Revista Brasileira de Zootecnia
Brazilian Journal of Animal Science
© 2018 Sociedade Brasileira de Zootecnia
ISSN 1806-9290
www.sbz.org.br

Board-invited review

R. Bras. Zootec., 47:e20160414, 2018
https://doi.org/10.1590/rbz4720160414

Biometeorology and animal welfare

Understanding heat stress in beef cattle

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ABSTRACT - Thermal stress is the result of a misbalance between heat produced or gained from the environment and the amount of heat lost to the environment. The level of thermal stress can range from minor or no effect to death of vulnerable animals. Under summertime conditions, thermal stress results in hyperthermia or heat stress. Heat stress in feedlot cattle is a common summertime occurrence in cattle-producing parts of the world (USA, Australia, Brazil, etc.). Effects on animals experiencing heat stress include decreases in feed intake, animal growth, and production efficiency. During these extreme events, animal losses can exceed 5% of all cattle on feed in a single feedlot. Luckily, these extreme events are generally very localized and last only a day or two. However, these losses can be devastating to individual producers within the affected area. The level of heat stress an individual animal will experience is a result of a combination of three distinct components: environmental conditions, individual animal susceptibility, and management of the herd. Environmental components include temperature, humidity, wind speed, and solar radiation. Several indices have been developed to summarize the different components into a single value. Individual animal susceptibility is influenced by many different factors including coat color, sex, temperament, previous health history, acclimation, and condition score. Finally, management greatly influences the effects of thermal stress. Management factors can be broken into four distinct categories: feed, water, environmental influences, and handling. Understanding these risk factors and how each one influences animal stress will aid in the development of management strategies and how to implement them. Management strategies that can be employed at the right time and to the correct groups of animals will increase benefits to the animals and limit costs for the producers.

Key Words: animal responses, feedlot, heat waves, management

Introduction

Heat waves are a reoccurring phenomenon in the Midwest region of the United States (Figure 1), where many feedlot cattle are raised. Many severe heat waves have occurred in the Midwestern US in the last 10 years that resulted in substantial losses for the feedlot industry. In July 1995, nearly 4,000 head of feedlot cattle were lost in southwestern Iowa with total losses approaching US$ 28 million. More than 5,000 head of feedlot cattle were lost in July 1999 in northeast Nebraska; monetary losses were reported between US$ 21.5 and 35 million. Other severe heat-related cattle losses occurred in northeast Nebraska (July 2005), in north-central South Dakota (July 2007), in central Nebraska (June 2009), and in central Kansas (July 2010). Each of these events resulted in the death of thousands of feedlot cattle and the loss of millions of dollars in revenue to the cattle industry, both in direct animal losses and indirect performance losses (Busby and Loy, 1996; Hahn et al., 1999; Hubbard et al., 1999).

A heat wave has been defined as "a period of abnormal hot and unusual humid weather of at least one day in duration, but conventionally lasting several days to several weeks …" (AMS, 1989). Hahn and Mader (1997) reported an operational definition of heat waves as "3-5 successive days with maximum temperatures above a threshold, such as 32 °C". During a heat wave, environmental conditions have negative effects on animal growth, performance, and ultimately well-being (Brown-Brandl et al., 2008).

Economic impact of heat stress in feedlot cattle

Hot weather affects animal bioenergetics and has negative effects on its performance and well-being. Reductions in feed intake, growth, and efficiency are commonly reported in heat-stressed cattle (Hahn, 1995). The effect of heat load on these production losses are quite varied, ranging from little to no effect in a brief exposure,

Received: December 27, 2016
Accepted: April 16, 2017

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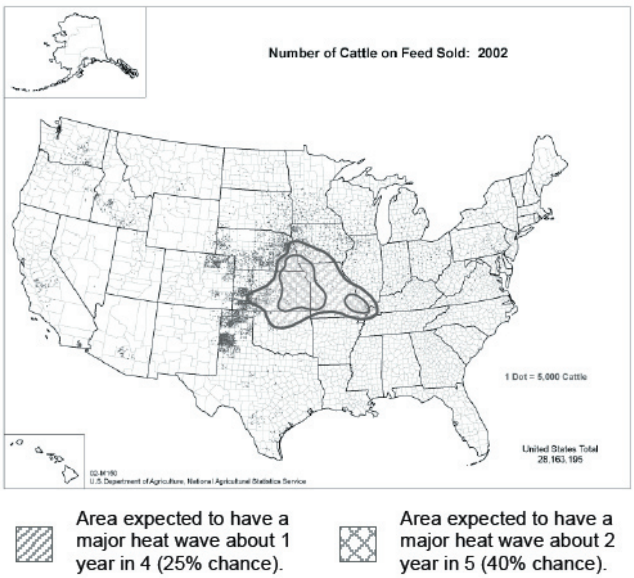


