Environmental Characteristics and Animal Welfare of Two New Dairy Housing Options in the Upper Midwest

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LITERATURE REVIEW

INTRODUCTION

This literature review focuses on housing options for dairy cattle including naturally ventilated freestall barns, cross-ventilated freestall barns, and compost bedded pack barns; outcome-based measurements of animal welfare such as lameness, hock lesion, hygiene and body condition; heat stress in dairy cattle; and environmental characteristics of housing such as ammonia, hydrogen sulfide, and light intensity.

HOUSING FOR DAIRY CATTLE

As average dairy size continues to grow, cattle are being moved off pastures and out of tie-stall barns into buildings with many animals per pen to reduce labor costs and comply with environmental concerns. Bringing cattle off the pasture and into housing facilities provides protection from the environmental elements and improves labor efficiency. Shading cattle provides a first defense against heat stress by significantly lowering the ambient temperature underneath the shade structure by approximately 5°C (Valtorta et al., 1997).

Naturally Ventilated Freestall Barns

Naturally ventilated freestall barns are one of the most common housing facilities for lactating dairy cattle in the upper Midwest (Janni and Allen, 2001). These barns are characterized by a roof pitch of 3/12 or 4/12, sidewall height of 3.7 to 4.3 m (12 to 14 ft) and curtains along the entire length of the sidewall to help regulate barn temperature. Barns can be configured with 2, 3, 4, or 6 rows with 4 or 6 rows more common with larger herds. Stalls surfaces can be mattress or concrete with a thin layer of organic bedding, deep bedded sand or recycled manure solids. Various strategies of heat abatement are used in naturally ventilated freestall barns. In the upper Midwest, one of the most commonly used heat abatement method is a combination of mixing fans and sprinkler systems. Janni and Allen (2001) examined three naturally ventilated freestall barns in Minnesota and Wisconsin and the barns were warmer than the outside temperature during the winter (2 to 8.6 °C) and spring (0.3 to 6.7 °C) which can reduce cold stress. However, the barns were only able to reduce the temperature by 0.1 to 2 °C during the summer months. Naturally ventilated barns are a good option for housing dairy cattle, however, other barns have been designed and built to improve cow welfare and more effectively reduce heat stress.

Low Profile Cross-Ventilated Freestall Barns

Low profile cross-ventilated barns are another housing option available to producers. These barns look slightly different with a low roof pitch of 0.5/12 as compared to a conventional naturally ventilated freestall barn with a roof pitch of 3/12 or 4/12 (Smith and Harner, 2007). They are built like conventional warehouse structures and are fully enclosed (Smith and Harner, 2008). Because these facilities are fully enclosed mechanical ventilation is needed. Air enters the barn through evaporative cooling pads that line one lengthwise side of the barn and the air is exhausted on the opposite wall which is lined with banks of fans (Sheffield et al., 2007). The interior compartments of the barn are similar to either a 4-row or 6-row barn; however cross-ventilated barns can have up to 20 rows and be over 150 m wide (Sheffield et al., 2007;

Jacobson et al., 2008). Low profile cross-ventilated barns are expected to improve summer time cooling and improve temperature control in the winter to allow the barn to be warmer than outside ambient temperatures (Jacobson et al., 2008). Other advantages of housing cows in a cross-ventilated barn include small building footprint, shorter walking distance to and from the parlor, and controlled lighting (Smith and Harner, 2008).

Low profile cross-ventilated barns are built based on the principles of a tunnel ventilated barn. In tunnel ventilated barns the air is pulled through the barn parallel to the ridge. To maintain airflow over the cow spaces, baffles were placed in the tunnel ventilated barns, however the placement was a challenge because the baffles had to be placed out of the way to not interfere with feeding and cleaning equipment (Sheffield et al., 2007). In cross-ventilated facilities the baffles can be placed over the feed alley and freestall areas in the pen to encourage eating and lying in warm weather (Harner et al., 2007). The baffles in tunnel ventilated barns have to be placed 3.7 to 4.0 m (12 to 13 ft) above the floor to prevent equipment interference as compared to cross-ventilated barns where the bottom of the baffle can be placed 1.8 to 3.0 m (6 to 10 ft) off the floor for increased air velocity over the cows (Sheffield et al., 2007). Baffles can increase the air speed in the stall area from 2-3 miles per hour to 6-8 miles per hour (Smith and Harner, 2008). Increasing the air velocity over the cows should allow for increased heat exchange for the cow and minimize heat stress.

Evaporative Cooling. Evaporative cooling has been used successfully in tunnel ventilated barns and other applications outside of agriculture. Using energy from the air to evaporate water lowers the temperature of the air and increases humidity in the facility (Bucklin et al., 1991). Evaporative cooling helps reduce the barn air temperature in arid climates, however, it is less effective when humidity increases (Brouk et al., 2003). Smith et al. (2006) predicted that the maximal cooling in a tunnel ventilated barn with evaporative cooling would be 8.8 temperature-humidity index (**THI**) units. During the two years of the study the tunnel ventilated barn was able to drop the average THI by 2.9 to 3.1 units as compared to ambient conditions and decreased exposure to moderate heat loss (THI >80) by 80%. The most common form of evaporative cooling in cross-ventilated barns includes cooling pads, pumps to circulate the water through the pads, and fans to pull the cooled air through the facility. Water trickles through the cooling pad and cooled air is pulled through by a pressure drop created by the fans on the opposite wall (Jacobson et al., 2008). Water usage by the evaporative cooling pads during the summer averaged 0.19 L/min^2 and had an average efficiency of 65%, which was lower than the 75% efficiency that the manufacturer stated (Harner et al, 2009b). During the summer in a low profile cross-ventilated dairy barn with evaporative cooling in an arid environment the barn temperature was reduced by 7.0 °C during the afternoon hours; amount of time with a THI above 72 was reduced by 58% (Harner et al., 2009a). When two four-row naturally ventilated barns were converted to a cross-ventilated barn with the use of misters instead of evaporative cooling pads the barn temperature was 1 to 2 °C cooler than ambient temperature (Jacobson et al., 2008). However, if the temperature in the barn is not lowered enough the added moisture can cause the THI to be greater than ambient (Brouk et al., 2001).

Smith et al. (2006) compared respiration rates and rectal temperatures of cows housed in a tunnel ventilated barn with evaporative cooling and cows housed in a naturally ventilated barn that used fans and sprinklers for heat abatement. Cows that were housed in the tunnel ventilated barn with evaporative cooling had 13.1 fewer breaths per minute and 0.4 °C lower rectal temperature than cows in the naturally ventilated barn. A dairy facility that used evaporative cooling had lower THI (77.1 vs. 84.1), and cows had lower rectal temperatures (38.9 vs. 40.1) and respiration rates (64.4 vs. 100.0 breaths per min) than cows housed outside with shade, respectively (Wise et al., 1988b). Cows housed in an evaporative cooling facility had improved pregnancy rates (35.2% vs. 23.2%), reduced days open (117.6 vs. 146.7) and increased milk production (27.7 vs. 26.8) than cows housed in a facility that used misting and forced air (Ryan et al., 1992). Chan et al. (1997) did not see differences between evaporative cooling and shade on rectal temperature and respiration rates; however, animals were moved and crowded to perform the rectal temperature with respiration rates taken 10 minutes after returning back to the pen.

Compost Bedded Pack Barns

Compost bedded pack barns are another housing option in the Upper Midwest. The first compost barn was built in Minnesota in 2001 (Barberg et al., 2007a). These barns are usually seen on smaller dairies for the milking herd or can be used as a special needs barn for larger herds. Compost barns have similar characteristics of a freestall barn; however, in a compost barn the freestall area is replaced with a bedding pack (Janni et al., 2007). Characteristics of these barns are a 3.6 m wide concrete feeding alley, resting area, and a 1.2 m high concrete wall that separates the pack from the feed alley (Janni et al., 2007). Compost barns typically have a 4.9 m high side wall with curtains that can be raised or lowered for desired barn conditions.

Compost barns sometimes are confused with conventional bedded pack barns. In bedded pack barns, the bedding is layered and never is mixed until it is cleaned out of the barn. In compost barns, the resting area is usually bedded with wood sawdust and aerated twice a day to a depth of 25 to 30 cm to incorporate oxygen into the bedding and aid in decomposition (Janni et al., 2007). Ventilation is important over the bedding pack to aid in drying the surface and provides a comfortable area for the cows. Due to high costs and limited availability of wood sawdust, alternative bedding materials such as wheat straw by-product, , wood chips, and soybean straw have successful been used (Shane et al., 2010). Janni et al. (2007) recommends that the pack be large enough to provide a minimum resting area of 7.4m^2/cow based on 540 kg cow. A new layer of bedding material is added as necessary when the pack material becomes too moist and adheres to the cows. Compost barns when managed well provide a dry and soft surface for the cows to lie down.

Unlike freestall barns where the entire walking areas are concrete, compost barns have a soft base where cows can lie or stand. Producers have built these barns to improve cow comfort, cow longevity, and reduce labor (Barberg et al., 2007a,b). Endres and Barberg et al. (2007) reported that mean lying times were 9.34 h/d, number of lying bouts was 11, and lying bout length was 50.8 min. Cows housed in mattress freestalls spent 11.7 h/d lying in the stall, had 11.5 lying bouts per day, and had lying bout duration of

1.16 h; cows in sand bedded stalls spent 12 h/d lying down, had 10.3 of lying bouts per day, and lying bout duration of 1.3 h (Cook et al., 2004). Cows on pasture spent approximately 10 to 11 h/d lying down (Hernandez-Mendo et al., 2007; Legrand et al., 2009). Even though cows spent less time lying down in compost barns than cows housed in freestalls, Barberg et al. (2007b) found that only 7.8% of cows in compost barns were clinically lame which was much lower than sand freestalls (17.1%) or mattress freestalls (27.9%) (Espejo et al., 2006). Compost barns are a good housing option for producers that want to improve cow welfare; however costs of bedding materials and ability to manage the pack may limit their use.

COW HEALTH AND WELFARE

Animal welfare is becoming more of a concern for consumers. Broom (1991) defines welfare as “the state of an individual in relation to its environment.”   Due to the concerns of the treatment of livestock the Farm Animal Welfare Council proposed the Five Freedoms that all animals should have: 1. Freedom from hunger and thirst; 2. Freedom from discomfort; 3. Freedom from pain, injury, or disease; 4. Freedom to express normal behavior; 5. Freedom from fear and distress.   Typically from the veterinarian and producer viewpoint, welfare includes that animals be free from disease and injury and be well nourished (von Keyserlingk et al., 2009). Some consumers would rather ensure that the animals are able to move around and perform natural behaviors. As the public becomes farther removed from the farm they are becoming increasingly concerned about how their food is produced. These five freedoms need to be addressed when a producer decides to build a certain housing system and how they will raise and manage their animals.

Lameness

Lameness in cattle is a major animal welfare and economic problem. Lameness in dairy cattle has been cited as the most significant indicator of welfare (Whay et al., 2003). Dairy producers try to keep their animals free of illness or injury; however, approximately 20 to 30 percent of lactating dairy cows in the U.S. are lame at any given time (Cook, 2003; Espejo et al., 2006). Ito et al. (2010) found similar results with 28.5% of cows housed in freestalls with a score of 3 and above. In Norwegian freestall herds mainly composed of Norwegian Reds the lameness prevalence was 17% (Keilland et al., 2009). At 101 Swedish dairy farms, the overall lameness prevalence was 5.1% with 72% of the animals having at least one hoof lesion, but many of the lesions did not cause pain (Manske et al., 2002). Even an individual unfamiliar with raising cattle can realize that lame animals are in pain. Lame cows have changes in stride and speed. When grouped by lameness category (normal, mildly lame, or moderately lame) cows that were moderately lame had slower walking speeds, reduced stride length and step length as compared to normal and mildly lame cows (Telezhenko and Bergsten, 2005). Reducing lameness is essential as the public is becoming more interested in learning where their food comes from and how humanely animals are treated. Not only is lameness an animal welfare problem, but there are economic losses due to increased treatment costs, reduced milk production, reduced fertility, and increased risk of culling.

Lameness can be due to infectious organisms, nutrition, or injury to the limbs or hoof. Risk factors for lameness include standing on concrete, excessive hoof wear, constant wet manure covered conditions, and changes in diet (Nocek, 1997; Wells et al., 1999; Galindo and Broom, 2000).

In two freestall housed dairies, claw horn lesions were responsible for 23.3 and 33.1 % of lameness events, respectively (Warnick et al., 2001). White line disease, sole bruising and septic pododermatitis accounted for 92% of lesions from grazing herds in New Zealand (Tranter et al., 1993). Sanders et al. (2009) in a case study at a 2100-cow sand bedded freestall dairy found that 20% of the lameness events were thin sole-induced toe ulcers, 16% sole ulcers, 13% thin soles, 10% white line disease, 8% heel ulcers, 6% from leg injuries, 4% sole punctures, 2% toe ulcers, and 20% were caused by infectious diseases, laminitis or unclassified hemorrhage. The percentage of hoof lesions in 4899 cows from 101 Swedish dairy farms were: 41% heel-horn erosion, 30% sole hemorrhages, 27% erosive dermatitis, 21% abnormal claw shape, 14% white-line hemorrhage, 8.8% white-line fissures, 8.6% sole ulcers, 3.3% double soles, 2.3% verrucose dermatitis, and 1.8% interdigital hyperplasia (Manske et al., 2002).

Acidosis and Subclinical Acidosis. Nutrition and hormonal changes have been proposed as a mechanism for laminitis. Nocek (1997) noted that a diet of highly fermentable carbohydrates, or forages low in effective fiber was associated with an increase of lactic acid in the rumen causing acidosis. This could be caused by rapid diet change or fresh cows given a diet that is very different than the dry period diet (Kleen et al., 2003). Stone (2004) noted that environmental conditions such as heat stress and overcrowding could alter feeding patterns leading to sorting or gorging. With a large ingestion of grain, the pH of the rumen decreases below 5.6 which disrupts rumen flora and allows for the proliferation of *Streptococcus bovis* (Owens et al, 1998). These bacteria produce large quantities of lactic acid which builds up in the rumen and blood. The build-up of lactic acid appears to be associated with reduced blood flow, causing tissue damage of the hoof (Nocek, 1997). It has also been shown that subacute acidosis may be caused by high levels of volatile fatty acids rather than high levels of lactic acid (Burrin and Britton, 1986). Hoof lesions associated with subclinical laminitis include white line disease, sole ulcers, and sole abscesses (Melendez et al., 2003).

Parturition. Near parturition, the hormones that elongate the tendons and ligaments for parturition may also stretch the collagen that is attached to the third phalanx of the hoof, allowing it to rotate and sink (Lischer et al., 2002). Dewes (1978) observed lameness starting 10 days after calving with a mean of 63 days in milk for first calf Holstein heifers.

Digital Dermatitis. Digital dermatitis (hairy warts, Papillomatous digital dermatitis) is a painful lesion on the foot often found on the interdigital space. It is believed to be multifactorial disease with the bacteria *Dichelobacter nodosus* involved and a virus, but to date none have been isolated (Merck Veterinary Manual, 2008). Mean lameness caused by digital dermatitis ranged between 32 and 57 percent in freestall and tie stall herds (Warnick et al., 2001; Cook, 2004).

Economics. Not only is there a cost to the lameness case itself, but also from the reduced milk production and fertility, and increased culling. Estimated losses due to treatment and reduced milk production from a lameness event were approximately US $134 per lame foot per cow (Enting et al., 1997). In Australia the estimated cost of lameness per cow was $42.90 (Harris et al., 1988). Miller and Dorn (1990) reported total cost for prevention and occurrence of lameness in Ohio dairy herds were $8 per head with $1.10 for prevention and $6.90 for each occurrence . Reducing the lameness cases on a farm will improve farm profitability.

Milk Production. In two New York herds, cows that were diagnosed lame produced less milk (0.8 – 1.5 kg/d) than their non-lame herd counterparts (Warnick et al., 2001). A study in the United Kingdom found milk production was reduced 360 kg per 305 d lactation if a cow was lame (Green et al., 2002). Lame cows in New Zealand produced 202 kg less milk, 9 kg less fat, and 8 kg less protein per lactation (Tranter et al., 1993). Juarez et al. (2003) found that milk production and milk protein yields decreased as locomotion score worsened.

