ENVIRONMENTAL CONDITIONS IN BEEF DEEP-BEDDED MONO-SLOPE FACILITIES: A DESCRIPTIVE STUDY

M. J. Spiehs, B. L. Woodbury, B. E. Doran, R. A. Eigenberg, K. D. Kohl, V. H. Varel, E. D. Berry, J. E. Wells

ABSTRACT: In the Northern Great Plains, interest in feeding cattle in enclosed beef deep-bedded mono-slope facilities (BDMF) has increased. Characterization of environmental factors impacting odor and gas emissions, nutrient excretion, and pathogens is needed to develop recommendations for management of BDMF. The objectives of this study were to determine spatial variability of ammonia (NH₃) in the air and odorous volatile organic compounds (VOC) in the bedded pack and to quantify environmental factors during various seasons. The effects of environmental factors on concentrations of NH₃ and VOC were determined. The nutrient content and occurrence of E. coli O157:H7 and generic E. coli concentrations in bedded pack material were also determined. High spatial variability was observed for steady-state NH₃ concentration on the pen surface. Ammonia concentration increased as pack and ambient air temperatures increased (p < 0.01). The temperature humidity index inside the barn was significantly greater than outside the barn during hot and cold months. Concentrations of VOC were highest in transition areas between the bedded pack and the concrete floor. Depth, moisture content, and pH of the bedded pack were poorly correlated to concentrations of NH₃ and VOC ($r^2 < 0.09$). Manure from BDMF contained 80% volatile solids. E. coli O157:H7 prevalence and generic E. coli concentrations reached high levels in BDMF and varied seasonally. Priority should be given to NH₃ and E. coli mitigation during hot months, but location-specific NH₃ mitigation will not be effective due to random distribution in the pen. Frequent cleaning of areas surrounding the bedded pack should reduce VOC concentrations.

Keywords. Ammonia, Beef, Deep-bedded system, Escherichia coli, Manure, Mono-slope barn, Nutrients, Odor.

A

n interest has developed in feeding beef animals in enclosed facilities in Iowa, South Dakota, Minnesota, and Nebraska. Confinement facilities are particularly attractive to feedlot producers in this area because the quad-state region receives more annual precipitation than other cattle feeding regions, such as Texas, Oklahoma, Kansas, and Colorado, and therefore has appreciatively more feedlot runoff that must be controlled and contained. Mono-slope barns are one popular style of deep-bedded facilities. Generally, beef deep-bedded mono-slope facilities (BDMF) have an east-west orientation and southern exposure. The mono-slope design facilitates natural ventilation and solar radiation. Producers cite ease of labor and manure management and improved performance compared to open-lot feedlots (Doran et al., 2010).

Like all concentrated animal feeding operations, BDMF can be a source of environmental concerns associated with manure accumulation, storage, and disposal. Even though no direct runoff results from these facilities, the nutrients and pathogens found in manure are a potential source of contamination of surface and groundwater when the manure mixture is land applied. Under certain conditions, the nutrients and bacteria in manure can generate odorous compounds and can negatively impact air quality. Therefore, comprehensive manure management for BDMF needs to address nutrients, pathogens, and odors associated with the livestock waste.

Numerous studies have demonstrated that branched-chain volatile fatty acids (BCFA), p-cresol, indole, skatole, and ammonia (NH₃) are important odorous compounds (O’Neill and Phillips, 1992; Mackie, 1994; Zahn et al., 1997; Zhu, 2000; Rappert and Muller, 2005). They can serve as an indicator of relative differences in odor potential on the pen surface. Previous studies in the swine industry have demonstrated that NH₃ concentration in the air is greater in deep-bedded facilities compared to conventional curtain-sided confinement facilities with underground deep pits (Jacobson et al., 2003, 2004). However, no data are currently available regarding concentrations of NH₃ or other volatile organic compounds (VOC) in BDMF.

Phosphorus (P), nitrogen (N), and sulfur (S) concentrations in livestock manure are also an environmental concern of concentrated animal feeding operations. Dietary P intake influences the amount of P excreted in livestock manure (Morse et al., 1992; Wu et al., 2000; Ebeling et al., 2002) and
impacts the amount of land necessary for manure application and the potential for P runoff following land application of manure. Excess N excretion has been shown to increase NH$_3$ emissions from beef cattle manure (Cole et al., 2005). Excreted S can contribute to hydrogen sulfide (H$_2$S) emissions from livestock manure (Shurson et al., 1998). Understanding the nutrient composition of the bedding/manure material would aid producers in land application of the material generated in BDMF and with air quality issues related to manure storage and handling.

