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Effects of Climate Change on Dairy Cattle Production

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Abstract: There are three dominant gene groups in the dairy cattle population [*Bos taurus*, *Bos indicus* and Sanga (hybrid of first two)] with varying levels of resistance to thermal stress. *Bos taurus* cattle have a greater sensitivity to elevated environmental conditions and superior resistance to cold stress than either *Bos indicus* or Sanga, due to increased levels of endogenous heat production associated with increased milk production and feed intake. However, there are also molecular and phenotypic differences in hair coat characteristics and cellular responses to thermal stress as well. Climate change associated with greenhouse warming will have the greatest impact on *Bos indicus* cattle populations, but will also adversely affect all breeds to some degree. New data suggests that the upper Temperature Humidity Index (THI) threshold for high-producing (>35 kg d^{-1}) *Bos taurus* cattle should be a THI daily minimum of 65 and average THI of 68. There is also strong evidence that the upper threshold THI for reproduction is lower than that for lactation. However, several new management technologies are now available to help reduce the negative impact of thermal stress on cattle reproduction. Additionally, only half of the loss in milk yield to thermal stress can be accounted for by a decrease in feed intake with the remainder likely associated with altered carbohydrate and fat metabolism and/or direct effects on milk synthesis and secretion. This suggests that nutritional management strategies may provide opportunities to improve lactation performance of dairy cattle during periods of thermal stress.

Key words: Climate, cattle, growth, lactation, reproduction, breed effects.

There is now a strong scientific consensus that human-induced climate change is occurring (CCSP, 2008). Projections are that this warming will continue throughout the 21st century with global average temperature rising an additional 1.1 to 5.4°C (CCSP, 2008). These changes will have large and measurable impacts on dairy cattle worldwide (Klinedinst *et al.*, 1993) through a variety of routes including changes in food availability and quality, changes in pest and pathogen populations, alteration in immunity and both direct and indirect impacts on animal performance such as growth, reproduction and lactation.

Genotype x Environment Interactions

As pointed out by several investigators the separate evolution of *Bos taurus*, Bos indicus and Sanga cattle has resulted in *Bos indicus and Sanga developing genotypes* that confer improved

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thermotolerance compared to *Bos taurus* breeds in both beef and dairy populations (Kadzere *et al.*, 2002; Lopes *et al.*, 2003; Hansen, 2004). Detection of large genotype x environment interactions for milk yield, (Cerón-Muñoz *et al.*, 2004; Ravagnolo *et al.*, 2000; Bohmanova *et al.*, 2008) in just the Holstein cattle population indicates there is considerable opportunity to improve thermal resistance and performance in dairy cattle. These differences include thermoregulatory capability, feed intake and production responses and cellular reactions in response to heat (Hansen, 2004; Collier *et al.*, 2007).

Climate Effects on Cattle

Lactation

Heat stress is a health and economic issue in every dairy producing area worldwide. The economic impact of heat stress (HS) on American animal agriculture is over $2 billion annually and the dairy industry is one of the most susceptible. Conservative estimates have the impact at $900 million/year, in the dairy industry alone (St. Pierre *et al.*, 2003). These fiscal losses result from the combination of reduced milk yield, poor reproductive performance, inferior milk quality, increased health care costs, reduced heifer growth and animal death.

The effect of ambient heat on dairy cattle milk production is well known and furthermore heavily influenced by relative humidity. Unabated HS can decrease feed intake by over 35%. Even on well- managed and cooled dairies, HS can decrease feed intake by more than 15% (Collier *et al.*, 1982; West, 2003). The other immediate consequence of HS is reduced milk yield. Even on well-cooled dairies, HS typically decreases milk yield by 10-15% and on non-cooled management systems milk yield can decrease by 40-50% during severe conditions (Collier *et al.*, 1982; West, 2003).

Few experiments have evaluated the effects of HS on endocrine parameters while simultaneously providing proper controls accounting for changes in feed intake. Despite the reduced dry matter intake (DMI), circulating growth hormone (GH) concentration tends to decrease in some studies (Mohammed and Johnson, 1985; McGuire *et al.*, 1991), but we have recently reported no differences in GH pulsatility characteristics nor pituitary responsiveness to GH secretegogues in HS vs. pair-fed thermal neutral controls (PFTN) controls (Rhoads *et al.*, 2007). Since circulating GH characteristics appear to change very little with HS, we investigated whether hepatic GH-responsiveness was altered with high ambient temperature by measuring early signaling molecules (i.e. GH receptor abundance and STAT-5 phosphorylation) in the GH signal transduction cascade (Rhoads *et al.*, 2007). In terms of milk production, hepatic GH-responsiveness is critical because circulating IGF-I has been implicated in the regulation of milk synthesis in dairy cattle and blood-borne IGF-I is produced in a GH-dependent fashion by the liver (Boisclair *et al.*, 2006). Heat stress, independent of reduced feed intake, decreased abundance of the GH receptor, however, both HS and malnutrition were sufficient to decrease STAT-5 phosphorylation. Consistent with reduced GH signaling through STAT-5, hepatic IGF-I mRNA abundance was lower in HS and PFTN animals. Thus, the reduced

hepatic GH responsiveness (in terms of IGF-I gene expression) observed during HS appears to involve mechanisms associated with reduced feed intake. The physiological significance of reduced hepatic GH receptor abundance during HS is unclear at this time, but may serve to alter other GH-dependent hepatic processes such as regulation of gluconeogenesis (discussed below). In addition, triiodothyronine tends to decrease in a variety of heat-stressed species (Messias de Braganca *et al.*, 1998; Garriga *et al.*, 2006), including lactating cows (Johnson *et al.*, 1991; McGuire *et al.*, 1991). However, it is unlikely these small endocrine changes play a major role in the mechanisms by which HS reduces milk synthesis.

A primary route for heat dissipation in animals is via the skin (radiation, conduction, convection and sweating) and this involves redistribution of blood flow. A negative consequence of enhanced skin blood flow is reduced plasma delivery to the gastrointestinal tract and mammary gland (McGuire *et al.*, 1989; Lough *et al.*, 1990). However, reductions in mammary gland blood flow can be accounted for by dietary changes (similar between HS and PFTN controls; Lough *et al.*, 1990) and despite the slight reduction in gastrointestinal uptake capacity during HS, other unknown mechanisms must be responsible for the marked reduction in milk yield (McGuire *et al.*, 1989).

Despite the enormous economic impact, there is little information on the HS-induced changes in metabolism and nutrient partitioning in lactating dairy cattle. An increased heat load decreases nutrient uptake in almost all species and the dairy cow appears extra sensitive as decreased DMI >30% is not uncommon. It is traditionally assumed that decreased DMI is primarily responsible for reduced milk yield (Fuquay, 1981; West, 1999). However, we have recently demonstrated that inadequate nutrient intake accounts for only ~40% of the reduced milk yield and we hypothesize that changes in carbohydrate metabolism are responsible for a large portion of the remainder (Rhoads *et al.*, 2008a).

Evidence from other species suggests that carbohydrate metabolism is altered during HS. For example, HS athletes consistently have increased hepatic glucose production and whole body enhanced carbohydrate oxidation at the expense of lipids (Fink *et al.*, 1975; Febbraio, 2001; Jentjens *et al.*, 2002). In addition, hepatic glucose production typically decreases after ingesting carbohydrates, but exogenous sugars are unable to blunt the HS-induced liver glucose output (Angus *et al.*, 2001). The increased hepatic glucose output originates from both increased glycogenolysis (Febbraio, 2001) and increased gluconeogenesis (Collins *et al.*, 1980). Furthermore, HS chicks have increased intestinal SGLT-I activity and thus glucose uptake (Garriga *et al.*, 2006) and *in vitro* experiments indicate an enhanced renal glucose reabsorptive capacity (via SGLT-I) during a thermal load (Sussman and Renfro, 1997; Ikari *et al.*, 2005). Collectively, evidence suggests many of these changes occur in order to maximize glucose availability in an effort to preferentially oxidize carbohydrates.