Figure 1 - Probable areas expected to have a major heat wave on a regular basis (Hahn et al., 2009; Nienaber and Hahn, 2007) superimposed on the cattle of feed distribution in the US from 2002 (NASS, 2008).

to death in vulnerable animals during an extreme event (Hahn and Mader, 1997).

Economic losses associated with heat stress originate from three primary factors including decreased performance, increased mortality, and decreased reproduction (St-Pierre et al., 2003). When losses are summarized for the United States over an entire summer season, the average estimated losses over all livestock species are US$ 2.4 billion, and US$ 369 million is associated with feedlot cattle.

The objective of this paper is to briefly describe the engineering principles of thermal balance, understanding environmental parameters; detail differences in animal response; examine different management strategies – particularly shade, moving animals, and sprinkle cooling; and discuss applications of precision animal management strategies.

Homeostasis

Cattle are homeotherms – meaning that they maintain a relatively constant body temperature over a wide range of environmental conditions. While the temperature range that cattle can adapt to is remarkable, cattle experience thermal stress. In feedlot cattle, heat stress occurs in various degrees and is a common summertime occurrence in cattle-producing parts of the world (United States, Australia, Brazil, etc.). Heat stress results from an imbalance in the homeostasis of the animals and has both physiological and thermodynamic components. Equation 1 describes the overall process of homeostasis in an animal (Watts and McLean, 1977), in which HP is heat production, HL is heat loss, ΔT_{body} is the change in body temperature (°K), c_p is the specific heat of the whole animal (J kg^{-1}°K^{-1}), and m is the mass of the animal (kg).

$$HP - HL = \Delta T_{body} \times c_p \times m \quad (1)$$

Total heat production subtracted from the total heat loss is equal to the accumulation of energy in the body, which is manifested as a change in body temperature (increase during heat stress and a decrease during cold stress). Numerically, this accumulation is the change in body temperature multiplied by the specific heat of the whole animal and mass of the animal. The specific heat of the whole body has been reported to be 3.47 kJ/(kg °K) (Blaxter, 1989).

Heat production is a byproduct of the breakdown and utilization of feedstuffs. Classically, heat production has been divided into four components: basal metabolism, heat of digestion, heat of activity, and production metabolism (heat from the production of milk, egg, etc.). Basal metabolism is the heat produced from the maintenance of body cells (no active digestion or movement). Basal metabolism is a very difficult measurement and is not typically completed on animals; therefore, fasting heat production is typically measured on animals instead of basal metabolism. Heat of digestion is the heat resulting from the intake and digestion of feedstuff. Heat of activity is the heat generated in muscles during physical activity. Production metabolism is the heat created during the physiological processes that yield products such as milk in the case of a dairy cow or eggs in the case of the laying hen.

Heat production can be measured by indirect calorimetry methods (Nienaber and Maddy, 1985). In this procedure, heat production is calculated (equation 2) by measuring the consumption of oxygen (O_2, L) and the production of carbon dioxide (CO_2, L) and methane (CH_4, L, in the case of ruminants) to calculate the total heat production (HP, units) of the animal.

$$HP = 16.18 \times O_2 + 5.02 \times CO_2 - 2.17 \times CH_4 \quad (2)$$

To maintain homeostasis, heat lost needs to either increase or decrease based on the thermal environment and the thermal status of the animal. Heat can be lost from the body by two physical processes: sensible and latent heat loss (Figure 2). Sensible heat loss is the process of losing heat by conduction (heat lost to another solid object), convection (heat lost from the body to a fluid, which can be air or water), and radiation (heat lost from the body