Reproduction. Lameness not only reduces economic returns by reduced milk production, but also reduced fertility. Lame cows were at 15% lower risk of becoming pregnant as compared to non-lame cows (Bicalho et al., 2007). Lame cows had a lower conception rate at first service (17.5% vs. 42.6%), lower pregnancy rate (85.0% vs. 92.6%) and had more ovarian cysts (25.0% vs. 11.1%) than cows that were not lame (Melendez et al., 2003). Garbarino et al. (2004) found lame cows had an incidence of delayed cyclicity of 17% compared to non-lame cows and were at 3.1 times greater odds of delayed cyclicity.

Culling Risk. Cows that are lame are more at risk of becoming culled versus non-lame herd mates. After a cow has become lame, her hazard for being culled increased by 45% and if she was severely lame by 74% (Bicalho et al., 2007). A study looking at survival of cows found that a cow diagnosed lame less than 60 days in milk was 2 times more at risk of being culled between days 121-240 than herdmates not diagnosed lame. Cows being diagnosed between 61-120 days in milk were 2, 1.7, and 1.5 times more at risk of being culled between days 61-120, 121-240, and greater than 240 days in milk, respectively (Booth et al., 2004). Melendez et al. (2003) found cows that were lame were six times more likely to be culled or leave the herd.

Housing. Housing and stall surface material are associated with varying lameness prevalence. A survey of Wisconsin herds housed in tie-stalls found the lameness prevalence to be 19.7% whereas cows that were housed in freestalls had 22.8% lameness prevalence in the summer and 27.8% in the winter (Cook, 2003). When cattle were housed in compost bedded pack barns the lameness prevalence was much lower (7.8%) and ranged from 0-22.4% (Barberg et al., 2007b). Cattle that were allowed to graze improved their gait by 0.22 units/wk whereas cows housed in freestalls did not change or got slightly worse (Hernandex-Mendo et al., 2007).

Stall Surface. Deep bedded sand freestall barns have less lameness prevalence (17.1%) than freestalls with mattress stalls (27.9%) (Espejo et al., 2006). Cook et al. (2006) found similar lameness prevalence for mattress stalls (26.8% summer and 33.7% winter), and slightly higher lameness prevalence for sand bedded stalls (18.4% summer and 21.2% winter; Cook, 2003). Severe lameness (score of 4 or greater) on mattress bedded stalls was 9.3% while deep bedded stalls had a severe lameness prevalence of 4.4% (Ito et al., 2010).

Floor Surface. Cows walked significantly slower on slatted concrete (0.97 m/s) than other walking surfaces except continuous rubber flooring (1.01 m/s). Slatted rubber (1.06 m/s) was not different from the continuous rubber or solid concrete (1.08 m/s), but was different from sand (1.12 m/s). Haufe et al. (2009) looked at three surfaces; rubber floor, slated concrete, and mastic asphalt and the fastest walking speed was on rubber flooring (1.80 m/s) with similar results on mastic asphalt and the slowest speed on slatted concrete (1.18 m/s). Stride length improved from 133.8 cm on slatted concrete to 160 cm when walking on sand (Telezhenko and Bergsten, 2005). Platz et al. (2008) examined slatted concrete flooring and rubberized flooring. Cows walking on slatted concrete flooring had a significantly shorter stride (58 cm) than cows walking on rubberized flooring (70 cm). Increasing the size of aggregates by epoxy coating the concrete, decreased the walking speed and increased step length. (Phillips and Morris, 2001). They suggested that optimal friction coefficient was between 0.4 and 0.5. Slatted concrete was the most slippery surface (0.31), rubber mats were intermediate (0.46) and solid concrete had the most friction (0.58) (Telezhenko and Bergsten, 2005).

Behavior. Lameness may modify the behavior of cows. Cows that were lame spent more time lying down than non-lame herdmates (Juarez et al., 2003; Walker et al., 2008). Severely lame cows in mattress stalls spent significantly more time lying (13.1 h/d) than severely lame cows in deep bedded stalls (10.9 h/d) (Ito et al., 2010). Cows that became lame spent 0.6 more h/d standing in stalls than cows that did not get lame

(Galindo et al., 2000). Galindo et al. (2000) found that lame cows were displaced less than cows that did not become lame. Lame cows showed 1 h less estrus behavior, spent less time walking, and standing than non-lame cows (Walker et al., 2008).

Lameness Incidence. Most of the research on lameness incidence has been conducted outside of the United States. Cases are usually diagnosed by farmers or veterinarians and the information is extracted from farm records. A case study of three dairy farms in New Zealand reported incidence of lameness of 16% ranging from 2 – 38% (Tranter and Morris, 1991). In the United Kingdom the annual incidence was 54.6 per 100 cows and ranged from 10.7 to 170.1 cases per 100 cows (Clarkson et al., 1996). Another UK study found an annual incidence of 68.9 cases per 100 cow years (Hedges et al., 2001). During a study in Canada the incidence was much lower at 8.9% (Ruegg and Milton, 1995). Two New York dairy herds had incidence of 40 and 52% (Booth et al., 2004).

Body Condition

Body condition scoring (**BCS**) is a subjective visual assessment of subcutaneous body fat (Domecq et al., 1997; Roche et al., 2009). Animals are scored on a 1 to 5 scale in 0.25 increments with an animal scoring a 1 being emaciated and a 5 being a severely obese animal. Areas assessed for body condition are typically the spinous and transverse processes of the lumbar vertebrae, the ileal tuberosities (hooks) and ischeal tuberosities (pin bones), the ileo-sacral and ishchealcoccygeal ligaments, tail head and the thurl region (Ferguson et al., 1994). Edmonson et al. (1989) scored cows in eight locations on the body and found that the condition scores of the pelvic and tailhead areas were most closely correlated to the overall BCS. Body condition will change throughout lactation. Body condition will decrease quickly during early lactation when milk production is increasing. Primiparous cows lost 0.73 points and multiparous cows lost 0.83 points of BCS from the dry period to minimal score in early lactation (Ruegg and Milton, 1995). Holstein cows in New Zealand lost 0.73 BCS units (1.73 BCS on 5 point scale; Roche et al., 2004) and 53 kg of weight from calving to lowest body condition and weight (Roche et al., 2007). After peak milk, body condition will start increasing until the end of lactation and remains constant during the dry period (Wildman et al., 1982). There are differences in BCS between breeds and even the same breed in different areas of the world. North American Holsteins lost BCS 14 days longer and had 0.32 points lower BCS at 270 days in milk than New Zealand cows (Roche et al., 2006). The heritability of BCS in Holsteins ranged from 0.27 to 0.37 (Barry et al., 2002). Body condition scoring has a weak correlation to body weight and frame size (Wildman et al., 1982; Roche et al., 2007).

Visual observation of body condition score allows producers to manage nutrition and help determine how the animal will perform in the following lactation. Excessive loss of body condition has been identified as a risk factor for lowered reproductive performance and health. Research conducted by Kim and Suh (2003) found cows that lost 1 to 1.5 points in body condition between the dry period and shortly after calving had greater metritis (62 vs. 23%) and metabolic disease incidence (27 vs. 2%) and had a longer interval to first breeding (103 vs. 87 d) compared to cows that lost less than 1 point in BCS. Cows that gained 1 point in BCS between dry-off and parturition were associated with 545.5 kg more milk during the first 120 d of lactation (Donmecq, 1997). Each 1 unit decrease in BCS (1-10 scale) from calving to 60 DIM and between 60 and120 DIM were associated with a 6 and 13.1 unit reduction of somatic cell score, respectively (Berry et al., 2007).

Excess Body Condition. The ideal body condition score at calving for Holstein-Friesian cattle is between 3.0 and 3.5 (Roche et al., 2009). Excessive body condition has been associated with health problems in dairy cows. Cows with a body condition score at calving greater than 3.5 were 2.4 times more at risk of ketosis than cows calving with a body condition score between 3.0 and 3.25 (Gillund et al., 2001). Ruegg and Milton (1995) did not find a relationship between over condition at calving and metabolic diseases. However, most of the cows in the study were in the optimal condition range leaving only 29 of the 429 cows with a BCS greater than or equal to 4.0.

Although heavier cows are more at risk for metabolic disorders there are mixed results for reproductive differences. Ruegg and Millton (1995) reported no differences in days to first observed estrus, days to first breeding, days to conception, or number of times bred based on calving BCS.

Hygiene

Several scoring systems have been used to assess cow hygiene. Schreiner and Ruegg (2003) developed a hygiene scoring system that is based on a four point scale from 1 = clean to 4 = very dirty that examines the udder and leg hygiene. They found that linear SCS increased as the udder hygiene score increased. Dirty cows (score 3 and 4) were 1.5 times more likely to have major pathogens isolated from the milk as compared to “clean cows.” Reneau et al. (2005) examined five areas of the body – tail head, upper thigh, abdomen, udder , and lower portion of hind leg on a 1= clean to 5 = very dirty and found that hygiene scores for only the lower leg and udder were associated with SCS.

Tail Docking. Producers often claim their reasons for tail docking are to improve hygiene and milk quality. However, results from Fulwider et al. (2007) indicated that SCC of dairies with tail docked animals was not different than non-docked cows. Schreiner and Ruegg (2002) and Tucker et al. (2001) reported similar results that tail docking did not improve SCC or cow hygiene over non-docked animals. Eicher et al. (2001) found that docked cows had improved hygiene over non-docked, however, docked animals had greater fly counts, increased fly-avoidance behaviors, and used foot stomping as an alternate behavior to remove flies. There was no difference on udder hygiene of first parity animals between docked and non-docked animals pre or post-calving (Compton et al., 2007).

Housing and Bedding. There was a higher percentage of cows with a hygiene score of 2 and a lower percentage of score 3 (1-4 scale) in barns with mattresses or waterbeds than in barns with sand bedded freestalls (Fulwider et al. 2007). It was also noted that cows housed on compost bedded packs had similar scores to waterbeds, but that housing system was not included in the comparison analysis. In another study, cows housed in compost bedded pack barns had a hygiene score of 3.04, based on a 1-5 scale (Barberg et al., 2007b). Cows using stalls with recycled manure solids on top of mattresses were cleaner than cows using stalls bedded with dolomitic limestone (Hippen et al., 2007).

Lesions

Hock and Knee. Stall surface can impact the prevalence of lesions. The mean hock lesion prevalence in Norwegian dairy farms was 60.5% (Kielland et al., 2009). Authors noted that the hock lesion odds ratio for animals lying on softer surfaces such as sawdust or wood shavings was 0.22 (78% reduction) compared to herds with concrete or hard rubber mats . Other risk factors for hock lesions were being lame, in their second parity or greater, and having a lying area in head-to-head stalls greater than 250 cm and lying area greater than 260 cm for stalls against a wall. However, Weary and Taszkun (2000) found longer stalls were associated with reduced hock lesion prevalence. Zurbrigg et al. (2005) found that open hock wounds increased by 35% when cows were housed with electric trainers over the stall. It was also noted that the prevalence of swollen hocks increased by 1% for each 2.54 cm reduction of tethering chain length in tie-stall barns. Fulwider et al. (2007) evaluated the prevalence of hock injuries for different stall surfaces and housing options. Cows in compost bedded pack barns had no hock injuries and cows that were housed on sand bedded (25%) or waterbed freestalls (35.2%) had less hock lesions than cattle housed on rubber filled mattresses (71.6%). There were less hock injuries in cows lying on mattresses with recycled manure solids than those lying on mattresses with dolomitic limestone (Hippen et al., 2007). Cows housed with deep bedded sand stalls had less hock lesions than those housed with waterbeds (Boone et al., 2009).

Cows housed on concrete stalls had more lesions to the knees (0.32) than cows housed on rubber tie-stalls (0.11) (Rushen et al., 2007). The prevalence of knee lesions in Norwegian herds was 35.3% (Kielland et al., 2009). Risk factors associated with knee lesions included hard freestall surface, farmers' negative attitude towards animals in pain, early lactation, and taller animals. Seven dairies on either sand bedded stalls or waterbeds had knee lesion prevalence between 28 and 61% (Fulwider et al., 2007).

Neck. When neck rails were 116 to 132 cm in height, there were 70% fewer neck lesions than with neck rails placed 99 to 114 cm in height (Zurbrigg et al., 2005). Forty-two percent of cows housed with post and rail feed barriers had neck lesions whereas only 4% of animals with vertical feeding barriers or headlocks had neck lesions (Kielland et al., 2010). Authors recommended that if post and rail design was going to be used that it should be above 109 cm for cows taller than 126 cm to minimize neck lesions.

Cow Comfort

As dairy farms became larger, cattle have moved from pastures to being housed in tie-stalls and freestall barns. While these facilities have allowed producers to manage more cattle efficiently, stall dimensions and bedding surfaces were not always built with cow comfort in mind. Cattle spend approximately 50-60% of the day lying down (Metz, 1985; Herlin, 1997). Munksgaard and Simonsen (1996) had lying times of just less than 14 h for controls and cows that were isolated from herd mates, but were given individual stalls. Herlin (1997) had 12.2, 12.5, and 14.8 h/d lying time when cows had lying surfaces of concrete, standard rubber mat, and a soft rubber mat, respectively. Cows in a large pen with rubber flooring, spent 14.7 h/d lying down compared to 10.6 h/d for cows housed in concrete tie-stalls (Haley et al., 2000). Another study reported that cows spent 12.3 h/d lying down on mattress tie-stalls compared to 10.4 h/d for concrete tie-stalls (Haley et al., 2001). The lying bout duration was less on mattresses (62 min) than concrete stalls (78 min), but the frequency of lying was higher on mattresses (13 vs. 9). This can indicate cows will get up and change positions more frequently when given a softer surface. The amount of sand bedding is associated with lying times. When sand bedding levels dropped 6.2 cm below the curb of the stall there was a reduction in lying time of 1.5 h/d (Drissler et al., 2005).

Another factor that can alter lying time is the amount of overcrowding. Producers often have more cows than stalls in each pen and the lower ranked animals will be displaced by more dominant individuals. When there was 25% overcrowding, the mean reduction was 44 min and subordinate animals had an average of 82 less minutes of lying time (Wierenga, 1983). After cows are prevented access to lying area they will try to recover the lying time that was lost (Munksgaard and Simonsen, 1996). When cows were deprived of 3 h/d of lying, within 12 h they had made up 50% of the lost lying time (Metz, 1985). Lying is an important physiological function and will have priority over eating and other activities.

Cow Comfort Index and Stall Usage Index. The cow comfort index (**CCI**) can be used to assess cow comfort. It is calculated by dividing the number of cows lying in a stall by the number of cows lying in a stall plus the number of cows standing in a stall multiplied by 100. It is recommended that CCI be greater than 85% (Nelson, 1996). Krawczel et al. (2008) compared stocking densities of 100, 113, 131, and 142% and the

CCI was 80.7, 81.9, 82.9, 82.6%, respectively with no difference between stocking densities. Cook et al. (2005) looked at stall surface in respect to CCI. Herds that had rubber mattresses had a CCI of 76% and herds with sand bedded stalls at 86%. They also noted that the highest correlation to 24-h time standing in the stalls was 2 h before the morning or afternoon milking. Overton et al. (2002) suggested collecting the CCI 1 h after cows returned from the morning milking.

Stall usage index (**SUI**) is similar to CCI, but the denominator includes all animals in the pen not eating. Stall usage index is more affected by stocking density than CCI because it includes animals standing idle in the alleys. When stocking density increased from 113% to 142% the SUI decreased from 70.2% to 66.3% (Krawczel et al., 2008). The SUI was 69.6% for mattress stalls and 76.3% for sand bedded stalls (Cook et al., 2005). Cows housed on recycled manure solids or limestone bedded freestalls had similar SUI of 73.7 and 74.1, respectively (Hippen et al., 2007).

