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Chapter 1: Basic Principles of the Thermal Environment and Livestock Energetics

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Introduction

Description of the thermal environment and the livestock response can be complex, and has been the subject of extensive research for over five decades inspired in part by a joint report sponsored by ASAE (now ASABE) and ASHRAE. This 1959 report presented the "State of the Art" of the thermal environmental requirements of poultry (Stewart and Hinkle, 1959), dairy cattle (Yeck, 1959), beef cattle (Nelson, 1959), swine (Bond, 1959) and sheep (Kelly, 1959). Even though the report was comprehensive, data were noted as being incomplete for understanding the biophysical interactions between the animal and its thermal environment as required for effective management and engineering design. Heat loss for poultry was primarily based on basal (fasted) conditions, for example, and the role of the skin and hair in heat dissipation from cattle was inadequate. Comprehensive studies have been conducted in the intervening 50 years to evaluate the effects of nutrition, acclimation or conditioning, dynamic changes in the environment, physiological state, and social interactions on livestock productivity responses to the thermal environment: temperature, humidity, radiation, and air velocity.

This chapter presents the basic principles associated with describing the thermal environment, the heat transfer parameters, and components of livestock responses to the thermal environment. These principles lead to the understanding needed for effective livestock management so that environmental stress and thus potential adverse consequences are minimized or eliminated. Additionally, this chapter provides an overview of the more detailed information in subsequent chapters of this monograph.

Characterization of Livestock Responses to Thermal Environments

When an animal encounters challenging thermal environments, its first response (either involuntary or voluntary) is coping in order to survive. Self-preservation in turn is linked to survival of the species. The next response is directed toward reproduction. Productive functions such as growth are the last in the sequence of responses. While all of these responses are important to livestock producers, those related to maintaining a high level of production and reproduction in an efficient and humane manner are crucial to survival of the livestock enterprise. Figure 1 provides a framework for understanding the complexities of the responses of the animal to its thermal environment.

Coping responses permit the animal to maintain normal production within a range of thermal environments. Farm animals are remarkable in their ability to mobilize coping mechanisms and maintain performance when challenged by thermal stressors. However, the intensity and duration of adverse environmental conditions, along with a reduced opportunity for recovery, can challenge the animal's ability to cope. The mechanisms involved in the coping responses are divided into physiological, behavioral, and immunological responses.

Responses of animals vary according to the type of thermal challenge. Short-term adaptive changes in physiological, behavioral, and immunological functions (survival-

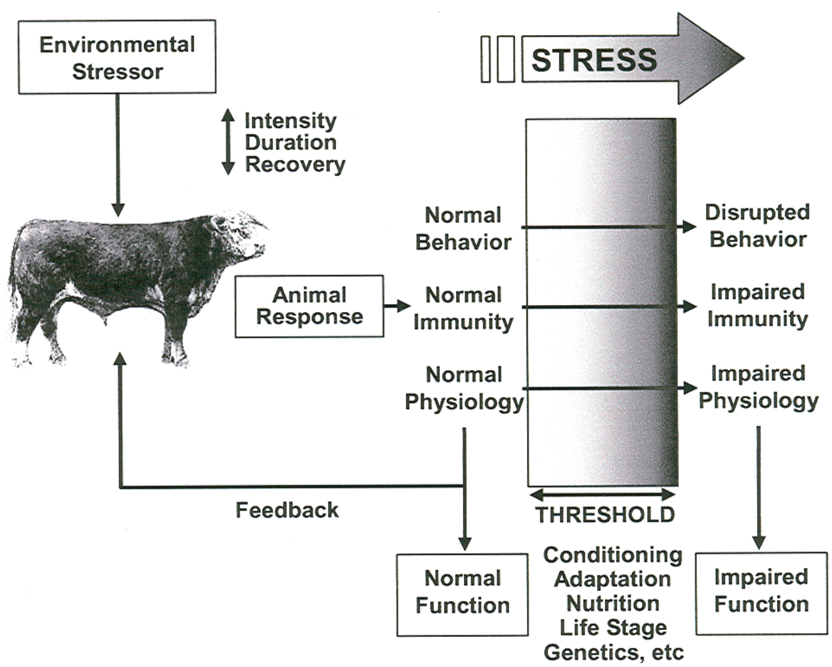

Figure 1. Responses of animals to potential environmental stressors that can influence performance and health (Hahn, 1999, as adapted from Hahn and Morrow-Tesch, 1993).

oriented) are the initial responses to acute events. Longer-term challenges impact performance-oriented responses (e.g., altered feed intake and heat loss, which affect growth, reproduction, and efficiency). Gaughan et al. (2009) reviewed adaptive components of the ability of farm animals to withstand thermal stressors, and the selection of animals (within breeds and between breeds/species) better suited to particular environmental conditions. However, selection of such animals may result in improved welfare and ability to cope at the expense of lower overall performance. The same authors cited a number of reports related to adaptive responses and the detrimental impact of thermal stressors on health, growth rate, feed intake, feed efficiency, tissue deposition, milk yield, health status, reproduction, and egg production of vulnerable animals.

As a general physiological model for mammals of all species, respiration rate serves as an early warning of increasing thermal stress as a result of high heat loads, and increases markedly above a baseline as the animals try to maintain homeothermy by dissipating excess heat. Research results illustrate that above a threshold environmental condition, body temperature begins to increase as a result of the animal's inability to adequately dissipate the excess heat load by increased respiratory vaporization. There is also concomitant decrease in feed intake as body temperature increases to reduce the heat load caused by diet-induced thermogenesis, which ultimately results in reduced performance (production, reproduction), health, and well-being if adverse conditions persist (Hahn et al., 1992*).* Diet-induced thermogenesis is discussed in more detail in the reference *Mammalian Thermogenesis* (Girardier and Stock, 1983).

Thresholds are species dependent and are affected by many factors. For shaded *Bos taurus* feeder cattle, Hahn (1999) reported respiration rates typically increased above a threshold of about 21°C air temperature, with a threshold for increasing body temperature and decreasing feed intake at about 25°C. A recent study (Brown-Brandl et al., 2005) also showed the influence of body condition, genotype, health history, and temperament on respiration rate of unshaded *Bos taurus* heifers, as noted in Figure 2.

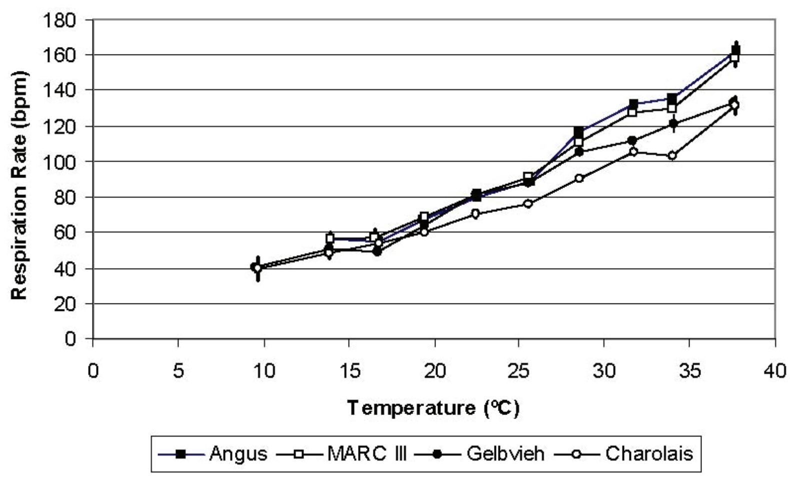

Figure 2. Respiration rates as a function of ambient temperature for unshaded cattle of four genotypes (Brown-Brandl et al., 2005).

Nutrition, physiological status (stage of pregnancy, stage of lactation, growth rate), age, and previous exposure to hot conditions may increase or decrease the impact of hot conditions. Genetic characteristics of animals can markedly alter how individual animals respond to thermal challenges. It is important to recognize that while advances in genetics manipulation will likely alter some of the biological and adaptive responses of livestock, the laws of physics will still apply—heat production and heat losses must balance within the limits of heat storage capacity of the animals

Livestock health and performance can be in jeopardy when the environmental condition exceeds a threshold limit that results in altered status of the physiological and immunological systems. In such instances, the adverse environment can lead to reduced performance and health of the animal, and even death. Based on the coping mechanisms, the transition can be noted by altered behaviors, impairment in the immune status, and/or change in the physiological status.