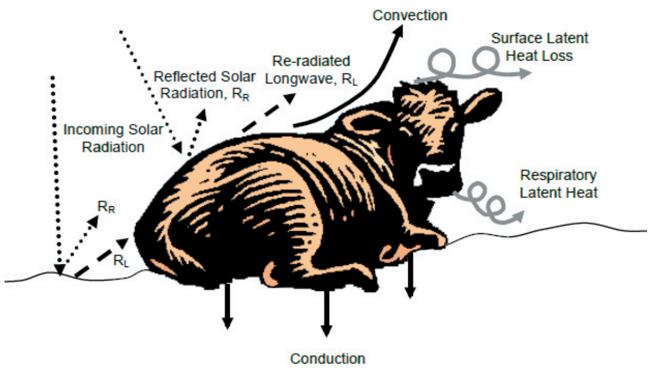


Figure 2 - Modes of heat transfer for an animal penned outside without access to shade.

to another body through radiant energy). Sensible heat can be gained or lost from an animal and is dependent on the temperature gradient between the body surface of the animal and its surroundings. Latent heat is the heat lost by evaporation of moisture from the surface of the skin or the respiratory tract of the animal. Although cattle are thought of as a panting species, they lose about 22% of their latent heat through panting, with the remaining amount lost through evaporation of water from the surface area of the skin (McArthur, 1987). Latent heat can only be lost to, never gained from, the environment. While the concepts of heat transfer are relatively simple, when applied to a static non-biological object, heat transfer from a dynamic living animal is quite complex.

Heat stress is a complex interaction between physiology and behavior of the animal and the physics of heat transfer. While the physics of the heat transfer component can be described using a set of equations, the physiology can only be approximated with equations and the behavior of the animals adds a dynamic component to heat transfer and heat balance equations. Therefore, to mathematically describe the thermal interactions of these factors is often quite difficult. However, understanding these factors is invaluable in further study of the effect and management of heat stress in feedlot cattle. Because of the complexity of the issue to continue the discussion and investigation of this topic, a more general approach must be taken. It is worth reminding that the basic heat balance equations presented earlier are applicable to nearly all the following discussion.

The level of heat stress that an animal experiences is related to three main factors: the weather conditions that exist (Hahn et al., 1999), susceptibility of the animal in question (Brown-Brandl and Jones, 2011), and management protocols used.

Quantifying the environment

While temperature is the primary parameter used to describe the weather, other parameters have been shown to influence the total heat load. Solar radiation, humidity, and wind speed are three additional parameters considered important to animal stress (MLA, 2002). Several mathematical models have been developed to help summarize these components into a single usable number (Thom, 1959; Eigenberg et al., 2005; Mader et al., 2006; Gaughan et al., 2008).

The Temperature Humidity Index (THI) has been used for many years and combines the effects of temperature and humidity (Thom, 1959). The THI equation is shown in equation 3, in which t_{db} is dry-bulb temperature in °C and RH is relative humidity in decimal form. Temperature Humidity Index was subsequently used by the transportation industry to provide livestock shipping guidelines during heat stress conditions (LCI, 1970). As a component of the guidelines, Livestock Conservation Inc. developed the Livestock Weather Safety Index based on the following four THI categories: normal, THI < 74; alert, 74 < THI < 79; danger, 79 < THI < 84; and emergency, THI > 84. Based on these categories, the National Weather Service issued advisories to livestock producers until the mid 90s, when budget cuts and increased availability of commercial weather services resulted in suspension of those weather advisories.

$$THI = 0.8t_{db} + RH\,(t_{db} - 14.4) + 46.4 \qquad (3)$$

While THI accounts for the effects of temperature and humidity, it disregards the effects of wind speed and solar radiation. In the case of housed animals exposed to low air velocity, THI does a reasonable approximation of summarizing the environment. However, in the case of beef cattle and other animals typically held in open-air pens, the wind speed and solar radiation contribute significantly to heat stress.