Although not thoroughly evaluated, evidence suggests that plasma NEFA (a product of adipose lipolysis and mobilization) is typically reduced or

unchanged in HS cattle (Ronchi *et al.*, 1999; Shwartz *et al.*, 2008) and especially when compared to PFTN controls (Rhoads *et al.*, 2008a). Reasons for this are not well-understood, but insulin is a potent antilipolytic signal and HS has been suggested to enhance insulin sensitivity (DeSouza and Meier, 1993). To better define these HS-induced metabolic shifts in lactating dairy cattle, we used a glucose tolerance test in an effort to examine an aspect of glucose homeostasis. We observe greater glucose disposal (rate of glucose entry into cells) in HS compared to PFTN cows (Wheelock *et al.*, 2006). Glucose disposal differences can be reconciled by a weaker insulin response to the glucose bolus by the PFTN cows whereas the insulin response remains unchanged during HS (Wheelock *et al.*, 2006). Despite similar nutrient intake, the PFTN group appears to reduce insulin-dependent glucose utilization whereas the HS group maintains insulin-dependent glucose uptake. We performed a second experiment to investigate HS effects on whole-body glucose production measured using stable-isotopically-labeled glucose and tracer kinetic methodologies. The liver, kidney and diet are sources of glucose appearance; however, this method is a proxy for hepatic gluconeogenesis since the diet and kidney are negligible sources of glucose in ruminants. Glucose production decreased by ~25% during HS (Rhoads, Waldron and Baumgard, unpublished observations), however, expressing the rate of glucose production per unit of milk yield may provide a more meaningful interpretation. A ratio of 20.5 (HS) vs. 18.3 (TN) is consistent with data suggesting that glucose is preferentially utilized for processes other than milk synthesis (ostensibly by insulin-responsive tissues) during HS (Rhoads, Waldron and Baumgard, unpublished observations).

If HS cows have an increased requirement for oxidizing glucose (similarly as in humans), then reducing substrate competition would be one logical mechanism by which this is accomplished as NEFA (Randle Effect) and ketones (Zorzano *et al.*, 2000) reduce the efficiency of insulin-mediated glucose utilization. Furthermore, enhanced intracellular hepatocyte NEFA levels reduce glucose production (Collins *et al.*, 1980). Collectively, minimizing adipose mobilization would allow the HS animal to maximize both systemic carbohydrate utilization and hepatic glucose production. Oxidizing glucose theoretically generates less metabolic heat compared to lipids and other fuels (Baldwin *et al.*, 1980; Baumgard and Rhoads, 2007) and this may be a mechanism to minimize metabolic heat production.

In stark contrast to monogastrics, ruminants absorb very little glucose from their diet and peak gluconeogenesis rates occur immediately after a meal. Complex carbohydrates are fermented in the rumen and the end products are acetate, butyrate and propionate. Propionate is the primary gluconeogenic precursor, but depending upon the energetic state, the contribution of amino acids, lactate and glycerol increase to meet glucose demands. Gluconeogenesis occurs primarily in the hepatocyte cytosol, although some precursors are generated in the mitochondria and must be transported to the cytosol for utilization. Although multiple reactions are responsible for the

gluconeogenic program, only four steps are considered rate-limiting. Pyruvate carboxylase (PC) catalyzes the conversion of pyruvate into oxaloacetate and is an important entry point for lactate and alanine (and other amino acids) into the gluconeogenic pathway. Oxaloacetate is converted to phosphoenolpyruvate by phosphoenolpyruvate carboxykinase 1 (PEPCK), which is the second rate-limiting step and is essential for shuttling propionate (the primary gluconeogenic precursor), into the gluconeogenic pathway. A mitochondrial isoform of PEPCK converts mitochondrial oxaloacetate into phosphoenolpyruvate continuing the conversion of amino acids and lactate into glucose. The next rate-limiting step occurs when fructose-6-bisphosphatase converts fructose-6-bisphosphate into fructose-6-phosphate. Finally, glucose-6-phosphatase allows glucose-6-phosphate to leave the cell as glucose.

Glucose metabolism is greatly influenced by a variety of stimuli including hormones, cytokines, and physiological state (i.e. pregnancy, lactation, malnutrition and disease), all of which increase the rate of hepatic gluconeogenesis (Bauman and Vernon, 1993; Velez and Donkin, 2004; 2005; Williams *et al.*, 2006). A strong- relationship between mRNA abundance for gluconeogenic enzymes and their activity has been demonstrated in cattle during various physiological states (Greenfield *et al.*, 2000). Hormones, such as glucagon and catecholamines, act to regulate gluconeogenesis by enlisting the transcriptional coactivator, peroxisome proliferator-activated receptor-ã coactivator-1á (PGC-1á; reviewed in Puigserver and Spiegelman, 2003). In this scenario, glucagon and catecholamines act through the cAMP pathway and CREB to stimulate PGC-1á gene expression. PGC- 1á participates with transcription factors at the promoter level of gluconeogenic genes (i.e. PEPCK) to activate expression. We asked whether changes in glucose metabolism were restricted to peripheral tissues (i.e. skeletal muscle and adipose tissue) or involved the liver, the primary site of glucose production in ruminants. We examined hepatic expression of key gluconeogenic genes in four lactating dairy cows. Feed restriction during PFTN conditions stimulated the expression of PGC-1á, PEPCK, and PC by ~30-60% (Wheelock *et al.*, 2008). In contrast, discordant changes (PC increased but PGC-1á and PEPCK were unaltered) in gluconeogenic gene expression were evident during HS (Wheelock *et al.*, 2008). Based on this information, it appears hepatic adaptation to reduced nutrient intake, in terms of glucose metabolism, differs with variations in environmental temperature.

Growth

In general, heat stress-induced production losses for beef cattle are not as severe as those for the dairy industry. Reasons why growing cattle tolerate higher THI conditions and exhibit a greater heat strain threshold than lactating dairy cows is not entirely clear, but may involve the combination of various issues including: (1) reduced surface area to mass ratio, (2) reduced rumen heat production (because of the mostly grain diet), and (3) reduced overall metabolic heat production (on a body weight basis). In addition, beef cattle will often experience compensatory gain after mild or short periods of heat stress (Mitlöhner *et al.*, 2001). The combination of these factors translate into heat-related

reduced gain that is typically less than 10 kg, which amounts to ~7 extra days in the feed lot (St. Pierre *et al.*, 2003). Furthermore, the impact of heat stress on reproductive indices is typically not as severe in beef cattle due to the seasonal nature of breeding programs (often occurring during the spring in the US).

To evaluate the differential effects of heat stress vs. reduced nutrient intake in beef cattle we studied growing Holstein beef bulls exposed to cyclically heat (29.4 to 40ºC, 25-40% humidity [conditions slightly warmer than during our dairy experiments]) or thermal-neutral conditions (18 to 20ºC) and pair-fed (86% concentrate, 14% protein, 2x/d) with HS bulls to maintain similar nutrient intake. The imposed heat regimen increased core body temperature and respiration rates while reducing DMI by ~12% (O'Brien *et al*, 2008a). As expected (and by design) PFTN bulls had a feed intake pattern similar to heat stressed cows (O'Brien *et al.*, 2008a). Heat stress eliminated body weight gain and thermal neutral pair-fed animals had a similar reduction in performance (O'Brien *et al.*, 2008a). Despite being exposed to a slightly more extensive heat load, heat stress did not reduce DMI to the same extent in growing beef cattle as it did in lactating dairy cows (12 vs. 30%). In addition, the reduction in feed intake accounted for only ~50% of the decrease in milk yield, but appears to explain most (if not all) of the reduction in growth.