The environmental range and limits within which animals can cope are influenced by various factors such as animal species, genetics, age or life stage, level of nutrition and prior conditioning. Thresholds (both cold and hot environmental challenges) beyond which potential thermal stressors can influence performance and health are important elements in describing environmental requirements for livestock. Such thresholds can form the upper or lower boundary conditions for functional relationships between attributes of performance and thermal parameters.

Observed animal responses to thermal environments are often considered in terms of the integrated, or averaged, effect over an extended time period (several days to several weeks or months). Short-term (a few seconds to a few days) or acute responses are also important in reflecting environmental influences on feed intake, the endocrine and immune system, thermoregulation, reproduction, and even survival. These short-term or dynamic responses provide a means for refining performance models and threshold limits, for the development of energetic and thermoregulatory models, and for evaluating potential linkages among physiological, immunological, neurological, and other components of the responses.

Behavioral responses are the first to be invoked in challenging thermal environments, and reflect the preferences of the animals exposed to specific conditions. The resting pattern of the animals provides a readily observable indicator of the environment adequacy and thus level of thermal balance, as this integrates both internal (health, physiological state, etc.) and external (thermal and nutritional) factors. For instance, huddling, resting next to one another, and increasing contact with the floor are the stereotypical postural patterns of animals that experience cold, comfortable, and warm-to-hot sensations, respectively (Mount, 1968). It also should be noted that behavioral responses may not always be the best for the animals (Hahn and Bond, 1977).

Animal caretakers often use animal behavioral patterns to fine-tune air temperature settings. However, it is laborious and impractical for the caretakers to perform such manual adjustments on a continual and consistent basis. Computer vision offers a potential alternative to replace human observation of the animals and adjustment of control set-point. Recent research has examined the feasibility and potential implementation of such an approach for assessment of thermal comfort based on image analysis of resting behavior of group-housed pigs (Geers et al., 1991; Shao et al., 1997, 1998; Xin, 1999; Hu and Xin, 2000; Ye and Xin, 2000; Shao, 2003).

Thermal Exchange and Animal Responses

The thermal exchange of the animal to its environment is complex as illustrated in Figures 3 and 4 for unbuffered (outside) and buffered (housed) conditions. The physical factors that directly impact heat transfer from and to the surface of an animal are presented in Table 1. The basic heat transfer equations governing these processes are presented in the *ASHRAE Handbook of Fundamentals* (2004), Chapter 3 of *Environmental Control for Animals and Plants* by Albright (1990), and the reference by Scott et al. (1983). The control of the surface characteristics by the animal is essential for its livelihood and productivity. The design of the livestock facility and weather conditions will also affect heat transfer between the animal and its surroundings.

Livestock discussed in this monograph (e.g., pigs, sheep, goats, cattle, chickens, and horses) are homeothermic. The physiological and behavioral controls of these animals strive to maintain the body temperature at a near-constant level by controlling

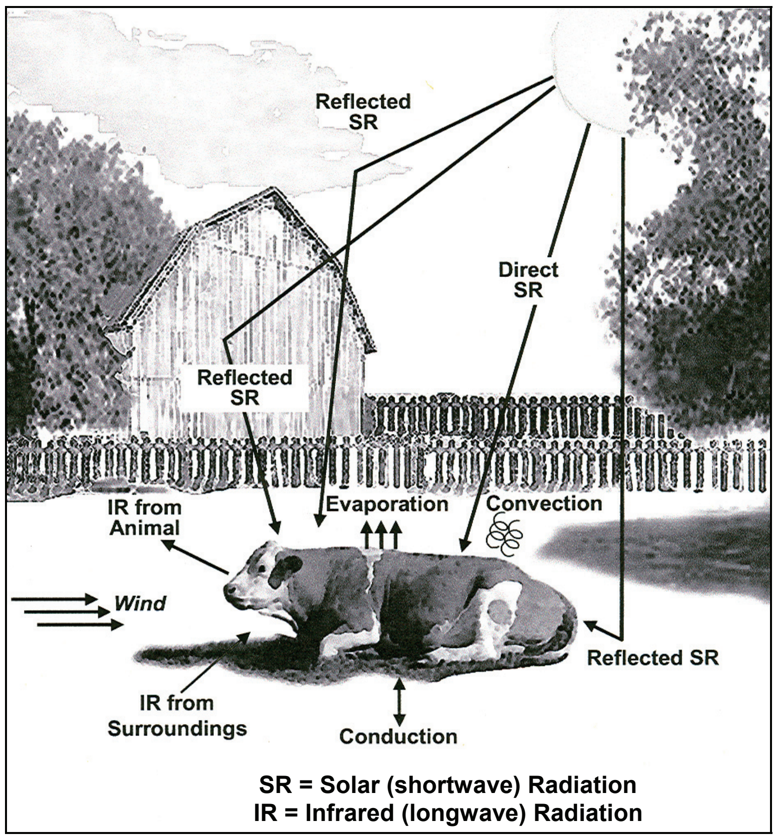

Figure 3. Thermal energy exchange between animal and the outside unbuffered environment (Hahn, 1994).

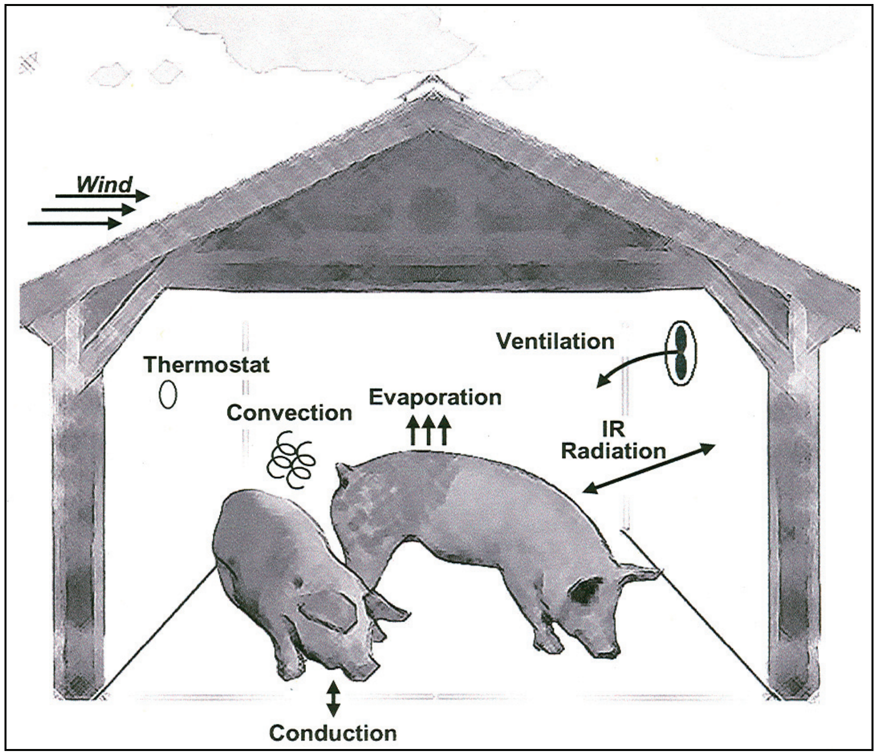

Figure 4. Thermal energy exchange between an animal and the enclosed buffered environment (Hahn, 1994).

Table 1. Physical factors influencing energy transfer from the surface of the animal (adapted from Hahn, 1976).

