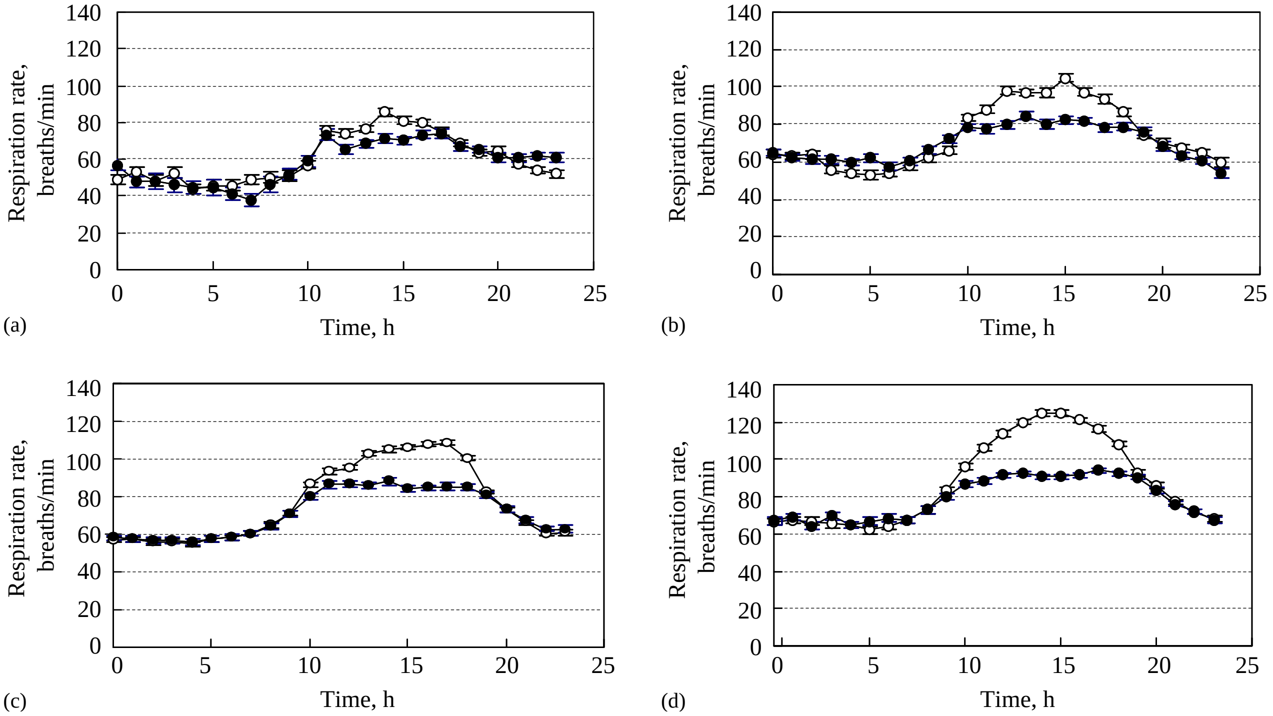

Fig. 4. Average hourly respiration rate for shaded (-●-) and non-shaded (-○-) feedlot cattle exposed to weather conditions for each of the four heat stress categories based on maximum daily temperature humidity index (maximum I_{TH}): (a) Normal, maximum $I_{TH} < 74$; (b) Alert, $74 \leqslant$ maximum $I_{TH} < 78$; (c) Danger, $78 \leqslant$ maximum $I_{TH} < 84$; (d) Emergency, maximum $I_{TH} \geqslant 84$; error bars represent standard error associated with each point

the current study were housed outside, while cattle in Hahn's and Gaughan's studies were in environmental chambers with no solar load and no wind). While some researchers have contended that this indicates a second phase in respiration, a slow depth breaths *versus* fast shallow breaths, these data suggest that respiration rate precedes dry-bulb temperature because it is being influenced by other weather factors, as respiration rate precedes dry-bulb temperature in all heat stress categories including the Normal category, which would not cause any heat stress. In a subsequent analysis it was shown that respiration rate lags solar radiation by slightly under 1 h. These lags ranged from 1·25 h in the Normal category to 0·5 h in the Alert category, and did not follow a distinct trend. Solar radiation precedes dry-bulb temperature by approximately 2 h, which means respiration rate peaks between these two environmental parameters. Based on this information, it appears that respiration rate is a good indicator of total heat load, thus environmental stress.