Preferences. When cows were given the choice between a soft rubber mat, standard rubber mat, or concrete, they spent 71% of the observation time lying on the soft rubber mat versus 55% for standard rubber mats and 18% for concrete flooring (Herlin, 1997). Tucker et al. (2003) used deep bedded sawdust, deep bedded sand, and mattress stalls with 2-3 cm of sawdust to test preference and lying times. In the first experiment nine of the twelve cows preferred the deep bedded sawdust stalls, but these cows were previously housed with deep bedded sawdust stalls. In the second experiment with cows previously housed with deep bedded sand stalls, half preferred the sand bedded stalls and half preferred sawdust. Haley et al. (2001) gave cows a large cubicle with rubber mat or concrete flooring and observed their lying and standing behavior. Cows that were housed on the rubber mat increased their total lying time by 1.8 h/ d than cows housed on concrete (12.2h/24 h vs. 10.4 h/24h). However, the cows housed on concrete had longer lying bouts (78 vs. 62 min) than the cows housed on the rubber floor. Limestone bedding appeared less comfortable than sand bedded stalls (Clanton et al., 2005). Gebremedhin et al. (1985) looked at four stall surfaces and cows preferred deep soil bedded stalls the most, rubber mats and carpets were intermediate, and concrete was the least preferred stall surface.

Stall surface is not the only factor affecting cow preference, poorly designed stalls that are too short or narrow can affect lying times and possible create injuries when the individual is rising. Total lying time improved when stall width increased from 106 cm (12.3 h/24 h) to 126 cm (13.0 h/24 h) (Tucker et al., 2004). They also looked at stall length to determine preference. Cows spent less time with the front two hooves in the stall when the length was increased from 229 cm (173 min/24 h) to 274 cm (131 min/24 h).

Heat Stress

Heat stress is another welfare and economic problem for dairy cattle. An animal's ability to tolerate heat depends on their age, sex, breed, level of performance, body condition, and environment in which the animal is housed (Gaughan et al., 2000). Heat stress is more of a problem than cold stress. It takes a drop in body temperature of 15-25 °C to cause death, whereas in the heat it only takes an increase in body temperature of about 3-6 °C (Bianca, 1976). There are two main ways that cattle can cool themselves:

evaporation, which includes sweating and panting, or sensible mechanisms such as conduction, convection, or radiation (Yousef, 1987). Evaporation works by a vapor pressure/gradient, whereas conduction, convection, and radiation work by a thermal gradient (Collier et al., 2006). The estimated thermoneutral temperature for lactating dairy cows is between 5 and 25 °C (Roenfeldt et al, 1998). Since not only temperature can affect cattle the THI was proposed. It takes into consideration the humidity along with temperature. Cattle begin to experience heat stress when the THI exceeds 72 (Armstrong, 1994). Vitali et al. (2009) observed an increase in cattle mortality rates when the THI was 70. They also observed when the THI reached 87 it was the maximum critical value of mortality in cattle. Behavior changes were observed when the THI reached 68 (Cook et al., 2003). Two main ways dairy cattle try to cope with hot temperatures is by increasing heat dissipation and by reducing feed intake to lower metabolic heat (Hahn, 1999). Because higher milk production results in greater metabolic heat, higher producing animals are more at risk of heat stress than those producing less milk. A 600-kg cow yielding 10 kg of milk/day will produce approximately 17,000 kcal and a cow yielding 50 kg/day will produce about 36,000 kcal (Bianca, 1976). A 700-kg cow producing 60 kg/day will produce 44,171 kcal of heat (Nardone et al., 2006).

Cattle color and hair coat type were found to be associated with ability to tolerate heat stress. Lactating dairy cows with white colored coats stayed outside for longer periods than darker colored coats (Frazzi et al., 2000). Feedlot cattle that had dark colored coats were found to be panting more and huddling together when the THI was greater than 74. These dark colored cattle had a higher tympanic (inner ear) temperature (0.2 – 0.6 °C) than light colored cattle (Mader et al., 2002). Holsteins that had slick hair coat were able to maintain lower respiration rates both indoors (67 vs. 79 breaths/minute) and outdoors (97 vs. 107 breaths/minute) compared to wild-type hair coats in environments that provided some heat abatement strategies (Dikmen et al., 2008).

Measuring Heat Stress. Heat stress in cattle can be measured by respiration rate, body temperature (rectal or vaginal), thermal imaging or any combination of these methods. The least invasive method to evaluate heat stress is to measure the respiration rate (Eigenberg et al., 2005). Each flank movement is counted for one minute to get the respiration rate. Since animals can vary on ability to tolerate heat, a minimum of two measurements should be taken; one at least 2-3 hours before the hottest part of the day when it is cooler and the second measurement mid-afternoon (Gaughan et al., 2000). Monitoring devices can be strapped on the animals to reduce labor of measuring respiration rates. These devices work by recording flank movements. Eigenberg et al. (2000) found a strong correlation (R = 0.77) between ambient temperature and respiration rate measured with a monitoring device when beef cattle were deprived of shade. However, the correlation was much weaker when animals were housed under a shade structure (R = 0.37).

A normal respiration rate for cattle not exposed to heat stress is 22 breaths per minute (Seath and Miller, 1946). Cattle that were not given shade had on average 16 breaths per minute more than those given shade during the day (Eigenberg et al., 2005). Lactating dairy cattle that were not offered shade had 82 breaths per minute versus 54 breaths per minute for cattle that had shade (Roman-Ponce et al., 1977). Schütz et al. (2010) reported that cattle housed under adequate amounts of shade (9.6 m^2 shade/cow) had the lowest respiration rates of 51 breaths per minute, those with 2.4 m^2 shade/cow had 57 breaths per minute and those with no shade had 62 breaths per minute. Shade, sprinklers, and shade with sprinklers significantly reduced respiration rates compared to controls (54, 30, 24, and 78 breaths/min, respectively) (Kendall et al., 2007). Frazzi et al. (2000) had the lowest respiration rates for cows with fans and misters (70 breaths/ min); for fans only was intermediate (78 breaths/min), and highest respiration rates with no fans or misters (94 breaths/min). Rectal temperatures followed a similar trend of 38.6, 38.9, 39.5 °C for fans and misters, fans only, and control, respectively.

Performance. Lactating dairy cows that experienced heat stress produced 7.5 kg/d less milk than those housed in a thermal neutral environment (Rhoads et al, 2009). Cows housed in a tunnel ventilated barn produced 5.7 kg/d more milk on week 4 and 2.8 kg/d over a 10-week study than cows housed in a naturally ventilated barn with mixing fans and misters (Smith et al., 2006). Strickland et al. (1989) reported that cows provided cooling produced 2.4 kg/d more than the control group. Providing shade improved average daily gain in dairy heifers by 14% and feed efficiency by 13% compared to providing sprinklers and no shade (Marcillac-Embertson et al., 2009). Heat abatement is important in both beef and dairy production. When beef feedlot cattle were given shade they had improved dry matter intake and average daily gain, and heifers that were provided shade reached their targeted body weight 20 days earlier (Mitlohner et al., 2001). Implementing heat abatement strategies improves animal performance and well-being.

Reproduction. Embryo quality and overall reproductive rates can be affected by heat stress. When Holstein heifers were superovulated and bred, then placed in a heat chamber for the first seven days of embryo development, only 20.7% of the 82 embryos were normal versus 51.5% of the 68 embryos recovered from heifers that did not experience heat stress (Putney et al., 1988). Decreases of luteinizing hormone pulses were seen on day 5 in cattle kept in corrals with only shade versus cattle that were housed in a refrigerated tie-stall barn (Wise et al., 1988a). Dairy cattle that were in a thermoneutral environment were more likely to have the dominant follicle from the second wave ovulate than heat stressed animals (91 vs. 18%, respectively) (Wilson et al., 1998). They also found that luteolysis was delayed 9 days in the heat stressed cows. Lactating dairy cattle that were given shade had higher conception rates (44.4%) than those not offered shade (25.3%) (Roman-Ponce et al., 1977). Cooled dairy cows with either evaporative cooling or refrigeration had higher pregnancy rates (28.6%) than cattle housed outside with shade (16.7%) (Wise et al., 1988b).

Economics. Heat stress not only causes decreased milk production, but also increased mortality, disease susceptibility, and decreased reproductive efficiency. It has been estimated that the U.S. dairy industry loses $848 to $1458 million each year from decreased milk production, increased mortality, culling, and days open from heat stress (St-Pierre et al., 2003). Estimating milk production losses of 4.5 kg/head per day with milk prices at $15/cwt would translate to $1.50 loss per head per day or $150 per day on a 100 cow dairy during each day of heat stress. These costs don't include the reproductive losses due to heat stress on increased days open, reduced fertility, additional labor, and drugs. Strickland et al. (1989) performed an economic analysis of adding evaporative cooling to an existing freestall and with the benefits of cooling on just milk production alone found an annual benefit of $96/cow for 210 days of operation. Igono et al. (1987) also saw an economic benefit of $0.22/cow per day by providing fans and sprinklers versus shade alone. Implementing heat abatement methods is important to maintain milk production and minimize income losses.

Behavior. The behavior of cattle changes during periods of heat stress. To minimize metabolic heat, dry matter intake decreases and cattle spend more time standing. Cook et al. (2007) found that lying time decreased from 10.9 to 7.9 h/d and time spent standing in the alley increased by 1.9 h/d between the coolest and hottest filming sessions. In compost bedded-pack barns, when the THI was greater than 72 there was a reduction in the length of lying bouts and cows increased the number of steps (Endres and Barberg, 2007). Schütz et al. (2010) found similar reduction of lying times as the temperature increased. Beef feedlot cattle housed with shades had similar results to cattle in freestalls and alternative housing. A study done in Texas found that beef feedlot heifers not misted or given any shade spent less time lying down than the mist, shade, and mist and shade groups (Mitlohner et al., 2001). Cows that were given 9.2 m^2 of shade/cow spent more time under the shade (50 vs. 24%) and engaged in fewer aggressive behaviors than cows that had access to 2.4 m^2 of shade/cow (Schütz et al., 2010). Cows preferred to stay indoors when solar radiation was high, even if the barn humidity was higher than outside (Frazzi et al., 2000).

AIR QUALITY AND ENVIRONMENTAL CHARACTERISTICS

Ammonia

As dairy operations are becoming larger, concerns have arisen on the air quality for neighbors and the animals in the facility. Ammonia can be emitted from animal housing, manure storage, and during field application. Livestock production is one of the largest contributors to ammonia emissions into the atmosphere (Arogo et al., 2006). Large concentrations of ammonia can have adverse and long-term effects on the respiratory system of humans and animals. Ammonia is not only a health concern, but can be a neighbor concern as ammonia is one many gases that gives off a pungent odor. Ammonia and other odor causing gases from manure lagoons from production facilities are a common cause of concern. Ammonia is formed by the degradation of urea when catalyzed by the enzyme urease which is produced by microorganisms found in manure or other organic nitrogen containing substances (Arogo et al., 2006). Ammonia concentrations will vary throughout the year with greater concentrations found during the warmer months (Marcillac et al., 2007). Concerns arise over nitrogen losses because of excessive ammonia emissions into the atmosphere contributing to ecosystem fertilization, acidification, and eutrophication (NRC, 2003).

Two Colorado freestall dairies housing 2000-2500 animal units had average ammonia concentrations measured downwind from 74.7 $\mu g\ m^{-3}$(Fall) to 393.7 $\mu g\ m^{-3}$ (Summer) (Marcillac et al., 2007). Marcillac-Embertson et al. (2009) examined ammonia emissions on outside corrals with heifers that were provided either shade or sprinklers. The ammonia emissions were 46% greater in the sprinkled versus shaded corrals. The percentage of average annual ammonia emissions (percentage of available N) on various dairy operations were 8% losses in tie stall barns, 16% freestalls, and 10% for grazing herds (Rotz, 2004). On a 120-cow naturally ventilated dairy, emission rates ranged from 2.52 to 4.15 g/animal unit (Wheeler et al., 2008). A 550-cow freestall operation in Minnesota had ammonia emission rates of 224 mg/h per 500 kg live weight during the winter and 481 mg/h per 500 kg live weight during the summer (Schmidt et al., 2002). Sheffield et al. (2007) reported emission rates of 856 mg/h per 500 kg live weight at a low ventilation rate and 678 mg/h per 500 kg during the summer in a low profile cross-ventilated barn. Ammonia emissions in a slatted floor facility ranged from 20.8 to 22.9 g/h and in the grooved concrete floor with closed perforations ranged from 9.7 to 13.1 g/h (Swierta et al., 2001).

Swierta et al. (2001) examined slatted and grooved floor that only allowed urine to permeate to reduce contact between urine and feces. During three trial periods, ammonia concentration in the grooved floor was almost half of the slatted floor 3.0 vs. 6.4, 4.8 vs. 8.1, and 4.9 vs. 8.0 g/m^3 (ppm) in period I, III, V, respectively. When scraped versus flush facilities were examined there were no significant differences in cumulative ammonia losses (Vaddella et al., 2009). Average ammonia concentrations in a low profile cross-ventilated barn were 1219 ppb (1.2 ppm) in the spring and 1117 ppb (1.1 ppm) in the summer (Sheffield et al., 2007). Two 675 head naturally ventilated freestall barns in Ohio had average ammonia concentrations from 0.3 to 3.0 ppm (Zhao et al., 2007). Mutula et al. (2002) reported ammonia concentrations from 2.4 ppm in the bedding area to 74 ppm in the feeding area in a Texas freestall herd. A 200 head dairy had ammonia concentrations at or below 1 ppm during the day of sampling (Zhu et al., 2000).

Bedding Sources on Ammonia Emissions. Bedding materials can have an effect on ammonia emissions. Sand and pine shavings had significantly lower ammonia emissions over chopped newspaper, chopped corn stalks, and recycled manure solids (Misselbrook and Powell, 2005). It was also concluded that physical structure of the bedding material was more important than the chemical properties on ammonia emissions. Another study looking at bedding sources in the barn had similar results of greater ammonia loss from composted manure solids than chopped straw and pine shavings (Powell and Misselbrook, 2006).

Hydrogen Sulfide

Hydrogen sulfide is a life threatening colorless gas that is produced anaerobically through bacteria decomposing sulfur-containing organic matter found in manure and reducing sulfate in feed and water (Arogo et al., 2000; Clanton and Schmidt, 2000; NRC, 2003). Low concentrations of hydrogen sulfide can cause irritations to the eyes, nose, and throat. Symptoms of moderate exposure include shortness of breath, headaches, nausea, dizziness, and fatigue. High concentrations of hydrogen sulfide can cause shock, convulsions, rapid unconsciousness, coma, and death occurring with only a few breaths (OSHA). Hydrogen sulfide is considered dangerous to life and health at 100 ppm (IDLH). Manure pH plays a role in which sulfide will be present. When the pH is under

5 only H_2S will be formed, at pH 7 H_2S and HS- are in equal quantities, at pH 10 all sulfides are HS-, and at pH 14 equal proportions of HS- and S_2- exist (Arogo et al., 1999). It is important to maintain low levels of hydrogen sulfide for worker and animal safety.

Hydrogen sulfide emissions in a 550-cow naturally ventilated freestall facility were 27 and 2919 µg/h per 500 kg live weight for winter and summer, respectively (Schmidt et al., 2002). Hydrogen sulfide concentrations on two naturally ventilated freestalls with 675 head ranged from 2 to 31 ppb during March, June, and August (Zhao et al., 2007). A 200-head dairy had hydrogen sulfide concentrations from 4 to 26 ppm during the day (Zhu et al., 2000). In an 800-cow low profile cross-ventilated barn hydrogen sulfide concentrations were 7 and 14 ppb with high or low ventilation rates, respectively (Harner et al., 2007).

Lighting

Lighting is necessary to safely and correctly perform tasks on a dairy. When the sun is not available as a lighting source there are three main types of electric light: incandescent/halogen, fluorescent, and high intensity discharge (HID). Fluorescent and high-pressure sodium lights are more efficient than metal halide by providing more lumens per Watt (Gooch and Ludington, 2003). However, the light color of metal halide is more desirable than high-pressure sodium. Gooch and Ludington (2003) noted that fluorescents have the longest life, followed by metal halide and finally high-pressure sodium. Recommended lighting to work with animals in the barn ranged from 200 lux in the parlor with 500 lux at the cow's udder and in the pens between 100 and 200 lux

(ASAE, 2003). Barn size, type of lamp, design of light diffuser, mounting height, and lamp depreciation need to be taken into consideration to achieve the desired light output.