As with odorous compounds and nutrient composition, there is a lack of information regarding the prevalence, concentration, and survival of zoonotic pathogens or fecal indicator bacteria in the bedding/manure material from BDMF. Characterization of the factors impacting nuisance emissions is needed to develop recommendations for managing these facilities to reduce odor and gas emissions and pathogens. Understanding the spatial variability of odorous compounds in the pen would allow producers to target management efforts at the areas of the pen contributing to offensive odors. Therefore, a study was initiated with the following objectives:

- Determine spatial variability in steady-state NH$_3$ concentration from air samples collected at the pen surface of BDMF.
- Determine spatial variability of odorous compounds in bedded pack material of BDMF.
- Quantify temperature, pH, moisture, and depth of bedding pack and relative humidity and temperature of the ambient air in BDMF during various seasons and determine the effect of these environmental factors on concentration of NH$_3$ and odorous compound in BDMF.
- Determine total nitrogen, total phosphorus, total potassium, total sulfur, and volatile solids content of bedded pack material from BDMF.
- Determine E. coli O157:H7 occurrence and generic E. coli concentrations in bedded pack material from BDMF.

**Materials and Methods**

**Facilities**

Two commercial deep-bedded facilities in northwest Iowa were used for this project. Both facilities were mono-slope barns with an east-west orientation and southern exposure (fig. 1). The barns had concrete floors in the pens. Barn A was 402 m$^2 	imes 30.8$ m. The south and north sides of barn A had a height of 8.5 m and 4.6 m, respectively. The north wall of barn A had a 2.7 m opening with adjustable curtains to allow for natural ventilation of the facility. In barn A, the area of pen 13 was 653.1 m$^2$ and pen 14 was 734.4 m$^2$ (fig. 2). A 3.7 m$^2$ concrete manure storage area separated the two sampling pens. Both pens had drive-by feed bunks on the north and south sides. Barn B was 146.3 m$^2 	imes 29.7$ m (fig. 3). The south side of barn B had a height of 8.5 m, and the north side was 4.9 m high. The north wall had a 2.7 m opening running the length of the wall with adjustable curtains. The area of each pen was 704.6 m$^2$, with drive-by feed bunks on the north and south sides. Barn B did not have manure storage in the barn. When manure could not be immediately applied to cropland, it was stockpiled outside the barn. In Iowa, stockpiles from deep-bedded barns must be land applied as soon as possible but no later than six months after they are established.

Management was site-specific, but the barns were typically cleaned and re-bedded one to two times per week. The bedded pack was allowed to accumulate in the center of the pen. The concrete area surrounding the bedded pack was cleaned, and the removed manure was either stockpiled temporarily or applied directly to cropland. Chopped corn stalks were the most common bedding material used, although wheat straw and soybean stalks were used for limited periods when corn stalks were not available. The amount of bedding used in the barns ranged from 1.26 to 5.19 kg per animal per day, but was affected by size of the animal, number of animals, and length of time cattle were in the pen. When cattle were housed in the pens for at least 100 days, bedding ranged from 1.95 to 3.37 kg per animal per day. Pen density for cattle that were housed for 100 or more days ranged from 3.22 to 6.13 m$^2$ per animal and was dependent on the size of the animal. Cattle and pen characteristics of barns A and B are listed in table 1.

**Sample Collection and Analysis**

Data were collected from two pens in each of two mono-slope barns every 5 to 7 weeks from March 2008 through October 2009. The sampling date was selected to correspond to producer availability and did not take into account the age of
Figure 2. Layout of pens 13 and 14 in barn A (not to scale). Barn A was 402 m × 30.8 m. Heights of the north and south sides of the barn were 4.6 m and 8.5 m, respectively. The circular area in the pen indicates the bedded pack (BP) area, which had a pack depth >15 cm. The transition (T) area had a pack depth of 7.6 to 15 cm, and the concrete (C) area had <7.6 cm of bedding material. Superimposed on pen 13 is an example of the 8 × 7 sampling grid used for each pen. Horizontal and vertical transects are 3 m apart. Each pen had 56 sampling points. The same 56 locations were sampled each time data was collected from the pen.

Figure 3. Layout of pens 1 and 4 in barn B (not to scale). Barn B was 146.3 m × 29.7 m, and the pens were identical. Heights of the north and south sides of the barn were 4.9 m and 8.5 m, respectively. The circular area indicates the bedded pack area, which had a pack depth >15 cm. The transition area had a pack depth of 7.6 to 15 cm, and the concrete area had <7.6 cm of bedding material.

the bedding on the bedded pack. On the sampling day, cattle were removed from the pens immediately prior to sample collection. In each pen, samples were collected from 56 locations on a 7 row × 8 column grid; the same 56 locations were sampled each time data were collected from the pen (fig. 2). Horizontal and vertical transects were 3 m apart. Samples for all analysis were collected simultaneously.