4.3. *Body temperature*

Mean daily core body temperature revealed differences between categories in both treatments. The Shade treatment showed a slow increase in mean daily core body temperature (Table 2). The No-shade treatment showed a distinct difference between Normal and Alert, and Danger and Emergency categories. Mean daily core body temperatures did not reveal differences between treatments.

In the analyses of the dynamic data, clear differences were found between the two treatments. The core body temperature of cattle exposed to any of the four weather categories was significantly affected by all parameters (animal, period, treatment, hour of the day, and the interaction of treatment and hour of the day).

The effect of shade on core body temperature in the four weather categories is shown in *Fig. 5*. In the Normal category, shaded cattle had lower core body temperature between 5:00–9:00 and 16:00–17:00 h; average core body temperature for Shade treatment was 37·7 °C and No-shade was 38·0 °C. In the Alert category, cattle in the Shade treatment had a lower core body temperature only 2 h during the day (15:00, 16:00 h $P < 0{\cdot}05$); the average difference was 0·3 °C (Shade, 38·3 °C; No-shade, 38·6 °C). Also in the Alert category, cattle in the Shade treatment had a higher core body temperature for 5 h of 24 h , 19:00 – 22:00 h, and 04:00 h (Shade, 38·6 °C; No-shade, 38·2 °C). Shade became a more important factor in the Danger category: between

