J. Dairy Sci. 86:2131–2144

Effects of Heat-Stress on Production in Dairy Cattle

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ABSTRACT

The southeastern United States is characterized as humid subtropical and is subject to extended periods of high ambient temperature and relative humidity. Because the primary nonevaporative means of cooling for the cow (radiation, conduction, convection) become less effective with rising ambient temperature, the cow becomes increasingly reliant upon evaporative cooling in the form of sweating and panting. High relative humidity compromises evaporative cooling, so that under hot, humid conditions common to the Southeast in summer the dairy cow cannot dissipate sufficient body heat to prevent a rise in body temperature. Increasing air temperature, temperature-humidity index and rising rectal temperature above critical thresholds are related to decreased dry matter intake (DMI) and milk yield and to reduced efficiency of milk yield. Modifications including shade, barns which enhance passive ventilation, and the addition of fans and sprinklers increase body heat loss, lowering body temperature and improving DMI. New technologies including tunnel ventilation are being investigated to determine if they offer cooling advantages. Genetic selection for heat tolerance may be possible, but continued selection for greater performance in the absence of consideration for heat tolerance will result in greater susceptibility to heat stress. The nutritional needs of the cow change during heat stress, and ration reformulation to account for decreased DMI, the need to increase nutrient density, changing nutrient requirements, avoiding nutrient excesses and maintenance of normal rumen function is necessary. Maintaining cow performance in hot, humid climatic conditions in the future will likely require improved cooling capability, continued advances in nutritional formulation, and the need for genetic advancement which includes selection for heat tolerance or the identification of genetic traits which enhance heat tolerance.

(**Key words:** dairy, heat stress, environment, lactation)

INTRODUCTION

One of the greatest challenges to production facing dairy farmers in the southeastern United States is heat stress and the strain that it causes the lactating dairy cow. Climatic conditions in the Southeast are such that the warm (or hot) season is relatively long, there is intense radiant energy for an extended period of time, and there is generally the presence of high relative humidity. Thus heat stress is chronic in nature, there is often little relief from the heat during the evening hours, and intense bursts of combined heat and humidity further depress performance. Lactating dairy cows create a large quantity of metabolic heat and accumulate additional heat from radiant energy. Heat production and accumulation, coupled with compromised cooling capability because of environmental conditions, causes heat load in the cow to increase to the point that body temperature rises, intake declines and ultimately the cow's productivity declines.

Virtually the entire southern United States is subject to extended periods of hot weather. In the more southern latitudes, high ambient temperature and humidity exist for 4 to 6 mo each year. Beede and Collier (1986) identified three management strategies to minimize the effects of heat stress: 1) physical modification of the environment (shading, cooling), 2) genetic development of heat-tolerant breeds, and 3) improved nutritional management practices. Based on current knowledge, it appears that a combination of these practices may be necessary to optimize production of dairy cows in hot, humid climates. This is particularly true given the continued genetic improvement in dairy breeds and the unknowns associated with global warming. The objectives for this paper are to define the environmental conditions to which dairy cattle are exposed in the southeast, examine the effects of heat stress on cattle from a physiologic and productive standpoint, and discuss management options which are available to the producer.

Received: August 1, 2002
Accepted November 12, 2002
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THE AMBIENT ENVIRONMENT OF THE DAIRY COW IN THE SOUTHEAST

Climatic Conditions

Climate is a combination of elements that include temperature, humidity, rainfall, air movement, radiation, barometric pressure, and ionization (Johnson, 1987). Climatic zones differ around the world and are dependent on latitude, prevailing winds, evaporative conditions, availability of water, elevation, proximity to mountains and other factors. The southeastern U. S. is classified as humid subtropical (Johnson, 1987) and is characterized by high though seasonal temperatures, humidity, and rainfall. The range and duration of ambient temperature is largely dependent on latitude, with latitudes closer to the equator experiencing conditions increasingly conducive to heat stress. Hahn and Osburn (1968) projected that cows producing 32 kg milk/d and living below a line drawn approximately through mid-Missouri, diagonally through Tennessee, and northern Georgia would lose approximately 180 kg of production during a 120 d period from June 1 through September 30, increasing gradually to 270 kg as one moves south to Florida and southern Alabama. Cows producing 45 kg/d were projected to lose from 272 to 454 kg for the same regions. At a point centered in Atlanta it was projected that at the 10th and 90th percentiles (lowest and highest losses expected one year in 10) losses would be 95 and 268 kg, respectively for cows producing 32 kg/d (Hahn and Neinaber, 1976). During an extremely hot summer in 1980 the actual declines were far greater than projections in southern states (Atlanta, 425 kg; Dallas 644 kg; Memphis 568 kg), suggesting that in reality the predicted declines could be conservative.

Homeotherms have optimal temperature zones for production within which no additional energy above maintenance is expended to heat or cool the body. The range for lactating dairy cows is estimated to be from –0.5 to 20°C (Johnson, 1987), while Berman et al. (1985) indicated that the upper critical air temperature for dairy cows is 25 to 26°C. While it is hot enough to cause significant heat stress for several months of each year in the southeastern region of the U. S. there are concerns that global warming will further accentuate the problem. Klinedinst et al. (1993) used several models to predict the impact of climatic change on the performance of lactating dairy cows. Depending on the model used, global warming was predicted to reduce milk yield for cows producing 33 kg/d by from 300 to 900 kg for a May 1 through September 30 season. Despite the wide range in predicted milk yield depression the models agreed that the greatest milk yield declines would occur in the southeastern and southwestern United States. The authors suggested that the predicted declines in milk yield for these regions would occur unless adequate environmental modifications were in place. They also suggested that the probability of extreme high temperature events (heat waves) would increase as mean temperature increased, and an increasing number of heat waves could significantly increase the negative impact of global warming, especially on livestock (Klinedinst et al., 1993). Severe heat waves increase the likelihood for mortality of feedlot cattle, and several hours of THI > 84 with little or no nighttime recovery of THI = 74 can result in the death of vulnerable animals (Hahn and Mader, 1997). Global warming could create conditions that not only impair productivity of cattle but increase mortality of cattle in the absence of protective facilities.