Ammonia Concentrations in Air Samples

Ammonia analysis was conducted from March 2008 until January 2009. To determine relative differences in steady-state NH₃ concentrations in the air at various locations in the pen, air samples were collected from the pen surface using stainless steel hemispherical flux chambers (Miller and Woodbury, 2006; Woodbury et al., 2006) with acid traps containing 0.5N sulfuric acid. The flux chambers were 7 L with a surface area of 640 cm². Inside the headspace of the chamber was a 40 mm, 12 V axial-flow fan moving approximately 130 L min⁻¹. The fan was suspended in the center of the headspace approximately 70 mm above the pen surface. Fan airflow direction was from surface up to the chamber top. The chamber head volumes were recycled through the acid traps for 20 min using the procedure described by Woodbury et al. (2006). The NH₃ content in the acid trap was analyzed using a modification of the Sigma urea N kit (Procedure No. 640, Sigma-Aldrich Chemicals, St. Louis, Mo.). Five microliters of each standard and sample were transferred to a well in a 96-well microtiter plate. This was followed by additions of 50 μL phenol nitroprusside, 50 μL alkaline hypochlorite, and 250 μL distilled water. Color was allowed to develop for 20 min at room temperature. Absorbance at 620 nm was measured using a microplate reader (Ceres UV900C, BioTek Instruments, Inc., Winooski, Vt.). The concentration of each 96-well plate was determined from a standard curve run with the plate. The coefficient of variation of each duplicate sample in the plate was less than 3%. To determine if high variability in ammonia concentration could be attributed to volatilization of recently excreted urine, the baseline NH₃ concentration of the pens was determined. Air samples were collected in June 2008 from one pen in barn A at 0, 4, and 10 h after the cattle were removed from the pen following the same procedure previously described. Air samples were collected in September 2008 from one pen in barn B at 0, 7, and 10 h after cattle were removed from the pen.
To determine VS, samples were dried at 60 °C for 24 h and then held at 4 °C overnight. To determine the presence of E. coli O157:H7, 500 µL of the sample enrichments were plated on double-strength Levine brilliant green agar (BD Diagnostics, Sparks, Md.) and then held at 4 °C overnight. Microorganism concentrations were determined by plating one-tenth of the Levin's agar plates on Levine brilliant green agar and then holding at 4 °C overnight. The number of colonies that formed was counted and then converted to a concentration using predetermined calibration curves.

Table 1. Cattle and pen characteristics in barns A and B.\(^{[a]}\)

<table>
<thead>
<tr>
<th>Barn A</th>
<th>Pen 13</th>
<th>Pen 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Animals</td>
<td>196</td>
<td>103</td>
</tr>
<tr>
<td>Sex</td>
<td>Steers</td>
<td>Steers</td>
</tr>
<tr>
<td>Breed</td>
<td>Beef</td>
<td>Beef</td>
</tr>
<tr>
<td>In weight (kg)</td>
<td>342</td>
<td>560</td>
</tr>
<tr>
<td>Out weight (kg)</td>
<td>598</td>
<td>764</td>
</tr>
<tr>
<td>Days on feed</td>
<td>162</td>
<td>158</td>
</tr>
<tr>
<td>Bedding (kilotonnes)</td>
<td>65.3</td>
<td>45.9</td>
</tr>
<tr>
<td>Bedding, (kg head(^{-1}) d(^{-1}))</td>
<td>2.07</td>
<td>2.82</td>
</tr>
<tr>
<td>Density (m(^2) head(^{-1}))</td>
<td>3.22</td>
<td>6.13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Barn B</th>
<th>Pen 1</th>
<th>Pen 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Animals</td>
<td>145</td>
<td>215</td>
</tr>
<tr>
<td>Sex</td>
<td>Heifers</td>
<td>NA</td>
</tr>
<tr>
<td>Breed</td>
<td>Beef</td>
<td>Beef</td>
</tr>
<tr>
<td>In weight (kg)</td>
<td>518</td>
<td>295</td>
</tr>
<tr>
<td>Out weight (kg)</td>
<td>547</td>
<td>341</td>
</tr>
<tr>
<td>Days on feed</td>
<td>34</td>
<td>42</td>
</tr>
<tr>
<td>Bedding (kilotonnes)</td>
<td>23.8</td>
<td>11.3</td>
</tr>
<tr>
<td>Bedding, (kg head(^{-1}) d(^{-1}))</td>
<td>4.84</td>
<td>1.26</td>
</tr>
<tr>
<td>Density (m(^2) head(^{-1}))</td>
<td>4.85</td>
<td>3.27</td>
</tr>
</tbody>
</table>

\(^{[a]}\) A group is defined as a set of cattle that entered and left the pen at the same time.