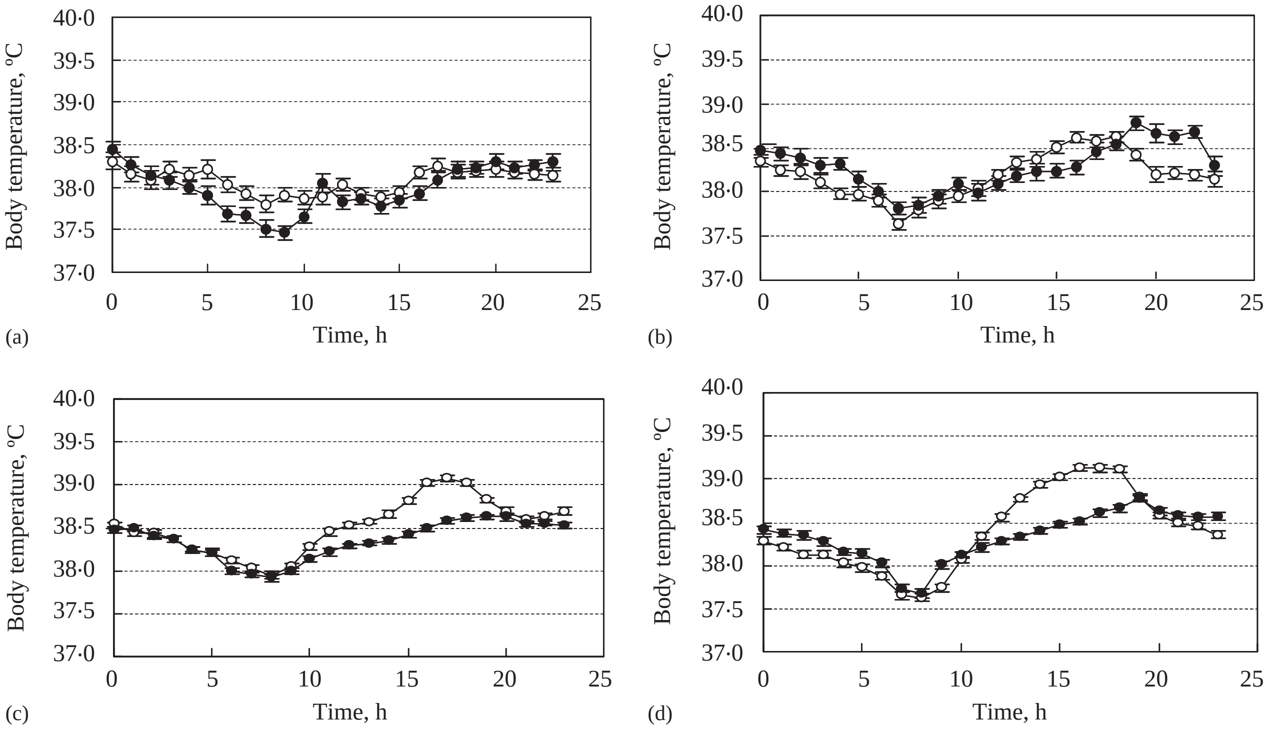

Fig. 5. Average hourly core body temperature for shaded (-●-) and non-shaded (-○-) feedlot cattle exposed to weather conditions for each of the four heat stress categories based on maximum daily temperature humidity index (maximum I_{TH}): (a) Normal, maximum $I_{TH}<74$; (b) Alert, $74\leqslant$ maximum $I_{TH}<78$; (c) Danger, $78\leqslant$maximum $I_{TH}<84$; (d) Emergency, maximum $I_{TH}\geqslant 84$; error bars represent standard error associated with each point

10:00 and 19:00 h, in addition to 23:00 and 06:00, shaded cattle had a lower core body temperature (38·4 °C) than non-shaded cattle (38·7 °C), with maximum difference being 0·5 °C. When cattle were exposed to weather conditions in the Emergency category, Shade treatment cattle had a lower core body temperature for a total of 7 h (12:00–18:00 h); Shade treatment had average core body temperature of 38·5 °C and No-shade treatment had 38·9 °C. The maximum difference between two treatments in the Emergency category was 0·6 °C. Between the 22:00 and 06:00 and also 09:00, the No-shade treatment had a lower core body temperature than Shade treatment (Shade, 38·3 °C; No-shade, 38·1 °C); maximum difference was −0·12 °C.

In all weather categories, shade reduced cattle's core body temperature during daytime hours. However, in all weather categories except the Danger category, animals in the shade treatment had higher core body temperature during nighttime hours. This response has been documented (Blackshaw & Blackshaw, 1994; Brown-Brandl *et al*., 2001), and it has been hypothesised that this is due to radiation losses to the night sky. Although these animals were not confined to the shaded portion of the pen, and behaviour data were not collected at night, it is possible the animals remained under shade during nighttime hours. Unlike respiration rate, the benefit of shade on core body temperature is not consistent during the diurnal period between categories.

4.4. *Feeding behaviour and feed intake*

Three days were eliminated from the data set (Julian Date 166, 215, and 262) due to missing data. A summary of feeding behaviour data is shown in Table 2. Daily feed intake was significantly affected by animal and category, and tended to have an interaction effect on treatment and category. Animals in Shade treatment had an increase in daily feeding intake from Normal to Alert and Danger categories, and then a significant decrease in the Emergency category. The No-shade treatment had a constant daily feed intake over the lower three categories, and then a significant decrease in the Emergency category. Animals in the Shade treatment had a higher intake in the Emergency category (Shade, 12·5 kg; No-shade, 11·3 kg); however, the reverse was true in the Normal category (Shade, 11·3 kg; No-shade, 13·6 kg). This indicates that animals in the No-shade treatment were compensated for the decrease in feed intake at higher temperatures. Total eating duration followed a similar pattern and also indicated some compensation in the Normal category. Although there were no significant differences between treatments in other meal parameters, there were differences between categories. The differences indicate that cattle compensate for higher temperatures by eating more frequent smaller meals. It appears that this compensation is in place through the lower three categories to maintain daily feed intake. However, it appears that conditions in the Emergency category cannot be compensated; in this category daily feed intake, number of meals, total duration, and meal size all decrease.

Twenty-four hour accumulative feed intake of cattle exposed to the weather conditions in Normal, Alert, and Danger categories was significantly affected by animal, period, and hour of the day (*Fig. 6*), while in the Emergency category accumulative feed intake was significantly affected by all parameters (animal, period, hour of the day, treatment, and the interaction of treatment and hour).