In the beef study, the PFTN controls did not gain or lose body weight suggesting nutrient and energy intake satisfied maintenance requirements (O'Brien *et al.*, 2008a). The heat-stressed bulls consumed similar quantities of the exact ration fed to the pair-fed thermal neutral control animals and also had static body weight. This latter observation may indicate that, at least in growing bulls, heat stress does not increase overall maintenance requirements. If heat stress were to increase maintenance costs as reported (Fox and Tylutki, 1998; NRC, 2001) then the energy requirements of heat-stressed bulls should have exceed the pair-fed thermal neutral counterparts. In turn, the heat-stressed bulls would have been consuming inadequate energy/nutrients and should have (by definition) lost body weight. However, this was not the case and heat-stressed bulls did not lose body weight (O'Brien *et al.*, 2008a); indicating that maintenance cost may not have been increased. Further research is needed to evaluate the effects of heat on maintenance requirements and to determine if physiological state (growth vs. lactation) influences energy partitioning during thermal challenges.

Although both the heat-stressed and PFTN controls quit growing, neither mobilized adipose tissue (plasma NEFA remained <100 μEq/L), which is agreement with a lack of body weight loss (O'Brien *et al.*, 2008a). However, despite similar changes in production and post-absorptive lipid variables, there were heat stress-induced changes in post-absorptive carbohydrate metabolism. Similar to lactating dairy cows, HS growing bulls appear to have enhanced glucose disposal rates and a much greater insulin response to glucose challenge (O'Brien *et al.*, 2008a). In an effort to determine if HS-induced changes in hepatic gluconeogenesis were also similar between dairy and beef cattle, we measured PC, PCK and PGC-1á in

thermally-challenged beef animals (O'Brien *et al.*, 2008b). Pyruvate carboxylase gene expression increased following HS exposure but remained unchanged during PFTN. Neither HS nor PFTN affected expression of the PCK gene. Despite altered PC gene expression, PGC-1á mRNA abundance was unaffected by HS. Similarly, reduced FI during PF did not alter PGC-1á gene expression. This data shows that modulation of PC gene expression by HS appears to occur via mechanisms which are independent of reduced nutrient intake and is consistent with data described above in HS lactating dairy cattle.

Clearly, evidence indicates that beef cattle experiencing heat stress undergo dramatic changes in energy and nutrient metabolism that may affect both their heat tolerance and production parameters, such as lean tissue accretion. A large proportion of animal mass is comprised of skeletal muscle, which can have a profound impact on whole-animal energy metabolism and nutrient homeostasis especially during periods of stress. We have initiated a series of studies to understand how environmental factors influence the set points of several metabolic pathways within skeletal muscle. One of our first studies examined the effect of heat strain on skeletal muscle during beef cattle adaptation to chronic HS conditions using microarray analysis (Rhoads *et al.*, 2008b). Skeletal muscle (semimembranosus) biopsies were obtained during thermal comfort conditions and again after exposure to HS conditions. Microarray analysis demonstrated that chronic HS alters skeletal muscle gene expression. Interrogation of the data by pathway analysis has revealed dramatic changes in the skeletal muscle transcriptional profile relating to mitochondrial function. This data appears to indicate that during HS bovine skeletal muscle experiences mitochondrial dysfunction leading to impaired cellular energy status. This may have broad implications for the reduced growth and heat intolerance observed during HS especially if skeletal muscle is not able to respond during HS-induced alterations in whole-body energy homeostasis.

In beef cattle, the magnitude of heat-induced decrease in feed intake is not sufficient enough to signal adipose mobilization PFTN controls. However, sufficient insulin response to supplemental glucose and an increase in exogenous glucose disposal remains. A possible reason why beef cattle appear to cope with heat stress better is that their production (tissue synthesis) does not rely on glucose to the extent that milk production does.

Reproduction

As mentioned earlier, genetic selection for milk production has increased metabolic heat output per cow. This has considerably increased the lactating dairy cows' susceptibility to HS. Ultimately, the physiological effects of HS decrease the reproductive performance of dairy cattle and several HS-related mechanisms are responsible for the observed decrease in fertility, and likely others that we have not yet elucidated.

As mentioned, HS induces NEBAL and several studies indicate that lactating dairy cows losing greater than 0.5 units BCS within 70 d postpartum had longer calving to first detected estrus and (or) ovulation interval (Butler, 2000; Beam and Butler,

1999). Garnsworthy and Webb (1999) reported the lowest conception rates in cows that lost more than 1.5 BCS units between calving and insemination. In addition, Butler (2000) reported that conception rates range between 17 and 38% when BCS decreases 1 unit or more, between 25 and 53% if the loss is between 0.5 and 1.0 unit, and is >60% if cows do not lose more than 0.5 units or gain weight.

Interestingly, another HS-related deterrent to dairy cow fertility is increased circulating plasma urea nitrogen concentrations. In terms of effects on fertility, most research has focused on the urea produced as a result of protein metabolism within the rumen. However, elevated urea concentrations can also be a consequence of increased skeletal muscle breakdown. The end result of these physiological changes that occur during HS are elevated plasma urea nitrogen concentrations in HS cows compared to PFTN controls (Wheelock *et al.*, 2006). Therefore, elevated plasma urea nitrogen concentrations may be exacerbating the decrease in fertility that is frequently observed during periods of HS.

Estrous Activity, Hormone Function, and Follicular Development

Heat stress reduces the length and intensity of estrus, making it more difficult to detect cows in estrus for artificial insemination. For example, in summer, motor activity and other manifestations of estrus are reduced (Hansen and Arechiga, 1999) and incidence of anestrous and silent ovulations are increased (Gwazdauskas *et al.*, 1981). Nebel *et al.* (1997) reported that Holsteins in estrus during the summer had 4.5 mounts/estrus vs. 8.6 mounts for those in winter. On a commercial dairy in Florida, undetected estrous events were estimated at 76 to 82% during June through September compared to 44 to 65% during October through May (Thatcher and Collier, 1986).

Heat stress impairs follicle selection and increases the length of follicular waves; thus reducing the quality of oocytes, modulating follicular steroidogenesis, and reducing fertility (Mihm *et al.*, 1994; Roth *et al.*, 2001). Summer HS has been shown to increase the number of subordinate follicles; while reducing the degree of dominance of the dominant follicle and decreasing inhibin and estrogen levels (Wolfenson *et al.*, 1995; Wilson *et al.*, 1998). These changes in ovarian follicular dynamics result in increased twinning rates in dairy cows during summer vs. winter (Ryan and Boland, 1991).

Oocytes and Early Developing Embryos

During summer, HS reduces pregnancy and conception rates, which can carry-over into the fall months (Wolfenson *et al.*, 2000). This occurs because the follicle destined to ovulate emerges 40-50 d prior to ovulation. Thus, oocytes contained in follicles that emerge near the end of the summer are damaged by HS months before they ovulate. Numerous *in vitro* and *in vivo* experiments have clearly demonstrated the devastating effects of HS on the developmental competence of oocytes (Edwards and Hansen, 1997; Putney *et al.*, 1988a; Rocha *et al.*, 1998; Rutledge *et al.*, 1999).

Heat stress can also affect the early developing embryo. When HS was applied

from d 1 to 7 after estrus, studies have shown a reduction in embryo quality and stage on d 7 (Putney *et al.*, 1989) and decreased developmental competence *in vitro* (Monty and Racowsky, 1987). It appears that some developmental stages are more susceptible to the deleterious effects of HS because *in vitro* HS at the 2- to 4-cell stage caused a larger reduction in embryo cell number and development than HS at the morula stage (Edwards and Hansen, 1997; Ju *et al.*, 1999; Paula-Lopes and Hansen, 2002). Heat stress is so devastating to the early developing embryo that pregnancy rates can be increased by transferring embryos produced in thermoneutral conditions to HS cows (as opposed to inseminating HS cows; Drost *et al.*, 1999).

Latter stages of embryo development

Not only can HS affect the oocyte and early embryo, it can also reduce embryo growth up to d 17, which is the period critical for maternal recognition of pregnancy. Adequate amounts of interferon-tau must be secreted from the embryo for luteolysis to be prevented and pregnancy to be maintained. However, HS has been shown to reduce the size of embryos recovered on d 17 after insemination (Biggers *et al.*, 1987) and also reduce interferon-tau secretion (Putney *et al.*, 1988b). Furthermore, *in vitro* endometrial secretion of the luteolytic hormone, $PGF_{2\acute{a}}$, increases in response to HS (Putney *et al.*, 1988b). Heat stress also decreases circulating concentrations of metabolic hormones and nutrients necessary for the early embryonic growth leading up to the maternal recognition of pregnancy (such as insulin, insulin-like growth factor-1, and glucose). Exogenous supplementation of these factors during HS may improve fertility (Bilby *et al.*, 2006). Collectively these studies demonstrate HS-induced affects on both the embryo and the uterine environment that can disrupt the events necessary for the maternal recognition of pregnancy, thereby reducing pregnancy rates.

