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 (NH_3) 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 NH_3 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 NH_3 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 NH_3 and VOC ($r^2 \leq 0.09$). Manure from BDMF contained 80% volatile solids.* E. coli *O157:H7 prevalence and generic* E. coli *concentrations occurred at high levels in BDMF and varied seasonally. Priority should be given to NH_3 and* E. coli *mitigation during hot months, but location-specific NH_3 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.*

An 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 (NH_3) 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 NH_3 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 NH_3 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

Submitted for review in September 2010 as manuscript number SE 8807; approved for publication by the Structures & Environment Division of ASABE in January 2011.

The authors are **Mindy J. Spiehs, ASABE Member,** Research Animal Scientist, and **Bryan L. Woodbury, ASABE Member Engineer,** Agricultural Engineer, USDA-ARS Meat Animal Research Center, Clay Center, Nebraska; **Beth E. Doran,** Beef Program Specialist, Iowa State University Extension, Orange City, Iowa; **Roger A. Eigenberg, ASABE Member Engineer,** Agricultural Engineer, USDA-ARS Meat Animal Research Center, Clay Center, Nebraska; **Kris D. Kohl,** Agricultural Engineer Program Specialist, Iowa State University Extension, Storm Lake, Iowa; **Vince H. Varel,** Microbiologist, **Elaine D. Berry,** Microbiologist, and **James E. Wells,** Microbiologist, USDA-ARS Meat Animal Research Center, Clay Center, Nebraska. **Corresponding author:** Mindy J. Spiehs, USDA-ARS Meat Animal Research Center, P.O. Box 166, Spur 18 D, Clay Center, NE 68933; phone: 402-762-4271; fax: 402-762-4273; e-mail: mindy.spiehs@ars.usda.gov.

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_2S) 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 × 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 × 21.6 m 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 × 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

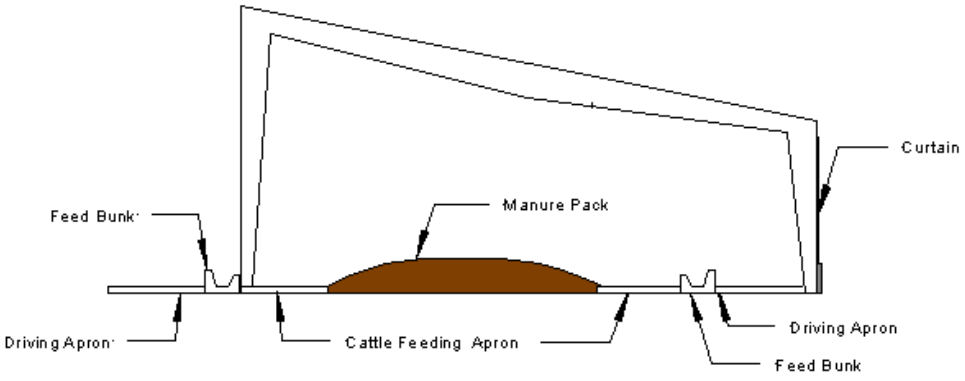

Figure 1. Side view of beef deep-bedded monoslope facility (not to scale). The south side of barn A had a 8.5 m opening. The north side of barn A had a 1.9 m concrete wall and 2.7 m opening with adjustable curtains. Barn B had a similar design, with an 8.5 m opening on the south side, a 2.2 m concrete wall, and a 2.7 m opening with adjustable curtains on the north side of the barn. Figure provided by Dr. Richard Nicolai, South Dakota State University.