Long Day Lighting. Long day lighting (16 h light with 114 to 207 lux) has been documented to increase milk production and weight gains in Holstein cattle by 10 to 15% (Peters et al., 1978). Lactating dairy cows exposed to long day photoperiod produced 2.7 more kg/d of milk, had higher prolactin levels, higher cholesterol, increased leptin mRNA, and higher leptin receptors Ob-Ra and Ob-Rb (Bernabucci et al., 2006). Leptin is a hormone secreted by the adipose tissue and was examined because of its role in the regulation of energy homeostasis and food intake (Bernabucci et al., 2006). When pregnant heifers were exposed to long and short day photoperiods there were no differences in mammary tissue development, however, serum prolactin was 1.7 times greater in the long day photoperiod (Newbold et al., 1991).

Short Day Lighting. It has been recommended that short day lighting be used in non-lactating dairy cows because it increases the surge of prolactin (Dahl et al., 2000). When dry cows were housed in either a long day photoperiod (16 h light; 8 h dark) or short day photoperiod (8 h light, 16 h dark) the cows housed in a short day photoperiod produced 3.2 kg/d more milk and 3.3 kg/d more energy corrected milk than the long day photoperiod cows (Miller et al., 2000). Short day photoperiods were associated with reduced circulating prolactin, but expression of prolactin receptor mRNA expression in the lymphocytes and mammary tissue were increased during the dry period and short day cows produced more milk during lactation (Auchtung et al., 2005).

EXPERIMENT 1: ENVIRONMENTAL CHARACTERISTICS OF LOW PROFILE CROSS-VENTILATED, NATURALLY VENTILATED, AND COMPOST BEDDED PACK DAIRY BARNS

SUMMARY

Low profile cross-ventilated freestall (CV) and compost bedded pack barns (CB) are two newer housing options for dairy producers in the Upper Midwest. The CV barns are fully enclosed facilities that rely on mechanical ventilation and typically use evaporative cooling for heat abatement during the warmer months. The CB barns are a loose housing system that is generally bedded with dry wood sawdust and tilled twice daily. The objectives of this study were to describe the housing system and assess air quality (aerial ammonia and hydrogen sulfide), air velocity, light intensity, temperature, and relative humidity in CV, CB, and naturally ventilated freestall barns (NV). The NV barns were used as a control. This cohort study was conducted on eighteen commercial dairy farms, six of each housing type, in Minnesota and Eastern South Dakota. Farms were visited once seasonally between January and November 2008. Ammonia, hydrogen sulfide, light intensity, and air velocity measurements were taken twice each visit with ten measurements per sampling time. Two sets of measurements were taken in the CV bans, one set for each pen closest to the air intake and exhaust. Aerial ammonia concentrations were significantly higher in CV barns than CB and NV barns (5.2, 3.9, and 3.3 ppm, respectively). Hydrogen sulfide concentrations were 18, 33, and 19 ppb in CB, CV, and NV barns, respectively. There was a trend for higher hydrogen sulfide concentrations in CV barns. Light intensity was significantly lower in CV barns than CB and NV barns (111, 480, and 392 lux, respectively). There were no differences in air velocity among the housing systems. The mechanically ventilated CV barns were warmer in the fall and winter than the naturally ventilated CB and NV barns. When outside temperature was above 27 °C, CV barns were 2.9 °C and 3.0 °C cooler than CB and NV barns, respectively. Although CV barns had significantly higher aerial ammonia and a trend for higher hydrogen sulfide concentrations than NV and CB barns, these differences were not biologically significant and were not expected to have adverse effects on the cows or workers. In conclusion, the three housing systems assessed had adequate air quality and ventilation to provide a safe environment for workers and animals.

Keywords. Cross-ventilated, Compost barn, Ammonia, Hydrogen sulfide, Light intensity, Air velocity.

INTRODUCTION

Cross-ventilated (**CV**) freestall barns and compost bedded pack (**CB**) barns are newer dairy housing options used in the Upper Midwest. The first CV barn was built in North Dakota in December 2005. These barns have a low roof pitch of 0.5/12 which is different than conventional naturally ventilated (**NV**) freestall barns typically with a roof pitch of 3/12 or 4/12 (Smith and Harner, 2007). They are built like conventional single story warehouse structures and are fully enclosed with air being pulled through the facility perpendicular to the ridge with fans (Smith et al., 2008; Smith and Harner, 2007). Air enters the barn through evaporative cooling pads that line one lengthwise side of the barn and is exhausted through the opposite wall which is lined with fans (Sheffield et al., 2007). Internally CV barns are laid out similar to multiple 4-row or 6-row barns side by side and can have up to 20 rows and be over 150 m wide (Jacobson et al., 2008; Sheffield et al., 2007).

Cross-ventilated barns have baffles placed over the freestall areas in the pen to encourage cows to lie down in warm weather (Harner et al., 2007). Baffles are typically made of metal, but can also be made of a canvas material. Baffles in CV barns are placed between 1.8 to 3.0 m above the floor to increase air velocity past the cows, whereas baffles in tunnel ventilated barns need to be placed 3.7 to 4.0 m above the floor to allow machinery passage (Sheffield et al., 2007). Baffles can increase the air speed in the stall area from 0.9-1.3 m/s to 2.7-3.6 m/s (Smith et al., 2008) which increases the air velocity over the cows and heat loss from the cows to minimize heat stress.

Evaporative cooling is used for heat abatement in CV barns. Evaporative cooling has been used successfully in tunnel ventilated barns and other applications and removes energy from the air by evaporating water which lowers the air temperature and increases the humidity in the facility (Bucklin et al., 1991). Evaporative cooling is able to reduce the barn air temperature in arid climates, however, is less effective as ambient humidity increases (Brouk et al., 2003). The most common form of evaporative cooling in CV barns uses cooling pads, pumps to circulate the water through the pads, and the cooled air is pulled through the barn by a pressure drop created by fans on the opposite wall (Jacobson et al., 2008).

Studies conducted in tunnel barns with evaporative cooling during the summer months have shown reduced respiration rates, lower rectal temperatures, improved pregnancy rates, reduced days open, and increased milk production compared to other heat abatement strategies (Smith et al., 2006; Ryan et al., 1992; Wise et al., 1988b). However, in humid climates the evaporative cooling is less effective and can cause the barn temperature-humidity index to be greater than ambient (Brouk et al., 2001).

Low profile CV barns with evaporative cooling are expected to improve summer time cooling and improve temperature control in the winter to allow the barn to be warmer than outside ambient temperatures (Jacobson et al., 2008). Other advantages of CV dairy barns include smaller building footprint, shorter walking distances to and from the parlor, and controlled lighting (Smith et al., 2008).

The other new housing option in the upper Midwest is a bedded pack system most commonly known as a Compost Bedded Pack barn (CB). The first CB barn was built in Minnesota in 2001. Characteristics of these barns include a resting pack area that is typically bedded with dry wood sawdust, but alternative bedding sources have been evaluated. Due to high cost and reduced availability of bedding materials these facilities are typically used for housing smaller herds of 50 to 200 cows or as a special needs barn in larger herds. Bedding can accumulate in the pack up to 1.2 m deep. Unlike conventional bedded packs, compost packs are tilled twice daily to incorporate the manure to provide a fresh, dry surface when cows return from the parlor. Various types of equipment can be used for tilling, including cultivator, rotary tiller and chisel plow, and the depth of tilling is usually approximately 25 cm. For more details on compost barn design and management see Barberg et al. (2007a) and Janni et al. (2007). Key reasons cited by producers to build these facilities were improved cow comfort and cow longevity (Barberg et al., 2007).

There has been limited research evaluating CV and CB housing systems. Therefore, the objectives of this observational study were to describe the housing systems and assess air quality (aerial ammonia and hydrogen sulfide concentrations), air velocity, light intensity, temperature, and humidity in CV, CB and conventional NV barns. Naturally ventilated freestall barns were included as controls.

MATERIALS AND METHODS

Farms

This cohort study was conducted on 18 dairy operations in Minnesota and South Dakota. Only barns occupied for at least one year prior to start of the study were included. This requirement limited the number of herds used to six of each housing type because we matched the number of herds from each system. Few CV herds were available and willing to participate in the study when the study was initiated. All of the CV and NV dairies had sand bedded freestalls and all but one used recycled sand for bedding.

Dairy farms were visited once seasonally between January and November 2008. Data collection included: building dimensions and layout, temperature-humidity index inside the barn and outside (nearest weather station), aerial ammonia and hydrogen sulfide concentrations, air velocity, light intensity, bedding cultures, and milk bulk tank cultures.

Environmental Measurements

Aerial ammonia and hydrogen sulfide concentrations, air velocity, and light intensity were measured twice daily during each visit. Ten measurements were taken each sampling time - five along the feed bunk and five inside the pen in the CB and NV barns. In the NV barns the high production group was the selected area for measurements. Compost bedded pack barns were measured the entire length of the barn due to their smaller size. In the CV barns, two sets of measurements were taken: one in a pen closest to the intake or cooling pads and another in a pen near the exhaust or fan side of the barn (for a total of twenty measurements at each sampling time). Ammonia concentration was measured using a Dräger Pac III meter (Dräger Safety Inc., Pittsburg, PA). Hydrogen sulfide concentration was measured with a Jerome 631-X meter (Jerome Hydrogen Sulfide Analyzer; Arizona Instrument LLC, Tempe, AZ). Air velocity was measured using an anemometer (TSI VELOCICHEC® Air Velocity meter, Model 8330; TSI, Inc., Shoreview, MN). Light intensity was measured with a digital light meter (model TES1337; TES Electrical Electronic Corp.; Taiwan, ROC). All measurements were taken approximately 1 meter from the floor.

The temperature and humidity inside the barn were recorded an entire year (January 2008 – January 2009) at hourly intervals using a datalogger (Temperature accuracy ±0.5°C; RH accuracy ±3%; Hobo® H8 Pro Series, Bourne, Mass.). The outdoor temperature and humidity were obtained from the nearest weather station to each barn (http://climate.sdstate.edu/airport/surface/archive.asp) and recorded on an hourly basis. The equation used to calculate the temperature-humidity index (**THI**) was: THI =

td – (0.55 – 0.55RH) (td – 58) where td was the dry bulb temperature in °F and RH is relative humidity expressed as a decimal (NOAA, 1976 as reported by West et al., 2003).

Bedding Bacterial Analysis

For the CV and NV barns the high production pen was selected. Surface samples from a minimum of 20 stalls randomly selected along the length of the pen were collected. For the CB barns, four main areas of the bedding pack were used with a minimum of five surface samples taken and composited within each of the four main areas. Samples were thoroughly mixed and immediately cooled upon collection and later frozen at -40°C. Frozen samples were taken to the Laboratory for Udder Health at the University of Minnesota for analysis. Samples were thawed in a refrigerator. Fifty cubic centimeters of bedding material was measured using a sterile container and placed into a Whirl-Pak® bag (Nasco, Fort Atkinson, Wis.). Two hundred fifty cubic centimeters (cc) of sterile distilled water was added to the bedding material which was mixed and allowed to stand for 10 min. The sample was mixed again, a liquid sample was removed by pipette and serial 10-fold dilutions were made in sterile Brain Heart Infusion broth. Sample dilutions were plated (200 μL) on colistin naladixic acid (CNA) agar (BBL, Sparks, Md.), MacConkey agar (BBL, Sparks, Md.), and thallium sulfate-crystal violet-B toxin blood (TKT) agar medium. Colony counts were determined for each sample after 24 h of incubation at 37°C. Bacterial groups were identified as coliforms (lactose-positive colonies on MacConkey's agar, which include *Klebsiella* by visual identification), *Streptococcus* species (growth on TKT agar), *Bacillus* species (growth on CNA agar and gram-positive) and coagulase negative staphylococci (growth on the CNA agar and catalase activity). Bacteria counts were expressed as colony forming units (cfu)/mL of bedding sample.

Milk Bacterial Analysis

Milk bulk tank samples were collected during winter and summer from five consecutive bulk tank pickups by the milk plant personnel at each dairy. Samples were immediately frozen after collection and shipped in a cooler to the Laboratory for Udder Health, University of Minnesota and used for bacterial culture. For analysis, samples were thawed in a refrigerator. Once thawed, samples were thoroughly mixed, and 2-mL were removed from each sample and pooled into a sterile tube. After mixing, serial 10-fold dilutions were made in sterile brain heart infusion broth. Two hundred microliters from each dilution were spread over the surface of separate MacConkey agar, TKT agar, and Factor agar plates. After 24 h of incubation at 37°C, the plates having 30 to 300 colonies were chosen for enumeration of bacteria. Those colonies that appeared to be *Staphylococcus aureus* were presumptively identified by catalase activity, tube coagulase test, and biochemical reactions using the API-STAPH (BioMerieux, Hazelwood, MO). Bacterial counts were recorded as number of bacteria per mL of bulk tank milk.

Statistical Analysis

Comparative analysis between housing systems and season were performed using PROC MIXED of SAS (SAS Inst. Inc., Cary, NC). Housing type was used as the explanatory variable in all models. An additional explanatory covariate included in the models was season of the year. Dependent variables were ammonia concentration (ppm), hydrogen sulfide concentration (ppb), light intensity (lux), air velocity (m/s), housing system temperature (°C), bedding bacterial counts (cfu/mL), and milk bulk tank bacterial counts (cfu/mL). Farm was included as a random variable in the analysis. Those variables identified in the univariate screening test ($P < 0.3$) were used to build the mixed model. Backwards stepwise elimination was used until remaining variables included were significant ($P < 0.05$). Least square means were adjusted with Tukey-Kramer. Hydrogen sulfide concentration, light intensity, and bacterial counts for milk and bedding were natural log transformed for analysis. The results were back transformed for interpretation. The relationships between barn temperatures and nearest weather station temperatures were analyzed using PROC CORR of SAS.

RESULTS AND DISCUSSION

Barn Characteristics

CV and NV barns had deep bedded sand freestalls. Stall dimensions were similar between CV and NV barns. Stall lengths were (cm; means ± SD) 238.8 ± 12.4 and 239.6 ± 11.4; stall widths were 117.3 ± 4.9 and 118.1 ± 5.3; neck rail heights were 117.3 ± 3.7 and 113.5 ± 10.0; body resting lengths were 165.7 ± 9.1 and 167.6 ± 10.3 in CV and NV barns, respectively. CB barns used mainly wood sawdust as a bedding source with the exception of one barn using a wheat straw by-product. Table 1 shows barn characteristics including barn dimensions, number of pens, cows per pen, stocking density, and linear water space. Description of lighting and fans are shown in Tables 2, 3, and 4.

Tables 2, 3 and 4 describe the ventilation and lighting by farm within each of the housing systems (i.e. CB, CV, NV).

Environmental Characteristics

Aerial ammonia and hydrogen sulfide concentrations, light intensity, and air velocity results are summarized in Tables 5, 6, 7, and 8, respectively, by housing system (i.e. compost barn (CB), cross-ventilated barn (CV), and naturally ventilated freestall barn (NV)) and season (i.e. winter, spring, summer, and fall).

Aerial Ammonia Concentrations. Ammonia concentrations (ppm, LS Mean ± SE) were 3.9 ± 0.35 for CB, 5.2 ± 0.35 for CV, and 3.3 ± 0.35 for NV barns (Table 5). CB barns had similar ammonia concentrations to NV barns. CV barns had greater concentrations than CB and NV barns ($P = 0.025$ and $P = 0.001$, respectively). Summer had the highest concentration of ammonia in all three housing systems. CV barns had greater concentrations of ammonia than NV barns during the winter and spring seasons. CB barns were not significantly different from CV or NV barns during that time. Concentrations during winter, spring, summer, and fall were 3.5 ± 0.22, 4.0 ± 0.22, 5.6 ± 0.22, and 3.5 ± 0.25, respectively. Summer had higher concentrations than winter, spring, and fall ($P < 0.001$). Spring ammonia concentrations were greater than fall and winter ($P = 0.003$ and $P = 0.009$, respectively). Winter concentrations were similar to fall. Zhu et al. (2000) reported that ammonia concentrations measured in the fall were approximately 1 ppm in a naturally ventilated barn. Schmidt et al. (2002) had similar results in a NV freestall barn with 1.1 ppm and 0.24 ppm during the summer and winter, respectively. Both of these studies only measured one dairy each and the size of the dairy was smaller than the farms included in this study. Sheffield et al. (2007) found concentrations from 1.1 to 1.4 ppm during the spring and 1.1 to 1.2 ppm during the summer in a cross-ventilated barn. According to the National Institute for Occupation Safety and Health (NIOSH) ammonia exposure should not exceed 25 ppm in a 40-hour week (up to a 10-hour day). None of the farms in the current study had concentrations reaching 25 ppm. The highest recorded ammonia concentration was 20 ppm during the fall in a CV facility.