\(^{[b]}\) Information was not available.

**Physical and Chemical Characteristics of Bedded Pack Material**

Depth, pH, and temperature of the bedded pack, as well as concentration of odorous compounds, dry matter (DM), total nitrogen (TN), total phosphorus (TP), total potassium (TK), total sulfur (TS), and volatile solids (VS) content of the material collected from the bedded pack and pen surface were measured from March 2008 to October 2009. Samples were collected simultaneously to ammonia (March 2008 to January 2009) and E. coli (March 2009 to October 2009) data collection. Temperature and pH of the pen surface were measured approximately 7.6 cm below the surface using a pH/mV/temperature meter (IQ150, Spectrum Technologies, Inc., Plainsfield, Ill.). Depth of the bedded pack was determined by measuring its elevation above the concrete floor with a laser level.

Grab samples of the bedding/manure mixture to be used for DM, VS, TN, TP, TK, and TS analysis were collected from the surface of the pen by hand or using a trowel, placed in 3.8 L plastic bags, and held on ice during transport to the laboratory. Samples were collected from no deeper than the top 10 cm of the bedding material. A 15 g subsample of the bedding/manure material from each plastic bag was transferred to a 50 mL conical tube to be analyzed for total volatile fatty acids (VFA), total straight-chain fatty acids (SCFA), BCFA, and total aromatic compounds (phenol, indole, skatole, and p-cresol). To each 50 mL conical tube, 1 N sulfuric acid was added to prevent fermentation during transport. All samples were held at 4 °C and processed within 24 h of collection.

**Determination of E. coli O157:H7 Occurrence and Generic E. coli Concentration**

Determination of E. coli O157:H7 occurrence and generic E. coli concentration was conducted on samples collected from the pen surface at each of the sampling locations in March, April, June, August, and October 2009. E. coli was enumerated using Columbia agar base (Difco, Sparks, Md.) and E. coli diagnostic media (Difco, Sparks, Md.). E. coli O157:H7 was detected using the O157 Dynabeads (Invitrogen Corp., Carlsbad, Calif.) immunomagnetic beads.
mixed with the enriched sample for 30 min at room temperature and concentrated into a 100 μL volume. Fifty microliters of the eluted beads were plated onto CHROMagar O157 (DRG International, Mountainside, N.J.), containing 5 mg L⁻¹ novobiocin and 2.5 mg L⁻¹ potassium tellurite (ntCHROM). The ntCHROM plates were incubated at 37 °C for 22 to 24 h before examination for suspect E. coli O157:H7 colonies. Presumptive colonies were tested for agglutination by using DrySpot E. coli O157 (Oxoid Limited, Basingstoke, U.K.), isolated, and confirmed by multiplex PCR, as described by Paton and Paton (1998).

For enumeration of generic E. coli, the retained volumes of the initial 10-to-1 sample dilutions in TSB were diluted further as necessary in 2% buffered peptone water and spiral-plated onto CHROMagar ECC (DRG International, Mountainside, N.J.). The CHROMagar ECC plates were incubated for 22 to 24 h at 37 °C, and blue E. coli colonies were counted.

**Ambient Air**

Ambient temperature and relative humidity (RH) were collected at locations inside and outside of each barn from March 2008 to October 2009 using HOBO Prov2 Temp/RH data loggers (Onset Computer Corp., Pocasset, Mass.). Outside temperature/RH sensors were located on an external support 3 m above the ground. Inside sensors were positioned 3.3 m above the feedlot surface on the north side of an I-beam in the middle of the pen. Temperature and RH data were collected once every 15 min throughout the entire experiment. The temperature humidity index (THI) was calculated using the following formula:

\[
\text{THI} = 0.81 \text{tdb} + \text{RH} (\text{tdb} - 14.4) + 46.4
\]

where tdb is the dry bulb temperature (°C), and RH is relative humidity expressed as a decimal (Thom, 1959).

**Statistical Analysis**

To determine spatial variability of NH3, VFA, SCFA, BCFA, total aromatics, manure moisture content, and temperature, data from all four pens were grouped according to bedded pack depth. Samples collected from areas of the pen with >15 cm of bedding were designated “bedded pack” (BP). Those collected from areas of the pen with 7.6 to 15 cm and those from areas of the pen with <7.6 cm of bedding were designated as “transition” (T) and “concrete” (C), respectively. A one-way analysis of variance was conducted using SAS Proc GLM. When significant p-test results were obtained, Fisher’s least significant difference (LSD) multiple comparison tests were performed to determine differences in bedded pack depths. Sampling location was the experimental unit, and pens served as the replicates. Simple linear regressions were used to determine the effect of temperature, manure moisture content, pH, and depth of bedded pack on NH3, VFA, SCFA, BCFA, and total aromatic compounds. Interactions were not considered in the regression equations.