Effect of Climatic Variables on Cow Body Temperature, DMI, Milk Yield

The term heat stress is used widely and rather loosely, and may refer to the climate, climatic effects on the cow, or productive or physiologic responses by the cow. Lee (1965) presented a definition of stress often used by physiologists, in which stress denotes the magnitude of forces external to the bodily system which tend to displace that system from its resting or ground state, and strain is the internal displacement from the resting or ground state brought about by the application of the stress. Therefore the environmental factors external to the cow would contribute to stress (in this case heat stress) while the displacement of the cow from the cow's resting state would be the response to the external stress, or heat strain.

The effects of hot, humid conditions are thought to be mediated through an effect on cow body temperature. Berman et al. (1985) suggested that the upper limit of ambient temperatures at which Holstein cattle may maintain a stable body temperature is 25 to 26°C, and that above 25°C practices should be instituted to minimize the rise in body temperature. However, in the Southeast one of the major challenges is the combined effects of high relative humidity with high ambient temperature. At a temperature of 29°C and 40% relative humidity the milk yield of Holstein, Jersey and Brown Swiss cows was 97, 93, and 98% of normal, but when relative humidity was increased to 90% yields were 69, 75, and 83% of normal (Bianca, 1965). One must understand the means of cooling used by homeotherms to grasp the reasons for the effects of high relative humidity. Cooling processes were summarized in a review (Shearer and Beede, 1990). The processes of conduction, convection and radiation are all dependent on a thermal gradient, thus as air temperature rises above a critical point the thermal gradient is reduced and heat dissipation is less effective. With increasing ambient temperature there is a marked shift from nonevaporative to evaporative cooling (Kibler and Brody, 1950). Evaporative cooling is an effective means of cooling cattle but is compromised by high relative humidity which impedes evaporation, making it difficult to cool the cow in the Southeast.

The effects of the ambient environment on cow performance have been measured by establishing critical ambient temperatures for the cow (Berman et al., 1985; Igono et al., 1992, Johnson, 1987), an equivalent temperature index incorporating temperature, humidity, and air velocity (Baeta et al., 1987), and temperature-humidity index (THI), which incorporates the combined effects of temperature and relative humidity (NOAA, 1976). In classical work, Johnson et al. (1963) reported that milk yield and DMI exhibited significant declines when maximum THI reached 77. Later research determined that the critical values for minimum, mean and maximum THI were 64, 72, and 76, respectively (Igono et al., 1992). Studies established that there is a significant negative correlation between THI and DMI for cows in the southeastern U. S. (Holter et al., 1996; Holter et al., 1997), and the effect of THI is probably mediated through the effects of increasing body temperature on cow performance. Estimated milk yield reduction was 0.32 kg per unit increase in THI (Ingraham, 1979), and milk yield and TDN intake declined by 1.8 and 1.4 kg for each 0.55°C increase in rectal temperature (Johnson et al., 1963). Umphrey et al. (2001) reported that the partial correlation between milk yield and rectal temperature for cows in Alabama was –0.135. West et al. (2002) found that changes in cow body temperature (measured as milk temperature) were most sensitive to same day climatic factors. The variable having the greatest influence on cow a.m. milk temperature was the current day minimum air temperature, while cow p.m. milk temperature was most influenced by the current day mean air temperature. Cow DMI and milk yield were most affected by climatic variables, not cow body temperature. Ravagnolo et al. (2000) reported that maximum temperature and minimum relative humidity were the most critical variables to quantify heat stress, and both variables are easily combined into a THI. Milk yield declined by 0.2 kg per unit increase in THI when THI exceeded 72. The authors concluded that THI can be used to estimate the effect of heat stress on production (Ravagnolo et al., 2000).

Many early studies used current day environmental conditions to determine effects on cow performance. However, there may be a lag of time between environmental events and the full effects on production by the cow. The most significant factors affecting milk yield during hot weather in South Carolina were the total number of hours when THI exceeded 74 during the preceding four days, and the number of hours exceeding THI of 80 on the preceding day (Linville and Pardue, 1985). In Florida the black globe temperature (a measure of temperature and radiant energy) had little effect on milk yield when measured on the same day as milk yield but black globe temperature 24 and 48 h prior were closely associated with depressed milk yield (Collier et al., 1981). West et al. (2002) reported that of the environmental variables studied during hot weather the mean THI two days earlier had the greatest effect on milk yield, while DMI was most sensitive to the mean air temperature two days earlier. Milk yield for Holsteins declined 0.88 kg per THI unit increase for the 2-d lag of mean THI, and DMI declined 0.85 kg for each degree (°C) increase in the mean air temperature. The decline in milk yield and DMI per unit of increase in the environmental measure was substantially less when evaluated on same day climatic measures in comparison with climatic measures two days earlier. Thus the full impact of climatic variables on production is delayed and may be related to altered feed intake, delay between intake and utilization of consumed nutrients, or changes in the endocrine status of the cow.

Though several combinations of temperature, relative humidity, and radiant energy impact heat load in the cow, it is apparent that given sufficient night cooling, cows can tolerate relatively high daytime air temperatures. Igono et al. (1992) reported that despite high ambient temperatures during the day a cool period of less than 21°C for 3 to 6 h will minimize the decline in milk yield. These findings suggest that it will be critical not only to minimize cow body temperature increases during the hot daylight hours, but to find ways to enhance cow cooling during the evening hours.