Hydrogen Sulfide Aerial Concentrations. Hydrogen sulfide concentrations were (ppb, LS Mean, 95% CI) 13, 10-19 for CB; 32, 23-44 for CV; and 17, 12-23 for NV barns (Table 6). There were no differences between CB and NV barns for hydrogen sulfide concentrations. CV barns had higher concentrations than CB and NV barns ($P < 0.001$ and $P = 0.021$, respectively). Hydrogen sulfide concentrations were lowest during the fall (12 ppb) and spring (15 ppb), intermediate during the summer (18 ppb) and highest during the winter (41 ppb). Hydrogen sulfide concentrations were 0 ppb and 2 ppb for the winter and summer, respectively in a naturally ventilated freestall barn (Schmidt et al., 2002). Zhu et al. (2000) had similar results to the current study for hydrogen sulfide concentrations. They ranged from 4 to 26 ppb for the fall sampling in a NV freestall barn. Spring hydrogen sulfide concentrations in a CV freestall barn ranged from 7 to 14 ppb (Harner et al., 2007). The recommended exposure limit for hydrogen sulfide by the NIOSH is 10 ppm for a 10-hour work day in a 40-hour work week. The highest recorded hydrogen sulfide concentration was 0.82 ppm during the summer in a

CV barn. No farm had hydrogen sulfide concentrations that were expected to interfere with the workers or the animals.

Light Intensity. Recommended light intensity for lactating dairy cattle over the feed bunk has ranged from 108 lux (10 foot candles; Dahl, 2001) to 215 lux (20 foot candles; Peters et al., 1978). The ASAE Standard EP344.3 (2005) recommends 70 lux or 6.5 foot candles (fc) for worker safety. Light intensity results were (lux, Geometric mean, 95% CI) 929, 585-1477 for CB barns; 118, 75-185 for CV; and 430, 270-684 for NV barns, respectively (Table 7). Overall, CV barns had lower light intensity than CB and NV barns ($P < 0.001$). There were no differences between CB and NV barns. CV barns had lower light intensity than CB and NV barns during each season except during the fall when it was not different from NV barns. The CV barns did not have the seasonal differences that the CB and NV experienced. CB barns had the greatest light intensity during the summer and winter. Spring and fall did not differ in light intensity. NV barns also had the greatest light intensity during the summer and winter, intermediate during the spring and lowest during the fall. Light intensity in CB and NV barns was mainly dependent on the outside conditions. Winter measurements were probably high due to the reflection off the snow. One set of fall measurements were taken during the dark in a NV barn and a CV barn and one winter measurement in a CV barn. Winter, spring, summer, and fall light intensities were 395, 343, 474, and 265 lux, respectively. Winter did not differ in light intensity from spring and summer. Fall light intensity was lower than spring, summer, and winter ($P = 0.002$, $P < 0.001$, $P = 0.025$, respectively). Summer light intensity was greater than spring ($P < 0.001$). Winter measurements may not adequately represent the housing systems in this study. The light meter that was used during the beginning of the study malfunctioned and data had to be excluded from analysis. Therefore only one farm from each housing system was included for analysis. There were instances in each of the housing systems during the four measured seasons when there was inadequate light intensity. CV barns were below the recommended light intensity for dairy cows by the end of the study. We recommend that producers building CV barns consider installing additional lighting as bulb output decreases over time due to dust and lamp depreciation.

Air Velocity. Air velocity for the three housing systems were (m/s, LS Mean ± SE) 0.78 ± 0.09 for CB, 0.90 ± 0.09 for CV, and 0.66 ± 0.09 for NV barns, respectively (Table 8). There were no differences in air velocity among the three housing systems except during the spring and summer months. The CV barns had greater air velocity than CB and NV barns during the spring ($P = 0.018$ and $P = 0.044$, respectively) with no differences between CB and NV barns. During the summer, CV barns had greater air velocity than CB barns ($P = 0.039$). There were no differences between NV and CB, and CV and NV barns for air velocity during the summer. Air velocities differed each season ($P < 0.001$). Winter had the lowest air velocity (0.34 m/s), intermediate were fall (0.70 m/s) and spring (0.96 m/s), and the highest air velocity was during the summer (1.12 m/s). The results of this study were lower than Harner et al. (2007) who observed air velocities ranged from 2.67 to 3.05 m/s in a CV barn during May and August . The discrepancy in the results is most likely due to sampling differences. For the current study, air velocities were measured both under the baffle and in the feed manger where air velocity decreased due to the lack of baffles. Harner et al. (2007) only had air velocity measurements under the baffle. When only using the measurements taken under the baffle air velocity averaged 2.08 m/s. Stowell et al. (2001) saw similar ranges in air velocities in a NV freestall barn with velocity ranging from 0.45 to 0.73 m/s.

Indoor and Outside Air Temperature and Relative Humidity

Table 9 describes the barn temperatures, relative humidity, and summer THI along with outside temperatures, relative humidity, and THI. The CB and the NV barns had high correlations (0.81-0.97) between inside barn temperature and ambient outside temperature, which would be expected with natural ventilation. The correlations in the CV barns were high during the spring, summer, and fall (0.84-0.90); however, they had warmer barn temperatures than outside during the winter which reduced the correlation to 0.62.

One weather station that was used for one CB and one CV barn reported extremely low relative humidity levels either from a malfunctioning hygrometer or data entry errors. The incorrect relative humidity data were excluded from analysis. Correlations were strong between barn and weather station relative humidity for spring and fall for all of the housing systems. During the winter the correlations were lower in the CV and NV barns (0.44 and 0.46, respectively). CB and NV barns had a high correlation of barn and outside relative humidity (0.91 and 0.88, respectively). However, summer barn and outside relative humidity were lower in the CV barns (0.52). This is most likely caused by the use of evaporative cooling which added additional moisture inside the barn.

Barn and outside THI correlations were only used from the summer measurements since THI is a measurement of heat stress. Correlations were relatively high between barn and outside THI (0.93-0.95). Both NV and CB barns had greater THI than outside ambient. The CV barns were 0.5 THI units less than outside.

Table 10 shows the barn temperatures and THI for the three housing systems. Overall barn temperatures were 8.4, 11.0, and 9.4°C in CB, CV, and NV barns, respectively. During the winter, CV barns were significantly warmer than CB and NV barns ($P < 0.001$). The CV barns were 5.3 and 7.6°C warmer than CB and NV barns in the winter most likely due to reducing the number of fans running in the barn and having a fully enclosed and insulated structure. During the fall the CB and NV barns were also colder than the CV barns ($P < 0.001$). As expected, within housing system there were differences in seasonal temperatures.

To investigate whether CV barns were cooler than NV and CB barns during the warmest part of the summer, we performed an analysis with all outdoor temperatures less than 27°C excluded from the dataset. CV barns were 3.6°C cooler than CB barns and 3.3°C cooler than NV barns ($P < 0.001$). There were no differences between NV and CB barns for summer barn temperature, which was expected from their similar ventilation and heat abatement methods. Summer THI in CV barns was 2.1 and 2.5 units lower than CB and NV barns, respectively. When excluding outdoor temperatures less than 27°C the THI in CV barns was 3.1 and 3.3 units lower than CB and NV barns, respectively ($P < 0.001$). All housing systems had THI greater than 72 which indicated that all cows were experiencing some heat stress (Armstrong, 1994).

Bedding Bacterial Counts

Geometric means of bacterial counts (cfu/mL) from bedding cultures are presented in Table 11. Overall counts (geometric mean) were 6,000; 31; 4,000,000; 2,000; and 197,000 cfu/mL for coliforms, *Klebsiella* environmental *Streptococcus*, *Staphylococcus* species, and *Bacillus*, respectively. There were no differences among the housing systems for coliform counts in the bedding; however, there was a seasonal effect with summer samples being higher than winter samples (P=0.002). This was also seen in NV barns where the coliform counts were greater in the summer (P = 0.027). There was a trend for *Klebsiella* counts to be higher in the summer than in the winter (P=0.10). There were no differences between seasons or housing systems for environmental *Streptococcus*. There was a trend for higher counts of *Staphylococcus* species in CB barns than NV and CV barns (P = 0.09) and a trend for higher counts in the summer than the winter (P = 0.09). *Bacillus* counts were greater in summer than winter in CB barns (P = 0.043) with no differences between NV and CV barns. Rendos et al. (1975) reported bedding culture results for used wood shavings of 6.6×10^6 for total coliforms, 8.6×10^6 for *Streptococcus* species and 4.9×10^7 for *Staphylococcus* species. Rendos et al. (1975) results were higher than those collected from the CB barns, possibly due to the heating of the pack which may have killed some of the bacteria (Barberg et al., 2007a). Harner et al. (2005) reported 4.9×10^5 for total coliforms, 4.3×10^5 for *Streptococcus* species, 3.6×10^5 for *Staphylococcus* species, and 6.7×10^4 for *Bacillus* on six dairies that used reclaimed sand. Bernard et al. (2003) had similar numbers of Bacillus and higher counts of coliforms, *Staphylococcus* species, and *Klebsiella* than current results. Bernard et al.

(2003) and Harner et al. (2005) did not state any log transformations on the data which may have led to the discrepancies in bacterial counts for the sand bedded freestalls.

Milk Bulk Tank Bacterial Counts

Results for the milk bulk tank samples are shown in Table 12. Producer cooperation was needed to assist in collecting milk samples. During the winter three CV and NV barns did not return samples. During the summer one CV and one NV barn did not return the samples. Overall counts (geometric mean) were 168.7, 564.3, 32.3, and 7.5 cfu/mL for coliforms, Non-ag *Streptococcus*, *Staphylococcus* species, and *Staphylococcus aureus*, respectively. There were no differences in bacterial numbers among housing systems for *Staphylococcus aureus*, Non-ag *Streptococcus*, *Staphylococcus* species and coliforms. There were no seasonal differences for bacterial counts, except for higher counts in the summer for coliforms (P=0.039). A study of Pennsylvania herds found a mean coliform count of 70 cfu/mL (Jayarao et al., 2004). The CB and NV barns had milk bulk tank bacterial counts greater than 70 cfu/mL, which may be caused by inadequate cow preparation procedures at milking time.

CONCLUSIONS

Low profile CV barns had statistically higher aerial ammonia and hydrogen sulfide concentrations than NV and CB barns; however, these differences were not biologically significant and were not expected to have adverse effects on the cows or workers. The CV barns in our study were near the minimum for recommended light intensity. Producers should consider additional lighting and better light fixture maintenance to provide adequate lighting for workers and animals. CV barns with evaporative cooling pads were 2 to 3 °C cooler than NV and CB barns when the outside temperature was greater than 27°C. Bacterial counts from the bedding and milk bulk tank samples were similar for CB, CV, and NV barns.

Table 1. Barn characteristics of 18 barns (six each compost bedded pack, low profile cross-ventilated and naturally ventilated barns) in Minnesota and Eastern South Dakota.

Barn	Barn Dimensions	Sidewall Height	Feed Alley Width[1]	# Pens	Pack or Pen Dimensions	# of Stalls	# of Cows	Pack Area	Linear Water Space
Compost	**m x m**	**m**	**m**		**m x m**			**m^2/cow**	**cm**
A	22 x 78	4.9	4.3	2	14 x 78	n/a	190	5.8	5.2
B	15 x 61	4.9	4.3	1	11 × 61	n/a	130	5.2	5.9
C	23 x 46	4.9	3.7	1	15 × 46	n/a	100	6.9	9.0
D	23 x 61	4.9	4.4	1	18 × 49	n/a	110	8.0	3.5
E	19 x 50	5.0	3.4	1	11 × 50	n/a	75	7.3	6.4
F	30 x 95	4.9	3.4	4	8 × 46[2]	n/a	50	7.4	7.3
Cross-ventilated								**Cows/Stall**	
A	90 x 198	4.1	3.1	10	14 x 92	204	240	1.2	6.1
B	69 x 101	4.7	3.7	4	11 x 82	122	125	1.0	4.5
C	90 x 198	4.1	3.1	10	14 x 92	204	240	1.2	6.4
D	64 x 95	4.0	3.7	8	12 x 41	63	85	1.3	5.0
E	65 x 73	4.3	4.0	4	13 x 67	99	110	1.1	4.3
F	98 x 184	4.3	4.0	12	11 x 88	130	150	1.2	7.3
Naturally Ventilated									
A	34 x 101	4.0	3.8	6	14 x 94	230	320	1.4	4.9
B	30 x 213	4.3	3.1	10	12 x 104	152	185	1.2	4.3
C	29 x 235	4.4	4.0	4	11 x 134	192	205	1.1	7.1
D	29 x 173	4.0	3.4	7	11 x 83	132	145	1.1	2.3
E	27 x 95	3.7	3.7	9	11 x 44	72	88	1.2	4.6
F	33 x 105	3.7	3.8	6	14 x 51	113	125	1.1	6.4

[1] Feed alley is the alley where cows stand inside the pen in order to eat off the feed platform.
[2] This barn had four pens of equal size.

Table 2. Description of fans and lights in six compost dairy barns in Minnesota.

Barn	Fan Description	Lighting Description
1	Four 7.3m diameter low- high volume fans, blowing downward, mounted horizontally, spaced uniformly over the pack; five 1.4m diameter fans mounted vertically over the headlocks, tilted downward towards the feed alley placed uniformly along barn length.	Twenty-four fluorescent lights over pack; twelve fluorescent lights over feed alley. All spaced uniformly along barn length.
2	Three 7.3m diameter low- high volume fans, blowing downward mounted horizontally uniformly over the pack.	Seven low bay halogen lights over pack; eight low bay halogen lights over feed alley. All spaced uniformly along barn length.
3	Ten 1.3m diameter fans mounted vertically above the headlocks blowing downwards toward the feed alley placed uniformly along barn length.	Twelve lights located over pack; six lights located over feed alley. All spaced uniformly along barn length.
4	Eleven 1.4m diameter fans mounted vertically over the wall between the feed alley and pack, blowing downward towards the pack, spaced uniformly along barn length.	Twenty-five fluorescent lights over pack; nine fluorescent lights down feed manger. All spaced uniformly along barn length.
5	Seven ceiling fans mounted horizontally, spaced uniformly over the pack.	Four fluorescent lights spaced uniformly over the feed alley along barn length.
6	Six 1.2m diameter fans mounted vertically above the pack, blowing downwards towards the pack; Three 1.2m diameter fans, mounted above the neck rail, blowing towards the feed alley, spaced uniformly along barn length.	Two halogen lights over pack; six halogen lights down feed manger. All spaced uniformly along barn length.

Table 3. Description of exhaust fans and lights in six cross-ventilated dairy barns in Minnesota and South Dakota.

Barn	Fan Description	Lighting Description
1	Seventy-eight 1.4m diameter fans located on east side of barn.	Thirteen fluorescent lights per pen; seven over feed alley, six over back stall area. One hundred thirty five total in the barn
2	Forty 1.4m diameter fans located on north side of barn.	Twenty-two Orion fluorescent in pens 2, 3, and 4; twenty – seven in first pen. Ninety-three lights total
3	Eighty-one 1.2m diameter fans located on north side of barn.	Thirteen fluorescent lights per pen.
4	Thirty-six 1.3m diameter fans located east side of barn.	Eight fluorescent lights per pen; five over feed bunk, 3 over back stall area. Sixty-four total lights.
5	Thirty-six 1.5m diameter fans north side of barn.	Seven low bay halogen lights over driveway; seven lights over back stall area. Total thirty-five lights.
6	Ninety 1.3m diameter fans and eleven 0.9m diameter fans south side of barn.	Twelve fluorescent lights over feed bunk; one hundred-fifty total lights.

Table 4. Description of fans and lights in six naturally ventilated freestall dairy barns in Minnesota and South Dakota.