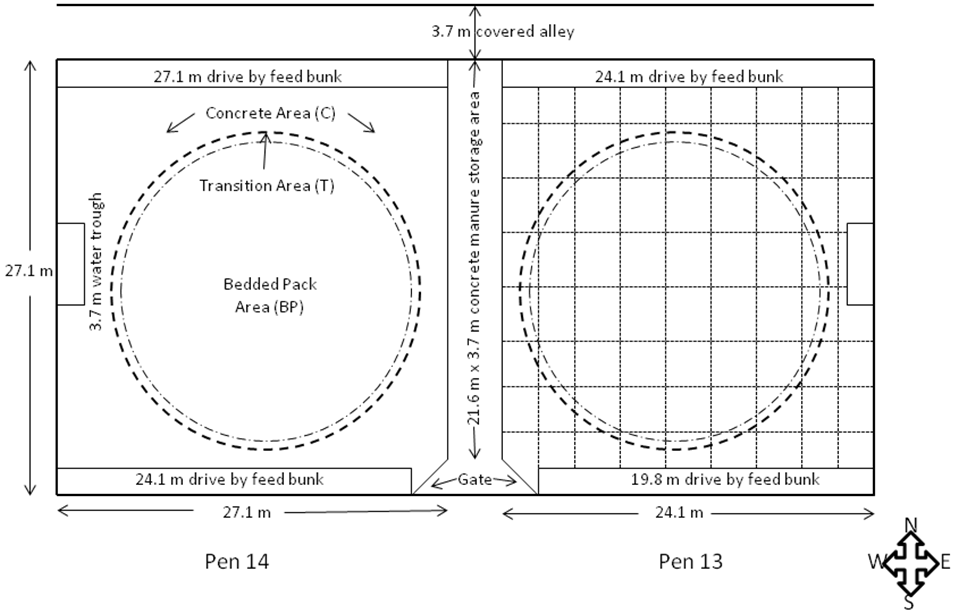

Figure 2. Layout of pens 13 and 14 in barn A (not to scale). Barn A was 402 m × 30.8 m. Heights of the north and south sides of the barn were 4.6 m and 8.5 m, respectively. The circular area in the pen indicates the bedded pack (BP) area, which had a pack depth >15 cm. The transition (T) area had a pack 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.

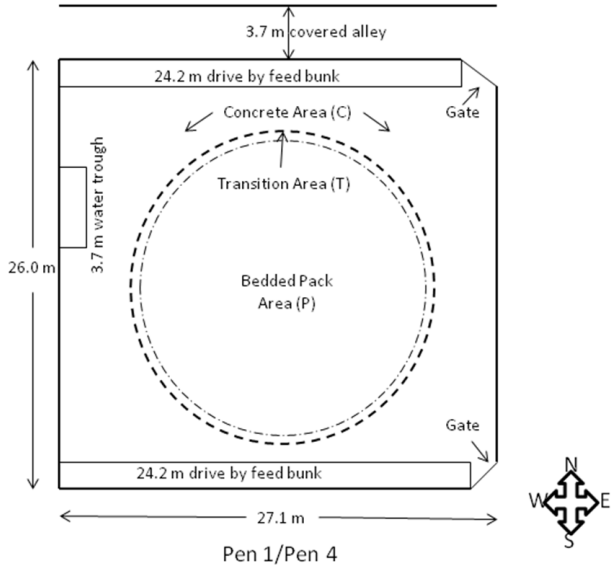

Figure 3. Layout of pens 1 and 4 in barn B (not to scale). Barn B was 146.3 m × 29.7 m, and the pens were identical. Heights of the north and south sides of the barn were 4.9 m and 8.5 m, respectively. The circular area indicates the bedded pack area, which had a pack depth >15 cm. The transition area 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 NH_3 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 cm^2. 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 NH_3 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 NH_3 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.

Table 1. Cattle and pen characteristics in barns A and B.[a]

	Pen 13				Pen 14				
Barn A	Group 1	Group 2	Group 3	Group 4	Group 1	Group 2	Group 3	Group 4	Group 5
No. of Animals	196	103	112	151	154	142	92	181	70
Sex	Steers	Steers	Heifers	Steers	Steers	Steers	Steers	Steers	Steers
Breed	Beef	Beef	Beef	Beef	Dairy	Beef	Beef	Beef	Beef
In weight (kg)	342	560	342	301	188	338	422	433	304
Out weight (kg)	598	764	607	NA[b]	564	638	NA	NA	NA
Days on feed	162	158	179	106	371	199	16	5	5
Bedding (kilotonnes)	65.3	45.9	67.5	36.3	158.6	77.1	4.9	1.8	1.8
Bedding, (kg head^{-1} d^{-1})	2.07	2.82	3.37	2.27	2.78	2.73	3.33	2.00	5.19
Density (m^2 head^{-1})	3.22	6.13	5.64	4.18	4.78	5.18	8.00	4.07	10.51