Factors	Modes of Heat Transfer			
	Convection	Conduction	Radiation	Evaporation
Animal characteristics				
Configuration of animal	X	X[a]	X[b]	X[c]
Surface temperature of animal	X	X	X	X[d]
Emissivity of animal's surface			X	
Environmental characteristics				
Surrounding surface temperature		X	X	
Air temperature	X			
Air velocity	X			X
Air vapor pressure				X
Surrounding shape factor for radiation			X	
Emissivity of surrounding surface			X	
Thermal resistance of contact surface		X		
Heat capacity of contact material		X		

[a] For standing animals, conductive heat transfer is negligible; for animals lying, the area of animal surface in contact with the floor or supporting structure, conductive heat transfer is a factor.
[b] Area of the animal exposed to the radiation source or sink.
[c] Wetted area of the animal surfaces, including the respiratory passages.
[d] Temperature of the animal surface is an indirect factor because vapor pressure is a function of temperature.

the thermal energy balance of the animal, so that heat (thermal energy) input through metabolism equals heat loss to the environment. The heat losses are by sensible means of convection, conduction, and radiation, and by latent means of water evaporation through the respiratory system and skin. As the environmental temperature changes, the animal initially copes by adjusting its surface temperature through physiological means (e.g., vasodilatation or vasoconstriction) and by changing its exposed surface area through behavioral means (e.g., recumbent vs. sternum resting posture). These physiological and behavioral adjustments allow for a relatively constant sensible heat loss of the animal.

Thermographical data show that the animal's surface temperature is quite responsive to ambient temperature. Hence it is speculated that changes in tissue thermal resistance play a large role in maintaining constant sensible heat loss. When the temperature gradient between the surface of the animal and the environment is reduced in warm or hot environmental conditions the animal will increase its evaporative heat loss to compensate for the decrease in sensible heat loss.

Conversely, as the environmental temperature decreases feed intake will generally increase. During cold conditions, the animal will increase its metabolism by either shivering or non-shivering thermogenesis, which includes diet-induced thermogenesis. The environmental temperature where the animal theoretically has reached its limit of vasoconstriction (minimum tissue conductance) is commonly referred to as the *lower critical temperature* (C). This is the environmental temperature at which the animal increases its metabolism for thermoregulatory control. By definition, it is the lower boundary of the animal's *zone of least thermoregulatory effort* or *thermoneutral zone*. An animal in a cold environment may also maintain its body temperature by reducing its exposure to the environment by changing its posture, moving to another location, huddling, and/or grouping. The environmental temperature at the upper end of the *zone of least thermal effort* may be referred to as the *upper critical temperature* (U) where theoretically the upper limit of vasodilatation (maximum tissue conductance) occurs and evaporative heat loss must increase. However, this condition cannot be recognized as easily as the lower critical temperature (Sällvik, 1999). These responses and the zone of least thermal effort are discussed in more detail in Chapter 2, "Thermoregulatory Physiology."

Young (1975) at the Brody Memorial Lecture XII presented a schematic representation of the flow of energy through the animal as shown in Figure 5. This illustration provides an excellent visual interpretation of the breakdown of the total energy intake into the components of waste material (feces, gases and urine), heat generation, and animal products.

The difference between the energy intake of the animal through feed intake and its heat loss is retained energy (RE) that can be used for production (e.g., meat, eggs, milk, and wool), reproduction, and work including eating and locomotion. Energy that is expended to keep the body temperature constant is energy that is not available for productive functions. Decreases in feed intake energy due to management practices and environmental conditions will cause a decrease in the difference between feed intake energy and heat loss, and thus causing a decrease in RE. Also, if the thermal environment requires an increased use of the feed intake energy for maintaining body temperature a decrease in productivity will occur.

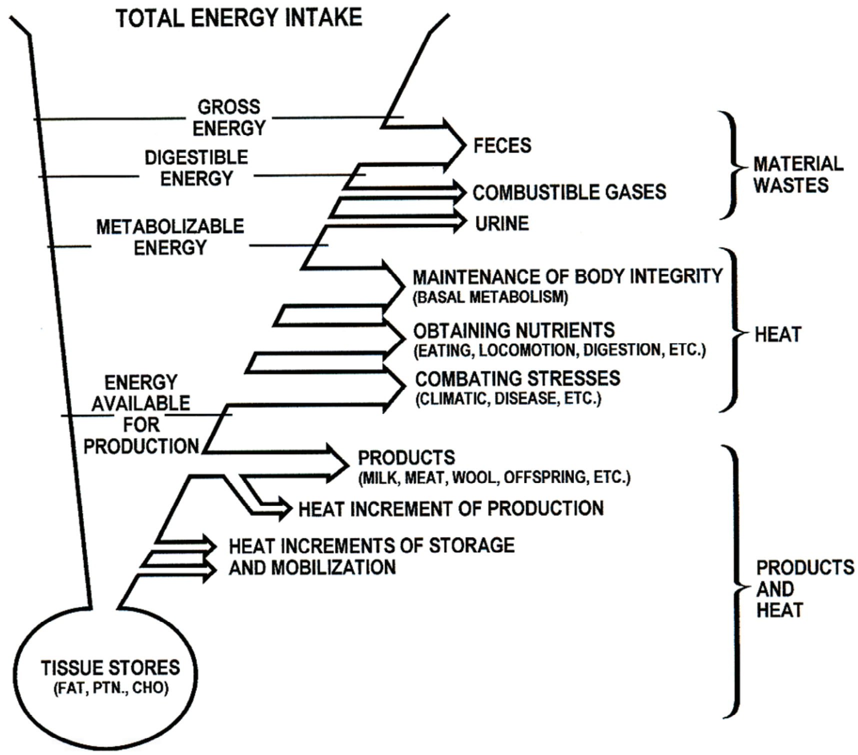

Figure 5. Schematic representation of the energy flow through an animal (Young, 1975).

This interplay between the heat loss of the animal and its feed energy intake as affected by the thermal environment is the essence of predicting the productivity of the animal. It enables the engineer, animal scientist, veterinarian, and herdsman to establish the thermal environmental requirements for livestock. The energetics of the biological processes in thermodynamic and nutritional terms are discussed in more detail in Chapter 3, “Energetics of Biological Processes,” along with graphical representations of the feed energy intake and utilization partitions.

Kleiber (1961) presented general curves showing the interplay between metabolizable energy intake (ME), heat loss, and environmental temperature. Engineers Teter and DeShazer (1976) used these graphical relationships to develop mathematical relationships between environmental temperature and performance of cattle, poultry, and swine. The basic principles of the interactions are shown in Figure 6. For mathematical modeling purposes the total heat loss curve was divided into two segments, S for the heat loss below the lower critical temperature C and L for heat loss above C.

A heat and moisture dissipation model representing how heat transfer applies in the thermoregulatory response of the homoeothermic animal to its environment was developed by Ehrlemark and Sällvik (1996). Sällvik (1999) subsequently used this model, illustrated in Figure 7, in a review of animal environmental requirements. The

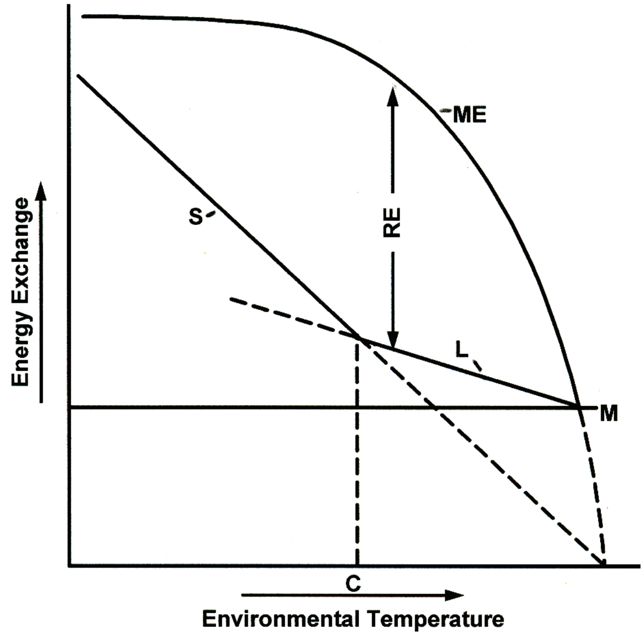

Figure 6. Environmental temperature vs. energy exchange showing the adjustment in metabolizable energy intake (ME) and heat loss (S or L) for changes in environmental temperature. Also shown are the retained energy (RE), maintenance energy level (M), and lower critical temperature (C) (adapted from Teter and DeShazer 1976).