Metabolic Heat Production

Heat production of metabolic functions accounts for approximately 31% of intake energy by a 600 kg cow producing 40 kg of milk containing 4% fat (Coppock, 1985). Physical activity increases the amount of heat produced by skeletal muscles and body tissues. Maintenance expenditures at 35°C increase by 20% over thermoneutral conditions (NRC, 1981), thus increasing the cow's energy expenditure, often at the expense of milk yield. Body heat production associated with milk yield increases as metabolic processes, feed intake, and digestive requirements increase with yield. The heat load accumulated by the cow subjected to heat stress is the sum of heat accumulated from the environment and the failure to dissipate heat associated with metabolic processes. Obviously with similar body size and surface area, the lactating cow has significantly more heat to dissipate than a nonlactating cow and will have greater difficulty dissipating the heat during hot, humid conditions. When cows that were nonlactating, or at low (18.5 kg/d) or high (31.6 kg/d) milk yield were compared, low and high yielding cows generated 27 and 48% more heat than nonlactating cows despite having lower BW (752, 624, and 597 kg for nonlactating, low, and high producers, respectively) (Purwanto et al., 1990). Berman et al. (1985) reported that rectal temperature of cows increased by 0.02°C/kg FCM for cows producing >24 kg/d, and greater heat production can explain the increasing rate of decline in milk yield for cows as production increased from 13.6 to 18.1 to 22.7 kg of milk per day and THI increased from 72 to 81 (Johnson et al., 1962). Despite the relatively low milk yield in this work, it suggests that high production will greatly accentuate heat stress in the lactating cow. The effects of high milk yield is demonstrated in work by West et al. (1990, 1991) who reported that milk temperature was greater for cows administered bST compared with controls in a hot, humid climate; low yielding cows were more responsive to bST than high yielding cows, possibly because of the higher body temperature associated with greater milk yield. Cows administered bST exhibited significantly greater heat production in both thermoneutral and hot environments, though cows were apparently able to dissipate the greater heat produced, evidenced by greater total evaporative heat losses and cooling heat loss for the bST treated cows which enabled cows to maintain normal body temperatures (Manalu et al., 1991). Administration of bST to both lactating and nonlactating cows in a hot, humid climate (Florida) resulted in elevated body temperature and respiratory rate for both groups of cattle, suggesting that the greater heat strain was not due solely to increased milk yield (Cole and Hansen, 1993). The authors suggested that either greater heat production or interference with heat loss could explain greater strain in nonlactating cattle and that although bST use is efficacious in hot climates, its use should be coupled with procedures to reduce the magnitude of heat stress during summer months.

Physiologic Effects of Heat Stress

Numerous physiologic changes occur in the digestive system, acid-base chemistry, and blood hormones during hot weather; some in response to reduced nutrient intake, but many changes occur as a result of strain in the cow. Neurons that are temperature sensitive are located throughout the animal's body and send information to the hypothalamus, which invokes numerous physiological, anatomical or behavioral changes in the attempt to maintain heat balance (Curtis, 1983). During heat stress cows exhibit reduced feed intake, decreased activity, seek shade and wind, increase respiratory rate, and increase both peripheral blood flow and sweating. These responses have a deleterious effect on both production and physiologic status of the cow.

Cows that were fed ad libitum in a thermal comfort environment, fed ad libitum in a thermal stress environment, or fed a restricted intake in a thermal comfort environment had similar milk yields for both restricted intake and thermal stress treatments, and mammary blood flow tended to be lower compared with ad libitum fed cows in thermal comfort, suggesting blood flow was responsive to level of DMI (Lough et al., 1990). For cows exposed to similar treatments as those of Lough et al. (1990), portal plasma flow was reduced about 14% for cows in thermal comfort with restricted intake or in thermal stress when compared with thermal comfort, ad libitum fed cows (McGuire et al., 1989). The authors concluded that a portion of the negative effects of heat stress on milk production could be explained by decreased nutrient intake and decreased nutrient uptake by the portal drained viscera of the cow. Blood flow shifted to peripheral tissues for cooling purposes may alter nutrient metabolism and contribute to lower milk yield during hot weather.

Hormonal alterations occur with heat strain but it is often difficult to separate effects of lower feed DMI and direct effects of heat strain. McGuire et al. (1991) reported a tendency for plasma somatotropin to decline with heat stress but no difference due to restricted DMI, while triiodothyronine concentration declined with heat and with restricted intake. Others have shown similar declines in triiodothyronine and thyroxine when cows were exposed to high ambient temperatures (Johnson et al., 1988; Magdub et al., 1982). Cows categorized as low, medium, and high producers had higher milk temperatures with increasing production (Igono et al., 1988) and concentrations of milk somatotropin declined significantly when THI exceeded 70. The authors speculated that the decline was due to suppression of hormone production to reduce metabolic heat production. Reduced concentrations of these key metabolic hormones with heat stress is logical and probably reflects the cows attempt to reduce metabolic heat production. Scott et al. (1983) reported a negative relationship for plasma thyroxine concentration and rectal temperature but the initiation of night cooling at the time that rectal temperature was highest was most beneficial to maintaining thermoneutral plasma thyroxine concentration, suggesting that strategically cooling the heat stressed cow could enhance her metabolic potential.

Heat stressed cows generally exhibit altered blood acid-base chemistry as a result of the shift in cooling from conductive, convective, and radiation to evaporative cooling (Kibler and Brody, 1950). Panting and sweating increase as the reliance on evaporative cooling increases. Panting sharply increases the loss of CO_2 via pulmonary ventilation, reducing the blood concentration of carbonic acid and upsetting the critical balance of carbonic acid to bicarbonate necessary to maintain blood pH, resulting in a respiratory alkalosis (Benjamin, 1981). Compensation for the respiratory alkalosis involves increased urinary bicarbonate excretion (Benjamin, 1981), leading to a decline in blood bicarbonate concentration. Heat-stressed cows had elevated rectal temperature and respiratory rate which was further exacerbated in cows receiving bST (Cole and Hansen, 1993) and cows receiving bST during summer in Georgia had higher milk temperature, and significant reductions in pCO_2, blood bicarbonate and base excess (West et al., 1991). Schneider et al. (1988) reported that cows exposed to heat stress in environmental chambers exhibited a diurnal variation in blood pH and blood bicarbonate levels, closely following the cow's rectal temperature and respiratory rate. Cow acid-base chemistry exhibited wide swings from alkalosis to a compensated acidosis over a 24 h period as cows compensate for the alkalotic condition caused by hyperventilation and overcorrect, excreting bicarbonate through the urine and resulting in a metabolic acidosis during the cooler evening hours. Reduced concentrations of blood bicarbonate compromise the buffering capability associated with the bicarbonate system, which may be critical during summer when producers typically feed high grain rations. In addition, cattle lose significant quantities of potassium (K) via sweat and losses increase with sweating rate (Jenkinson and Mabon, 1973).