More recently developed equations combine temperature, humidity, wind speed, and solar radiation (Eigenberg et al., 2005; Mader et al., 2006; Gaughan et al., 2008). The estimated respiration rate (RR_{est}) equation is shown in equation 4, in which t_{db} is dry-bulb temperature, RH is relative humidity in percentage, v_w is wind speed in m/s, and r_s is solar radiation in W/m^2. Four categories of RR_{est} were established based on the original THI categories using the values of solar radiation of 800 W/m^2 and a wind speed of 0 m/s. The categories for RR_{est} have the following thresholds: normal, 90; alert, 90-110; danger, 110-130; and emergency, ≥130.

$$RR_{est} = 5.1t_{db} + 0.58RH - 1.7v_w + 0.039r_s - 52.8 \qquad (4)$$

Animal susceptibility

When cattle under the same management are exposed to the same environmental conditions, the level of stress varies widely between them. When the animal stress data (e.g., respiration rate, [breaths per minute]) is viewed in relation to environmental parameters (dry-bulb temperature, °C), the variation in responses is evident (Figure 3).

The variation of the effect of temperature on individual measurements is immense. For example, the two extremes in respiration rate (78 to 167 bpm) were recorded on the same day (t_{db} = 32.9 °C) for two different heifers in the same feedlot under the same management. To evaluate these differences and ensure the effect is not random, all the observations for these two individual heifers were extracted and plotted on a separate graph (Figure 4). Upon closer inspection, it is apparent that, while there are fluctuations in the respiration rate, there are distinct differences in the responses of these individual animals (Figure 4) to the same environmental conditions and management practices.

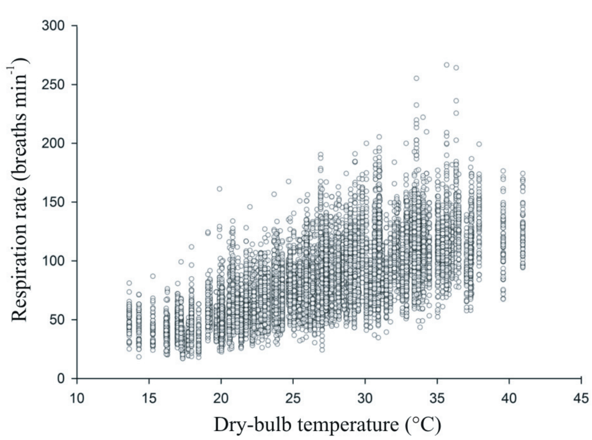
Brown-Brandl and Jones (2011) developed a model to compile different animal factors into a single value of susceptibility (Figure 5). The model was created as a hierarchal knowledge-based fuzzy inference system model with 11 inputs and eight fuzzy inference system models.

This model highlights the known factors that influence the response of an animal to hot weather. Whereas this model may allow a producer to sort animals according to their predicted susceptibility, there is still a need to classify the responses of an individual animal for experimental or genetic evaluation reasons. Respiration rate is the measure of animal responsiveness and t_{db} is the measure of environment. Respiration rate has been shown to be a good indicator of heat stress (Brown-Brandl et al., 2005b). It is noteworthy the challenge of using the direct and simple measure of RR as a useful parameter, since RR changes with temperature, resulting in multiple values for each animal (Figure 3). Even though RR is a useful measure, by using a single value, it is not possible to describe how an animal responds to changes in t_{db}.

A parameter that combines a physiological response to temperature change into a single value for each animal is desirable. There are a number of potential statistics to summarize the response of an animal to the environment, for example, minimum, maximum, average, median, etc; however, none of these parameters captures the range of influence of t_{db}.

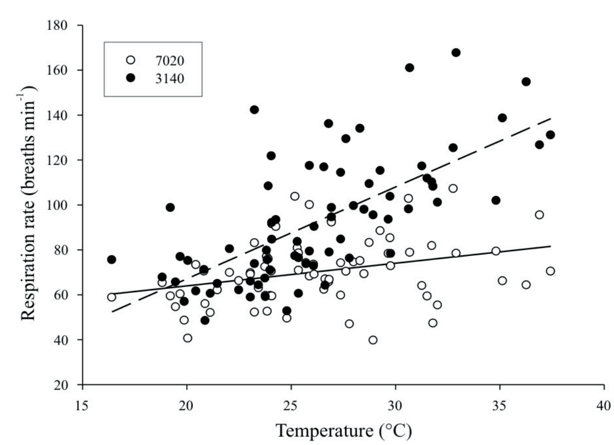
For a heat stress parameter to be useful, it must combine the response and t_{db} in a way that differentiates each animal and accounts for the influence of the range of t_{db}. Slope values are unique for each animal, they consider the response of each animal over all temperatures experienced by the animal, and therefore describe the dynamic response of a single variable and t_{db}. For example, the slope of RR to t_{db} has been shown as a useful parameter (Brown-Brandl and Jones, 2016).