Barn	Fan Description	Lighting Description
1	Fourteen 1.2m fans mounted vertically, blowing downwards, placed over the middle bank of stalls, spaced uniformly along barn length.	Seven metal halide lamps spaced uniformly along the length of the feed manger; fourteen lamps spaced uniformly along barn length.
2	Nine 1.2mfans per pen mounted vertically, blowing downwards, placed over middle stalls, spaced uniformly along pen length.	Three fluorescent lights per pen over feed alley; twelve total spaced uniformly along barn length.
3	Ten 1.3m fans per large pens and seven fans per small pens mounted vertically blowing downwards, placed over the middle bank of stalls spaced uniformly along pen length.	Thirteen fluorescent lights in two pens; seven lights in two smaller pens. Three lights spaced uniformly along barn length in the feed manger.
4	Seven 0.9m fans over outer stalls; Seven 0.9m fans spaced uniformly over middle stalls; Nine 1.3m fans spaced uniformly over feed bunk.	Four metal halide lamp per pen over middle bank of stalls; three lights located over the feed bunk and vice versa for adjacent pen. Four lights above alley to the parlor. Thirty-two lights total.
5	Forty-six 1.2m & 0.9m fans spaced uniformly along barn length. Four fans each are mounted vertically above the middle and back bank of stalls blowing downward; Three or four fans are mounted vertically over the headlocks blowing downward over the feed alley.	Seven low bay halogen lights spaced uniformly along length of driveway; seven lights spaced uniformly along back stall area. Total thirty-five lights.
6	Fifty-six 0.9m fans mounted vertically, blowing downward over both stalls & feed alley, spaced uniformly along barn length.	Seventeen halogen lamps spaced uniformly along the length of the feed bunk; twelve lights spaced uniformly along the length of back stall area.

Table 5. Ammonia concentrations (ppm) in compost bedded pack (CB), low profile cross-ventilated freestall (CV) and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

	Housing System							
	CB		**CV**		**NV**		**Overall**	
Season	LSMean	SE	LSMean	SE	LSMean	SE	LSMean	SE
Winter	$3.5^{b,x,y}$	0.39	$5.3^{b,x}$	0.37	$1.7^{c,y}$	0.38	3.5^{c}	0.22
Spring	$3.8^{b,x,y}$	0.38	$5.0^{b,x}$	0.36	$3.1^{b,y}$	0.39	4.0^{b}	0.22
Summer	4.9^{a}	0.38	6.2^{a}	0.36	5.8^{a}	0.38	5.6^{a}	0.22
Fall	3.4^{b}	0.38	4.3^{c}	0.36	2.8^{b}	0.38	3.5^{c}	0.22
Overall	3.9^{y}	0.35	5.2^{x}	0.35	3.3^{y}	0.35	4.2	0.27

[a,b,c] Significant differences among rows ($P < 0.05$)
[x,y] Significant differences among columns ($P < 0.05$)

Table 6. Hydrogen sulfide concentrations (ppb) in compost bedded pack (CB), low profile cross-ventilated freestall (CV) and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

	Housing System							
	CB		CV		NV		Overall	
Season	LSMean	95% CI	LSMean	95% CI	LSMean	95% CI	LSMean	95% CI
Winter	$31^{a,y}$	21-45	$75^{a,x}$	53-107	$31^{a,y}$	21-44	41^{a}	34-51
Spring	12^{b}	8-17	21^{a}	15-30	13^{b}	9-18	15^{c}	12-18
Summer	$10^{b,y}$	7-15	$26^{b,x}$	19-37	$22^{a,x,y}$	16-32	18^{b}	15-22
Fall	$9^{b,y}$	6-12	$24^{b,x}$	17-33	$9^{b,y}$	7-14	12^{c}	10-15
Overall	13^{y}	9-19	32^{x}	23-44	17^{y}	12-23	18	14-24

^{a,b,c} Significant differences among rows ($P < 0.05$)
^{x,y} Significant differences among columns ($P < 0.05$)

Table 7. Light intensity (lux) in compost bedded pack (CB), low profile cross-ventilated freestall (CV) and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

	Housing System							
	CB		**CV**		**NV**		**Overall**	
Season	LSMean	95% CI	LSMean	95% CI	LSMean	95% CI	LSMean	95% CI
Winter	$881^{a,b,x}$	507-1709	120^{y}	76-189	$583^{a,b,}$	300-1131	395^{ab}	275-569
Spring	$769^{b,x}$	475-1236	130^{y}	82-206	$404^{b,x}$	249-656	343^{b}	261-451
Summer	$1318^{a,x}$	819-2119	119^{y}	76-189	$675^{a,x}$	420-1086	474^{a}	361-621
Fall	$836^{b,x}$	520-1344	104^{y}	66-164	$215^{c,y}$	134-346	265^{c}	303-348
Overall	929^{x}	585-1477	118^{y}	75-185	430^{x}	270-684	351	211-584

^{a,b,c} Significant differences among rows ($P < 0.05$)

^{x,y,} Significant differences among columns ($P < 0.05$)

Table 8. Air velocity (m/s) in compost bedded pack (CB), low profile cross-ventilated (CV) and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

	Housing System							
	CB		**CV**		**NV**		**Overall**	
Season	LSMean	SE	LSMean	SE	LSMean	SE	LSMean	SE
Winter	0.50^{b}	0.13	0.22^{c}	0.10	0.29^{c}	0.11	0.34^{d}	0.07
Spring	$0.79^{a,y}$	0.12	$1.30^{a,x}$	0.10	$0.80^{a,b,y}$	0.12	0.96^{b}	0.06
Summer	$0.93^{a,y}$	0.11	$1.41^{a,x}$	0.10	$1.01^{a,x,y}$	0.11	1.12^{a}	0.06
Fall	0.88^{a}	0.11	0.66^{b}	0.10	0.55^{b}	0.11	0.70^{c}	0.06
Overall	0.78	0.09	0.90	0.09	0.66	0.09	0.82	0.06

^{a,b,c,d} Significant differences among rows ($P < 0.05$)
^{x,y} Significant differences among columns ($P < 0.05$)

Table 9. Correlation (R^2) between barn and ambient temperatures, relative humidity (RH), and temperature-humidity index (THI) in compost bedded pack (CB), low profile cross-ventilated freestall (CV) and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

Barn	Season	n	Barn Temp °C	Min	Max	n	Outside Temp °C	Min	Max	R^2
CB										
	Winter	7108	-3.8	-27.1	14.5	6433	-10.2	-40.6	12.2	0.81
	Spring	12751	11.8	-9.5	32.3	11873	10.0	-13.3	31.1	0.96
	Summer	13248	20.7	5.4	35.7	12242	20.1	1.1	32.8	0.96
	Fall	13108	5.0	-23.4	31.1	12800	2.1	-39.4	30.0	0.97
CV										
	Winter	3669	4.4	-5.9	15.8	4670	-9.5	-40.6	11.7	0.62
	Spring	13248	12.2	-5.3	30.1	12339	9.9	-13.3	30.6	0.90
	Summer	13392	19.6	5.0	30.9	12298	20.5	2.2	35.0	0.90
	Fall	12965	8.2	-9.1	25.2	12700	2.3	-39.4	31.1	0.84
NV										
	Winter	8439	-1.8	-24.3	16.8	8190	-8.5	-31.1	11.1	0.92
	Spring	13248	12.2	-6.8	30.7	12512	10.2	-13.3	30.0	0.97
	Summer	13248	20.8	3.3	32.8	12392	20.1	1.1	32.8	0.95
	Fall	13110	6.4	-22.6	28.7	12899	2.9	-30.6	30.0	0.97

Barn	Season	n	Barn RH%	Min%	Max%	n	Outside RH%	Min%	Max%	R^2
CB										
	Winter	7055	83.2	14.6	99.9	6269	60.2	3.0	100	-0.17
	Spring	12596	68.9	14.6	99.9	11594	56.5	3.0	100	0.57
	Summer	12009	72.2	23.5	99.8	11633	62.0	3.0	100	0.55
	Fall	11707	78.0	18.6	99.9	12801	62.5	3.0	100	0.43
CV										
	Winter	3652	81.0	44.2	99.7	4506	51.4	3.0	100	-0.17
	Spring	13048	69.3	13.5	99.7	12060	58.2	3.0	100	0.51
	Summer	11733	81.0	19.6	99.8	11682	62.9	3.0	100	0.29
	Fall	11446	76.9	22.3	99.8	12203	66.1	3.0	100	0.41
NV										
	Winter	7698	77.8	39.2	99.9	8098	72.7	3.0	100	0.44
	Spring	11234	66.8	18.2	99.9	12512	64.9	15.0	100	0.90
	Summer	9159	72.1	27.9	99.9	12392	68.7	22.0	100	0.88
	Fall	8919	74.7	26.6	99.9	12865	72.5	16.0	100	0.84

Barn	Season	n	Barn THI	Min	Max	n	Outside THI	Min	Max	R^2
CB	Summer	12009	67.7	42.0	83.3	10287	65.7	35.1	83.0	0.95
CV	Summer	11733	65.9	40.8	83.0	10319	66.4	37.0	83.9	0.93
NV	Summer	9159	68.2	42.6	85.3	12392	65.8	35.1	82.8	0.94

Table 10. Barn temperatures (Temp °C) and barn temperature-humidity index (THI) in compost bedded pack (CB), low profile cross-ventilated freestall (CV) and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

		Housing System							
Temp °C		**CB**		**CV**		**NV**		**Overall**	
	Season	LSMean	SE	LSMean	SE	LSMean	SE	LSMean	SE
	Winter	-3.7[d,y]	0.49	3.9[d,x]	0.50	-1.4[d,y]	0.49	-0.4[d]	0.28
	Spring	11.8[b]	0.49	12.2[b]	0.49	12.2[b]	0.49	12.1[b]	0.28
	Summer	20.7[a]	0.49	19.6[a]	0.49	20.8[a]	0.49	20.8[a]	0.28
	Fall	5.0[c,y]	0.49	8.2[c,x]	0.49	6.4[b,x,y]	0.49	6.5[c]	0.28
	Overall	8.4[x]	0.48	11.0[y]	0.48	9.4[xy]	0.48	11.2	0.49
THI									
	Summer[1]	68.0[x]	0.44	65.9[y]	0.44	68.4[x]	0.44	67.3	0.36
	≥ 27 °C[2]	76.2[x]	0.47	73.1[y]	0.47	76.4[x]	0.47	75.2	0.43

[1] Barn THI during the summer season (June 21 – September 22, 2008)
[2] THI after outside ambient temperatures less than 27 °C were excluded from analysis
[a,b,c,d] Significant differences among rows (*P* < 0.05)
[x,y] Significant differences among columns (*P* < 0.05)

Table 11. Bedding bacterial counts (cfu/mL) in compost bedded pack (CB), low profile cross-ventilated freestall (CV) and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

		Housing System							
Season	**Bacteria (cfu/mL)**	**CB**		**CV**		**NV**		**Overall**	
Winter		Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
	Coliforms (‘000’s)	3	0.3-26	1	0.2-12	0.3^{b}	0-2	1^{a}	0.3-4
	Klebsiella	167	1-19596	0.8	0-87	6	0-681	9	0.6-141
	Environ. Strep (‘000,000’s)	7	2-18	2	0.9-6	3	1-9	4	2-7
	Staph Species (‘000’s)	0	0-9.5	0	0-9.5	0	0-9.5	0	0-4
	Bacillus (‘000’s)	$0.8^{b,y}$	0.01-40	$348^{x,y}$	7-17817	$9,881^{x}$	185-526836	14	6-3505
Summer									
	Coliforms (‘000’s)	61	70-505	27	3-223	21^{a}	3-171	32^{b}	10-111
	Klebsiella	469	4-55188	44	0.4-4882	72	0.6-8515	114	7-1771
	Environ. Strep (‘000,000’s)	1	0.5-4	5	2-12	6	2-17	3	2-7
	Staph Species (‘000’s)	116	12-1101	0	0-9.5	0	0-9.5	5	1-18
	Bacillus (‘000’s)	798^{a}	15-42571	59	1-3004	366	7-19542	258	26-2542
Overall									
	Coliforms (‘000’s)	14	2-74	6	1-33	2	0.4-12	6	2-16
	Klebsiella	280	5-14870	6	0.12-275	20	0.4-1089	31	3-288
	Environ. Strep (‘000,000’s)	3	1-7	3	1-7	5	2-11	4	2-6
	Staph Species (‘000’s)	11	2-53	0	0-4.9	0	0-4.9	2	1-6
	Bacillus (‘000’s)	25	0.9-67	143	6-3506	1,902	70-51593	197	28-1367

^{a,b} Significant between winter and summer within same bacteria species ($P < 0.05$)
^{x,y} Significant between housing systems within season ($P < 0.05$)

Table 12. Milk bulk tank bacterial counts (cfu/mL) in compost bedded pack (CB), low profile cross-ventilated freestall (CV) and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

		Housing System							
Season	**Bacteria (cfu/mL)**	**CB**		**CV**		**NV**		**Overall**	
Winter		Mean	95% CI	Mean	95% CI	Mean	95% CI	Mean	95% CI
	Coliforms	64	6-735	2.1	0-145	54	0.1-20488	19[a]	1-252
	Non-Ag Strep	911	138-6011	349.0	32-3820	278	20-3858	445	116-1704
	Staph Species	26	2-443	32.5	0.2-4383	561	0.5-577059	78	4-1544
	Staph aureus	6.2	1.3-30.1	52.4	3.4-801	16	0.3-757	17	3.3-91.2
Summer									
	Coliforms	2598	179-37677	147.1	7-2930	267	18-3885	467[b]	94-2333
	Non-Ag Strep	847	125-5751	1447.7	173-12115	185	23-1460	610	188-1977
	Staph Species	106	5-2360	12.3	0.4-395	15	0.7-342	27	4-175
	Staph aureus	2.0	0.4-11.5	6.0	.9-41.5	20	2.9-139.1	6.3	2.1-18.5
Overall									
	Coliforms	407	59-2801	17.7	1.3-251	120	4-3377	167	50-566
	Non-Ag Strep	878	137-5617	710.8	88-5730	227	26-2009	564	227-1403
	Staph Species	53	6-430	20.0	1-403	93	2-4149	32	11-94
	Staph aureus	3.6	1.1-115	17.8	3.3-94.5	18	2.1-155.3	7.5	3.7-15.5

[a,b] Significant between winter and summer within same bacteria species ($P < 0.05$)

EXPERIMENT II: ANIMAL WELFARE IN CROSS-VENTILATED, COMPOST BEDDED PACK, AND NATURALLY VENTILATED DAIRY BARNS IN THE UPPER MIDWEST USA

SUMMARY

The objective of this cohort study was to investigate animal welfare in two newer dairy housing options in the Upper Midwest, cross-ventilated freestall barns (**CV**) and compost bedded pack barns (**CB**), compared to conventional naturally ventilated freestall barns (**NV**). The study was conducted on 18 commercial dairy farms, six of each housing type, in Minnesota and eastern South Dakota. Farms were visited once seasonally between January and November 2008 and approximately 90 percent of the milking herd at each location was scored on each visit. Outcome-based measurements of welfare (locomotion, hock lesions, body condition, hygiene, respiration rates, and mastitis infection rates) were collected on each farm. Lameness prevalence (proportion of cows with locomotion score ≥3 on a 1-to-5 scale, where 1 = normal and 5 = severely lame) in CB barns (6.4%) was lower than NV barns (17.7%); CV barns (14.2%) were not different from CB and NV barns. Hock lesion prevalence (proportion of cows with a lesion score ≥ 2 on a 1-to-3 scale where 1= normal, 2 = hair loss, and 3 = swelling) was lower in CB barns (11.3%) than CV (31.5%) and NV barns (28.0%). Hygiene scores (1-to-5 scale where 1 = clean and 5 = very dirty) were 3.18, 2.83, and 2.77 in CB, CV, and NV barns, respectively. There were no differences in body condition scores, respiration rates, or mastitis infection rates among housing systems. The CV and NV barns were evaluated using the cow comfort index (proportion of cows lying divided by all animals touching a stall) and the stall usage index (proportion of cows lying divided by all animals in the pen not eating). CV barns had greater cow comfort index (86.4%) and stall usage index (73.4%) than NV barns (80.3% and 67.5%, respectively). These results indicate that CB barns provided a more welfare friendly environment than CV and NV barns with no adverse associations in body condition, heat stress, or mastitis infection rates. In addition, CV barns had greater cow comfort indices than NV barns, especially in summer, an indication of possibly improved heat abatement in those facilities.