IMPROVING COW PERFORMANCE IN HOT, HUMID CONDITIONS

Effects of Altering the Cow's Environment

Shading. One of the first steps that should be taken to moderate the stressful effects of a hot climate is to protect the cow from direct and indirect solar radiation. It was estimated that total heat load could be reduced from 30 to 50% with a well-designed shade (Bond and Kelly, 1955), and shading is one of the more easily implemented and economical methods to minimize heat from solar radiation. Cows in a shaded versus no shade environment had lower rectal temperatures (38.9 and 39.4°C) and reduced respiratory rate (54 and 82 breaths/min), and yielded 10% more milk when shaded (Roman-Ponce et al., 1977). Cattle with no shade had reduced ruminal contractions, higher rectal temperature and reduced milk yield compared with shaded cows (Collier et al., 1981). Armstrong (1994) reviewed shade and cooling for cows and discussed the benefits and deficiencies of various types of shade. The author suggested differing shade orientations, depending on whether the application was in a dry or wet climate. In the humid Southeast cows should be allocated 4.2 to 5.6 m^2 of space beneath the shade, and a north-south orientation to allow for penetration of sunlight beneath the shade for drying the ground beneath if earthen floors are used.

Numerous types of shading are available, from trees (which are easily killed by high cow density), to metal and synthetic materials (shade cloth). Concerns exist regarding the transfer of radiant energy through metal roofs. The temperature at the underside of bare metal and insulated roofs differed by approximately 10°C during the peak heat of the day averaged over a 38 d period, and on the hottest day the temperatures were 37 and 57°C under insulated and uninsulated roofs (Buffington et al., 1983). However cost and practicality of insulated roofing has deterred extensive use of the practice. Bucklin et al. (1993) reported a reduction of 2 to 3°C when roofing with a reflective coating was used over totally enclosed poultry housing with no ventilation. However when the same coated roofing was used over well ventilated poultry and dairy housing, no benefits were noted in either temperature or animal performance. The authors indicated that although reflective coatings can reduce the temperature of galvanized roofing, the coatings add expense and effectiveness drops rapidly with time due to reduced reflectivity. The reflective coatings added little benefit to well ventilated facilities.

Much of the emphasis on environmental modification in the southeastern U. S. has focused on the use of free stall and loose housing barns with high, steeply pitched (4 in 12 pitch) roofs, often with open or capped ridge vents. These barns minimize the transfer of infrared radiation due to the high roof, encourage a venturi effect due the rising of hot air up the roof incline and exiting the ridge vent, and also encourage cross ventilation from wind movement through the barn because of the high eaves. Although shade is critical, much of the discussion in this paper will focus on cooling in the presence of shading, with the assumption that shade is a requirement in any environmental management program for dairy cattle in the southeastern U. S.

Cooling for Dairy Cows. Although shade reduces heat accumulation from solar radiation there is no effect on air temperature or relative humidity and additional cooling is necessary for lactating dairy cows in a hot, humid climate. A number of cooling options exist for lactating dairy cows based on combinations of the principles of convection, conduction, radiation, and evaporation. Air movement (fans), wetting the cow, evaporation to cool the air, and shade to minimize transfer of solar radiation are used to enhance heat dissipation. Any cooling system that is to be effective must take into consideration the intense solar radiation, high ambient temperature, and the typically high daytime relative humidity, which increases to almost saturation at night. These challenging conditions tax the ability of any cooling system to maintain a normal body temperature for the cow. However evaporative cooling was predicted to improve milk yield for cows yielding 45 kg/d by 140 kg in the Missouri to Tennessee area, 230 kg in southern Georgia, and 320 kg in Louisiana and Texas during a 122 d summer season (Hahn and Osburn, 1970).

Various cooling systems have been evaluated, and air conditioning dairy cows for 24 h/d improved 4% FCM yield by 9.6% in Florida (Thatcher, 1974). Missouri work showed that air conditioning was not an economical venture (Hahn et al., 1969). Zone cooled cows (cooled air blown over the head and neck) averaged 19% greater milk yield than controls (Roussel and Beatty, 1970), though other scientists concluded that a well designed shade structure provided greater economic returns than the additional benefits derived from zone cooling (Canton et al., 1982). The costs associated with air conditioning and facilities necessary to provide an enclosed environment or ducting for zone cooling have proven cost prohibitive and these types of systems are rare today.

Early work (Seath and Miller, 1948) established the benefits of air movement and wetting the cow to aid cooling. The cooling benefits of using fans, wetting the cow, and the combination of fans and wetting were compared. Cows tied outside in the sun from noon to 2 p.m. to induce heat stress were moved inside to the respective treatments. Although cows were only sprayed down once during treatment the scientists found that after one hour of exposure to treatments, rectal temperature declined the least for cows with no cooling, was intermediate and similar for cows receiving either sprinkling only or fans only, and the greatest cooling occurred with the combination of fans and wetting the cows. Cows cooled with ducted air and spray for 20 min on, 10 min off, yielded 2 kg/d more milk than shaded controls, maintained rectal temperature near normal (below 39°C), and maintained higher plasma growth hormone compared with shaded controls (Igono et al., 1987). They found that when all costs were considered, there was a $0.22 /cow per d profit via improved milk yield. Returns did not consider potential returns from improved maintenance of body weight or reproductive performance. Similarly, Florida workers reported an 11.6% improvement in milk yield when cows were sprayed for 1.5 min of every 15 min of operation (Strickland et al., 1988). Cooled cows had sharply reduced respiratory rate (57 versus 95 breaths/min), and efficiency of production (kg milk per kg DMI) was improved for cooled cows, probably due to lower energy expenditures for body cooling. Comparisons showed little additional benefit to cooling in the holding pen, possibly due to the short duration that cows are present. Day-long cooling in the free stall barn provides for continuous cooling, minimizing the elevation of body temperature during the day. The Florida workers (Strickland et al., 1988) reported that there was an annual return of $96 per cow for 210 days of operation, again only considering increased milk yield in the economic analysis. Internal rates of return in excess of 57% for Florida conditions (210 d annual use, 10 to 15 yr depreciation) or 26.7% for more moderate conditions (100 d annual use, 10 yr depreciation) demonstrated economical returns over a broad geographic range for this type of system. Benefits from sprinkling and fans were reported in a temperate, humid climate (Kentucky), where cows yielded 3.6 kg more milk (15.9%) while consuming 9.2% more feed per day than controls (Turner et al., 1992). Missouri and Israeli work showed milk yield increases of 0.7 kg/d in moderate temperatures (Igono et al., 1985) and 2.6 kg increase in warm, humid conditions (Her et al., 1988). Frequency of wetting and duration of cooling was critical to the effectiveness of cooling systems. Wetting cows for 10 s was less effective in cooling cows than wetting for 20 or 30 s, which were similar (Flamenbaum et al., 1986), while cooling for 15, 30, and 45 m reduced rectal temperature by 0.6, 0.7, and 1.0°C, respectively. Thus length of time for both wetting and fans had dramatic effects on the amount of cooling achieved.