The distribution of responsiveness (slope of individual animal's respiration rates with dry-bulb temperatures) (Figure 6) represents responses from a total of 384 animals (128 heifers in each of three years – each representing four different breed/composite breeds ranging in color from



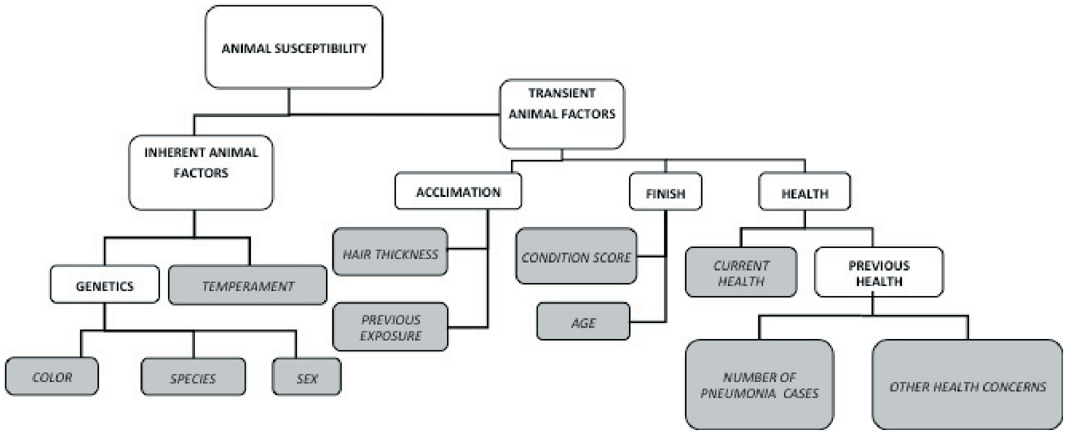
Heifers were from four distinct breeds/composites selected based on their hide color and included: Angus (black), MARC III composite (dark red) [¼ Pinzgauer, ¼ Red Poll, ¼ Hereford, and ¼ Angus], MARC I composite (tan) [¼ Charolais, ¼ Braunvieh, ¼ Limousin, ⅛ Angus, and ⅛ Hereford], and Charolais (white).

Figure 3 - Respiration rate data collected from a total of 384 heifers over a three-year period (128 heifers per year).



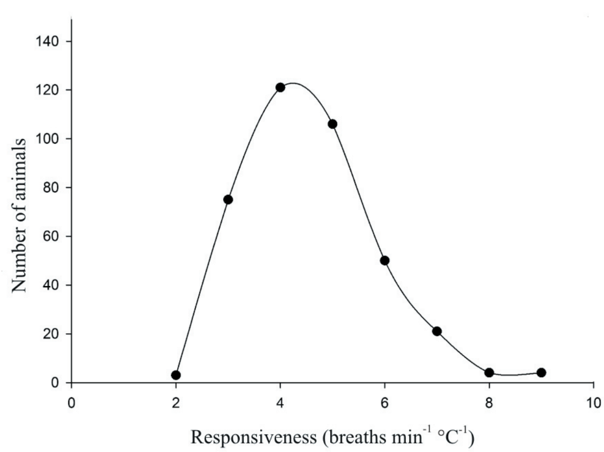
The white dots represent the response of Heifer #7020; black dots represent a dark red *Bos taurus* heifer #3140. Animals were under the same management scheme and respiration rates of these two animals were recorded at the same time.

Figure 4 - Respiration rate response of two feedlot heifers over a three-month summer period exposed to a variety of environmental conditions.



The model consists of eight unique FIS (white boxes) and 11 user inputs (gray boxes) to predict the susceptibility of an individual animal to heat stress.

Figure 5 - Schematic of animal susceptibility used to develop a hierarchal knowledge-based fuzzy inference systems (FIS).