There were no significant differences in accumulative feed intake in the Normal, Alert or Danger categories. However, in the Emergency category shaded cattle had significantly more accumulative feed intake starting at 14:00 h through the remainder of the day. Although no significant differences were found, it appeared that No-shade animals exposed to Emergency conditions shifted their feed intake to the cooler hours of the day; No-shade animals had a higher hourly intake at the hours of 02:00–0600 and 19:00 h.

5. Discussion

Based on these results, it appears that I_{TH} may be a useful indicator, especially on a daily basis. However, it lacks input from two key weather elements—solar radiation and wind speed. Both impact the total heat load on an animal, which in turn affect the animal's stress and well-being. An indicator of stressful conditions is needed so a producer can better manage animals through stressful conditions. At a minimum, this indicator must be able to summarise the important current weather parameters (temperature, humidity, wind speed, and solar radiation). Additionally, an indicator may include parameters such as the animal's colour, relative fatness, sex, prior exposure to heat, and health status (Gaughan *et al.*, 1999; Brown Brandl *et al.*, 2004). For risk estimation, it might be helpful if this indicator could account for important weather history.

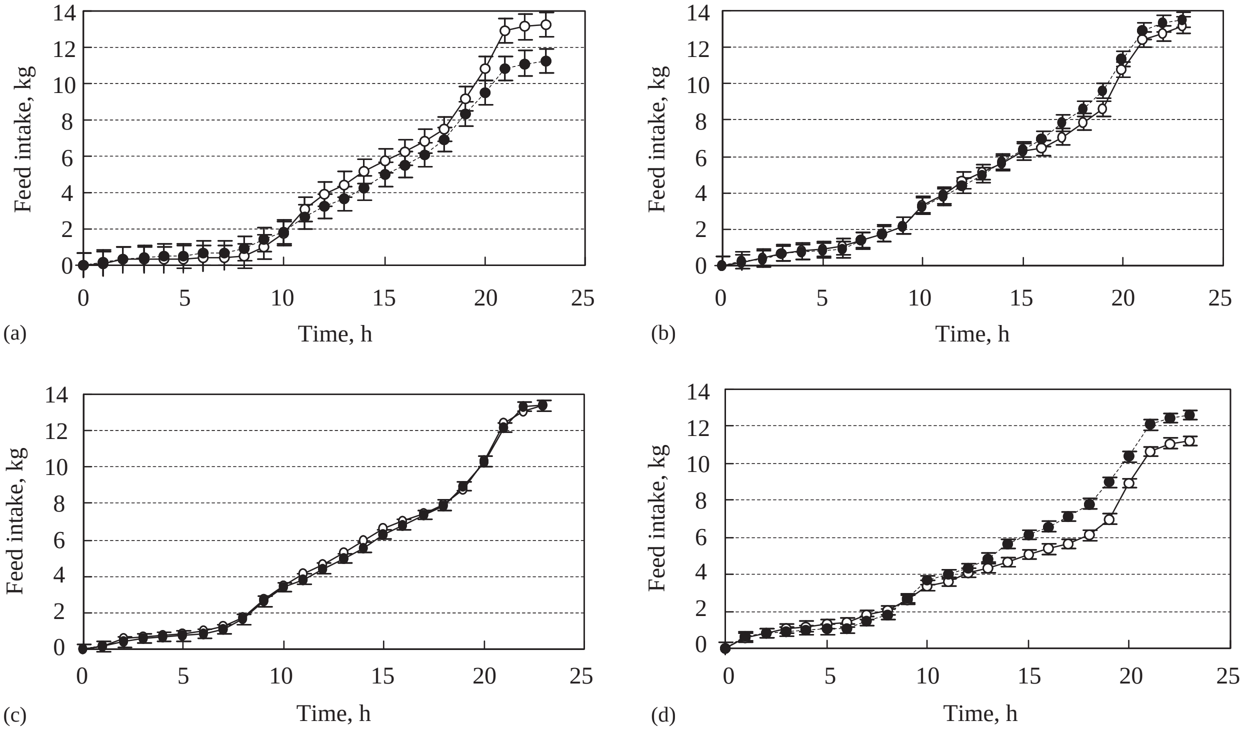

Fig. 6. Average accumulative feed intake for shaded (–●–) and non-shaded (–○–) feedlot cattle exposed to weather conditions for each of the four heat stress categories based on maximum daily temperature humidity index (maximum I_{TH}): (a) Normal, maximum $I_{TH}<74$; (b) Alert, $74\leqslant$maximum $I_{TH}<78$; (c) Danger, $78\leqslant$maximum $I_{TH}<84$; (d) Emergency, maximum $I_{TH}\geqslant 84$; error bars represent standard error associated with each point