Seasonal effects were determined by grouping data collected from all four pens according to the average ambient temperature on the day of sampling. Cold, moderate, and hot seasons were defined as having an average ambient temperature at or below 0 °C, between 0 °C and 20.6 °C, and at or above 20.6 °C, respectively. Data were analyzed using the one-way analysis of variance procedure described previously.

Differences in temperature, RH, and THI between the inside and outside of the deep-bedded mono-slope facility were analyzed as a 2 × 3 factorial with three seasons (cold, moderate, and hot) and two shelters (inside or outside) included in the model. Data from all four pens were grouped together for this analysis.

Data collected from pens 13 and 14 during April, June, and August 2009 (N = 336) were used to determine the effect of shallow- and deep-bedded management. Data were analyzed using one-way analysis of variance with Fisher’s LSD multiple comparison tests.

Generic E. coli populations were converted to log colony forming units (CFU) per gram of bedding/manure for statistical analyses. Analysis of variance and the Tukey-Kramer multiple comparisons test were performed on the converted population data to determine the effect of season. The frequencies of positive samples for E. coli O157:H7 during each season were compared using Pearson’s chi-square test. Differences in the prevalence of E. coli O157:H7 within a pen across sampling periods and within a sampling period across pens were assessed using the two-tailed Fisher exact test. For all analyses, differences were considered significant when p < 0.01.

**RESULTS AND DISCUSSION**

**Spatial Variability of Ammonia**

High spatial variability of steady-state NH3 concentration was observed in air samples collected from the pen surface. No specific area of the pen had consistently higher concentration of NH3 in the air than another (table 2). Areas of high NH3 concentration were found in air samples collected from the bedded pack, at the transition area between the bedded pack and concrete, and on the concrete pen surface (fig. 4). Within a pen, areas of high NH3 concentration varied from one sampling period to the next (data not shown). Ammonia emissions from feedlot pens appear to occur primarily where cattle recently urinated (Cole et al., 2007), with a majority of the urinary N rapidly volatilized to NH3 (Varel, 1997; Flesch et al., 2007). Measurements were taken with small flux chambers. We speculated that when the chambers were placed directly over an area where cattle had recently urinated, higher NH3 readings were observed. When the time series collection was conducted, NH3 concentration declined significantly between 0 and 4 to 7 h after the cattle were removed from the pen, with no further significant decrease at 10 h (table 3).

Variability of NH3 concentration in air samples within the pen also decreased between 0 and 4 to 7 h after the cattle left the pens. Concentration of NH3 in barn A ranged from 0 to 282.0 mmol L⁻¹ (SD = 64.4) immediately after the cattle left the barn. After 4 and 10 h, the NH3 concentration in barn A ranged from 4.4 to 101.9 mmol L⁻¹ (SD = 26.9) and from 8.8 to 140 mmol L⁻¹ (SD = 31.1), respectively. A similar trend was observed in barn B, with initial readings ranging from 8.4 to 773.6 mmol L⁻¹ (SD = 96.4), air samples collected at 7 h ranging from 4.4 to 134.5 mmol L⁻¹ (SD = 31.1), and air samples collected at 10 h ranging from 8.8 to 140.6 mmol L⁻¹ (SD = 30.0). This indicated that locations in the pen with high NH3 concentration were likely areas where cattle had recently urinated instead of areas with consistently high NH3 concentration. It appeared that a majority of the NH3 volatilization occurred within the first 4 h after excretion.
This rapid volatilization of urinary N is consistent with the findings of Varel (1997), who reported that 88% of urea in cattle slurries was volatilized to NH₃ within 3 h, with complete volatilization of urinary urea by 24 h. Unfortunately, this meant that areas of high NH₃ concentration occurred randomly throughout the pen, and location-specific mitigation (i.e., use of site-specific urease inhibitors or increased frequency of cleaning in a particular area of the pen) would not effectively lower NH₃ concentration in the facility.