The data are from animals equally distributed among four *Bos taurus* breed/composite breeds and two treatments (shaded and unshaded pens) over the three years of the study.

Figure 6 - Distribution of responsiveness (slope of individual animal respiration rates with dry-bulb temperatures) of 384 feedlot heifers.

white, tan, red, and black, and represented animals equally allocated to shade and non-shaded pens).

Animal management strategies

Researchers have been looking for management options to reduce heat stress for many years. Management strategies can influence not only the response of the animal to heat, but also the overall economics of the production system. Management strategies can also have unintended consequences. The management strategies can be broken down into four subcategories: feed (Brosh et al., 1998; Holt et al., 2004; Mader and Davis, 2004; MLA, 2006a), water (Beck et al., 2000; Bicudo and Gates, 2002), environment modifications (Blackshaw and Blackshaw, 1994; Garner et al., 1989; Mader et al., 2007), and handling changes (Brown-Brandl et al., 2010). In interest of brevity, only sprinkle cooling, shade, and handling of animals will be discussed.

Sprinkle cooling

A management strategy used in some feedlots is sprinkling or wetting the animals. To maximize the added latent heat loss when sprinkling cattle, the hair coat of the animal must be saturated to the skin surface and then allowed to dry completely. While the cool water has a small convective heat loss component, the real benefit comes from the evaporation of water from the skin surface. The benefits to sprinkled cattle include lowering body temperature, decreasing respiration rate, and maintaining feed intake (Garrett, 1963; Gaughan et al., 2004). The size of the droplets influences the effectiveness of the sprinkling treatment. A fine mist has a difficult time saturating the hair coat and the droplets tend to set on top of the hair coat. If this happens, the water forms a barrier, which reduces heat transfer. Therefore, misting does not have the same effect on cattle as sprinkling (Mitloehner et al., 2001) and can actually have a negative effect.

Shade

Shade is one of the most commonly studied management strategies. Artificial shade can be made up of many different materials with various levels of effectiveness (Bond et al., 1954; Kelly and Bond, 1958;

Eigenberg et al., 2010). The most effective shade materials are solid metal shade with insulation; however, with higher initial cost and more maintenance required, other materials need to be considered. For example, shade structures constructed of snow fence material provide only about 30-50% effectiveness; however, this type of shade can substantially reduce the heat load under extreme conditions (Eigenberg et al., 2010). Another advantage of snow fence material is the smaller wind and snow load, which reduces the cost of a structure. The need for shade is also dependent on the intensity of the summer weather in the area where the feedlot is located (Figure 7) (Garrett, 1963). Shade has been shown to improve performance of feedlot animals in areas with more than 700 h/year above 29.4 °C. In areas with 500-700 h/year, the effects are variable and depend on the year. Factors to be considered in shade design include area of shadow, location of shade, orientation of the shade structure, and type of material to be used (MLA, 2006b).

Providing shade for animals can reduce their radiant heat load by 30 or more (Bond et al., 1967). Providing shade for feedlot cattle reduces respiration rate at the peak of the day in all environments and body temperature in moderate to hot environments (Brown-Brandl et al., 2005b). Feed intake is maintained at a higher level in animals that have access to shade in hot weather (Brown-Brandl et al., 2005b). However, the influence of shade on animal performance is varied (Blackshaw and Blackshaw, 1994), most likely due to different environmental extremes (Garrett, 1963). Shades have been shown to significantly reduce death losses during an extreme event (Busby and Loy, 1996). Shade has been shown to have a positive effect on performance in areas that receive on average over 700 h above the threshold of 29.4 °C and have a mixed effect in areas that receive between 500-700 h of temperatures above the threshold. However, areas that typically receive less than 500 h of temperatures above 29.4 °C will not normally observe an increase in performance with the addition of shades (Figure 7).