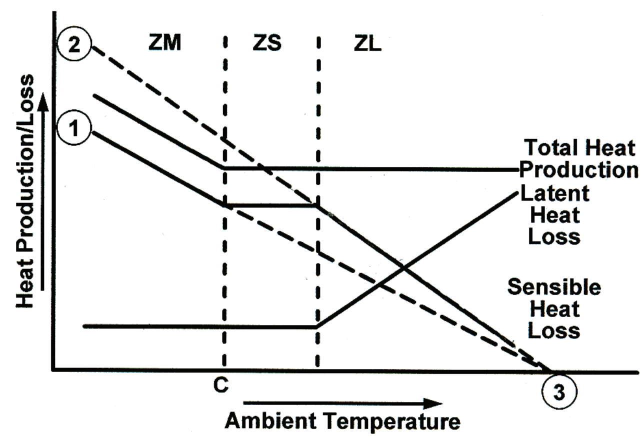

Figure 7. Basic thermoregulatory responses in relationship to ambient (environmental) temperature. ZM = metabolic zone, ZS = sensible heat loss zone, ZL = latent heat loss zone, and C = lower critical temperature. Lines 1-3 and 2-3 are the limits of the heat loss factor for sensible heat loss of the animal in units of W/°C (Ehrlemark and Sällvik, 1996; Sällvik, 1999).

model demonstrates three basic thermoregulatory response zones: the zone of metabolic regulation (ZM), the zone of sensible heat loss regulation (ZS) and the zone of latent heat loss control (ZL). The ZM occurs at environmental (ambient) temperatures where the animal needs to increase its metabolism to maintain body temperature. The environmental temperature at which this necessary increase in metabolism occurs is lower critical temperature, C. Just above C is the ZS, where the animal is able to control its body temperature primarily by controlling blood flow to the peripheral region by vasomotor control, thus changing its surface temperature. This zone is also referred to as the zone of least thermoregulatory effort (ZLTE). The last zone is the ZL, where vasodilatation is at its maximum and latent heat loss is mainly used to control body temperature.

In certain cases the sensible heat loss of the animal is not a straight-line response below the lower critical temperature but curves upwards, as demonstrated by the data of Ames (1980), indicating an increase in the thermal tissue conductance as the temperature decreases below C. These data were graphically presented in Figure 3 of the publication by Hahn et al. (1987). The change in the tissue conductance below C could possibly be a result of increased feed intake, which also increased below C. This observation has also been noted from data reported by Stevens (1980) for dairy cattle subjected to extreme cold temperatures in Alaska.

The slopes for the lines between point C and the body temperature (line 1-3) and the maximum vasodilatation (line 2-3) are the boundaries of values for the effective surface area of the animal (A) divided by its relative thermal resistance (R). This is analogous to the physical heat loss factor of a building. Line 1-3 is defined as the heat requirement line; its slope is used to determine the metabolic increase needed for each increment of environmental temperature change below the lower critical temperature. Thus, the rate of sensible heat loss of the animal ($\dot{Q}_S$) as portrayed in Figure 7 is:

$$\dot{Q}_S = A/R\ (T_b - T_e) \tag{1}$$

where $\dot{Q}_S$ = rate of sensible heat loss, W or J/s

A = effective surface area of the animal, m^2

R = effective thermal resistance of the animal between its core and the environment, $m^2/W°C$

T_b = body temperature, °C

T_e = environmental or ambient temperature, °C.

Determined graphically, the lower critical temperature, C, is the point on the sensible heat loss curve having the minimum value for the heat loss factor (A/R). The heat loss factor line in this case would be line 1-3 as presented in Figure 7.

This application is demonstrated by using the energetic results of Close and Mount (1978) shown in Figure 8 for pigs weighing between 22 and 50 kg with four levels of metabolizable energy (ME) intake and five environmental temperatures. To determine C, the latent heat loss of the pigs is subtracted from the total heat loss. The latent heat loss of the pigs at the low environmental temperatures for all four diets was essentially constant at 200 $kJ/kg^{0.75}$ per day. Thus, the variation in total heat loss results from sensible heat loss for pigs of similar weight. Gain is near a maximum when the environ-

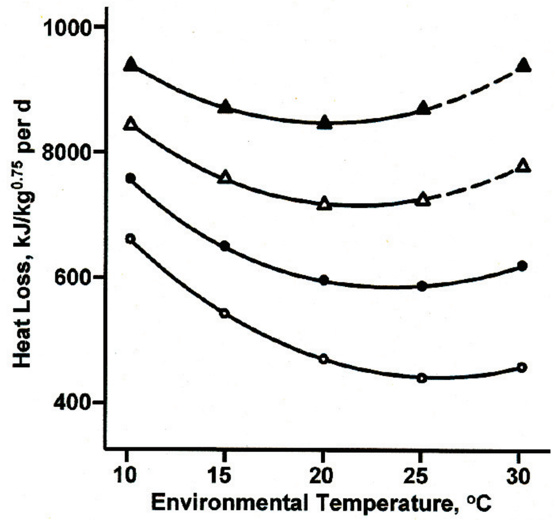

Figure 8. Heat loss of growing pigs at diets of 440 (open circle), 880 (closed circle), 1320 (open triangle), and 1760 (closed triangle) kJ ME/kg$^{0.75}$ per day. Dashed lines are predicted. (From Close and Mount, 1978.)

ment is at the lower critical temperature (Close and Mount, 1978). Graphically, point C can be determined by having the pivot point for the A/R line at the intersection of the above graph at 39°C (approximate body temperature of the pig) and 200 kJ/kg$^{0.75}$d. Using the tangent point on the heat loss curve as C, it is noted that C decreases as the feed energy intake increases from maintenance at 440 kJ/kg$^{0.75}$d to four times maintenance at 1760 kJ/kg$^{0.75}$d. C values are 20°, 15°, 12.5° and 10°C as the metabolizable energy (ME) intake increases.

Several basic points can be made from this example. The level of nutrition needs to be taken into consideration when establishing a thermally appropriate environment for livestock. Also, different species show different results. Note, for example, that for sheep, the A/R value will remain constant with increasing feed intake below C (Graham et al., 1959). Webster (1983) noted that common farm animals could be divided into two groups according to the way they maintain homeothermy. One group, poultry and swine, maintains a constant body temperature primarily by regulating metabolism. The second group, horses and ruminants, maintains body temperature primarily by regulating heat loss. This may be the reason why sheep and swine are different in the changes of the heat loss factor. Many other models are categorized and applications discussed in Chapter 7, "Modeling of Livestock Bioenergetics for Environmental Management Applications."

The genetics of modern animals have advanced considerably in the last five decades. These advancements have led to changes in bioenergetics of modern species (Xin et al., 2001, Brown-Brandl et al., 2004; Chepete et al., 2004; Chepete and Xin, 2004). Updated information about heat losses of farm animals are presented in Chapter 4, "Measuring Energetics of Biological Processes."

Driving Forces for Heat Exchange

The thermal environment is made up of those factors that influence the heat loss of the animal. These factors are air temperature, air velocity, building conductance, surface temperature, mean radiant temperature, and water vapor pressure. Sensors to measure these factors are described in detail in Chapter 6, "Instrumentation for Research and Management in Animal Agriculture." Gradients providing driving forces for heat exchange between an animal's surface or core and the immediate surroundings (microenvironment) are discussed in the following sections.

Gradients

Air Temperature

Air temperature is a primary descriptor of the environment even though, as noted in Table 1, it only directly affects the convective heat loss of the animal. Thus caution needs to be used when relying solely on air temperature in describing the thermal environment. Other factors are usually integrated with air temperature to form environmental indices, as discussed in Chapter 5, "Thermal Indices and Their Applications for Livestock Environments."

Warm air will rise in a building since it is less dense than cooler air. Also, air currents due to wind, the ventilation system, and undesirable openings will cause air temperature in the building at, for example, caretaker height to be considerably different from that at the animal level. Thus air temperature needs to be measured at a location close to the animal to obtain an accurate representation of its thermal environment. As a practical matter, the sensor location needs to be such that the animal cannot destroy it. The sensor also needs to be shielded from thermal radiation sources such as the sun or the underside of a hot or cold roof.