### SPATIAL VARIABILITY OF VOLATILE ORGANIC COMPOUNDS

Concentrations of VFA, SCFA, BCFA, and aromatic compounds were lower on the BP area compared to the T or C areas of the pen (table 2). The samples collected from the BP area contained feces and bedding material, while samples collected from the T and C area contained primarily feces. Livestock excreta is composed of undigested organic residues, including proteins, carbohydrates, and fats. Aerobic and anaerobic digestion of organic residues by bacteria produces VOC such as NH₃, VFA, S compounds, and aromatic compounds (Mackie et al., 1998). Therefore, it is not surprising that the concentration of VOC is higher in the areas of the pen where feces are most concentrated. This emphasizes the importance of frequent cleaning around the bedded pack to reduce the volatilization of VOC, which can decrease air quality in the BDMF.

### SEASONAL DIFFERENCES IN CHEMICAL AND PHYSICAL CHARACTERISTICS OF THE BEDDED PACK

Ammonia concentration in air samples collected on the pen surface was lowest during the cold months and highest during the warm months, with intermediate values during months with moderate ambient temperature (table 4). Seasonal variation in NH₃ volatilization from livestock facilities is well documented in the literature. Whitehead and Raistrick (1991) measured NH₃ volatilization of simulated livestock urine applied to soil and reported an increase in volatilization...
Hot and winter ammonia emissions of 7810 kg d⁻¹ and 5800 kg.

Carter (1983) found that the rate of urea hydrolysis in soil was linearly related to temperature over the range of 10°C to 20°C. Values are least square means with standard errors. Different letters within a row indicate a significant difference (p < 0.01).

For each variable, data are included from both barns. Ammonia N = 1547; pack temperature N = 1795; pack moisture N = 1662; pack depth N = 2383; pH N = 1268; total VFA, total SCFA, total BCFA, and total aromatics N = 1298; E. coli O157:H7 and generic E. coli N = 1045. Values are least square means with standard errors. Different letters within a row indicate a significant difference (p < 0.01).

Average ambient temperature for both barns on the day of collection was at or below 0°C.

Average ambient temperature for both barns on the day of collection was between 0°C and 20.6°C.

Average ambient temperature for both barns on the day of collection was at or above 20.6°C.

Ammonia concentration in air samples collected from the pen surface.

VFA = total volatile fatty acids.

SCFA = total straight-chain fatty acids, which included acetate, butyrate, propionate, valerate, caproate, heptanoate, and caprylate.

BCFA = total branch-chain fatty acids, which included isobutyrate, isovalerate, and iso-caprate.

Aromatics included p-cresol, phenol, 4-ethylphenol, skatole, and indole.

The concentrations of total VFA, SCFA, and total aromatic compounds were higher in the bedding material collected from the pen surface during the cold and moderate months compared to the hot months. This may be a reflection of the bedding-to-feces ratio during the cold and moderate months than an actual temperature effect. With decreasing pack and ambient temperatures, cattle tended to spend more time on the bedded pack, which increased fecal and urine accumulation on the bedded pack. The pH of the bedding/manure material was significantly higher during months with moderate temperatures compared to those with cold or hot temperatures, although this difference may not have biological importance, as pH did not appear to affect NH₃ or VOC concentration under the conditions of this study.

Doran et al. (2010) surveyed 15 producers from across Iowa who were feeding cattle in deep-bedded mono-slope facilities. When asked how the performance parameters of the BDMF compared to open lots, 86.7% of producers indicated increased average daily gain and improved feed efficiency in the mono-slope facility (Doran et al., 2010). Anecdotally, producers claim that the ability to protect the cattle from weather extremes decreases fluctuation in feed intake, resulting in improved feed efficiency and increased average daily gain. During each season, the ambient air temperature inside the barn was significantly higher than the air temperature outside the barn (table 5). Relative humidity was similar inside and outside of the barn during all three seasons. The THI inside the barn was significantly greater compared to outside the barn during the months when the weather was most extreme. A higher THI during the summer months seems to contradict producer reports that BDMF provide a more favorable environment for cattle during the hot months. However, we did not collect any data to measure solar radiation, and THI fails to account for the effect of solar radiation. Solar radiation can contribute substantially to the heat load of cattle. Previous research has clearly demonstrated the benefits of shade structures in reducing heat stress in cattle (Brosh et al., 1998; Mader et al., 1999; Mihöchner et al. 2001; Eigenberg and Brown-Brandl, 2009). The shade provided by the mono-slope facilities would likely decrease heat stress and improve performance during hot summer months.