Embryonic loss following the maternal recognition of pregnancy is also elevated during periods of HS. Dairy cows conceiving with singletons or twins are 3.7 and 5.4 times more likely to lose their embryo, respectively, during the hot versus cool season (Lopez-Gatius *et al.*, 2004). In addition, the likelihood of pregnancy loss has been shown to increase by a factor of 1.05 for each unit increase in mean maximum temperature-humidity index (THI) from d 21–30 of gestation (Fig. 1).

Improving reproduction by cooling dry cows

Traditionally, dry pregnant cows are provided little protection from HS because they are not lactating; and it is incorrectly assumed they are less prone to HS. Additional stressors are imposed during this period due to abrupt physiological, nutritional, and environmental changes. These changes can increase the cows' susceptibility to HS and have a critical influence on postpartum cow health, milk production, and reproduction. The dry period is particularly crucial since it involves mammary gland involution and subsequent development, rapid fetal growth, and induction of lactation. Heat stress during this time period can affect endocrine responses that may increase fetal abortions,

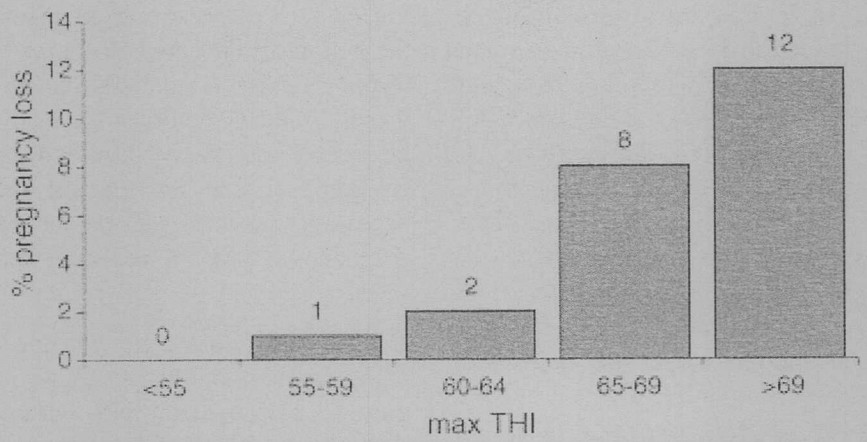

Fig. 1. Pregnancy loss rates for different maximum temperature-humidity indices (THI) during d 21-30 of gestation (adapted from Garcia-Ispierto et al., 2006).

shorten the gestation length, lower calf birth weight, and reduce follicle and oocyte maturation associated with the postpartum reproductive cycle.

Many studies reporting subtle effects of HS on subsequent fertility were published over 20 years ago when the average milk yield was much less than it is today. In addition, our cooling systems and knowledge of proper cooling (when, where, and to what extent) to reduce HS has increased substantially. A study conducted in Saudi Arabia on 3 different farms observed an improvement in peak milk production (90.9 vs. 87.2 lb), decreased services per conception (3.1 vs. 3.7 services), and reduced culling for reproductive failure (7.7 vs. 19%) for dry cows evaporative cooled vs. shade only (Wiersma and Armstrong, 1988). More recently, Avendano-Reyes *et al.* (2006) concluded that cooling dry cows with shades, fans, and water spray vs. cows with only shade decreased services per conception and days open, while milk yield increased during the postpartum period. In 2006, Urdaz *et al.* observed that dry cows with feed line sprinklers, fans, and shade compared to cows with only feed line sprinklers had an increased 60 d milk yield with no difference in body condition score (BCS) changes, incidence of postparturient disorders, or serum nonesterified fatty acid (NEFA) concentrations. Although reproductive parameters were not measured, cooling dry cows with shades, fans, and sprinklers compared with only sprinklers improved total 60 d milk production by 185.5 lb/cow, and increased estimated annual profits by $ 8.92/cow (based on milk only).

The problem of carry over effects from summer HS to fall fertility (discussed earlier) may be accentuated due to HS during the dry period. Cooling dry cows may reduce HS effects on the antral follicle destined to ovulate 40-50 d later, which coincides with the start of most breeding periods, and possibly increases first service conception rates.

The greatest opportunity to reduce the negative effects of HS during both the pre- and postpartum periods is through cooling.

As mentioned previously, cooling dry cows with feed line sprinklers, fans, and shades proved to be beneficial for reducing services per conception, reproductive culls, and days open; as well as increasing milk yield with a significant return on investment compared to cows with either shades alone or feed line sprinklers alone (Wiersma and Armstrong, 1988; Avendano-Reyes *et al.*, 2006; Urdaz *et al.*, 2006). In addition to proper cooling, changing management decisions may help reduce the severity of HS in areas of intermittent heat waves. For instance, at dry-off, many cows receive vaccines that can cause a fever spike which, when coupled with HS, can cause body temperature to rise above normal (101.3-102.8°F). Possibly, during severe heat waves it would prove beneficial to delay vaccinations at dry-off, if the dry pen does not contain adequate cooling.

Reducing negative effects of postpartum heat stress

Current and past research has resulted in dramatic improvements in dairy cow management in hot environments. Two primary strategies are to minimize heat gain by reducing solar heat load and maximize heat loss by reducing air temperature around the animal or increasing evaporative heat loss directly from animals. Following are several strategies to potentially help reduce the negative impacts of HS on reproduction in lactating dairy cows.

Cow comfort and cooling

Locating where HS is occurring on the dairy facility by identifying hot spots is key to implementing the proper cooling or management strategy to eliminate these hot spots. Temperature devices have been used to monitor core body temperatures in cows by attaching a temperature monitor to a blank continuous intravaginal drug release (CIDR®, Pfizer Animal Health, New York, NY) device for practical on-farm use. The device is inserted into the cow's vagina, measuring core body temperature every minute for up to 6 d. This allows monitoring of the cow's body temperature and identification of where the cow is experiencing HS.

Providing enough shade and cow cooling is vital for proper cow comfort. There should be at least 38 to 45 sq. ft of shade/mature dairy cow to reduce solar radiation. Spray and fan systems should be used in the holding pen, over feeding areas, in some freestall barns, and under shades on drylot dairies in arid climates. Exit lane cooling is an inexpensive way to cool cows as they leave the parlor. Providing enough access to water during HS is critical. Water intake needs to increase 1.2 to 2 times during HS conditions and lactating cattle daily require 35 to 45 gallons of water during thermal-neutral conditions. Access to clean water troughs when cows leave the parlor, at 2 locations in drylot housing, and at every crossover between feeding and resting areas in freestall housing is recommended. Keep in mind milk is approximately 90% water; therefore water intake is vital for milk production and to maintain thermal homeostasis.

The holding pen is often an area of elevated HS conditions. Cows are crowded into a confined area for several minutes to hours. Cows should not spend more than 60 to 90 minutes in the holding area. In addition, provide shade, fans, and sprinklers in the holding pen. An Arizona

study showed a 3.5°F drop in body temperature and a 1.76 lb increase in milk/cow/d when cows were cooled in the holding pen with fans and sprinklers (Wiersma and Armstrong, 1983). Cattle handling such as sorting, adding cattle to the herd, vet checks, and lock-up times should be completed in the early morning. The cow's warmest body temperature occurs between 6 p.m. and midnight. Reducing lock-up times can also reduce HS, especially in facilities with little or no cooling above head locks.

Nutritional modifications

The nutritional impacts on reproduction are well documented. Reducing metabolic diseases will further enhance our ability to improve reproduction during the summer months. Some simple feeding and nutritional strategies can be implemented to reduce the negative effects of summer HS on reproduction.