Contact Temperature

Farm animals spend considerable time lying on the floor or ground. The contact temperature of the animal is the same as the surface temperature of the animal when the heat flow is in equilibrium or steady state. An analysis by Bruce (1979) showed that the actual heat flow down into the floor or ground was negligible in comparison to the heat flow from the animal to the floor and back into the air. Thus, the significant gradient for the heat loss by conduction of large animals (e.g., pigs and cattle) is the difference between body temperature and room or outside air temperature. The thermal resistance or conductance of the animal is a modifier to this heat loss and is discussed below in the section "Modifiers to Driving Forces."

However, the heat loss from the animal to the floor surface is not simple. The animal has control of its own shell conductance by vasomotor control. Spillman and Hinkle (1971) found that a finishing pig in contact with a cool surface could decrease its blood flow to its peripheral region and thus limit the amount of heat loss to a cooled floor. Also, posture can limit the contact area and thus decrease heat loss by conduction. Restrepo et al. (1977) confirmed Spillman and Hinkle's findings noting that the percentage of conductive heat loss of 24 to 46 kg pigs in contact with a 10°C floor was less than for a floor at 15°C and 20°C. These latter two temperatures had the highest percentage of conductive heat loss. On the other hand, floor temperatures of 25°C, 30°C and 35°C resulted in a steady decline in the percentage of conductive heat loss, probably because of a decrease in the temperature gradient between the floor and the skin of the pig. Vacha and DeShazer (1983) and Vacha (1985) studied the heat dissipation of nursery pigs (5 to 13 days after weaning) on heated floors at air temperatures between 30°C and 16°C. The data showed, as anticipated, a reduction in sensible heat for increased floor heat at a given air temperature. However, the ratio of the conductive heat loss to total sensible heat loss generally increased with increased floor heat. This suggested that floor heating caused an increase in air temperature of the microenvironment of the pig while causing a decrease in tissue thermal resistance. The main point in relating these observations is to recognize that animals can change their tissue thermal resistance, sometimes resulting in unanticipated consequences.

Cooling the perches of broilers has been shown to relieve or reduce heat stress (Okelo et al., 2003) because of heat loss through the birds' feet, with a magnitude ranging from 0.65 to 5.09 W/bird. The cooled roost was more effective in relieving heat stress when the air temperature was below 30°C than above 30°C. The interaction of air temperature with roost temperature is important, and again illustrates the complexity of the physiological response of the animal to its environment.

Radiant Temperatures

Surface temperatures of an animal's surroundings vary in both indoor and outdoor conditions. For example, in Figures 3 and 4 the surroundings consisting of the sun, sky, trees, ground, floors, walls, and ceiling are all at different temperatures. Esmay (1969) provides an excellent discussion of the effect of the environment and its modification of radiant heat exchange. Thermal radiation is emitted at a value proportional to the absolute temperature of the surface to its fourth power. Shortwave radiation emitted from the sun reaches the earth's surface (either directly or as diffuse sky radiation) with a wavelength of 0.3 to 4.0 μm. Longwave radiation from low-temperature sources (e.g., the earth or terrestrial objects) has wavelengths between 4.0 and 100 μm. The importance of knowing the origin or wavelength of the radiation is that the amount absorbed by the receiving body varies according to the absorptivity of that body at different wavelengths. For example, white-colored animals have low absorptivity for shortwave radiation and will reflect much of the sun's rays. Dark-colored animals have high absorptivity for shortwave radiation. However, longwave radiation is absorbed equally by animals of any color. In other words, the color of the animal doesn't make a difference for absorbing longwave radiation, but makes a distinct difference for absorbing shortwave radiation.

Mean radiant temperature (MRT) is one measurement used to assess the thermal environment of the animal. It is defined in the *ASHRAE Handbook of Fundamentals* (2004) as the uniform temperature of a black enclosure that causes the same heat loss by radiation from the animal as from the actual enclosure. One type of instrumentation for assessing MRT consists of a small globe painted flat black (Bond and Kelly, 1955), with concurrent measurements of globe temperature, air temperature, and air velocity. The air temperature and air velocity are used to eliminate the convective component of the thermal balance of the globe, thus obtaining the integrated surrounding surface temperature of the animal. The difference between the fourth-powered MRT in °K and that of the animal's surface temperature in °K is the driving gradient for radiant heat exchange.

Gagge et al. (1967) introduced the term *effective radiant field* (ERF) that makes a simpler gradient using MRT minus the surrounding air temperature. This value multiplied by the linear radiation heat transfer coefficient approximates well the radiant heat absorbed by the animal from a high temperature radiant heater. Overhults and DeShazer (1982) used ERF to conduct infrared heating experiments with weaned pigs.

Vapor Pressure

The vapor pressure difference between the skin or respiratory tract and the ambient air drives the rate of cutaneous or respiratory moisture loss of the animal. To approximate those losses, the vapor pressure at the skin or respiratory tract is assumed to be the saturated vapor pressure at the respective surface temperature. When sweating, the rate of moisture loss is dictated by the rate of sweating. The heat loss from the respiratory system is dictated by the difference in vapor pressure of expired air and inspired (ambient) air. To guide engineering design, functional relationships have been developed that depict surface wetting needs of broilers (Tao and Xin, 2003) and laying hens (Yanagi et al., 2002) as affected by vapor pressure deficit and air velocity.

Modifiers to Driving Forces

Air Velocity

Air velocity can markedly affect the animal's convective heat transfer, aiding cooling in warm environments but chilling the animal in cool environments. Increased air velocity around the animal will effectively shift both lower critical temperature and upper critical temperature of the animal to a higher temperature. However, the effectiveness of air velocity on the convective heat loss declines as the air velocity is increased, since the convective heat loss increases at approximately the one-half power of air velocity. Thus, when air velocity is doubled the convective heat loss will be increased by about 40% and when the air velocity is increased by ten times (e.g., by fans), the heat loss is only increased approximately three times. In warm environments, air temperature needs to be below body temperature for this cooling action to be effective.

Air velocity also affects the evaporative heat loss of the animal, especially for those animals with significant cutaneous moisture loss such as horses and cattle. Additionally, increased air velocity in a building will increase moisture vaporization from water sources (e.g., manure, litter, spilled water). This in effect will decrease the sensible heat load of the building and increase the latent heat load by the same amount. This cooling effect is advantageous in the summer but may cause an increase in the supplemental heat requirement in the cold periods.

Thermal Conductance

For animals in contact with floors and other surfaces, the rate of heat loss by conduction depends on the contact surface area, the temperature of the contact surface, and the thermal conductance of the contact material. Thermal conductance values are available from handbooks such as the *ASHRAE Handbook of Fundamentals* (ASHRAE, 2004). Bruce (1979) experimentally determined the thermal resistance (the inverse of thermal conductance, °C m^2/W) of different types of floors using the thermal gradient between air temperature and the 39°C body temperature and thermal tissue resistance of a 45 kg pig. The values ranged from 0.66°C m^2/W for 60 mm of dry straw on concrete to 0.042°C m^2/W for a bare concrete floor.

Psychrometrics

Psychrometrics is the term used to describe the thermodynamic properties of moist air. It is discussed in detail in Chapter 6 of the *ASHRAE Handbook of Fundamentals* (ASHRAE, 2004) and in Chapter 2, “Psychrometrics,” in *Ventilation of Agricultural Structures* (Mangold et al., 1983). Additionally, Albright (1990) provides an excellent overview of psychrometrics in Chapter 2 of his textbook *Environment Control for Animals and Plants*. Barometric air pressure and two other independent properties are required to establish the thermodynamic state of moist air. For livestock environments, standard barometric pressure (101.325 kPa or 29.921 inch Hg) is usually assumed. Thus, two independent properties determine the thermodynamic state of moist air. The relationship of parameters describing the thermodynamic properties of moist air is illustrated schematically in Figure 9.