	Pen 1			Pen 4			
Barn B	Group 1	Group 2	Group 3	Group 1	Group 2	Group 3	Group 4
No. of Animals	145	215	188	195	200	205	210
Sex	Heifers	NA	Steers	Heifers	Heifers	Heifers	Steers
Breed	Beef	Beef	Holstein	Beef	Beef	Beef	Beef
In weight (kg)	518	295	346	518	445	436	418
Out weight (kg)	547	341	643	584	588	561	472
Days on feed	34	42	230	68	146	70	28
Bedding (kilotonnes)	23.8	11.3	98.9	32.3	57.0	35.1	14.2
Bedding, (kg head^{-1} d^{-1})	4.84	1.26	2.29	2.44	1.95	2.45	2.41
Density (m^2 head^{-1})	4.85	3.27	3.74	3.60	3.51	3.43	3.35

[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 in the laboratory until subsequent analysis. Dry matter was determined by weighing samples before and after drying at 100°C in a forced-air oven for 24 h. To determine VS, samples were dried at 60°C for 24 h and weighed before and after ashing in a muffle furnace at 550°C for 15 h. The following formula was used to determine percent VS:

$$VS = (1 - M_{Ash}/M_{Dry}) \times 100 \quad (1)$$

where M_{Ash} is the mass of the ashed sample, and M_{Dry} is the mass of the dry sample. Samples collected from the pen surface were dried, ground through a 1 mm screen, and sent to a commercial laboratory (Ward Laboratory, Inc., Kearney, Neb.) for TN (Watson et al., 2003), TP, TK, and TS analysis (Wolf et al., 2003). A Hewlett-Packard 6890 gas chromatograph (Agilent Technologies, Palo Alto, Cal.) equipped with flame-ionization and mass-selective detectors was used to determine concentrations of VFA, SCFA, BCFA, and aromatic compounds, as previously described by Miller and Varel (2001).

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

Determination of *E. coli* 0157: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. Samples were collected on these five dates only due to limited resources for the labor-intensive laboratory analysis. Grab samples (approx. 20 g) for microbial analysis were collected by hand using clean latex gloves for each sample. Samples were placed in separate 50 mL conical tubes and held on ice packs for transport to the laboratory. Samples were held overnight at 4°C and processed within 24 h of collection. Ten grams of each sample were measured into separate sterile filtered sample bags (Nasco, Ft. Atkinson, Wisc.), 90 mL of tryptic soy broth (TSB; Difco, Becton, Dickinson and Co., Sparks, Md.) were added, and the bags with contents were mixed by hand. One milliliter volumes were removed to sterile tubes for enumeration of generic *E. coli* as described below. The remaining sample mixtures were enriched by incubation at 37°C for 7 h and then held at 4°C overnight. To determine the presence of *E. coli* O157:H7, 500 µL of the sample enrichments were added to 500 µL of phosphate-buffered saline with 0.5% Tween 20 and 20 µL of anti-*E. coli* O157 Dynabeads (Invitrogen Corp., Carlsbad, Cal.). The immunomagnetic beads were

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:

$$THI = 0.81t_{db} + RH(t_{db} - 14.4) + 46.4 \quad (2)$$

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

Statistical Analysis

To determine spatial variability of NH_3, 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 NH_3, 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 NH_3 concentration was observed in air samples collected from the pen surface. No specific area of the pen had consistently higher concentration of NH_3 in the air than another (table 2). Areas of high NH_3 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 NH_3 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 NH_3 (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 NH_3 readings were observed. When the time series collection was conducted, NH_3 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 NH_3 concentration in air samples within the pen also decreased between 0 and 4 to 7 h after the cattle left the pens. Concentration of NH_3 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 NH_3 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 = 23.3), 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 NH_3 concentration were likely areas where cattle had recently urinated instead of areas with consistently high NH_3 concentration. It appeared that a majority of the NH_3 volatilization occurred within the first 4 h after excretion.