Sprinkler and fan cooling systems generate a large volume of waste water which must be processed. The cooling system used by Strickland et al. (1989) used 454.2 L/cow per d, which totaled 54,504 L/cow for a 120 d cooling season. However when differing rates of water application for cooling were compared, a system using 313.4 L/h (215.9 L/cow per d) cooled cows as well as a system delivering 704.1 L/h (Means et al., 1992). Large droplets from a low-pressure sprinkler system that completely wet the cow by soaking through the hair coat to the skin were more effective than a misting system (Armstrong, 1994). A combination of misters and fans was as effective as sprinklers and fans in Alabama work, where intake and milk yield were similar for the misted cows (Lin et al., 1998). The fan/sprinkler system used about 10 fold more water than the fan/mist system. Thus attention to water delivery rate through nozzle size or the use of fans and misters has proven effective in cooling cows while using substantially less water than systems evaluated in earlier research.

Evaporative cooling systems use high pressure, fine mist and large volumes of air to evaporate moisture and cool the air surrounding the cow. Because of the evaporation there is little wastewater to process in this type of cooling system, which is beneficial when developing a water budget for the dairy farm. Evaporative cooling systems improve the environment for lactating dairy cows in arid climates (Takamitsu et al., 1987; Ryan et al., 1992), and the reduced air temperature results from the removal of heat energy required to evaporate water. Evaporative cooling can be accomplished by passing air over a water surface, passing air through a wetted pad, or by atomizing or misting water into the air stream. There are questions regarding the effectiveness of evaporative systems in climates with high relative humidity. In Florida work where evaporative cooling pads were used there was an effective reduction in air temperature of the barn but milk yield was not altered although rectal temperature and respiratory rate were reduced (Taylor et al., 1986). Similarly, cows in Mississippi that were cooled using evaporative pads had reduced respiratory rate and body temperature and slight increases in DMI with little to no effect on milk yield (Brown et al., 1974). Evaporative cooling lowered air temperature during the hottest part of the day in summer by 4.5 and 5.9°C during two consecutive years but the authors questioned whether this type of evaporative cooling would be cost effective over a period of years. Another form of evaporative cooling incorporates the use of high-pressure mist injected into the fan stream, with fans directed downward to blow cooled air on the cow. Lin et al. (1998) reported that misters and fans cooled cows as well as a low-pressure sprinkler and fan system. However positioning was important and misters were much more effective when mounted low near the cow and much less effective when mounted higher in the barn. When a high pressure mist and fan system was compared with sprinklers and fans, respiratory rates were 87 versus 72 breaths/m and rectal temperatures were 39.6 versus 39.1°C for the mist and fan system and sprinkler/fan system, respectively (Bray, personal communication).

There is renewed interest in other systems to cool cows. Tunnel ventilation using evaporative cooling, fans with injection of high pressure mist, and combinations of cooling over feed bunks and free stalls are currently being investigated. Improved systems capable of either cooling the cow directly or cooling the surrounding environment are necessary to better control the cow's body temperature and maintain production in hot, humid climates.

Cooling Dry Cows. Much of the cooling research conducted in the past has targeted the lactating cow, largely because of the amount of heat generated by the lactating cow, her greater susceptibility to heat stress, and the more easily quantified and economically beneficial measures of feed intake and milk yield. In recent years greater concern has been focused on the late gestation, dry dairy cow and the potential benefits of cooling during the dry period. Maximum degree days for 60 d prepartum had a significant negative effect on early and mid-lactation milk and fat yield for cows in Mississippi (Moore et al., 1992), suggesting that dry cows do suffer the deleterious effects of heat stress and may benefit from protection from the environment. When cows shaded during the dry period were compared with unshaded controls, the shaded cows delivered calves that were 3.1 kg heavier and yielded 13.6% more milk for a 305 d lactation, even though all cows were handled similarly following parturition (Collier et al., 1982). The shaded cows had lower rectal temperature, respiratory rate, and heart rate and altered hormone patterns during the dry period. Similarly, cows that were cooled using sprinklers and fans during the dry period maintained lower body temperatures and delivered calves that were 2.6 kg heavier and cows averaged 3.5 kg more milk daily for the first 150 d of lactation than shade only controls (Wolfenson et al., 1988). Heat stress alters blood flow, potentially altering fetal development. Heat-stressed ewes delivered lambs that were 20% smaller than controls and uterine blood flow was reduced by 20 to 30% by heat stress. Livers and brains of fetuses from heat stressed ewes were substantially smaller than controls (Drieling and Carman, 1991). Similar results have been reported in beef cattle, where fetus weights for cows that were heat-stressed from d 100 to d 174 of pregnancy were reduced by 22% and uterine and umbilical blood flows were reduced by 51 and 30% (Reynolds et al., 1985). This suggests that lambs and calves delivered to heat-stressed mothers were not only smaller at birth but are likely to be less vigorous and lacking the metabolic machinery to thrive following birth. Shading and cooling cows during late gestation will improve subsequent lactation performance and may result in stronger, more vigorous calves at birth.