Considering air as a perfect gas, so that Dalton’s law of partial pressure applies, the pressure exerted by each gas in a mixture of gases is independent of the presence of other gases, so that the total pressure exerted by a mixture of gases equals the sum of the partial pressures. The humidity ratio is defined as the mass of water vapor in kilograms per kilogram of dry air in an air-water vapor mixture, and is directly related to the ratio of partial pressure of water vapor to the partial pressure of dry air. Relative humidity is defined as the ratio of the partial pressure of the water vapor in moist air to the vapor pressure of that same air at saturation and at the same temperature (units are percent). Specific volume is used in ventilation design and refers to the space occupied per kilogram of dry air. To establish the psychrometric state of the air, required meas-

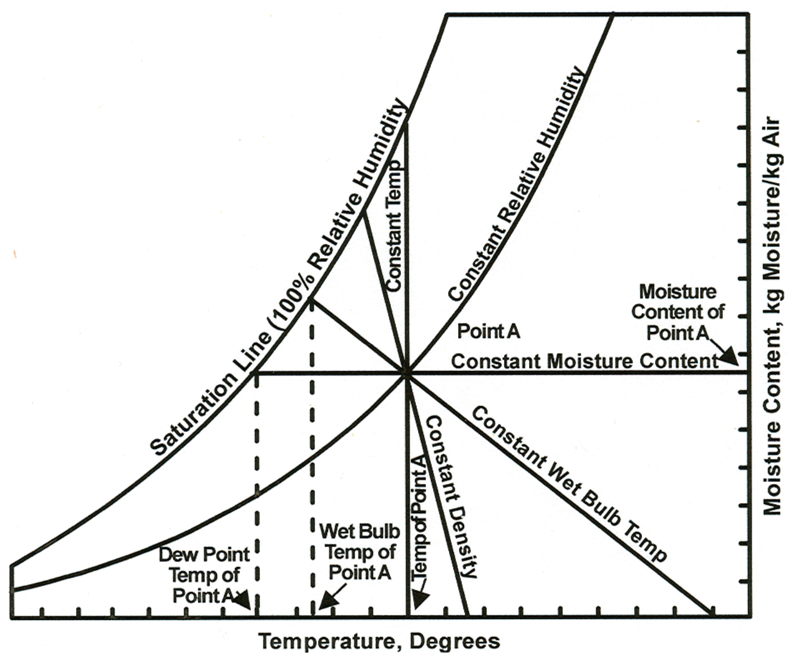

Figure 9. Pyschrometric chart showing the various thermodynamic components of moist air at Point A.

urement choices are dry-bulb and either wet-bulb or dew-point temperature. The dry-bulb temperature is commonly used to define an environment, and is measured with a bare temperature-sensing device (e.g., a mercury thermometer). The wet-bulb temperature is a value indicated on an ordinary thermometer, the bulb of which has been wrapped with a wick moistened in distilled water and placed in a moving stream of air. The evaporation of the water from the wick into the surrounding air attains a steady state in which sensible heat is transferred just rapidly enough from the surroundings to provide energy for evaporation. The wet bulb is cooled by evaporation of the water from the bulb. Dew-point temperature is the temperature at which dew will form on a cooled surface, and hence is the temperature at which the air will be saturated. This temperature is directly related to the saturated vapor pressure and thus the moisture content of the air.

Enthalpy of the air refers to the energy content of moist air, and reflects both the energy of sensible heat related to dry-bulb temperature and latent heat of vaporization (expressed in kJ/kg of dry air). The constant wet-bulb temperature line (Figure 9) and a constant enthalpy line are considered the same for animal environmental design.

Rational Environmental Management Decisions

Livestock are produced in a wide variety of environments, ranging from the unbuffered or naturally-occurring to buffered (with the naturally-occurring environment modified by shelters or other means). The general climate of the geographic area where a livestock enterprise is located largely determines the potential for adverse consequences of acute and chronic thermal challenges, as it highly influences the local environment of the animals in unbuffered production systems (e.g., feedlots, open range), and also impacts the microclimate within buffered housing systems. Figure 10 presents a generalized diagram of how the acute and chronic thermal changes affect the animal and management responses.

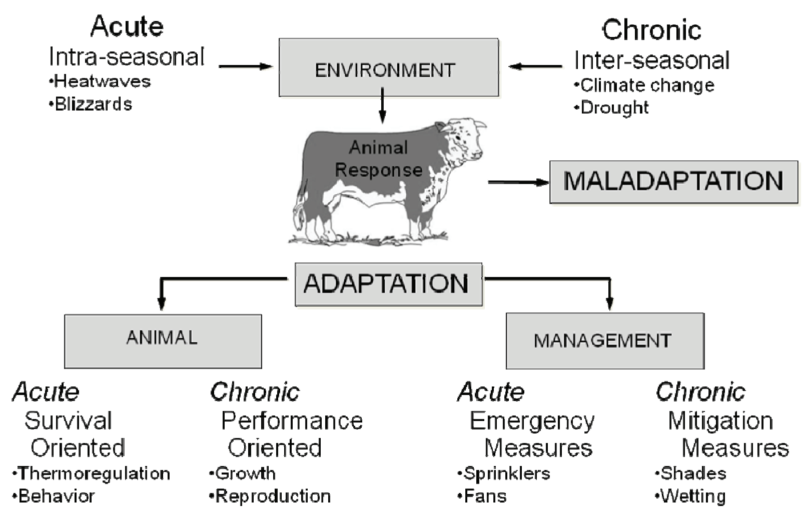

Figure 10. Responses of animals and production systems to challenging thermal environments (Hahn, 2009).

Within the general climate, weather can vary greatly, both within a year and between years (intra-annual and inter-annual variability), and many local microclimates can exist within the geographic area. Seasonal stressor intensity and duration, and the opportunity for relief from thermal stressors (periods for recovery) are directly related to the general climate. These aspects are usually taken into account when determining the type of livestock (species, breeds) to be produced in a given area, and also have an impact on the type and siting of production facilities selected.

From a livestock management perspective, two key questions are (1) what are the penalties associated with a given thermal environment, and (2) is there a need for intervention to reduce those penalties and the associated risk to the well-being of the animals or to the production enterprise? The general concept of thresholds for performance losses and adaptability of animals previously discussed is illustrated more fully in Figure 11 with respect to environmental management. Using dairy cow milk production as an example, genetics, performance level, and environmental influences can combine to create a low level of vulnerability as shown in situation A. Increased performance level, as in a moderately high-production cow, increases the vulnerability for the animal (situation B). Coupling situation B with an adverse environment can put the animal at risk for loss (B^1). A high-performance animal, even in a moderate environment, can be at risk for loss (C). Combining an adverse environment with high performance pushes the level of vulnerability and consequent risk to even higher levels. In situation D, inherent genetic characteristics that are disadvantageous to the animal in coping with potential environmental stressors immediately put the animal at risk for substantial loss of performance. When combined with a high performance level, any environment other than optimal can increase animal vulnerability and managerial risk to unacceptable levels.

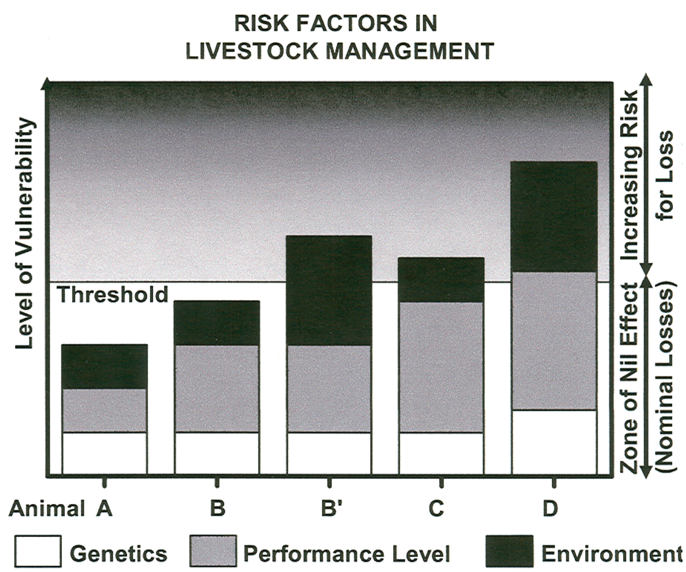

Figure 11. Concept of risk as related to animal performance level, genetic adaptability, and the environment (adapted from Simensen, 1984, by Hahn, 1994).

Biologic responses in terms of performance and well-being of animals can be used to assess penalties associated with exceeding optimal or nominal loss environmental limits (Hahn and McQuigg, 1970; see further discussion in Chapter 5). Relatively flat response functions for performance of many classes of livestock obviate the need for narrow thermal control bands for animals acclimated to their environment. Wide thermal fluctuations can, however, be quite detrimental to unhealthy animals, as they are less capable of exerting adaptive capabilities, and immune responses may be compromised. In addition, neonatal animals of all species require closer attention to potential adverse consequences of microclimate conditions.