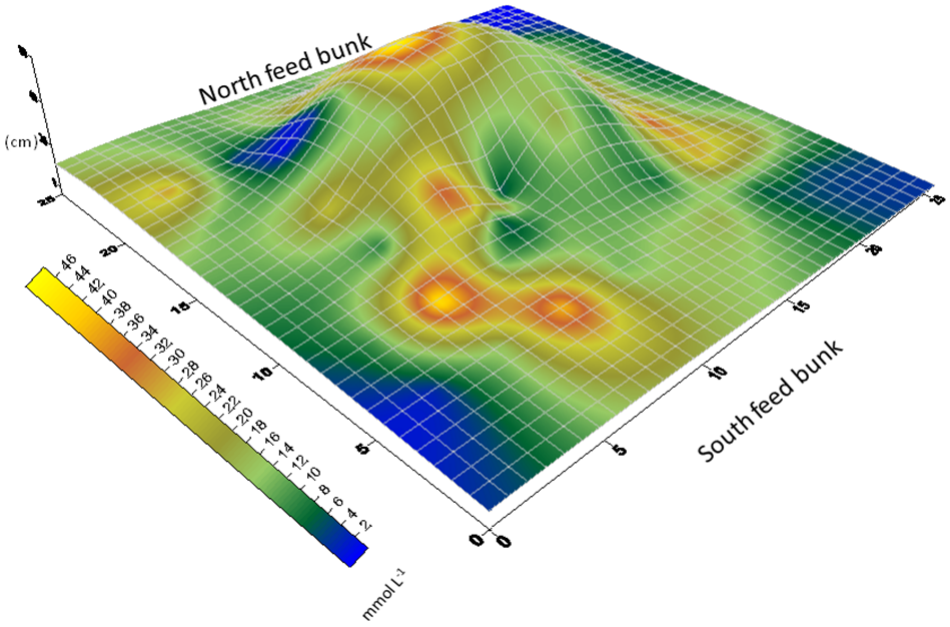

Figure 4. Example of spatial variability of steady-state ammonia concentration (mmol L^{-1}) in air samples collected from a deep-bedded mono-slope facility (barn B, pen 1). Areas of high ammonia concentration, indicated in light colors, are found at random locations throughout the pen.

Table 2. Concentration of ammonia in the air and volatile organic compounds in the bedding/manure material at various locations in beef deep-bedded mono-slope facilities.[a]

	Bedded pack[b]	Transition[c]	Concrete[d]
Ammonia (mmol L^{-1})	68.3 ±2.8	63.9 ±3.9	70.2 ±3.4
VFA (mmol g^{-1})[e]	88.5 ±5.8 b	163.0 ±8.2 a	168.1 ±6.3 a
SCFA (mmol g^{-1})[f]	80.2 ±5.6 b	154.0 ±8.0 a	162.6 ±6.2 a
BCFA (mmol g^{-1})[g]	2.6 ±0.2 b	3.8 ±0.3 a	3.7 ±0.2 a
Aromatics (mmol g^{-1})[h]	2.2 ±0.6 b	12.8 ±0.8 a	11.7 ±0.6 a
Temperature (°C)	25.7 ±0.3 a	19.0 ±0.5 b	17.3 ±0.4 c
Moisture (%)	64.6 ±0.3 b	70.4 ±0.5 a	71.3 ±0.4 a

[a] *N* = 1257 and included data from both barns. Values are least squares means with standard errors. Different letters within a row indicate a significant difference ($p < 0.01$).
[b] Bedded pack = area of pen having pack depth >15 cm.
[c] Transition = area in pen having pack depth 7.6 to 15 cm.
[d] Concrete = area of pen having pack depth <7.6 cm.
[e] VFA = total volatile fatty acids.
[f] SCFA = total straight-chain fatty acids, which included acetate, butyrate, propionate, valerate, caproate, heptanoate, and caprylate.
[g] BCFA = total branch-chain fatty acids, which included isobutyrate, isovalerate, and isocaproate.
[h] Aromatics included *p*-cresol, phenol, 4-ethylphenol, skatole, and indole.

Table 3. Relative differences in ammonia concentration (mmol L^{-1}) in air samples collected from the feedlot surface of beef deep-bedded mono-slope facilities after cattle were removed from pens.[a]

Location	0 h	4 to 7h	10 h
Barn A[b]	102.9 ±9.2 a	43.7 ±5.0 b	37.8 ±3.3 b
Barn B[c]	88.2 ±11.9 a	54.1 ±3.8 b	51.4 ±3.7 b

[a] Data do not represent absolute emissions. *N* = 168 for each barn. Values are least square means with standard errors. Different letters within a row indicate a significant difference ($p < 0.01$).
[b] Samples collected at 0, 4, and 10 h after cattle were removed from pen in June 2008.
[c] Samples collected at 0, 7, and 10 h after cattle were removed from pen in September 2008.