### EFFECT OF BEDDED PACK CHARACTERISTICS ON AMMONIA CONCENTRATION IN AIR AND VOC CONCENTRATION IN BEDDED PACK

Ammonia concentration in the air increased as the ambient air and bedded pack temperatures increased (table 4). The bedded pack was warmer and drier during the hot months compared to cold and moderate months, which may have contributed to higher NH₃ concentrations from the bedded...
pack during the hot months. A higher bedded pack temperature increases the breakdown of urea to ammonium (Aarnink et al., 1993), directly affects the rate of desorption of NH₃ (Voorburg and Kroodsma, 1992), and increases the mineralization of organic N (Voorburg and Kroodsma, 1992; Jeppsson, 1999). Conditions that promote rapid drying of the pen surface also encourage NH₃ volatilization (Ernst and Massey, 1960), and higher ambient air temperatures in the hot months promote rapid drying of the surface. Jeppsson (1999) reported an increase in NH₃ emissions in deep-bedded dairy barns when the temperature of the bedded pack increased from 21.4°C to 30.0°C. Elevating the temperature of the soil has been shown to increase NH₃ losses from the surface of open feedlots (Sherwood et al., 2006) and from soils receiving urea fertilizer (Liu et al., 2007). Higher temperatures also increased NH₃ losses from waste treatment lagoons (Aneja et al., 2001) and poultry litter (Liu et al., 2006). Lockyer and Whitehead (1990) summarized nine experiments in which the volatilization of NH₃ from cattle urine applied to grass swards was assessed over 15-day periods using a system of wind tunnels. They concluded that soil temperature during the three days following urine application had the greatest influence on NH₃ volatilization. Therefore, it is likely that, in the current study, the increase in bedded pack temperature contributed to the increased NH₃ concentration in air samples collected from the bedded pack surface of the mono-slope barns.

Moisture content also influences NH₃ emissions. In dry soil, the transport of NH₄⁺ ions from the soil surface down to the deep soil horizon is restricted; hence, increased losses of nitrogen occur as NH₃ emissions from the soil (Liu et al., 2007). Sherwood et al. (2007) reported an increase in NH₃ losses from the surface of open feedlots when the moisture content of the soil was decreased. Liu et al. (2007) measured NH₃ volatilization following application of N fertilizer on four different soil types. The results for all four soil types showed that the lower the soil moisture content, the higher the amount of NH₃ volatilization (Liu et al., 2007). Water acts as a solvent to transport NH₄⁺ away from the soil surface (Liu et al., 2007). The drier bedded pack during the hot months may have contributed to higher concentration of NH₃ in the air samples from the pen surface of BDMF.

Ammonia volatilization is also influenced by pH (Van Horn et al., 1996; Kirchmann and Witter, 1989). The pH level regulates the equilibrium between NH₄⁺ ions and NH₃ in nature. If the pH value is decreased, then the equilibrium is displaced toward NH₄⁺ and less NH₃ is formed (Kirchmann and Witter, 1989). The pH of the bedded packs in the two barns studied was poorly correlated to NH₃ concentration ($r^2 = 0.09$), likely due to small biological differences in pH levels within the pen. Depth of the bedded pack varied between seasons but also was poorly correlated to NH₃ concentration ($r^2 = 0.01$). Temperature, pH, moisture, and depth of the bedded pack were all poorly correlated to concentration of VFA, SCFA, BCFA, and total aromatics ($r^2 < 0.24$).

The temperature of the bedded pack influenced animal behavior. As previously stated, producers observed cattle lying on the concrete area surrounding the bedded pack instead of on the bedded pack area during the hot months. To improve
animal comfort, barn A changed bedding management in one pen during the second summer of the study. Instead of allowing the bedding pack to accumulate in the center of the pen during the summer months, all bedding and manure were removed from the pen once every three weeks. Fresh bedding material was added to cover the entire pen surface to a depth of approximately 30 cm, and additional bedding was added once or twice weekly as needed. This resulted in a shallow-bedded pack with a cooler temperature and higher moisture content, intended to improve animal comfort in the facility (table 6). Ammonia concentration was not measured on these dates. However, because of the cooler temperature and higher moisture content of the shallow-bedded pack, this management system may decrease NH₃ emissions compared to deep-bedded management, making it an effective management tool during hot months when NH₃ emissions are highest. A possible negative consequence of the shallow-bedded management is increased concentration of odorous compounds. The concentration of VFA, SCFA, BCFA, and total aromatic compounds were higher when shallow-bedded management was used, due to less bedding material in the pen, which resulted in a higher manure-to-bedding ratio.

**Nutrient Composition of Pen Surface Material**

Nutrient composition of the bedding/manure material from BDMF (table 7) was similar to reported values for manure from a beef earthen lot. When converted to a dry matter basis, *ASABE Standards* (2005) reports 17.6 g kg⁻¹ total N, 7.5 g kg⁻¹ total P, 18.7 g kg⁻¹ total K, and 4.2 g kg⁻¹ total S. The VS content of the manure from the BDMF was 80%. This is very high compared with other beef housing systems. Woodbury et al. (2007) reported 21% VS in manure collected from soil-surfaced open feedlots and 51% for manure from pens with pond ash used as a surfacing material. Volatile solids for beef earthen lots have been reported at 30.2% (*ASABE Standards*, 2005). This high organic matter, low ash manure may have additional value beyond use as a fertilizer, possibly for combustion.