Rational strategic decisions require an estimate of the likelihood of challenging environmental conditions. Probability analyses are a particularly useful and objective way of expressing the uncertainty of climate in a given location or area (Hahn and

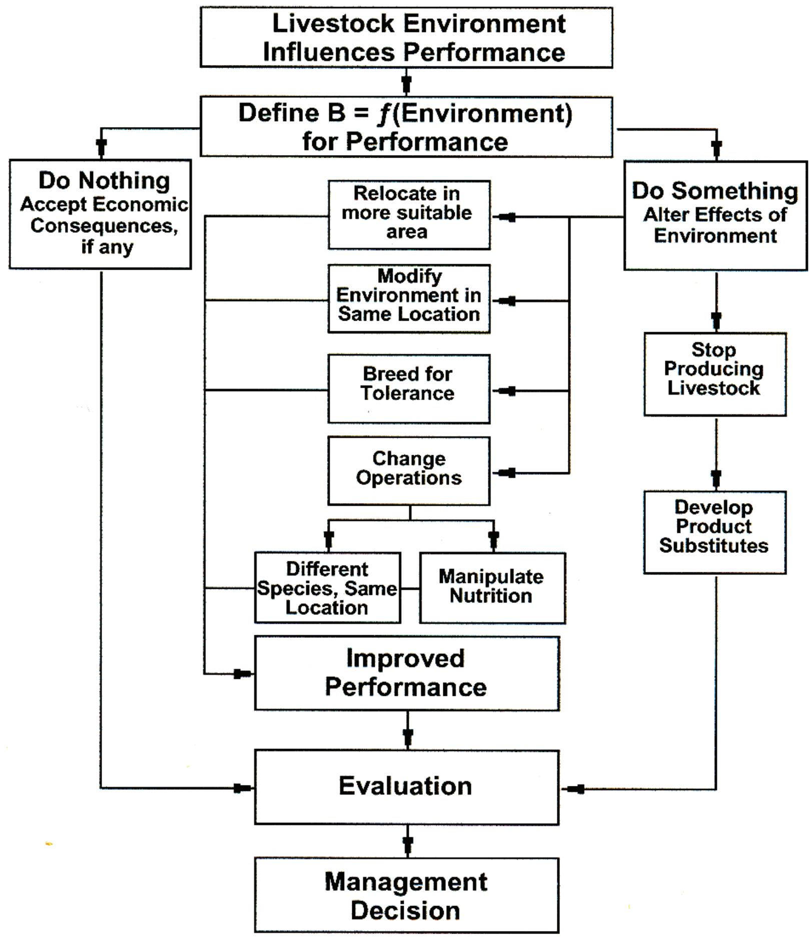

Figure 12. Decision tree diagram for managers considering livestock environmental modification (Hahn, 1981).

Osburn, 1969). They provide a rational basis for strategic decisions (e.g., providing housing, changing breeds or species of livestock, selecting a better location), so that the manager can select a risk level compatible with his estimation of the utility value of alternatives. The potential benefits of specific alternatives can then be assessed for comparison with the alternative of doing nothing and accepting the potential consequences. Figure 12 summarizes the information and process needed to make rational environmental management decisions.

Economics, Uncertainty, and Risk

Environments for livestock are primarily managed based on animal needs. However, the impacts of environment on performance obviously have economic consequences, as well. The value of performance penalties resulting from adverse environments differs for individual production systems because of varying production costs and returns. Environmental requirements are therefore somewhat farm dependent, and the application of available technical solutions to counter the environmental effects is further dependent on the producer.

In particular, managerial and technical skills and capabilities, acceptance of or aversion to risk, and the uncertainty associated with a proposed technology are factors to consider in addition to animal well-being and availability of resources. It is noted that risk implies statistical measurements (usually probabilities) associated with deviations from average or optimal values. Uncertainty implies that responses associated with departures from average or optimal values are largely indeterminate with no definite assessment of penalties or benefits.

Production systems that provide management and shelter options to mitigate thermal environmental challenges can reduce the risk of adverse consequences. Evaluating risk involves three elements: perception, assessment (the primary focus of quantifying animal responses), and management. There are two approaches to managing risk: crisis management, whereby managers react after a challenging thermal situation develops (and live with the consequences), or proactive risk management, whereby livestock managers recognize the threat of thermal challenges (e.g., heat waves), assess the potential consequences, make strategic plans for mitigation (e.g., providing shades and/or sprinklers), and take tactical action when appropriate to avert or reduce the threat of a thermal challenge. Chapter 8, “Environmental Management,” presents the topic of human interaction with livestock and the resulting interventions and options.

Conclusions

The response of the animal to its environment is complex both in its biological responses and in the description of the environment. Many considerations need to be observed to make a valid assessment of the animal’s response and its application to environmental management. The state of the animal as dictated by nutrition, management (e.g., movement of animals and feeding schedule), and social adjustments all need to be taken into consideration. Knowing the basics is the first step in professionally evaluating the needs of the animal for an acceptable, productive, and profitable environment.

References

Albright, L. D. 1990. Chapter 2: Psychrometrics; Chapter 3: Heat transfer basics. In *Environment Control for Animals and Plants*. St. Joseph, Mich.: ASAE.

Ames, D. R. 1980. Thermal environmental affects livestock performance. *Bioscience* 30: 457-460.

ASHRAE. 2004. Chapter 3: Heat transfer; Chapter 6: Psychrometrics; Chapter 13: Measurement and instruments. In *ASHRAE Handbook of Fundamentals* Atlanta, Ga.: American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.

Bond, T. E. 1959. Environmental studies with swine. *Agric. Eng.* 40(9): 544-549.

Bond, T. E., and C. F. Kelly. 1955. The globe thermometer in agricultural research. *Agric. Eng.* 36(4): 251.

Brown-Brandl, T. M., J. A. Nienaber, H. Xin, and R. S. Gates. 2004. A literature review of swine heat and moisture production. *Trans. ASAE* 47(1): 259-270.

Brown-Brandl, T. M., R. A. Eigenberg, and J. A. Nienaber. 2005. Heat stress risk factors for feedlot cattle. In *Livestock Environment VII, Proc. 7th Intl. Livestock Environment Symposium.* 559-565. St. Joseph, Mich.: ASABE.

Bruce, J. 1979. Heat loss from animals to floors. *Farm Building Progress* 57(1): 1-4.

Chepete, H. J., and H. Xin. 2004. Heat and moisture production of poultry and their housing systems: Molting layers. *Trans. ASHRAE* 110(2): 274-285.

Chepete, H. J., H. Xin, M. C. Puma, and R. S. Gates. 2004. Heat and moisture production of poultry and their housing systems: Pullets and layers. *Trans. ASHRAE* 110(2): 286-299.

Close, W. H., and L. E. Mount. 1978. The effects of plane of nutrition and environmental temperature on the energy metabolism of the growing pig: 1. Heat loss and critical temperature. *Brit. J. Nutr.* 40: 413-421.

Ehrlemark, A. G., and K. G. Sällvik. 1996. A model of heat and moisture dissipation from cattle based on thermal properties. *Trans. ASAE* 39(1): 187-194.

Esmay, M. L. 1969. Chapter 8: Radiant heat loss from animal. In *Principles of Animal Environment.* Westport, Conn.: AVI Publishing.

Gagge, A. P., G. M. Rapp, and J. D. Hardy. 1967. The effective radiant field and operative temperature necessary for comfort with radiant heating. *Trans. ASHRAE* 73(Part I): I. 2.1-I.2.9.

Gaughan, J., N. Lacetera, S. Valtorta, H. Khalifa, L. Hahn, and T. Mader. 2009. Chapter 7: Response of domestic animals to climate challenges. In K. Ebi, I. Burton, G. McGregor, eds. *Biometeorology for Adaptation to Climate Variability and Change,*131-170. Berlin: Springer-Verlag Publ.

Geers, R., H. Ville, and V. Goedseels. 1991. Environmental temperature control by the pig's comfort behavior through image processing. *Trans. ASAE* 34(6): 2583-2586.