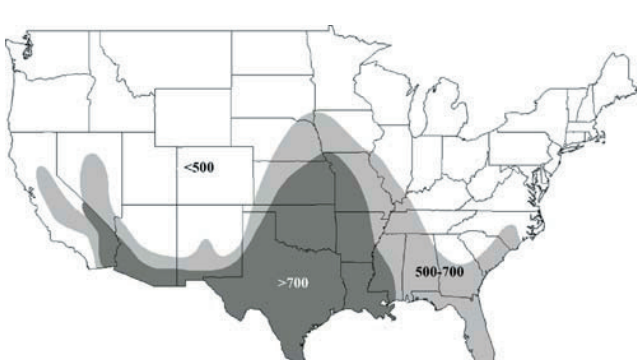
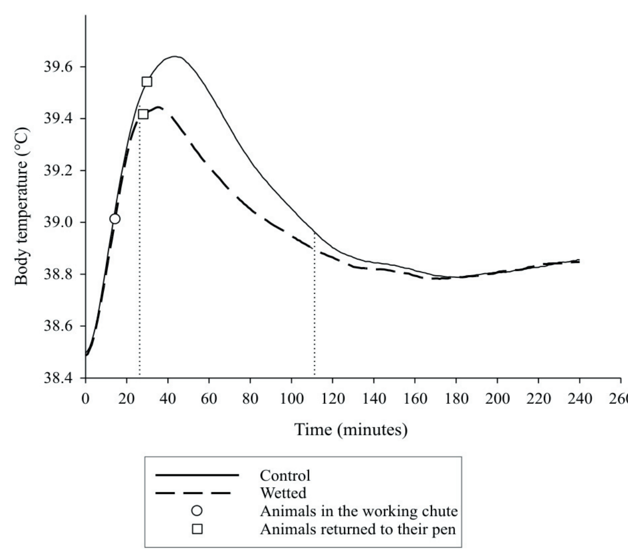


Figure 7 - Areas of the continental United States with three thresholds of hours above 29.4°C. Producers located in both shaded areas would benefit from providing shade to feedlot cattle. Data from Garrett (1963).

Handling

The animal activity associated with handling and transporting cattle causes an increase in body temperature (Fazio and Ferlazzo, 2003; Mader et al., 2005; Brown-Brandl et al., 2010) due to the heat produced from muscle activity. The extent of the rise in body temperature is affected by the distance the animals are moved, ambient conditions (Mader et al., 2005), and the temperament score of the individual animal (Brown-Brandl, 2008). Mader et al. (2005) found that the time for the body temperature to return to normal ranged from 1 to 3.5 h depending on the environmental conditions (longer recovery in winter than spring). Under summertime conditions, the effect on heat load from moving animals is minimum when completed in the early morning and should to be avoided on days that are forecast to be extremely hot. During periods of hot temperatures, the body temperature of cattle lags environmental temperature between 1 and 5 h (Scott et al., 1983; Hahn et al., 1999; Hahn et al., 2003; Brown-Brandl et al., 2005a); therefore, if animals are processed in the evening after sundown, the



The animals were removed from their pens (time 0), moved between 160 and 200 m, processed through a scale and a squeeze chute. While in the squeeze chute, one-half of the animals were sprayed with cool water (WETTED).
The open circle (○) indicates when the animals entered in the squeeze chute, while the open square (□) indicates when the animals were returned to their pen.

Figure 8 - Comparison of body temperature taken during a working event.