Heat Stress Effects On Heifers. Heifers generate far less metabolic heat than cows, have greater surface area relative to internal body mass and would be expected to suffer less from heat stress. However research from the southern United States and Caribbean regions indicates that Holstein females raised at latitudes less than 34°N weighed 6 to 10% less at birth and average approximately 16% lower BW at maturity than those in more northern latitudes, even when sired by the same bulls (NRC, 1981). There appear to be several factors contributing to slower growth and smaller body size, including greater maintenance requirements during hot weather, poor appetite and lower quality forages which are influenced by the same environmental conditions that slow growth in cattle. The NRC (1981) publication stated that "It appears, therefore, that it could be prohibitively expensive to produce 600 kg or more Holsteins at maturity in warm climates." Although it may be more expensive to grow heifers in hot climate, the U. S. dairy industry demands relatively large cows capable of high production and which are as large as their more northern relatives.

Immunity may be compromised in newborns during hot weather, and calves born in February and March had higher serum Ig levels than those born in summer (Donovan, 1986). Other Florida work with dairy cows suggested that colostrum was of higher quality during summer than winter, and that Holsteins had the highest quality of the breeds compared (Shearer et al., 1992). This was surprising since the stressful period of summer would be expected to yield lower quality colostrum. Although 79.8% of total samples tested in the low quality range (20 mg Ig/ml), Holsteins were 1.8 times more likely than other breeds to have good quality colostrum. No physiological reason is apparent for this difference and the authors speculated that perhaps Holstein calves born to heat-stressed dams were less vigorous, less likely to nurse immediately after birth, and consequently the colostrum from the first milking was of higher quality due to little or no nursing. This is consistent with the Florida and Israeli work (Collier et al., 1982; Wolfenson et al., 1988) where smaller calves were born to heat-stressed cows, and suggestions that calves were less vigorous.

When primiparous Holsteins were in a cool (THI of 65) or hot environment (THI of 82 from 0900 to 2000 h, THI of 76 from 2100 to 0800 h) for the last 3 wk of gestation and the first 36 h post-calving, cows in the hot environment had lower concentrations of immunoglobulins in colostrum and IgG concentrations were reduced by 22.3% (Nardone et al., 1997). The heat-stressed heifers had a slower rate of decline of their own plasma immunoglobulin concentrations during the final two weeks of pregnancy, suggesting that the transfer of maternal immunoglobulins to colostrum was impaired by heat stress. Work with sows that were heat-stressed from d 100 of pregnancy to about 8 d before farrowing showed that total protein and Ig concentration in colostrum was reduced compared with controls (Machado-Neto et al., 1987). Hot conditions may also compromise the ability of the calf to absorb immunoglobulins. In Arizona, calves housed under corrugated metal shades with no side walls, or the same shade with evaporative coolers were compared with hutches of tubing and corrugated steel (Stott et al., 1976). Calves in the hutches had greater mortality and lower serum IgG at 2 and 10 d of age. Mortality reached 25% (9 of 36) for calves in hutches while 1 and 2 calves died for each of the other treatments. Hutches were hotter and resulted in significantly greater stress and death losses of calves.

During hot weather reduced feed intake is common but increased maintenance costs reduce efficiency of feed conversion. In a study from the 1950's where Holsteins, Brown Swiss, and Jersey heifers were raised from one to thirteen months of age in environmental chambers with constant temperatures of 10 or 26.7°C, Holstein heifers raised in the 26.7°C environment were lighter than heifers in the cool environment by 8.2 kg at 3 months and 30.4 kg at 11 months of age. It took Holsteins in the warm environment 1½ months longer to reach 299 kg BW (Johnson and Ragsdale, 1959). Although the temperature was constant with no diurnal variation, 26.7°C is not extremely hot. In Australia, Friesians, Brahman × Friesian F_1 crosses, and Brahmans were exposed to 17.2 and 37.8°C temperatures (Colditz and Kellaway, 1972). Comparing the hot versus the cool temperature environments, rectal temperature and respiration rates increased the most for Friesians and least for Brahmans. Intake declined about 17% for Friesians, 1.4% for F_1 crosses, and 12% for Brahmans, but initial intake was greater for Friesians and thus a greater decline would be expected. Gains for Friesians were greatest during cool temperatures, but were the least of the three groups when exposed to high temperatures.

Because heifers generate less body heat and can dissipate heat more readily than lactating cows, do heifers benefit from additional cooling? In Egypt, heifers were exposed to winter conditions (17.3°C, 54.5% RH), summer conditions (36°C, 47% RH), and summer conditions with water spraying and an oral diaphoretic (Marai et al., 1995). A diaphoretic (in this study ammonium acetate was used) is a compound fed orally to cattle to increase perspiration. Heifers were sprayed with water seven times daily during the hottest period of the day. Heifers that were cooled had lower rectal temperature and respiratory rate and gain was improved by 26.1% with cooling during summer, a sharp increase even though heifers were only sprayed during the hottest part of the day without the benefit of fans.

Genetic Selection

There are many aspects of genetics that influence the response to heat stress, and variation among breeds is large. One of the challenges associated with managing high producing cattle in a hot environment is that selection for increased performance is often in conflict with maintaining homeothermy. Strictly regulated body temperature was found to promote the greatest productivity in beef cattle and even small increases in body temperature have a negative effect on metabolic processes (Finch, 1986). The maintenance of body temperature is heritable through characteristics including sweating competence, low tissue resistance, coat structure and color, but there is evidence that within Bos taurus cattle that an increased capacity for thermoregulation is accompanied by a reduction in energy metabolism (Finch, 1986). Turner (1982) reported that there was genetic variation of rectal temperature and there was a negative correlation between rectal temperature and fertility, suggesting that selection for lower rectal temperature would improve fertility. However the authors acknowledged that such selection had the potential to favor lower metabolic rate or feed intake. Selection for heat tolerance without selection for an accompanied greater productivity would likely result in lower overall performance by the animal. Sweating response was found to be negatively correlated with metabolic rate, suggesting the difficulty in combining desirable traits of heat adaptation and metabolic potential in cattle (Finch et al., 1982).