Key Words. Cross-ventilated, Compost Bedded Pack, Lameness, Hock Lesion, Respiration Rate

INTRODUCTION

Housing can impact the welfare of dairy cattle. Increased interest in farm animal welfare by the general public has fostered a need to investigate the relationship between housing options and welfare of dairy cattle. Consideration needs to be taken when designing and building housing systems to provide a welfare friendly environment.

Outcome-based measurements such as respiration rates and locomotion, hock lesion, hygiene, and body condition scores can be used as indicators of animal welfare. Lameness, which can be assessed by locomotion scoring, has been recognized as one of the most important welfare concerns in the dairy industry (Whay et al., 2003) and ranks third after mastitis and infertility for income loss on dairy farms (Enting et al., 1997). Body condition scoring provides a visual assessment of subcutaneous body fat and nutritional status (Domecq et al., 1997). Hygiene scoring assess the cleanliness of the animal and has been associated with somatic cell score (Reneau et al., 2005). Housing and stall surface can result in increased hock lesions (Fulwider et al., 2007; Kielland et al., 2009). Heat stress causes behavioral changes and increases mortality risk in cattle (Cook et al., 2007; Vitali et al., 2009).

Cross-ventilated freestall (**CV**) dairy barns and compost bedded pack (**CB)** barns are newer dairy cattle housing options in the Upper Midwest. The first cross-ventilated barn was built in North Dakota in 2005 and since that time many more barns have been built in various areas of the United States. Cross-ventilated barns are generally a fully enclosed facility characterized by a low roof pitch of 0.5/12 and a warehouse-type structure (Smith and Harner, 2007). On the air intake side of the barn, evaporative cooling pads fill the wall and air is pulled through the pads by exhaust fans on the opposite side (Jacobson et al., 2008). Inside the barn, baffles are placed over the stalls to maintain airflow. Baffles are installed parallel to the feed alley to reduce equipment interference (Sheffield et al., 2007).

The CV barns use evaporative cooling for heat abatement during the warmer months. Evaporative cooling in tunnel ventilated dairy facilities resulted in reduced respiration rates, lower rectal temperatures, improved pregnancy rates, reduced days open, and higher milk productions compared to other heat abatement strategies (Wise et al, 1988b; Ryan et al., 1992; Smith et al., 2006). In addition, CV barns have reduced footprint compared to conventional freestall barns, cows walk shorter distances to the milking parlor, and they offer better barn environmental control (Harner et al., 2007; Jacobson et al., 2008). However, to our knowledge no previous studies have investigated animal welfare in these barns.

The first compost bedded pack barn was built in Minnesota in 2001 (Barberg et al., 2007a). This barn is typically built for improved cow comfort by removing the lying restrictions of standard stalls. The barn is characterized by a large, loose housing pack area that is separated from the feed alley by a 1.2 m-high wall. The pack is usually bedded with dry wood sawdust or other organic materials and tilled twice daily (Barberg et al., 2007a). Lameness prevalence in these barns was 7.8% (Barberg et al., 2007b) compared to a lameness prevalence of 25% in freestall barns (Espejo et al, 2006) and 20% in tie-stalls (Cook, 2003).

The objective of this study was to investigate animal welfare using outcome based measurements (locomotion, body condition, hygiene, hock lesions, respiration rates and mastitis infection rates) in CV and CB barns compared to naturally ventilated freestall barns (**NV**).

MATERIALS AND METHODS

This cohort study was performed in 18 commercial dairy farms in Minnesota and eastern South Dakota between January and November 2008. Only barns occupied for at least one year prior to the start of the study were included. This requirement limited the number of herds used to six of each housings type because we matched the number of herds. Few CV herds were available and willing to participate in the study when it was initiated. Dairy farms were selected for convenience and matched as closely as possible by geographical location and herd size. To reduce variation in hock lesion and lameness prevalence, all freestall barns used deep bedded sand stalls. Five of the 6 CB barns used dry wood sawdust as the primary bedding material and one barn used a wheat straw by-product. All CV barns used manually driven equipment to scrape alleys. Two NV barns used a flush system and four barns used manually driven equipment. All six compost barns scraped the feed alley with manually driven equipment.

Data Collection

Farms were visited once seasonally for a total of four visits per farm. Visits during January and February were considered winter; April and May, spring; July and August, summer; and October and November, fall. On each visit approximately 90% of the milking herd was visually scored for locomotion, body condition, hygiene, and hock lesions. Cow comfort and stall usage indices were collected as described by Krawczel et al. (2008). Respiration rates were measured during the summer visit. Fifteen out of the 18 herds were on DHIA testing and on farm records were collected when available.

Animal Measurements. Cows were evaluated for lameness using a 5-point locomotion scoring system (Flower and Weary, 2006). Locomotion scores (**LS**) were identified as 1 = normal locomotion, 2 = imperfect locomotion, 3 = lame, 4 = moderately lame, and 5 = severely lame. Locomotion scoring was performed by the same observer as cows were exiting from the milking parlor. Lameness prevalence by pen was calculated for each visit as the number of animals with LS ≥ 3 divided by the total number of animals scored in each pen on that day. Severe lameness prevalence was calculated by the number of animals with LS ≥ 4 divided by the total number of animals scored in the pen on the day of visit.

Animals were scored for body condition by the same observer as they exited the milking parlor using a 5-point scale, where 1 = emaciated and 5 = obese (Ferguson et al.

1994). Hygiene scores were assessed by the amount of dirt on the udder and hind leg based on a 5 point scale with 1 = clean and 5 = dirty (Reneau et al., 2005). Average body condition and hygiene scores were calculated for each pen for analysis. Hock lesions (**HL**) were classified by 1 = no lesion, 2 = hair loss (mild lesion), 3 = swollen hock with or without hair loss (severe lesion). Hock lesion prevalence was calculated as HL ≥ 2 divided by the total number of animals scored in the pen on that day. Severe hock lesion prevalence was calculated as HL =3 divided by the total number of animals scored in the pen on the day of visit. Hygiene and hock lesion scoring was performed by the same observer in the parlor before milking unit was attached.

Respiration Rate. During the summer visit, 75 animals from the high production group were randomly selected for measurement of respiration rates in the CV and NV barns. In most CB barns, only one pen was used to house all animals, therefore 75 animals from the mixed pen were scored. Two measurements were taken during the day, including mid afternoon. Breaths were counted by observing the movements of the flank for 30 seconds and multiplying the number by 2 for breaths per minute.

The temperature and relative humidity were recorded hourly for one year inside each barn using a datalogger (Hobo H8 Pro Series, temperature accuracy ± 0.5°C, relative humidity accuracy ±3%, Hobo, Bourne, MA) located centrally in the CB and NV barns. Cross-ventilated barns had a logger placed in a pen closest to the air intake side and another one in a pen closest to the exhaust fans. Dataloggers were positioned approximately 2.5 m above the bedding surface. One exhaust area datalogger from a CV barn was lost and only 3 months of the year were collected from that logger. Hourly outside temperature and relative humidity were collected from the nearest weather station to each barn (South Dakota Climate and Weather, http://climate.sdstate.edu/airport/surface/archive.asp).

Cow Comfort and Stall Usage Indices. CB barns were excluded from the analysis as these indices are only applicable to freestall barns. Cow comfort index (**CCI**) was calculated as the number of animals lying down in the stalls divided by total number of animals touching a stall (lying, two feet in a stall, or standing with all four feet in the stall). Stall usage index (**SUI**) was calculated as the number of cows lying down in the stalls divided by all animals in the pen not eating. Pens were observed at least 2 hrs before or after milking and all pens were observed at least once during the day with most pens observed 2 to 3 times per visit.

Mastitis Infection Prevalence. Mastitis infection prevalence was calculated as the[mie1] number of animals on each test date with a somatic cell count greater than 200,000 cells/mL divided by the total number of animals in the pen. The test date nearest to farm visit was used for analysis. Three farms (1 NV and 2 CV barns) were not members of DHIA and were excluded from analysis.

Statistical Analysis

The PROC MEANS procedure (SAS Institute Inc. Cary, NC) was used to describe average housing system measurements such as herd size, days in milk (DIM), parity, 305 day mature equivalent (305ME), somatic cell counts (SCC), stocking density, and pack density. The PROC MIXED (SAS Institute Inc. Cary, NC) procedure was used to evaluate the association between housing system and lameness prevalence, hock lesion prevalence, body condition score, hygiene score, CCI, SUI, and mastitis infection rate. Housing type was the explanatory variable used in all models. Additional explanatory covariates included in the models were season, average pen parity, average pen DIM, average pen milk production, and outside temperature-humidity index. Categorical variables used in the model included season, average pen parity, average pen days in milk, and outside temperature-humidity index (**THI)**. Pen parity was categorized into two groups: primiparous when average pen parity was ≤ 1.5 lactations and multiparous when average pen parity was >1.5 lactations. Days in milk was categorized into three groups: pen average ≤30DIM, >30<150DIM, and ≥150DIM. Farm was used as random variable with pen (farm) as the experimental unit. Three categories were used for THI: THI<70, THI≥70≤78, and THI>78. Variables identified in the univariate screening test ($P < 0.3$) were used to build the mixed model. Backwards stepwise elimination was used until remaining variables included were significant ($P < 0.05$). Tukey-Kramer adjustment was used to compare the least square means in categorically distributed variables.

RESULTS AND DISCUSSION

Farm selection was based on willingness to participate, use of the housing system for at least one year prior to the beginning of the study, and preference for farms that used DHIA testing. Descriptive characteristics of the barns are shown in Table 1. Two CV barns and 1 NV barn were not members of DHIA. Farms were located in southeast, southwest, and central Minnesota, and eastern South Dakota. Number of lactating animals on each farm ranged from 75 to 214, 399 to 1564, and 394 to 1552 for CB, CV, and NV barns, respectively. Milking herd size was 121, 1000, and 825 cows for CB, CV, and NV barns, respectively. A total of 45,536 animals were scored over the duration of the study. Milk production was 34.7, 37.5, and 37.1 kg of FCM/cow per day for CB, CV, and NV barns, respectively. Estimated 305ME production was 11,154; 11,536; and 11,236 kg for CB, CV, and NV, respectively. Stall dimensions were similar in the two freestall housing systems (Table 1).Neck rail height was the most variable characteristic but this measurement was influenced by the sand level in the stall the day of visit.

Lameness

Lameness prevalences were 6.4, 14.1, and 17.7% in CB, CV, and NV barns, respectively. These results were similar to 17.1% for sand based freestalls (Espejo et al., 2006) and 7.8% for CB in Minnesota (Barberg et al., 2007b). Compost barns had lower lameness prevalence most likely because cows spend less time standing on concrete and don't have restrictions when lying or rising in this type of housing. Lameness prevalence by pens ranged from 0 to 43.3%, 0 to 60%, and 1.3 to 65.3% in CB, CV, and NV barns. Size of the farm may have some influence on lameness prevalence; CB barns tend to be smaller operations where producers can probably more easily observe cows and identify lameness cases. Whitaker et al. (2000) reported that larger herds tended to have more lameness problems.

Lameness prevalence increased as parity increased. There was a housing system and parity interaction (Table 2.). Lameness prevalence was greater for multiparous pens housed in NV barns than multiparous pens in CB barns (P = 0.02). There were no differences between multiparous pens in NV and CV barns. When examining the primiparous pens there were no differences between the housing systems. Wells et al. (1993) and Espejo et al. (2006) reported a significant association between lameness prevalence and lactation number.

Winter, spring, summer, and fall lameness prevalences were 17.0, 14.9, 9.5, and 9.8%, respectively. Winter and spring lameness prevalences were greater than summer and fall ($P < 0.001$). We observed during our winter visit that footbaths were not being used due to freezing conditions. Cook (2003) scored cows for lameness during the summer and winter and saw a similar pattern of higher lameness prevalence during the winter in the Midwest. Similarly, Clarkson et al. (1996) reported greater lameness incidence in the winter compared to summer. However, Wells et al. (1993) did not observe a difference in lameness prevalence between spring and summer.

High milk yield has been reported as a risk factor for lameness (Warnick et al., 2001; Green et al., 2002). Milk yield was not significantly associated with lameness in the current study possibly due to using pen averages rather than individual animals for the analysis. Another factor not significant was DIM.

Lameness Analysis without CB. Because CV and NV barns were more similar in size and pen design, an analysis without the inclusion of CB barns was also performed. Lameness prevalences were 14.1 and 17.8% in CV and NV barns (SE = 2.3), respectively. Winter, spring, summer, and fall lameness prevalence were 20.3, 18.2, 12.3, and 13.0% (SE = 1.8), respectively. Summer and fall lameness prevalences were lower than both winter and spring ($P < 0.001$). There were no differences between summer and fall and winter and spring. There was an interaction between parity and housing system. Multiparous pens had a lameness prevalence of 15.5 and 23.4% in CV and NV barns, respectively (SE = 2.3; P = 0.082). There was no difference in lameness prevalence for primiparous pens and they averaged 12.7 and 12.2% for CV and NV barns, respectively (SE = 2.6). Multiparous pens had greater lameness prevalence than primiparous pens in NV barns (P < 0.001). There were no differences between primiparous and multiparous pens in CV barns.

Severe Lameness. There were no differences between the housing systems for severe lameness prevalence (Table 3). Severe lameness prevalences (LS ≥ 4) were 1.6, 2.2, and 3.1% for CB, CV, and NV barns, respectively. Winter, spring, summer, and fall severe lameness prevalences were 4.3, 2.3, 1.0, and 1.6%, respectively. Peak severe lameness prevalence occurred >30<150DIM. Dewes (1978) observed lameness occurred as early as 10 days after calving with a mean of 63 DIM in primiparous animals. Rowlands et al. (1985) noted that lameness incidence was greatest during the first 3 months of lactation. A strong association between sole disorders and the period between 60 to 120 DIM was observed by Vaarst et al. (1998). Multiparous pens had greater severe lameness prevalence than primiparous pens (P = 0.01).

Hock Lesions

Compost bedded pack barns had lower hock lesion prevalence (7.8%) than CV and NV barns (30.9%, P = 0.003 and 27.8%, P = 0.012, respectively; Table 4). Results for the CV and NV barns were slightly higher than the 24% prevalence for sand bedded freestalls reported by Weary and Taszkun (2000) and the 25% reported by Fulwider et al. (2007). Barberg et al. (2007b) reported a higher (24.1%) hock lesion prevalence for CB barns. Those authors hypothesized that hock lesions were present or recovering from previous housing. As the case with Barberg et al. (2007b) most of the hock lesions observed in the CB barns in the current study were from cows that were recently acquired and were previously housed in tie stalls or freestalls. Krohn and Munksgaard (1993) also found that dairy cattle in loose housing, in addition to pasture did not have any hock or knee inflammation. Average pen prevalences ranged from 0 to 29.1%, 2.2 to 82.7%, and 0 to 83.3% in CB, CV, and NV barns, respectively. Hock lesion prevalence was greater during the spring and summer months. Although there was a seasonal relationship for hock lesion prevalence, possibly hair losses were covered by the longer hair during the colder months and not observed. Multiparous pens had more lesions than primiparous pens ($P < 0.001$). Kielland et al. (2009) reported greater odds ratio for hock lesions in multiparous animals compared to primiparous. Multiparous animals may have more lesions from being exposed to abrasive surfaces longer than primiparous animals or may have a permanent scar tissue from a previous insult.

Hock Lesion without CB. Hock lesion prevalences were 32.5 and 26.5% for CV and NV, respectively and not statistically different (SE = 5.6). Winter, spring, summer and fall hock lesion prevalences were 25.2, 31.3, 35.7, and 26.0%, respectively. Hock lesion prevalence increased throughout lactation. Hock lesion prevalences were 26.5, 28.1, and 34% for ≤30DIM, >30<150DIM, and ≥150DIM, respectively (SE = 4.4). Both ≤30DIM and >30<150DIM had lower prevalence than ≥150DIM ($P = 0.003$ and $P < 0.001$, respectively), with no differences between ≤30DIM and >30<150DIM. There was an interaction between housing system and parity. Multiparous hock lesion prevalences were 32.4 and 31.6% and primiparous hock lesion prevalences were 32.6 and 21.5% in CV and NV barns, respectively. Multiparous cows had greater hock lesion prevalence than primiparous animals in NV barns ($P < 0.001$) with no differences between primiparous and multiparous animals in CV barns.