The maintenance requirement of lactating dairy cows is thought to increase substantially as environmental temperature increases. When possible, increase the number of feedings and (or) push-up times in order to increase DMI. In addition, feed during cooler parts of the day and increase moisture content in the ration from an average of 35 to 40% to an average of 45 to 50%.

The HS cow is prone to rumen acidosis and many of the lasting effects of warm weather (laminitis, low milk fats, etc.) can probably be traced back to a low rumen pH during the summer months. As a consequence, care should be taken when feeding hot rations during the summer. Obviously fiber quality is important all the time, but it is paramount during the summer as it has some buffering capacity and stimulates saliva production. Furthermore, dietary HCO_3- may be a valuable tool to maintain a healthy rumen pH.

Feeding dietary fat (rumen inert/rumen bypass) remains an effective strategy of providing extra energy during a time of negative energy balance. Compared to starch and fiber, fat has a much lower heat increment in the rumen; thus provides energy without a negative thermal side effect.

Wheelock *et al.* (2006) previously demonstrated that maximizing rumen production of glucose precursors (i.e. propionate) may be an effective strategy to maintain production during HS. However, due to the rumen health issue, increasing grains should be conducted with care. A safe and effective method of maximizing rumen propionate production is with monensin (approved for lactating dairy cattle in 2004). In addition, monensin may assist in stabilizing rumen pH during stress situations. Proplyene glycol is fed typically in early lactation, but may also be an effective method of increasing propionate production during HS. With the increasing demand for biofuels and subsequent supply of glycerol, it will be of interest to evaluate glycerol's efficacy and safety in ruminant diets during the summer months.

Having a negative dietary cation-anion difference (DCAD) during the dry period and a positive DCAD during lactation is a good strategy to maintain health and maximize production. It appears that keeping the DCAD at a healthy lactating level (approx. +20 to +30 meq/100 g DM)

remains a good strategy during the warm summer months (Wildman *et al.*, 2007).

Unlike humans, cattle utilize potassium (K^+) as their primary osmotic regulator of water secretion from their sweat glands. As a consequence, K^+ requirements are increased (1.4 to 1.6% of DM) during the summer and this should be adjusted for in the diet. In addition, dietary levels of sodium (Na^+) and magnesium (Mg^+) should be increased, as they compete with potassium (K^+) for intestinal absorption.

Reproduction protocol changes

Improve estrous detection during summer by increasing the time and number of visual observations for estrus. Tail head paint is the most popular estrous detection aid and should be applied in adequate amounts with easily observable colors. This should be coupled with visual estrous detection. There are several technologies available to improve identification of estrus. The HeatWatch® (CowChips, LLC, Denver, CO) system records the number and times mounted during estrus through the use of a radiotelemetric pressure transducer placed on the tail head to transmit information to a computer. Pedometers can also be used to measure the increased amount of activity associated with estrus.

Heat stress significantly impairs bull fertility in the summer. Semen quality decreases when bulls are continually exposed to ambient temperatures of 86°F for 5 weeks or 100°F for 2 weeks despite no apparent effect on libido. Heat stress decreases sperm concentration, lowers sperm motility, and increases percentage of morphologically abnormal sperm in an ejaculate. After a period of HS, semen quality does not return to normal for approximately 2 mo because of the length of the spermatic cycle, adding to the carry-over effect of HS on reproduction. It may prove beneficial to periodically check semen quality. In addition, many dairy producers use A.I. for a set number of breedings (i.e. 3 A.I. breedings) and then move the cow to the bull pen; however it may be advantageous to continue to A.I. for several more breedings to by-pass the deleterious effects described above during and immediately after periods of HS.

The use of fixed timed AI (TAI) to avoid the deleterious effects of reduced estrous detection has been well documented. Utilizing some type of TAI (i.e. Ovsynch, Cosynch72, or Ovsynch56), either coupled with or without estrous detection, can improve fertility during the summer. A study conducted in Florida during the summer months observed an increase in pregnancy rate at 120 d postpartum (27% vs. 16.5%, respectively) and a decrease in days open, interval from calving to first breeding, and services per conception in cows TAI versus inseminated at estrus (De la Sota *et al.*, 1998).

Another possible way to improve fertility in the summer is through an injection of GnRH at estrus. Ullah *et al.* (1996) injected GnRH into lactating dairy cows at detected estrus during late summer in Mississippi and increased conception rate from 18% to 29%. In agreement with this study, lactating dairy cows were injected with GnRH at the first signs of standing estrus during the summer and autumn months in Israel, and conception rates increased compared to untreated controls (41% to 56%, respectively; Kaim *et al.*, 2003).

Management opportunities to improve summer fertility

Embryo transfer can significantly improve pregnancy rates during the summer months (Drost *et al.*, 1999). Embryo transfers can by-pass the period (i.e. before d 7) in which the embryo is more susceptible to HS. Nevertheless, embryo transfer is not a widely adopted technique. Improvements need to be in made in the in vitro embryo production techniques, embryo freezing, timed embryo transfer, and lowering the cost of commercially available embryos before this becomes a feasible solution.

Selecting particular genes that control traits related to thermotolerance make it possible to select for thermal resistance without inadvertently selecting against milk yield (Hansen and Arechiga, 1999). Traits that could possibly be selected for include coat color, genes controlling hair length, and genes controlling heat shock resistance in cells (see review by Hansen and Arechiga, 1999). In addition, genetic modification or altering biochemical properties of the embryo before embryo transfer may be possible to improve thermal resistance and increase summer fertility.

There may be feed additives, which can partially alleviate HS through increased heat dissipation; thereby lowering internal body temperature. In some (but not all) studies, dietary fungal cultures decreased body temperatures and respiration rates in hot, but not cool weather (Huber *et al.*, 1994). A recent experiment in Arizona showed an increase in sweating rates and lower core body temperatures when encapsulated niacin was fed to lactating cows compared to thermal neutral controls (Zimbelman *et al.*, 2007). A follow-up study was conducted on a commercial dairy farm during the summer months in AZ with rumen-protected niacin being fed to late lactation dairy cows. Results showed similar effects with lower core body temperatures during the hot part of the day with an additional increase in fat- and energy-corrected milk (Zimbelman *et al.*, 2008). Feeding unsaturated fatty acids to ewes has been shown to alter lipid composition of oocytes, improving thermotolerance (Zeron *et al.*, 2002). The use of encapsulation techniques to by-pass the rumen, feed additives to improve heat loss, and (or) manipulating cellular biochemical composition may improve reproductive function during the summer months; however, more studies are warranted.

The THI is calculated using both ambient temperature and relative humidity. To date, researchers suggest that cows experience HS beginning at a THI of 72. The THI values were categorized into mild, moderate, and severe stress levels for cattle by the Livestock Conservation Institute (Armstrong, 1994). Berman (2005) pointed out that the supporting data for these designations are not clear. For example, the index is based on a retrospective analysis of studies carried out at the University of Missouri in the 1950's and early 1960's on a total of 56 cows averaging 15.5 kg milk d^{-1} with a range of 2.2 to 31.8 kg d^{-1}. In contrast, average production per cow in the United States is presently over 30 kg d^{-1} with many cows producing over 45 kg d^{-1} at peak lactation. Current studies recently completed suggest that the upper THI limit should be a daily minimum THI

of 65 and a daily average THI of 68. Lactating dairy cattle require additional cooling above these thresholds. The resulting management changes could reduce the negative effects of HS on reproduction.

References

Al-Katanani, Y.M., Webb, D.W. and Hansen, P.J. 1999. Factors affecting seasonal variation in 90-day nonreturn rate to first service in lactating Holstein cows in a hot climate. *Journal of Dairy Science* 82: 2611-2616.

Angus, D.J., Febbraio, M.A., Lasini, D. and Hargreaves, M. 2001. Effect of carbohydrate ingestion on glucose kinetics during exercise in the heat. *Journal of Applied Physiology* 90: 601-605.