**Generic *E. coli* and Prevalence of *E. coli* O157:H7**

Among a total of 1046 bedding/manure samples examined for *E. coli* O157:H7 during the study, 418 (40.0%) were positive for this pathogen. Pen prevalence of *E. coli* O157:H7 ranged from 0% to 94.6% and varied widely both within a pen across all sampling periods and within a sampling period across all pens (table 8). Our previous work indicated that *E. coli* O157:H7 prevalence in feedlot pen surface manure is reflective of *E. coli* O157:H7 fecal prevalence among cattle in the pen (Berry et al., 2010). Furthermore, this high degree of variation in pen prevalence is similar to that seen for pen fecal prevalence of *E. coli* O157:H7 in cattle in open-lot feedlots (Arthur et al., 2009; Smith et al., 2001; Wells et al., 2009). *E. coli* O157:H7 prevalence in the bedding/manure was higher during the hot months (table 4), which was likely due to the characteristic seasonality of prevalence of this pathogen in cattle. The prevalence of fecal shedding of this pathogen typically increases during the warmer months and is often highest in the summer and early fall (APHIS, 2001; Barkocy-Gallagher et al., 2003; Van Donkersgoed et al., 1999). Van Donkersgoed et al. (1999) reported that fecal prevalence of *E. coli* O157:H7 in yearling beef cattle and cull cows was highest in the summer at 19.7%, compared to 4.7%, 0.7%, and 4.9% in the fall, winter, and spring, respectively. Similarly, fecal prevalence of *E. coli* O157:H7 in beef cattle at harvest was 12.9% during the summer, compared to 6.8%, 0.3%, and 3.9% during the fall, winter, and spring. The observation of higher *E. coli* O157:H7 prevalence in the hot months may also be due in part to temperatures that are more favorable for growth and/or survival of this pathogen.

The generic *E. coli* concentrations ranged from a low of 2.30 to a high of 8.22 log₁₀ CFU per g of bedding/manure material, with an average level of 6.38 log₁₀ CFU per g of material. Similar to steady-state NH₃ concentration, there were no consistent patterns of generic *E. coli* level with regard to location within the pens, with high and low concentrations of generic *E. coli* observed throughout the pens (data not shown). This may be due in part to the mixing action of animal movement. Generic *E. coli* concentrations were higher during the moderate and hot months compared to cold months. Similar to *E. coli* O157:H7 prevalence observations, this likely reflects the occurrence of warmer temperatures that may promote growth or survival of *E. coli* (table 4) in the bedding/manure material of the deep-bedded barns.

**Conclusions**

High spatial variability was observed for steady-state NH₃ concentration on the pen surface of BDMF. Areas with a high NH₃ concentration were the result of recent urination by cattle. Ammonia concentration was higher when the pack and ambient air temperature increased and was consistently lower in the cold months compared to moderate and hot seasons. Therefore, priority should be given to NH₃ mitigation strategies in BDMF during months when average ambient temperatures are 20.6 °C or higher. The calculated THI was higher inside the BDMF during hot and cold seasons but was similar to the outdoor THI when ambient temperatures were between 0 °C and 20.6 °C. Volatile organic compounds were more concentrated in areas with little bedding and were poorly correlated to the temperature, moisture content, pH, and
depth of the bedded pack. Frequent cleaning around the bedded pack should reduce the volatilization of VOC. Nutrient composition of the bedding/manure is similar to manure from a beef earthen lot. The bedding/manure mixture generated in BDMF has 80% VS, which is much higher than the reported VS content in manure from open-lot feedlots. Both *E. coli* O157:H7 prevalence and generic *E. coli* concentrations can occur at high levels in the bedding/manure material of BDMF and may vary with differences in ambient seasonal temperatures. Shallow-pack management may be a system that can be used to lower barn NH3 emissions during hot months. A possible negative consequence of shallow-bedded management is increased concentration of odorous compounds in the manure on the pen surface.

**ACKNOWLEDGEMENTS**

The authors thank the producers and barn managers for their willingness to participate in this study. Sincere appreciation is expressed to Todd Boman, John Holman, Shannon Kempers, and Maria Verburg for assistance with data collection and to Alan Kruger, Shannon Ostdiek, Dee Kucera, Bruce Jasch, and Sue Wise for laboratory analysis of the samples. We gratefully acknowledge the grant awarded by the Iowa Beef Center to partially fund this project.

**REFERENCES**