There is genetic variation in heat loss via tissue conductance, nonevaporative heat loss, and evaporative heat loss, but more efficient heat loss occurred for Brahman and Brahman cross cattle than with Shorthorn cattle (Finch, 1985). Using Brahman, Friesian, and Brahman x Friesian F_1 cross heifers, the Brahman × Friesian crosses had superior gains at 38°C, but were similar to Friesians at 17° (Colditz and Kellaway, 1972). Brahmans gained more slowly at 38°C. Thus there appear to be benefits from hybrid vigor under heat stress conditions. However it is questionable that crosses with Zebu breeds could be sufficiently productive to meet the needs of the U. S. dairy industry. The potential for crossing Holstein cattle with other domestic dairy breeds such as Jerseys may have more potential in the U. S.

There is evidence that hair color influences the susceptibility of the cow to heat stress because coat color is related to the amount of heat absorbed from solar radiation. In Bos indicus cattle the inward flow of heat at the skin of black steers was 16% greater than for brown steers, and 58% greater than for white steers (Finch, 1986). Bos taurus cattle with dark coats exhibited greater heat transfer to the skin, higher body temperature and sharply reduced weight gains than those with white coats, with increasing woolliness of the coat accentuating the effect (Finch, 1986). When dairy cows from an Arizona herd were categorized into white (less than 40% black), mixed (40 to 60% black), or greater than 60% black, no production traits were different (perhaps because cows were cooled for the first 130 d of lactation), but white cows calving in February and March required fewer services per conception and had fewer open days than mixed and black cows (King et al., 1988). Heritability of coat color was 0.22. In a Florida study using cows characterized as greater than 70% white or greater than 70% black, white cows had slightly lower body temperatures and greater milk yield, regardless of whether they were in shade or no shade conditions (Hansen, 1990). Though coat color is heritable, it is not clear if it is useful to select for color. Perhaps the greatest benefit would be derived when cows are exposed heavily to radiant energy, such as in a grazing situation.

Because genetic variation exists for traits important to thermoregulation, the potential to select sires that can transmit important traits must be considered. However when bulls were evaluated for genotype by environment interactions using daughters in California, New York, and Wisconsin, there was no sire by region interaction for milk or fat yield (Carabano et al., 1990). If these states are considered representative of their region, daughters in one region would not perform differently from those in another region. However for a large data set of cows in Georgia, when THI was near 72 variance for heat tolerance was zero, but when THI was 86 (equivalent to 36°C and 50% humidity) the additive variance for heat tolerance was as large as the general variance (Ravagnolo and Misztal, 2000). Because the genetic correlation between production and heat tolerance was approximately –0.3, the continued selection for production ignoring heat tolerance would result in decreasing heat tolerance. However because the correlation is small, a combined selection for production and heat tolerance is possible. Further investigation into this area is necessary to determine the potential to exploit a genetic approach to heat tolerance while selecting for high milk yield potential.

Nutritional Management

There have been several extensive reviews of nutritional management for the lactating dairy cow in hot climates (Fuquay, 1981; Collier et al., 1982a; Beede and Collier, 1986; Huber et al., 1994; Sanchez et al., 1994; West, 1994; West, 1998). There are several key areas of nutritional management which should be considered during hot weather. These include reformulation to account for reduced DMI, greater nutrient requirements during hot weather, dietary heat increment, and avoiding nutrient excesses. Though the NRC (2001) did not consider the effects of heat stress on the nutritional requirements of dairy cattle there is extensive literature that demonstrates that nutrient requirements for cattle should be modified during hot weather.

Water is arguably the most important nutrient for the dairy cow. Water intake is closely related to DMI and milk yield, but minimum temperature was the second variable to enter a stepwise regression equation (after DMI), indicating the influence that ambient temperature exerts on water consumption (Murphy et al., 1983). Water intake increased by 1.2 kg/°C increase in minimum ambient temperature, but regardless of rate of increase it is obvious that abundant water must be available at all times under hot conditions. In addition, Texas work demonstrated that offering chilled drinking water enhanced milk yield for lactating cows (Milam et al., 1986) by reducing body temperature through absorbed heat energy.

Intake of DM usually declines with hot weather and nutrient density of the diet must increase. The tendency is to increase dietary protein concentration above requirements, but there is an energetic cost associated with feeding excess protein. Excess N above requirements reduces ME by 7.2 kcal/g of N (Tyrrell et al., 1970). When 19 and 23% CP diets were fed, milk yield was reduced by over 1.4 kg (Danfaer et al., 1980) and the energy cost associated with synthesizing and excreting urea accounted for the reduced milk yield (Oldham, 1984). Blood NPN content was positively correlated with rectal temperature (Hassan and Roussel, 1975), suggesting reduced energy efficiency and greater heat production with excessive dietary N.

Dietary protein degradability may be particularly critical under heat stress conditions. Diets with low (31.2% of CP) and high (39.2% of CP) RUP fed during hot weather had no effect on DMI; however, milk yield increased by 2.4 kg/d and blood urea N declined from 17.5 to 13.3 mg/100 ml for the diet containing higher RUP (Belibasakis et al., 1995). In addition, cooling the cow may affect the response of the cow to protein supplementation. When diets with a similar RUP content from high quality (blood, fish, and soybean meals) or lower quality (corn gluten meal) proteins were fed to cows housed in shade or shade plus evaporatively-cooled environments, cows fed high quality RUP yielded 3.8 and 2.4 kg more milk in the evaporatively-cooled and shaded environments, respectively, than those fed low quality proteins (Chen et al., 1993). Although the interaction of protein quality by environment was not significant the authors theorized that the greater response to high quality protein for cows in the cooled environment was because the amount of protein metabolized for energy was reduced and less energy was used in converting NH_3 to urea. In addition, cows in the cooled environment had higher milk yield and greater protein demand. Arizona work summarized by Huber et al. (1994) suggested that when cows are subject to hot weather conditions RDP should not exceed 61% of dietary CP, and total protein should not exceed NRC recommendations by greater than 100 g N/d. One hundred grams N is equivalent to about 3.1% CP in the diet, assuming 20 kg DMI/d. High dietary lysine (241 g/d, 1% of DM) increased milk yield by 3 kg over diets containing 137 g/d lysine (0.6% of DM) (Huber et al., 1994). There is much to be learned about protein nutrition for heat-stressed cows.