Severe Hock Lesion. Severe hock lesion prevalences (HL = 3) were 0.7 ± 2.6, 7.4 ± 1.9, 7.8 ± 1.9% for CB, CV, and NV barns, respectively (Table 4). Fulwider et al. (2007) and Lombard et al. (2010) reported 2.5% and 0.7%, respectively for severe hock lesion prevalence for sand bedded freestalls. Lower hock lesion prevalence was observed in the fall (4.1 ± 1.3%) than spring and summer (6.9 ± 1.3%, $P < 0.001$ and 6.8 ± 1.3%, $P < 0.001$, respectively) and was not different in winter (3.7 ± 1.3%,). Winter was lower than spring and summer ($P < 0.001$). Spring and summer hock lesion prevalences were not different. Pens that were ≤30DIM had a prevalence of 3.6 ± 1.6%, pens >30<150DIM, 4.7 ± 1.3%, and pens ≥150DIM, 7.7 ± 1.2%. Pens ≤30DIM and pens >30<150DIM were lower than pens ≥150DIM ($P < 0.001$ and $P < 0.001$, respectively) with no differences between ≤30DIM and >30<150DIM. There was an interaction between housing system and parity. Primiparous pens hock lesion prevalences were 0.2, 7.0, and 5.4% in CB, CV, and NV barns, respectively. In multiparous pens severe lesion prevalences were 1.3, 7.8, and 10.2% in CB, CV, and NV barns, respectively. The only difference was observed between primiparous and multiparous pens in NV barns ($P < 0.001$).

Hygiene

Hygiene scores were 3.18 ± 0.11, 2.83 ± 0.08, 2.77 ± 0.08 for CB, CV, and NV, respectively. Barberg et al. (2007b) reported an average hygiene score of 3.04 in compost barns. Fulwider et al. (2007) reported cows housed on mattresses or waterbeds were cleaner than sand bedded freestalls and noted that compost barns had similar hygiene scores to waterbed housed cows. There was a housing system by season interaction (Table 5). Winter hygiene scores were greater in CB barns than CV and NV barns, respectively ($P = 0.007$ and $P = 0.029$). In the winter it was more difficult for producers to keep the CB pack clean and dry. Hygiene scores improved throughout lactation. Scores were 3.01, 2.95, and 2.82 (SE = 0.08) for ≤30DIM, >30<150DIM, and ≥150DIM, respectively. Pens ≤30DIM and >30<150DIM had greater hygiene scores than pens ≥150DIM (P =0.004 and $P = 0.018$), with no differences between the early lactation groups.

Body Condition

There were no differences between housing systems for BCS (Table 6). Seasonally, the BCS scores were higher in the winter than summer and fall ($P < 0.001$) with no differences between spring and winter. Spring BCS were greater than summer ($P < 0.001$). Multiparous pens had greater body condition than primiparous pens ($P < 0.001$). Domecq et al. (1997) reported that primiparous animals maintained a greater BCS than multiparous animals in the first 120 DIM. Contrary to those results, primiparous pens in the current study had lower BCS than multiparous pens; however the difference was only 0.08 units of BCS and probably not biologically significant. Pens

≤30DIM had lower BCS than pens ≥150DIM (*P* < 0.001). Pens >30<150DIM had a trend for lower BCS than pens ≤30DIM and were lower than pens ≥150DIM (*P* = 0.068 and *P* < 0.001, respectively). Each additional kg of milk yield reduced BCS by 0.001 ± 0.001 (*P* < 0.001).

Cow Comfort

NV barns had lower CCI than CV barns (80.3 ± 1.9 vs. 86.4 ± 1.8; *P* = 0.015; Table 7). Summer had lower CCI (79.9 ± 1.4) than winter (84.1 ± 1.9; *P* = 0.039), spring (84.8 ± 1.8; *P* = 0.006), and fall (84.4 ± 1.5; *P* = 0.002). There were no differences in CCI between winter, spring and fall. Pens >30<150DIM had lower CCI (78.4 ± 2.1) than pens ≤30DIM (84.7 ± 1.7; *P* = 0.009) and ≥150DIM (86.9 ± 1.4; *P* < 0.001). There were no differences between pens >30<150DIM and ≥150DIM . Nelson (1996) recommended that CCI be at least 80% and ideally greater than 85% as indication of good stall comfort. The CV barns and three of the seasonal averages were near the recommended percentage. The NV barns were 4.7 percentage units lower than the recommended 85%, however, the current results were higher than previously reported 76% with mattress stalls (Cook et al., 2005) and 76% averaged across mattress and sand bedded freestalls (Espejo and Endres, 2007). Krawczel et al. (2008) reported CCI between 85 and 86% on mattress freestalls with pen stocking densities from 100 to 131%. Stocking densities in the current study were 112% in CV and 109% in NV barns, which were similar to Espejo and Endres (2007) and Cook et al. (2005).

Recommended SUI is greater than 75% (Overton et al., 2003). NV barns had a lower SUI (67.5 ± 2.1) than CV barns (73.4 ± 2.0; *P* = 0.031). Cook et al. (2005)

observed a SUI of 76.3% in sand bedded stalls which was slightly higher than observed in this study. Mattress freestalls with a stocking density of 100, 113, and 131% had SUI of 80.3, 79.5, and 74.8%, respectively (Krawczel et al., 2008). In the current study summer had a lower SUI (66.9 ± 1.6) than spring (71.6 ± 2.0; $P = 0.035$), and fall (72.3 ± 1.7; $P = 0.001$). There were no differences between summer and winter (71.1 ± 2.1) and spring and fall. Pens ≤30DIM had lower SUI (63.7 ± 2.3) than pens >30<150DIM (72.7 ± 1.8; $P < 0.001$) and ≥150DIM (75.1 ± 1.5; $P < 0.001$). There were no differences between pens <30>150DIM and ≤30DIM.

Respiration Rate

Armstrong (1994) reported heat stress started to occur when the THI exceeded 72. Vitali et al. (2009) observed increased mortality rates when the THI was 70 and Cook et al. (2007) noted that there were behavioral changes when the THI reached 68. Due to some of the discrepancies on what THI is considered as the beginning of heat stress we used the THI of 70 as the onset of heat stress. Mild to moderate heat stress was classified as THI ≥70≤78 and severe heat stress when THI was >78. Twenty-seven percent of the observations were taken when the THI<70, 66.5% when THI≥70≤78, and 6.4% when THI>78. Approximately 75% of the observations were taken when there was some heat stress. Average summer barn temperatures were 20.7, 19.6, and 20.8 °C in CB, CV, and NV barns, respectively. CV barns had a 2.0 and 2.1 unit decrease in THI compared to CB ($P = 0.023$) and NV ($P = 0.018$) barns, respectively during the entire summer (June 21 to September 22).

Respiration rates were 59.5, 57.9, and 59.4 breaths/min and were not significantly different in CB, CV, and NV barns, respectively. Roman-Ponce et al. (1977) and Schütz et al. (2010) reported slightly lower respiration rates (50 breaths/min) for animals that were given the option to be under a shade structure.

The variables included in the model used to evaluate the association between housing system and respiration rates were parity, milk production, SCS, and outside THI. Only milk production and outside THI were significant ($P < 0.001$). Respiration rates were 51.2, 57.5, and 67.5 breaths/min forTHI<70, THI≥70≤78, and THI>78, respectively. Each additional kg of milk yield was associated with an increase in respiration rate of 0.13 ± 0.03 ($P < 0.001$). Higher milk production increases a cow's susceptibility to heat stress (Nardone et al., 2006). Current results show a positive association between milk yield and respiration rates. During hot weather dairy cows try to combat heat stress by reducing dry matter intake and eventually milk production decreases (Strickland et al., 1989; Rhoads et al., 2009).

Mastitis Infection Prevalence

Subclinical mastitis infection prevalences (SCC > 200,000 cells/ml) were 33.4, 26.8, and 26.8% for CB, CV, and NV barns, respectively with no differences among housing systems. No other adjustment factors were significant in the model. Barberg et al. (2007b) reported a similar average infection rate in 12 compost bedded pack barns (27.7%.).

CONCLUSIONS

Of the three dairy cattle housing options examined in this study, CB barns provided the most welfare friendly facility. Dairy cattle housed in CB barns had reduced lameness and hock lesions compared to CV and NV barns with no adverse associations with body condition, heat stress, or mastitis infection prevalence. Respiration rates were numerically lower in CV barns during the summer than CB and NV barns, however, there was no significant difference. When comparing the two freestall housing options, CV barns had improved CCI and SUI compared to NV barns. Although CB barns provide a better environment, ability of acquiring bedding and managing the bedding pack can limit the use of compost bedded packs barns.

Table 1. Characteristics of compost bedded pack (CB), cross-ventilated freestall (CV), and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

	Housing System					
	CB		CV		NV	
Item	Mean	SD	Mean	SD	Mean	SD
Cows, n[1]	699	15.6	5646	616	4718	397
Days in milk[2]	201	131	190	133	192	130
Parity[2]	2.5	1.6	2.0	1.1	2.3	1.4
3.5% FCM yield kg/cow per day[2]	34.7	11.6	37.5	11.9	37.1	12.1
Somatic cell count (‘000’s)[2]	434	1,197	309	841	300	851
Stocking density, cows/stall (%)	-	-	111.6	19.5	108.6	19.8
Pack density (m^2/cow)	7.6	1.1	-	-	-	-
Stall length (cm)	-	-	238.8	12.4	239.6	11.4
Stall width (cm)	-	-	117.3	4.9	118.1	5.3
Body resting length (cm)	-	-	165.7	9.1	167.6	10.3
Neck rail height (cm)	-	-	117.3	3.7	113.5	10.0

[1] Total number of cows per housing system (6 farms per system) from DHIA when available (15 farms) and from on-farm records when DHIA records were not available (3 farms).
[2] Did not include 3 farms that were not members of DHIA (2 - CV and 1 – NV).

Table 2. Lameness prevalence (%) least squares means by parity in 3 housing systems - compost bedded pack (CB), cross-ventilated freestall (CV), and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

	Housing System					
	CB		CV		NV	
Parity	Means	SE	Means	SE	Means	SE
Primiparous	1.3	1.3	12.9	2.5	12.6[b]	2.5
Multiparous	12.0[y]	2.8	15.5[x,y]	2.2	23.5[a,x]	2.2

[a,b] Significant between rows within housing system (*P* < 0.05)
[x,y] Significant among columns across housing systems (*P* < 0.05)

Table 3. Severe lameness (LS ≥ 4) prevalence least squares means in 3 housing systems - compost bedded pack (CB), cross-ventilated freestall (CV), and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

	Severe lameness prevalence (%)	
Housing	LSMean	SE
CB	1.6	1.4
CV	2.2	1.0
NV	3.1	1.0
Season		
Winter	4.3[a]	0.8
Spring	2.3[b]	0.8
Summer	1.0[c]	0.8
Fall	1.6[b,c]	0.8
Parity		
Primiparous	1.6[e]	0.8
Multiparous	3.0[d]	0.7
Stage of lactation		
DIM ≤ 30	1.1[g]	1.1
DIM >30<150	3.4[f]	0.8
DIM ≥ 150	2.4[f,g]	0.7

[a,b,c] Significant among rows (Season; $P < 0.05$)
[d,e] Significant among rows (Parity; $P < 0.05$)
[f,g] Significicnat among rows (Stage of lactation; $P < 0.05$)

Table 4. Hock lesion and severe hock lesion prevalence (%) least squares means in 3 housing systems - compost bedded pack (CB), cross-ventilated freestall (CV), and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

	Hock Lesions ≥ 2, (%)		Hock Lesion = 3, (%)	
Housing	LSMean	SE	LSMean	SE
CB	11.3[b]	5.3	0.3[b]	2.1
CV	31.5[a]	4.8	7.0[a]	1.8
NV	28.0[a]	4.8	8.1[a]	1.7
Season				
Winter	19.2[e]	3.0	4.0[d]	1.2
Spring	24.1[d]	3.0	6.6[c]	1.2
Summer	30.6[c]	3.1	6.5[c]	1.2
Fall	20.6[e]	3.0	3.4[d]	1.2
Parity				
Primiparous	21.1[g]	3.1	4.0[g]	1.3
Multiparous	26.1[f]	2.9	6.3[f]	1.1
Stage of lactation				
DIM ≤30	21.6[h,i]	3.5	3.4[i]	1.5
DIM>30<150	22.7[i]	3.1	4.3[i]	1.2
DIM≥150	26.6[h]	2.9	7.7[h]	1.1

[a,b] Significant among rows (Housing; $P < 0.05$)
[c,d,e] Significant among rows (Season; $P < 0.05$)
[f,g] Significant between rows (Parity; $P < 0.05$)
[h,i] Significant among rows (Stage of lactation; $P < 0.05$)

Table 5. Hygiene scores least squares means in 3 housing systems - compost bedded pack (CB), cross-ventilated freestall (CV), and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

	Housing System					
	CB		CV		NV	
Season	LSMean	SE	LSMean	SE	LSMean	SE
Winter	3.33[a]	0.13	2.71[by]	0.09	2.78[b]	0.09
Spring	2.95	0.13	2.67[y]	0.09	2.66	0.09
Summer	3.21	0.13	3.05[x]	0.09	2.84	0.09
Fall	3.22	0.13	2.87[xy]	0.09	2.82	0.09
Overall	3.18	0.11	2.83	0.08	2.77	0.08

[a,b] Significant differences among columns (housing systems) within season ($P < 0.05$)

[x,y] Significant differences among rows (season) within housing system ($P < 0.05$)

Table 6. Body condition scores least squares means in 3 housing systems - compost bedded pack (CB), cross-ventilated freestall (CV), and naturally ventilated freestall (NV) barns in Minnesota and Eastern South Dakota.

	Body Condition Scores (1-5 scale)		
Housing	LSMean	SE	
CB	2.91	0.03	
CV	2.97	0.03	
NV	2.96	0.02	
Season			
Winter	2.99[a]	0.02	
Spring	2.97[a]	0.02	
Summer	2.91[b]	0.02	
Fall	2.92[b]	0.02	
Parity			
Primiparous	2.91[d]	0.02	
Multiparous	2.98[c]	0.01	
Stage of lactation			
DIM ≤ 30	2.87[g]	0.03	
DIM >30<150	2.93[f]	0.02	
DIM ≥ 150	3.04[e]	0.02	
	Estimate	SE	P-value
Milk (kg)	-0.01	0.001	< 0.001

[a,b] Significant among rows within Season ($P < 0.05$)
[c,d] Significant between rows within Parity ($P < 0.05$)
[e,f,g] Significant among rows within DIM ($P < 0.05$)

Table 7. Cow comfort index and stall usage index least squares means in cross-ventilated (CV) and naturally ventilated (NV) freestall barns in Minnesota and eastern South Dakota.

	Cow Comfort Index[1] (%)		Stall Usage Index[2] (%)	
Housing	LSMean	SE	LSMean	SE
CV	86.4[a]	1.8	73.4[a]	2.0
NV	80.3[b]	1.9	67.5[b]	2.1
Season				
Winter	84.1[c]	1.9	71.1[c,d]	2.1
Spring	84.8[c]	1.8	71.6[c]	2.0
Summer	79.9[d]	1.4	66.9[d]	1.6
Fall	84.4[c]	1.5	72.3[c]	1.7
Stage of Lactation				
DIM≤30	78.4[f]	2.1	63.7[f]	2.3
DIM>30<150	84.7[e]	1.7	72.7[e]	1.8
DIM ≥150	86.9[e]	1.4	75.1[e]	1.5

[1] Cow comfort index = cows lying/all cows touching a stall
[2] Stall usage index = cows lying/all cows in a pen not eating
[a,b] Significant between housing systems ($P < 0.05$)
[c,d] Significant among seasons ($P < 0.05$)
[e,f] Significant among stage of lactation ($P < 0.05$)

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