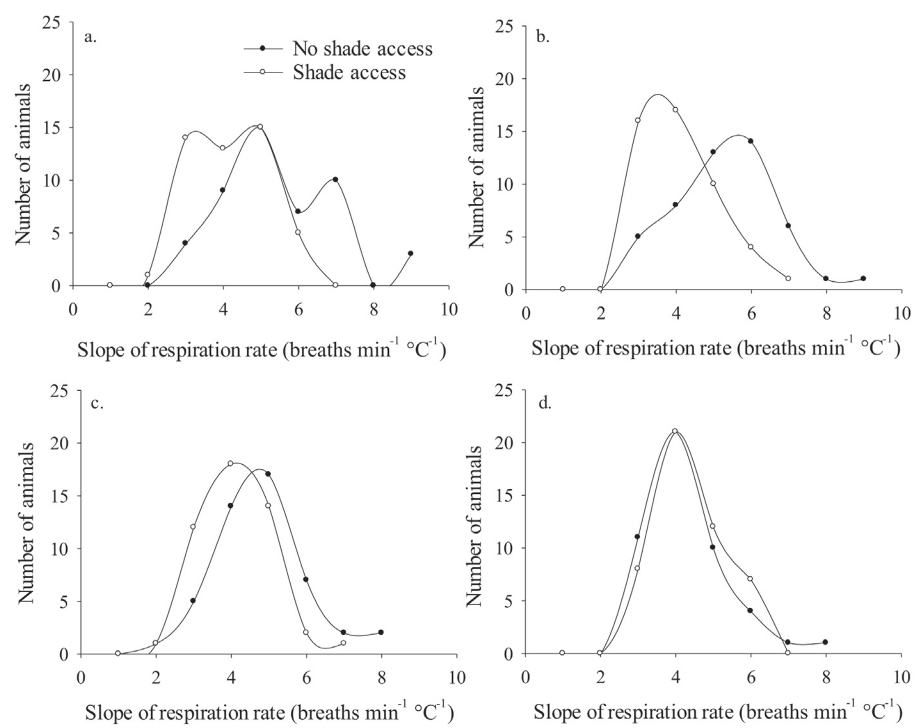
increased body temperature due to handling would coincide with the maximum diurnal body temperature (Mader et al., 2000). When cattle are sprinkle cooled during a moving event, the body temperature maximum is reduced and the recovery is improved (Figure 8).

Application of management strategies

Although many management strategies have been researched, all have both positive and negative aspects associated with them. The advantage for all of the management options is that they lower heat stress, but some have a greater effect than others. The disadvantages include poorer performance of the animals in the case of changing feeds, increased labor or different work schedule for employees (timing of meals and cleaning), and increased odor generation with the addition of water on the feedlot surface. While decisions are always based on cost to benefit ratios, the costs and benefits are sometimes difficult to estimate and often include costs other than monetary. For example, the cost of changing the timing of the meals includes not only the cost of the extra labor, but also worker dissatisfaction, a cost the feedlot operator cannot always afford. Another example is the increased odor generation associated with sprinkle cooling, which can affect the people who live in the vicinity of the feedlot. Depending on the location of the feedlot, this may have a particularly high cost. Therefore, choosing a single correct management strategy for an entire feedlot is very difficult.

The interactive nature of the three components (environment, animal susceptibility, and management) would make the management of heat stress a candidate for precision animal management. Precision animal management in this sense is applying the correct level of management to different animals. To apply precision animal management, the first step involves assessing individual animals for susceptibility to heat stress. The second step is to separate animals into groups with similar susceptibilities. Finally, management strategies are selected that will work best for that group of animals. Application of management strategies based on the needs of the animals maximizes benefits while minimizes cost.

Some examples include providing shade for different colors of cattle (Figure 9). Research has shown that shade provides more relief to cattle with darker-colored hides (Brown-Brandl et al., 2013).



a - Angus heifers (black); b - MARC III composite heifers (red); c - MARC I composite heifers (tan); d - Charolais heifers (white).
Each breed/treatment group is represented by 48 heifers.

Figure 9 - Distribution of responsiveness (slope of respiration rate and exposure temperature) of different breeds/composite of cattle provided with and without access to shade.

Conclusions

Summertime weather has periods of unseasonable hot weather, which at times can cause hyperthermia in animals housed outdoors, like feedlot cattle. The response of cattle to hot weather can be broken down into three components: the environment, animal susceptibility, and management.

The stress level of a given environment includes many different parameters such as temperature, humidity, wind speed, solar radiation, and overnight temperature. There are several different models that will combine the factors into one parameter. This most well-known of these is Temperature Humidity Index.

Many factors affect level of response a given animal will have to a particular environment. These animal susceptibility factors include coat color, sex, species (*bos Indicus, bos Taurus*), temperament, health and health history, prior exposure, hair thickness, condition score, and age. It has been shown that individual animal response can be summarized using the slope of respiration rate of an individual animal with respect to the environment.

Management of animal exposure to summertime conditions can reduce the stress and improve the welfare of the animal. Management options are quite varied and include providing shade, sprinkle cooling, changing the diets, changing the time, or eliminating handling of the animals.

All management options have positive and negative aspects to them. Overall, if a precision animal management scheme (applying management strategies consistent to the individual or group of individual needs) can be employed. Thus the cost to benefit ratio can be maximized.

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