An indicator based on animal physiology would provide an integrated response of environmental factors. This study examines two physiological parameters (respiration rate and core body temperature), feed intake, and behaviour parameters (shade usage and feeding behaviour parameters). The indicator should allow continuous measures and respond to environmental dynamics. Feed intake and feeding behaviour parameters would not be good choices, as they are intermittent. Also, feed intake has the disadvantage of delayed response as the animals adjust their feed intake based on many factors in addition to current temperature, including the previous few days feed intake.

Two candidates for an animal based indicator for heat stress monitoring are respiration rate and core body temperature. Core body temperature has apparent value since by definition it is a summary of all thermoregulatory events. Any imbalance of the heat loss and heat production or gain results in a change in core body temperature. However, based on the results of this study and others (Hahn, 1989; Mader, 2003; Scott *et al.*, 1983; Hahn, 1999), core body temperature lags ambient temperature by 1–5 h, and is dependant on ambient conditions. The lag time in core body temperature may seriously delay indication of stress until it is too late for the producer to respond.

Respiration rate increases with ambient temperature, lags solar radiation by approximately 1 h, and is affected similarly in all heat stress categories; it appears to be a logical choice for an indicator of heat stress. Several researchers have noted that respiration rate could have a maximum ranging from under 100 to approximately 200 breaths/min (Kibler & Brody, 1949, 1950; Worstell & Brody, 1953; Hales, 1969, Spiers *et al.*, 1994; Gaughen *et al.*, 1999). However, this study and others have not noted this ceiling or maximum respiration rate (Spain & Spiers, 1996; Hahn *et al.*, 1997; Brown-Brandl *et al.*, 2004). The studies that found this ceiling or maximum respiration rate all applied a constant high temperature to the animals for an extended period (10 h—several days), while the researchers that have not found this ceiling had applied a cyclic temperature pattern, or observed animals under field conditions. There are several possible reasons for this ceiling in respiration rate: increased alveolar ventilation, possible muscle fatigue, and acclimation to the environment. Because the experiments that found the ceiling in respiration rates were conducted under artificial conditions (extended high temperatures lasting 10 h to several days), the results may not be applicable to field conditions. These extreme events in many cases are constant temperatures stepped up from thermoneutral over a period of days (Spiers *et al.*, 1994) to even months (Kibler & Brody, 1949, 1950; Worstell & Brody, 1953). These conditions might confound increasing temperature with acclimation to high temperatures. Gaughan *et al.* (1999) exposed cattle for 10 h of constant high temperature with partial fasted cattle. The results of the study indicate that respiration of Hereford cattle numerically increase for the first 6 h and then decrease. This decrease could be due to possible muscle fatigue or a decreasing metabolic heat load, as the animals were approaching 24 h without feed. In summary, it appears that the studies which found a levelling off in respiration rate had been conducted using a constant temperature, possibly changing the physiological response (Table 3).

The increase in alveolar ventilation occurs during periods of extreme weather. Visual observations of cattle during periods of heat stress indicate cattle occasionally take a deep breath in the midst of panting. As an animal pants, the air moves only through the upper part of the respiratory tract to evaporate moisture, but not completely ventilating the lungs. An occasional deep breath is necessary to exchange oxygen and carbon dioxide (Hales & Findlay, 1968). As the animal's body temperature increases, the rate of chemical reactions in the body increase (Van't Hoff effect; Blaxter, 1989), thus increasing the carbon dioxide production, which would

Table 3
Associated lags between physiological responses and environmental factors