Metabolic heat production, though advantageous during cold weather is a liability during hot weather due to the difficulty in maintaining heat balance. Heat production for a 600 kg cow yielding 40 kg of 4% fat milk amounted to 31.1% of consumed energy, which was second to fecal energy losses of 35.3% (Coppock, 1985). While maintenance was responsible for 23.5% of the heat produced, greater milk yield also increases heat production. Cows at high (31.6 kg/d) and medium (18.5 kg/d) milk yield had 48.5 and 27.3% greater heat production than dry cows (Purwanto et al., 1990). Use of some dietary ingredients may contribute less to heat increment of the diet, thus reducing total heat production by the cow. Can these differences in energy efficiency be exploited in practical diets for animals in hot weather? Lower efficiency for use of acetate may account for the low net energy of feeds high in fiber (Moe, 1981), and supports the feeding of low fiber diets during hot weather. A high efficiency for fat use and its low heat increment suggests that fats are undervalued by current feed evaluation systems when they are fed above thermal neutrality (Coppock, 1985).

The most limiting nutrient for lactating dairy cows during summer is usually energy intake and a common approach to increase energy density is to reduce forage and increase concentrate content of the ration. The logic is that less fiber (less bulk) will encourage intake, while more concentrates increase the energy density of the diet. High fiber diets may indeed increase heat production, demonstrated by work showing that for diets containing 100, 75, or 50% of alfalfa, with the remainder being corn and soybean meal, efficiency of conversion of ME to milk was 54, 61, and 65%, respectively (Coppock et al., 1964). Heat production was 699, 647, and 620 kcal per megacalorie ME for the 100, 75, and 50% alfalfa diets, respectively. When cattle were fed pelleted diets of 75% alfalfa and 25% concentrate, or 25% alfalfa and 75% concentrate, the diet containing 75% alfalfa resulted in greater heat production and less retained energy, and the greater O_2 intake by portal drained viscera and liver accounted for 44 and 72% of heat increment for low and high alfalfa diets, respectively (Reynolds et al., 1991). While heat increment is a consideration for high fiber diets, total intake has a much greater impact on metabolic heat production by the animal. Growing heifers fed pelleted rations containing 75% alfalfa or 25% alfalfa produced 48.8 and 45.5 MJ/d of heat (Reynolds et al., 1991), but heat production for low and high intake heifers (4.2 and 7.1 kg/d DMI) was 38.2 and 56.1 MJ/d. Therefore intake has a substantial effect on heat production and must be considered in designing an effective nutritional and environmental management program. Intake normally declines for high fiber diets, and West et al. (1999) demonstrated that the DMI decline for diets with a range of NDF concentration from 27 to 35% was less severe with increasing NDF during hot weather. The total DMI was less during hot weather and suggests that the less severe decline in hot weather was due to lower intake, and not higher NDF content. Low fiber, high fermentable carbohydrate diets may lower dietary heat increment compared with higher fiber diets, but this effect must be balanced with the potential for acidosis associated with high grain diets.

During hot weather, declining DMI and high lactation demand requires increased dietary mineral concentration. However, alterations in mineral metabolism also affect the electrolyte status of the cow during hot weather. The primary cation in bovine sweat is K (Jenkinson and Mabon, 1973), and sharp increases in the secretion of K through sweat occur during hot climatic conditions (Jenkinson and Mabon, 1973, Johnson, 1967, Mallonee et al., 1985). Lactating cows subjected to hot climatic conditions and supplemented with K well above minimum NRC recommendations (NRC, 2001) responded with greater milk yield (Mallonee et al., 1985, Schneider et al., 1984, West et al., 1987). However, the cow subjected to hot climatic conditions is often subject to a respiratory alkalosis due to panting, with subsequent renal compensation by increasing urinary excretion of bicarbonate and Na and renal conservation of K (Collier et al., 1982a). Although the respiratory alkalosis indicated by elevated blood pH suggests an excess of bicarbonate, the elevated pH actually results from a carbonic acid deficit created by CO_2 expiration due to panting (Benjamin, 1981). When the cow pants, bicarbonate (HCO_3^-) is converted to carbonic acid, which is broken down to CO_2 and water for expiration and excretion.

Feeding diets that have a high dietary cation-anion difference (DCAD) improved DMI and milk yield (Tucker et al., 1988; West et al., 1991). During heat stress conditions DMI was improved as DCAD was increased from 12.0 to 46.4 meq Na + K − Cl/100 g feed DM, regardless of whether Na or K was used to increase DCAD (West et al., 1992). This suggests that the DCAD equation is more significant than the individual element concentrations (barring deficiencies). Additional research is needed to more closely define the desired DCAD for lactating dairy cows and to resolve the issue of K vs. Na supplementation. Nutritional modifications to account for changing nutrient requirements are necessary to adjust for the impact of heat stress due to reduced DMI and altered nutrient requirements.

SUMMARY

Extended periods of high ambient temperature coupled with high relative humidity compromise the ability of the lactating dairy cow to dissipate excess body heat. Cows with elevated body temperature exhibit lower DMI and milk yield and produce milk with lower efficiency, reducing profitability for dairy farms in hot, humid climates. Although adequate cooling systems exist their efficiency in humid climates is less than in arid climates and these systems often lack the ability to maintain normal body temperature. Continued genetic selection for improved DMI and milk yield results in cows that are less heat tolerant, and coupled with the unknowns associated with global warming in the future, suggest that heat stress will become worse for dairies in the future. Improved cooling systems that are more efficient and that can cool cows at night when humidity is high are needed to meet challenges in the future. There is genetic variation in cattle for cooling capability, which suggests that more heat tolerant cattle can be selected genetically, and cross-breeding may also offer opportunities. Continued advances in feeding are needed as cattle are selected for greater milk yield, but are subject to lower intake because of environmental stress. Developing nutritional strategies which support yield but which also address metabolic and physiologic disturbances induced by heat strain will help the cow to maintain a more normal metabolism which should enhance performance.

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