Armstrong, D.V. 1994. Heat stress interactions with shade and cooling. *Journal of Dairy Science* 77: 2044-2050.

Avendano-Reyes, L., Alvarez-Valenzuela, F.D., Correa-Calderon, A., Saucedo-Quintero, J.S., Robinson, P.H. and Fadel, J.G. 2006. Effect of cooling Holstein cows during the dry period on postpartum performance under heat stress conditions. *Livestock Science* 105: 198-206.

Baldwin, R.L., Smith, N.E., Taylor, J. and Sharp, M. 1980. Manipulating metabolic parameters to improve growth rate and milk secretion. *Journal of Animal Science* 51: 1416-1428.

Bauman, D.E. and Vernon, R.G. 1993. Effects of exogenous bovine somatotropin on lactation. *Annual Review of Nutrition* 13: 437-461.

Baumgard, L.H. and Rhoads, R.P. 2007. The effects of hyperthermia on nutrient partitioning. *Proceedings of the Cornell Nutrition Conference.* pp. 93-104.

Beam, S.W. and Butler, W.R. 1999. Effects of energy balance on follicular development and first ovulation in postpartum dairy cows. *Journal of Reproduction and Fertility* 54: 411-424.

Berman, A.J. 2005. Estimates of heat stress relief needs for Holstein dairy cows. *Journal of Animal Science* 83: 1377-1384.

Berman, A., Folman, Y., Kaim, M., Mamen, M., Herz, Z., Wolfenson, D., Arieli, A. and Graber, Y. 1985. Upper critical temperatures and forced ventilation effects for high-yielding dairy cows in a subtropical environment. *Journal of Dairy Science* 68: 1488-1495.

Biggers, B.G., Geisert, R.D., Wettemann, R.P. and Buchanan, D.S. 1987. Effect of heat stress on early embryonic development in the beef cow. *Journal of Animal Science* 64: 1512-1518.

Bilby, T.R., Sozzi, A., Lopez, M.M., Silvestre, F., Ealy, A.D., Staples, C.R. and Thatcher, W.W. 2006. Pregnancy, bovine somatotropin, and dietary n-3 fatty acids in lactating dairy cows: I. Ovarian, conceptus and growth hormone – Insulin-like growth factor system responses. *Journal of Dairy Science* 89: 3375-3385.

Bohmanova, J., Misztal, I., Tsuruta, S., Norman H.D. and Lawlor, T.J. 2006. Short communication: Genotype by environment interaction due to heat stress. *Journal of Dairy Science* 91: 840-846.

Boisclair, Y.B., Wesolowski, S.R., Kim, J.W. and Ehrhardt, R.A. 2006. Roles of growth hormone and leptin in the periparturient dairy cow. In *Running Physiology: Digestion, Metabolism and Impact of Nutrition on Gene Expression, Immunology and Stress* (Eds. K. Sejrsen, T. Hvelplund and M.O. Nielsen), pp. 327-346. Wageningen Academic Publishers, Wageningen.

Butler, W.R. 2000. Nutritional interactions with reproductive performance in dairy cattle. *Animal Reproduction Science* 60-61: 449-457.

CCSP 2008. The effects of climate change on agriculture, land resources, water resources, and biodiversity in the United States. A report by the US Climate Change Science Program and the Subcommitee on Global Change Research (Eds. P. Backlund, A. Janetos, D. Schimael, J. Hatfield, K. Boote, P. Fay, L. Hahn, C. Isaurralde, B. A. Kimball, T. Mader, J. Morgan, D. Ort, W. Polley, A. Thomson, D. Wolfe, M.G. Ryan, S.R. Archer, R. Birdsey, C. Dahm, L. heath, J. Hicke, D. Hollinger, T. Huxman, G. Okin, R. Oren, J. Randerson, Wl Schlesinger, D. Lettenmaier, D. Major, L. Poff, S. Running, L. Hansen, D. Inouye, B.P. Kelly, L. Meyerson, B. Peterson, R. Shaw), US Department of Agriculture, Washington, DC, USA.

Collier, R.J., Beede, D.K., Thatcher, W.W., Isreael, L.A. and Wilcox, C.J. 1982. Influences of environment and its modification on dairy animal health and production. *Journal of Dairy Science* 65: 2213-2227.

Collier, R.J., Collier, J.L., Rhoads, R.P. and Baumgard, L.H. 2007. Genes involved in the Bovine heat stress response. *Journal of Dairy Science* 91: 445-454.

Collins, F.G., Matros, F.A. and Skibba, J.L. 1980. Effect of palmitate on hepatic biosynthetic functions at hyperthermic temperatures. *Metabolism* 29: 524-531.

De la Sota, R.L., Burke, J.M., Risco, C.A., Moreira, F., DeLorenzo, M.A. and Thatcher, W.W. 1998. Evaluation of timed insemination during summer heat stress in lactating dairy cattle. *Theriogenology* 49: 761-770.

De Souza, C.J. and Meier, A.H. 1993. Daily intervals of heat exposure alter the phase of the daily variation of plasma hormones in Holtzman rats. *American Journal of Physiology* 265: R1115-R1120.

Drost, M., Ambrose, J.D., Thatcher, M.J., Cantrell, C.K., Wolsdorf, K.E., Hasler, J.F. and Thatcher, W.W. 1999. Conception rates after artificial insemination or embryo transfer in lactating dairy cows during summer in Florida. *Theriogenology* 52: 1161-1167.

Edwards, J.L. and Hansen, P.J. 1997. Differential responses of bovine oocytes and preimplantation embryos to heat shock. *Molecular Reproduction and Development* 46: 138-145.

Febbraio, M.A. 2001. Alternations in energy metabolism during exercise and heat stress. *Sports Medicine* 31: 47-59.

Fink, W.J., Costill, D.L. and Van Handel, P.J. 1975. Leg muscle metabolism during exercise in the heat and cold. *European Journal of Applied Physiology and Occupational Physiology* 34: 183-190.

Fox, D.G. and Tylutki, T.P. 1998. Accounting for the effects of environment on the nutrient requirements of dairy cattle. *Journal of Dairy Science* 81: 3085-3089.

Fuquay, J.W. 1981. Heat stress as it affects production. *Journal of Animal Science* 52: 167-174.

Garriga, C., Hunter, R.R., Amat, C., Planas, J.M., Mitchell, M.A. and Moreto, M. 2006. Heat stress increases apical glucose transport in the chicken jejunum. *American Journal of Physiology* 290: R195-R201.

Garcia-Ispierto, F. Lopez-Gatius, G. Bech-Sabat, Santolaria, P., Yaniz, J.L., Nogareda, C., De Rensis, F. and Lopez-Bejar, M. 2007. Climate factors affecting conception rate of high producing dairy cows in northeastern Spain. *Theriogenology* 67: 1379-1385.

Garnsworthy, P.C. and Webb, R. 1999. The influence of nutrition on fertility in dairy cows. In *Recent Advances in Animal Nutrition* (Eds. P.C. Garnsworthy and J. Wiseman), pp. 39-57. Nottingham University Press, UK.

Greenfield, R.B., Cecava, M.J., Johnson, T.R. and Donkin, S.S. 2000. Impact of dietary protein amount and rumen undegradability on intake, peripartum liver triglyceride, plasma metabolites, and milk production in transition dairy cattle. *Journal of Dairy Science* 83: 703-710.

Gwazdauskas, F.C., Thatcher, W.W., Kiddy, C.A., Paape, M.J. and Wilcox, C.J. 1981. Hormonal patterns during heat stress following $PGF_{2á}$-tham salt induced luteal regression in heifers. *Theriogenology* 16: 271-285.

Hahn, G.L. 1985. Management and housing of farm animals in hot environments. In Stress Physiology in Livestock (Ed. M. Yousef), Vol. 2, pp. 151-174. CRC Press, Boca Raton, FL.

Hansen, P.J. 2004. Physiological and cellular adaptations of zebu cattle to thermal stress. *Animal Reproduction Science* 82-83: 349-360

Hansen, P.J. and Arechiga, C.F. 1999. Strategies for managing reproduction in the heat-stressed dairy cow. *Journal of Animal Science* 82(Suppl. 2): 36-50.