Parameter/category	*Lag, h*	*Equation*[1]	R^2
Respiration rate and dry-bulb temperature			
Normal[*]	4·0	$R_R = 4{\cdot}05t_{db} - 22{\cdot}07$	0·85
Alert	1·0	$R_R = 4{\cdot}55t_{db} - 21{\cdot}15$	0·93
Danger	1·75	$R_R = 4{\cdot}63t_{db} - 41{\cdot}6$	0·94
Emergency	1·5	$R_R = 4{\cdot}39t_{db} - 34{\cdot}75$	0·95
Respiration rate and solar radiation			
Normal	6·5	$R_R = 0{\cdot}048r_s + 45{\cdot}85$	0·84
Alert	2·5	$R_R = 0{\cdot}050r_s + 59{\cdot}29$	0·93
Danger	3·75	$R_R = 0{\cdot}058r_s + 61{\cdot}45$	0·97
Emergency	3·0	$R_R = 0{\cdot}067r_s + 67{\cdot}01$	0·98
Core body temperature and dry-bulb temperature			
Normal	4·0	$t_{core} = 0{\cdot}023t_{db} + 37{\cdot}64$	0·15
Alert	1·0	$t_{core} = 0{\cdot}071t_{db} + 36{\cdot}53$	0·65
Danger	1·75	$t_{core} = 0{\cdot}073t_{db} + 36{\cdot}51$	0·85
Emergency	1·5	$t_{core} = 0{\cdot}096t_{db} + 35{\cdot}57$	0·92
Core body temperature and solar radiation			
Normal	6·5	$t_{core} = 0{\cdot}00025r_s + 38{\cdot}04$	0·12
Alert	2·5	$t_{core} = 0{\cdot}00077r_s + 37{\cdot}99$	0·64
Danger	3·75	$t_{core} = 0{\cdot}00083r_s + 38{\cdot}15$	0·74
Emergency	3·0	$t_{core} = 0{\cdot}00139r_s + 37{\cdot}82$	0·86

R^2, coefficient of determination.

[1] R_R, respiration rate, breaths/min; t_{core}, core body temperature, °C; t_{db}, dry-bulb temperature, °C; r_s, solar radiation, W/m^2.

[*] Heat stress categories assigned based on maximum daily temperature humidity index (maximum I_{TH}): Normal, $I_{TH} < 74$; Alert, $74 \leqslant$ maximum $I_{TH} < 78$; Danger, $78 \leqslant$ maximum $I_{TH} < 84$; Emergency, maximum $I_{TH} \geqslant 84$.

tend to increase the number of occasional deep breaths the animal takes. However, these periodic deep breaths do not lower overall respiration rate. The added advantage is this pattern can be easily identified in electronic format (respiration rate taken using the respiration rate monitors as in this study), or while taking hand counts using a stopwatch in the field. Even though respiration rate is influenced by both thermal cooling and the body's need for oxygen, the fact remains that respiration rate precedes ambient temperature by approximately one hour and lags solar radiation by an hour. Respiration rate peaks almost perfectly between solar radiation and temperature maximums, thus providing the producer with a physiological parameter, which reveals the animal's thermal status, to alert them of impeding severe thermal conditions.

6. Conclusions

Shade was found to impact physiological responses in all weather categories, with the largest response observed in Danger and Emergency categories. As expected, the largest impact of shade was at higher temperature categories. It appeared that physiological parameters (respiration rate and core body temperature) were impacted at lower temperature categories than production-related parameters (daily feed intake, feeding behaviour) or behaviour changes (shade usage). Respiration rate showed the most consistent diurnal response pattern between animals with and without access to shade. Beneficial effects of shade on core body temperature were largest in the Danger and Emergency categories. While shade did not influence accumulative feed intake in the Danger category, it had a 1·2 kg advantage in the Emergency category, which should be favourable for maintaining growth in such conditions.

When managing animals during hot weather, it is critical to have an early indicator of stress. Based on these data, respiration rate is the best physiological indicator of stress in a production setting for several reasons: (1) little or no lag is associated with it, (2) it is consistently affected in all weather categories (shade lowers respiration rate at the same time of day in all categories), (3) it is easy to monitor without costly equipment (manually counting of flank movements using only a stopwatch).

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