Girardier, L., and M. L. Stock. 1983, Chapter 1: Mammalian thermogenesis: An introduction. In *Mammalian Thermogenesis,* 1-7. L. Girardier and M. L. Stock, eds. New York, N.Y.: Chapman and Hall.

Graham, N. McC., K. L. Blaxter, F. W. Wainman, and D. G. Armstrong. 1959. Environmental temperature, energy metabolism and heat regulation in sheep: I. Energy metabolism in closely clipped sheep *J. Agric. Sci. Camb*. 52(1): 13-24.

Hahn, G. L. 1976. Shelter engineering for cattle and other domestic animals. In *Progress in Animal Biometeorology*, 1(1): 496-503. H. D. Johnson, ed. Amsterdam: Swets & Zenlinger.

Hahn, G. L. 1981.Housing and management to reduce climatic impacts on livestock. *J. Anim. Sci*. 52(1): 175-186.

Hahn, G. L. 1994. Environmental requirements of farm animals. In *Handbook of Agricultural Meteorology,* 220-235. J. F. Griffith, ed. New York, N.Y.: Oxford Univ. Press.

Hahn, G. L. 1999. Dynamic responses of cattle to thermal heat loads. *J. Anim. Sci*. 77(Suppl. 2): 10-20.

Hahn, G. L. 2009. Climate change and animal production: Challenges and adaptive responses of animals and production systems. *Proc. 1st Intl. Congress on Climate Change and Agriculture* (in press).

Hahn, G. L., and T. E. Bond. 1977. Behavioral responses of livestock to environmental factors. *Reports, CIGR Section II Seminar on Agricultural Buildings*: *Band* 1: 11-19.

Hahn, G. L., and J. D. McQuigg. 1970. Evaluation of climatological records for rational planning of livestock shelters. *Agric. Meteorol.* 7(2): 131-141.

Hahn, G. L., and D. D. Osburn. 1969. Feasibility of summer environmental control for dairy cattle based on expected production losses. *Trans. ASAE* 12(4): 448-451.

Hahn, G. L., P. L. Klinedinst, and D. A. Wilhite. 1992. Climate change impacts on livestock production and management. ASAE Paper 927037. St. Joseph, Mich.: ASAE.

Hahn, G. L., and J. L. Morrow-Tesch. 1993. Improving livestock care and well-being. *Agric. Eng.* 74(3): 14-17.
Hahn, G. L., J. A. Nienaber, and J. A. DeShazer. 1987. Air temperature influences on swine performance and behavior. *Applied Eng. Agric.* 3(2): 295-302.
Hu, J., and H. Xin. 2000. Image-processing algorithms for behavior analysis of group-housed pigs. *Behavior Research Methods, Instruments, & Computers* 32(1): 72-85.
Kelly, C. F. 1959. Environmental studies with sheep. *Agric. Eng.* 40(9): 549, 551.
Kleiber, M. 1961. *The Fire of Life.* New York, N.Y.: John Wiley and Sons.
Mangold, D. W., D. S. Bundy, and M. A. Hellickson. 1983. Chapter 2: Psychrometrics. In *Ventilation of Agricultural Structures*. ASAE Monograph No. 6. M. Hellickson and J. Walker, eds. St. Joseph, Mich.: ASAE.
Mount, L. E. 1968. *The Climate Physiology of the Pigs*. Baltimore, Md.: Williams and Welkins.
Nelson, G. L.1959. Effects of climate and environment on beef cattle. *Agric. Eng.* 40(9): 540-544.
Okelo, P. O., L. E. Carr, P. C. Harrison, L. W. Douglass, V. E. Byrd, C. W. Wabeck, P. D. Schreuders, F. W. Wheaton, and N. G. Zimmermann. 2003. Effectiveness of a novel method to reduce heat stress in broilers: A cool roost system. *Trans. ASAE* 45(6): 1675-1663.
Overhults, D. G., and J. A. DeShazer 1982. Infrared heat for reducing environmental stress on weaned pigs. In *Livestock Environment II, Proc. of the 2nd Intl. Livestock Environment Symposium,* 362-369. St. Joseph, Mich.: ASAE.
Restrepo, G., M. D. Shanklin, and G. L. Hahn. 1977. Heat dissipation from pigs as a function of floor and ambient temperature. *Trans. ASAE* 20: 145-147.
Sällvik, K. 1999. Section 2.1: Animal environment requirements, Chapter 2: Environment for animals. In *CIGR Handbook of Agricultural Engineering Vol. II: Animal Production and Aquacultural Engineering,* 31-41. St. Joseph, Mich.: ASAE.
Scott, N. R., J. A. DeShazer, and W. L. Roller. 1983. Chapter 7: Effects of the thermal and gaseous environment on livestock. In *Ventilation of Agricultural Structures,* 121-165. ASAE Monograph No. 6. M. Hellickson and J. Walker, eds. St. Joseph, Mich.: ASAE.
Shao, B. 2003. A real-time imaging system for assessment and control of swine thermal comfort. PhD diss. Ames, Iowa: Parks Library, Iowa State Univ.
Shao, J., H. Xin, and J. D. Harmon. 1997. Neural network analysis of postural behavior of young swine to determine their thermal comfort state. *Trans. ASAE* 40(6): 755-760.
Shao, J., H. Xin, and J. D. Harmon, 1998. Comparison of image feature extraction for classification of swine thermal comfort behavior. *Computer & Electronics in Agric.* 19: 223-232.
Simensen, E. 1984. Livestock environment and health: General concepts and research strategies. Report 7. Oslo, Norway: Dept. Animal Husbandry and Genetics, Norwegian College of Veterinary Medicine.
Spillman, C. K., and C. N. Hinkle. 1971. Conductive heat transfer from swine to controlled temperature floors. *Trans. ASAE* 14: 301-303.
Stevens, D. G. 1980. Personal communications with J. A. DeShazer during his studies at the University of Nebraska, Lincoln, while Stevens was on study leave from USDA-ARS.
Stewart, R. E., and C. N. Hinkle. 1959. Environmental requirements for poultry shelter design. *Agric. Eng.* 40(9): 532-535.
Tao, X., and H. Xin. 2003. Surface wetting and its optimization to cool broiler chickens. *Trans. ASAE* 46(2): 483-490.
Teter, N. C., and J. A. DeShazer. 1976. Effects of temperature on nutrient requirements of meat animals. In *Proc. 1st Intl. Symposium Feed Composition, Animal Nutrient Requirements, and Computerization of Diets,* 497-504. Logan, Utah: Utah State Univ.
Vacha, K. L. 1985. Floor heating for nursery pigs. MS thesis. Lincoln, Nebr.: Univ. Nebraska, Dept. Agricultural Engineering.
Vacha, K. L., and J. A. DeShazer. 1983. Energetic interaction between a heated floor mass and nursery age pig. ASAE Paper 83-4519. St. Joseph, Mich.: ASAE.
Webster, A. J. F. 1983. Chapter 16: Nutrition and the thermal environment. In *Nutritional Physiology of Farm Animals*, 639-669. J. A. F. Rook and P. C. Thompson, eds. New York, N.Y.: Longman.
Xin, H. 1999. Assessing swine thermal comfort by image analysis of postural behaviors. *J. Anim. Sci.* 77(Suppl. 2): 1-9
Xin, H., I. L. Berry, G. T. Tabler, and T. A. Costello. 2001. Heat and moisture production of poultry and their housing system: Broilers. *Trans. ASAE* 44(6): 1853-1859.

Yanagi, Jr., T., H. Xin, and R. S. Gates. 2002. Optimization of partial surface wetting to cool caged laying hens. *Trans. ASAE* 45(4): 1091-1100.
Ye, W., and H. Xin. 2000. Measurement of surface temperature and postural responses of group-housed pigs to thermal conditions by thermography. *Trans. ASAE* 43(6): 1843-1851.
Yeck, R. G. 1959. Environmental research with dairy cattle. *Agric. Eng.* 40(9): 536-540.
Young, B.A. 1975. Some physiological costs of cold climates. Brody Memorial Lecture XII. Special Report 175. Columbia, Mo.: Agricultural Experiment Station, Univ. Missouri, Columbia.