Huber, J.T., Higginbotham, G., Gomez-Alarcon, R.A., Taylor, R.B., Chen, K.H., Chan, S.C. and Wu, Z. 1994. Heat stress interactions with protein, supplemental fat, and fungal cultures. *Journal of Dairy Science* 77: 2080-2090.

Hulme, M. 1997. Global warming. *Progress in Physical Geography* 21: 446-453.

Ikari, A., Nakano, M., Suketa, Y., Harada, H. and Takagi, K. 2005. Reorganization of ZO-I by sodium-dependent glucose transporter activation after heat stress in LLC-PK1 cells. *Journal of Cellular Physiology* 203: 471-478.

Jentjens, R.L.P.G., Wagenmakers, A.J.M. and Jeukendrup, A.E. 2002. Heat stress increases muscle glycogen use but reduces the oxidation of ingested carbohydrates during exercise. *Journal of Applied Physiology* 92: 1562-1572.

Johnson, H.D., Li, R., Manalua, W., Spencer-Johnson, K.J., Becker, B.A., Collier, R.J. and Baile, C.A. 1991. Effects of somatotropin on milk yield

and physiological responses during summer farm and hot laboratory conditions. *Journal of Dairy Science* 74: 1250-1262.

Ju, J-C., Parks, J.E. and Yang, X. 1999. Thermotolerance of IVM-derived bovine oocytes and embryos after short-term heat shock. *Molecular Reproduction and Development* 53: 336-340.

Kaim, H., Bloch, A., Wolfenson, D., Braw-Tal, R., Rosenberg, M., Voet, H. and Folman, Y. 2003. Effects of GnRH administered to cows at the onset of estrus on timing of ovulation, endocrine responses, and conception. *Journal of Dairy Science* 86: 2012-2021.

Klinedinst, P., Wilhite, D.A., Leroy Hahn, G. and Hubbard, K.G. 1993. The potential effects of climate change on summer season dairy cattle milk production and reproduction. *Climatic Change* 23: 21-36.

Leroy, J.L.M.R., Vanholder, T., Opsomer, G., Van Soom, A. and de Kruif, A. 2006. The in vitro development of bovine oocytes after maturation in glucose and â-hydoxybutyrate concentrations associated with negative energy balance in dairy cows. *Reproduction in Domestic Animal* 41: 119-123.

López-Gatius, F., Santolaria, P., Yániz, J.L., Garbayo, J.M. and Hunter R.H. 2004. Timing of early foetal loss for single and twin pregnancies in dairy cattle. *Reproduction in Domestic Animal* 9: 429-433.

Lough, D.S., Beede, D.L. and Wilcox, C.J. 1990. Effects of feed intake and thermal stress on mammary blood flow on other physiological measurements in lactating dairy cows. *Journal of Dairy Science* 73: 325-332.

Maia, A.S.C, da Silva, R.G. and Bertipaglia, E.C.A. 2005. Environmental and genetic variation of the effective radiative properties of Holstein cows under subtropical conditions. *Livestock Production Science* 92: 307-315.

McGuire, M.A., Beede, D.K., Collier, R.J., Buonomo, F.C., DeLorenzo, M.A., Wilcox, C.J., Hutington, G.B. and Reynolds, C.K. 1991. Effects of acute thermal stress and amount of feed intake on concentrations of somatotropin, insulin-like growth factor (IGF)-I and IGF-II, and thyroid hormones in plasma of lactating Holstein cows. *Journal of Animal Science* 69: 2050-2056.

McGuire, M.A., Beede, D.K., DeLorenzo, M.A., Wilcox, C.J., Huntington, G.B., Reynolds, C.R. and Collier, R.J. 1989. Effects of thermal stress and level of feed intake on portal plasma flow and net fluxes of metabolites in lactating Holstein cows. *Journal of Animal Science* 67: 1050-1060.

Messias de Braganca, M., Mounier, A.M. and Prunier, A. 1998. Does feed restriction mimic the effects of increased ambient temperature in lactating sows? *Journal of Animal Science* 76: 2017-2024.

Mihm, M., Bagnisi, A., Boland, M.P. and Roche, J.F. 1994. Association between the duration of dominance of the ovulatory follicle and pregnancy rate in beef heifers. *Journal of Reproduction and Fertility* 102: 123-130.

Mitlöhner, F.M., Morrow, J.L., Dailey, J.W., Wilson, S.C., Galyean, M.L., Miller, M.F. and McGlone, J.J. 2001. Shade and water misting effects on behavior, physiology, performance, and carcass traits of heat-stressed feedlot cattle. *Journal of Animal Science* 79: 2327-2335.

Mohammed, M.E. and Johnson, H.D. 1985. Effect of growth hormone on milk yields and related physiological functions of Holstein cows exposed to heat stress. *Journal of Dairy Science* 68: 1123-1133.

Monty, D.E. and Racowsky, C. 1987. In vitro evaluation of early embryo viability and development in summer heat-stressed, superovulated dairy cows. *Theriogenology* 28: 451-465.

National Research Council 2001. *Nutrient Requirements of Dairy Cattle*, 7th rev. ed. National Academies Press, Washington, DC.

Nebel, R.L., Jobst, S.M., Dransfield, M.B.G., Pandolfi, S.M. and Bailey, T.L. 1997. Use of radio frequency data communication system, HeatWatch®, to describe behavioral estrus in dairy cattle. *Journal of Dairy Science* 80 (Suppl. 1): 179 (Abstr.).

O'Brien, M.D., Cole, L.C., Wheelock, J.B., Sanders, S.R., Duff, G.C., Baumgard, L.H. and Rhoads, R.P. 2008b. Thermal and nutritional regulation of hepatic gluconeogenic genes in growing beef cattle. *Journal of Animal Science* 86(E-Suppl. 2): 455.

O'Brien, M.D., Wheelock, J.B., Sanders, S.R., Duff, G.C., Rhoads, R.P. and Baumgard, L.H. (2008a) Differential effects of heat stress and reduced nutrient intake on production and metabolism

in young growing beef cattle. *Journal of Animal Science* 86(E-Suppl. 2): 373.

Paula-Lopes, F.F., Chase, C.C., Jr., Y.M. Al-Katanani, C.E. Krininger III, R.M. Rivera, S. Tekin, Majewski, A.C., Ocon, O.M., Olson, T.A. and Hansen, P.J. 2003 Genetic divergence in cellular resisitance to heat shock in cattle: Differences between breeds developed in temperate versus hot climates in responses of preimplantation embryos, reproductive tract tissues and lymphocytes to increased culture temperatures. *Reprod. or Biology Reproduction* 125: 285-294.

Paula-Lopes, F.F. and Hansen, P.J. 2002. Heat-shock induced apoptosis in bovine preimplantation embryos is a developmentally-regulated phenomenon. *Biology Reproduction* 66: 1169-1177.

Puigserver, P. and B.M. Spiegelman. 2003. Peroxisome proliferator-activated receptor-gamma coactivator 1 alpha (PGC-1 alpha): transcriptional coactivator and metabolic regulator. *Endocrine Reviews* 24: 78-90.

Putney, D.J., Drost, M. and Thatcher, W.W. 1988a. Embryonic development in superovulated dairy cattle exposed to elevated ambient temperature between days 1 to 7 post insemination. *Theriogenology* 30: 195-209.

Putney, D.J., Malayer, J.R., Gross, T.S., Thatcher, W.W., Hansen, P.J. and Drost, M. 1988b. Heat stress-induced alterations in the synthesis and secretion of proteins and prostaglandins by cultured bovine conceptuses and uterine endometrium. *Biology Reproduction* 39: 717-728.

Putney, D.J., Drost, M. and Thatcher, W.W. 1989. Influence of summer heat stress on pregnancy rates of lactating dairy cattle following embryo transfer or artificial insemination. *Theriogenology* 31: 765-778.

Ravagnolo, O, Misztal, I. and Hoogenboom, G. 2000. Genetic component of heat stress in dairy cattle, development of heat index function. *Journal of Dairy Science* 83: 2120-2125.

Rhoads, M.L., Rhoads, R.P., Sanders, S.R., Carroll, S.H., Weber, W.J. Crooker, B.A., Collier, R.J., VanBaale, M.J. and Baumgard, L.H. 2007. Effects of heat stress on production, lipid metabolism and somatotropin variables in lactating cows. *Journal of Dairy Science* 90 (E-Suppl. 1): 230.

Rhoads, M.L., Rhoads, R.P., VanBaale, M.J., Collier, R.J., Crooker, B.A. and Baumgard, L.H. 2008a. Effects of heat stress and plane of nutrition on lactating Holstein cows: I. Production, metabolism and aspects of circulating somatotropin. *Journal of Dairy Science,* in press.

Rhoads, R.P., O'Brien, M.D., Greer, K.A., Cole, L.C., Sanders, S.R. and Baumgard, L.H. 2008b. Consequences of heat stress on the profile of skeletal muscle gene expression in beef cattle. *FASEB Journal* 22: 1165.1.

Rocha, A., Randel, R.D., Broussard, J.R., Lim, J.M., Blair, R.M., Roussel, J.D., Godke, R.A. and Hansel, W. 1998. High environmental temperature and humidity decrease oocyte quality in *Bos taurus* but not in *Bos indicus* cows. *Theriogenology* 49: 657-665.

Ronchi, B., Bernabucci, U., Lacetera, N., Supplizi, A.V. and Nardone, A. 1999. Distinct and common effects of heat stress and restricted feeding on metabolic status of Holstein heifers. *Zootecnia e nutrizione animale* 25: 11-20.

Roth, Z., Arav, A., Bor, A., Zeron, Y., Braw-Tal, R. and Wolfenson, D. 2001. Improvement of quality of oocytes collected in the autumn by enhanced removal of impaired follicles from previously heat-stressed cows. *Reproduction* 122: 737-744.

Rutledge, J.J., Monson, R.L., Northey, D.L. and Leibfried-Rutledge, M.L. 1999. Seasonality of cattle embryo production in a temperate region. *Theriogenology* 51(Suppl. 1): 330 (Abstr.).

Ryan, D.P. and Boland, M.P. 1991. Frequency of twin births among Holstein x Friesian cows in a warm dry climate. *Theriogenology* 36: 1-10.

Shwartz, G., Rhoads, M.L., Dawson, K.A., VanBaale, M.J., Rhoads, R.P. and Baumgard, L.H. 2008. Effects of a supplemental yeast culture on heat stressed lactating Holstein cows. *Journal of Dairy Science*, in press.

St. Pierre, N.R., Cobanov, B. and Schnitkey, G. 2003. Economic losses from heat stress by US livestock industries. *Journal of Dairy Science* 86: E52-E77.

Sussman, C.R. and Renfro, J.L. 1997. Heat shock-induced protection and enhancement of Na+-glucose cotransport by LLC-PK1 monolayers. *American Journal of Physiology* 273: F530-F537.

Thatcher, W.W. and Collier, R.J. 1986. Effects of climate on bovine reproduction. In *Current Therapy in Theriogenology 2* (Ed. D.A. Morrow), pp. 301-309. WB Saunders, Philadelphia.

Ullah, G., Fuquay, J.W., Keawhoong, T., Clark, B.L., Pogue, D.E. and Murphy, E.J. 1996. Effect of gonadotrophin-releasing hormone at estrus on subsequent luteal function and fertility in lactating Holstein during heat stress. *Journal of Dairy Science* 79: 1950-1953.

Urdaz, J.H., Overton, M.W., Moore, D.A. and Santos, J.E.P. 2006. Effects of adding shade and fans to a feedbunk sprinkler system for preparturient cows on health and performance. *Journal of Dairy Science* 89: 2000-2006.

Velez, J.C. and Donkin, S.S. 2004. Bovine somatotropin increases hepatic phosphoenolpyruvate carboxykinase mRNA in lactating dairy cows. *Journal of Dairy Science* 87: 1325-1335.

Velez, J.C. and Donkin, S.S. 2005. Feed restriction induces pyruvate carboxylase but not phosphoenolpyruvate carboxykinase in dairy cows. *Journal of Dairy Science* 88: 2938-2948.

West, J.W. 1999. Nutritional strategies for managing the heat-stressed dairy cow. *Journal of Animal Science* 77(Suppl. 2): 21-35.

West, J.W. 2003. Effects of heat-stress on production in dairy cattle. *Journal of Dairy Science* 86: 2131-2144.

Wheelock, J.B., Sanders, S.R., Shwartz, G., Hernandez, L.L., Baker, S.H., McFadden, J.W., Odens, L.J., Burgos, R., Hartman, S.R., Johnson, R.M., Jones, B.E., Collier, R.J., Rhoads, R.P., VanBaale, M.J. and Baumgard, L.H. 2006. Effects of heat stress and rbST on production parameters and glucose homeostasis. *Journal of Dairy Science* 89 (Suppl. 1): 290-291 (Abstr.).

Wheelock, J.B., La Noce, A.J., O'Brien, M.D., Sanders, S.R., Collier, R.J., Baumgard, L.H. and Rhoads, R.P. 2008. The effect of heat stress and exogenous bovine somatotropin on expression of genes associated with hepatic gluconeogenesis in lactating dairy cows. *Journal of Dairy Science* 91(E-Suppl. 1): 455.

Wiersma, F. and Armstrong, D.V. 1983. Cooling dairy cattle in the holding pen. *ASAE Paper No. 83-4507*. ASAE, St. Joseph, MI.

Wiersma, F. and Armstrong, D.V. 1988. Evaporative cooling dry cows for improved performance. *ASAE Paper No. 88-4053*, St. Joseph, MI.

Williams, E.L., Rodriguez, S.M. Beitz, D.C. and Donkin, S.S. 2006. Effects of short-term glucagon administration on gluconeogenic enzymes in the liver of midlactation dairy cows. *Journal of Dairy Science* 89: 693-703.

Wildman, C.D., West, J.W. and Bernard, J.K. 2007. Effect of dietary cation-anion difference and dietary crude protein on performance of lactating dairy cows during hot weather. *Journal of Dairy Science* 90: 1842-1850.

Wilson, S.J., Marion, R.S., Spain, J.N., Spiers, D.E., Keisler, D.H. and Lucy, M.C. 1998. Effects of controlled heat stress on ovarian function of dairy cattle. 1. Cows. *Journal of Dairy Science* 81: 2139-2144.

Wolfenson, D., Thatcher, W.W., Badinga, L., Savio, J.D., Meidan, R., Lew, B.J., Braw-Tal, R. and Berman, A. 1995. Effect of heat stress on follicular development during the estrous cycle in lactating dairy cattle. *Biology Reproduction* 52: 1106-1113.

Wolfenson, D., Roth, Z. and Meidan, R. 2000. Impaired reproduction in heat-stressed cattle: Basic and applied aspects. *Animal Reproduction Science* 60/61: 535-547.

Zeron, Y., Sklan, D. and Arav, A. 2002. Effect of polyunsaturated fatty acid supplementation on biophysical parameters and chilling sensitivity of ewe oocytes. *Molecular Reproduction and Development* 61: 271-278.

Zimbelman, R.B., Collier, R.J. and Bilby, T.R. 2008. Effect of encapsulated niacin on resistance to acute thermal stress in lactating Holstein cows. *Journal of Dairy Science* 87(Suppl. 1):Abstr. (in press).

Zimbelman, R.B., Muumba, J., Hernandez, L.H., Wheelock, J.B., Shwartz, G., O'Brien, M.D., Baumgard, L.H. and Collier, R.J. 2007. Effect of encapsulated niacin on resistance to acute thermal stress in lactating Holstein cows. *Journal of Dairy Science* 86(Suppl. 1): 231 (Abstr.).

Zorzano, A., Fandos, C. and Palacin, M. 2000. Role of plasma membrane transporters in muscle metabolism. *Biochemical Journal* 349: 667-688.