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 NH_3 within 3 h, with complete volatilization of urinary urea by 24 h. Unfortunately, this meant that areas of high NH_3 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 NH_3 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 NH_3, 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 NH_3 volatilization from livestock facilities is well documented in the literature. Whitehead and Raistrick (1991) measured NH_3 volatilization of simulated livestock urine applied to soil and reported an increase in volatilization

Table 4. Effect of season on pack characteristics in beef deep-bedded mono-slope facilities.[a]

	Cold[b]	Moderate[c]	Hot[d]
Ammonia (mmol L^{-1})[e]	14.8 ±5.4 c	57.6 ±2.3 b	99.5 ±2.9 a
Pack temperature (°C)	15.4 ±0.4 c	19.2 ±0.3 b	29.0 ±0.3 a
Pack moisture (%)	69.9 ±0.5 a	68.1 ±0.4 a	63.4 ±0.5 b
Pack depth (cm)	22.0 ±0.9 a	17.0 ±0.7 a	33.0 ±1.1 b
pH	7.5 ±0.04 a	8.0 ±0.04 b	7.5 ±0.04 a
Total VFA (mmol g^{-1})[f]	156.1 ±7.0 b	154.5 ±6.5 b	91.5 ±6.5 a
Total SCFA (mmol g^{-1})[g]	145.1 ±6.7 b	143.2 ±6.3 b	88.5 ±6.3 a
Total BCFA (mmol g^{-1})[h]	3.5 ±0.23	3.1 ±0.21	3.0 ±0.22
Total aromatics (mmol g^{-1})[i]	9.7 ±0.69 b	9.63 ±0.65 b	4.21 ±0.65 a
E. coli O157:H7 (% positive samples)	30.0 a	33.0 a	50.2 b
Average generic *E. coli* (log_{10} CFU g^{-1})	5.99 ±0.05 a	6.41 ±0.04 b	6.47 ±0.02 b

[a] 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 ($p < 0.01$).

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

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

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

[e] Ammonia concentration in air samples collected from the pen surface.

[f] VFA = total volatile fatty acids.

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

[h] BCFA = total branch-chain fatty acids, which included isobutyrate, isovalerate, and isocaproate.

[i] Aromatics included *p*-cresol, phenol, 4-ethylphenol, skatole, and indole.

from 25% to 38% as the temperature of incubation increased from 4˚C to 20˚C. Misselbrook et al. (1998) reported NH_3 emissions of 8.0 g N m^2 d^{-1} during the summer and 1.1 g N m^2 d^{-1} during the winter from concrete yards used to house dairy cattle. Similarly, Todd et al., (2008) reported summer and winter ammonia emissions of 7810 kg d^{-1} and 5800 kg d^{-1}, respectively. Ammonia nitrogen losses from cattle defecation and urination measured under pasture field conditions were reported as 1.8% in winter and 20.9% during summer months (Mulvaney et al., 2008). Ammonia emissions arise primarily from the hydrolysis of urea in the urine. Vlek and Carter (1983) found that the rate of urea hydrolysis in soil was linearly related to temperature over the range of 10˚C to 40˚C. Average pack temperatures and standard errors in the BDMF during the cold, moderate, and hot months were 15.4˚C ±0.3˚C, 19.2˚C ±0.3˚C, and 29.0˚C ±0.3˚C, respectively. It is likely that the same linear relationship exists in the bedded pack, although urea hydrolysis was not directly measured in this study.

Temperature of the bedded pack was higher during the hot months compared to the moderate and cold months (table 4). This is likely a result of increased ambient air temperature. The increase in bedded pack temperature could also be caused in part by increased microbial activity in the bedded pack during the hot months. Free air space, C/N ratio, and other indicators of composting potential were not measured in this study. However, the moisture content of the bedded pack during the hot months was slightly lower than during cold or moderate months and within the recommended range of 40% to 65% for composting (NRAES, 1999). Fewer void spaces filled with water would increase oxygen availability for composting. Oxygen transfer into the bedded pack may have also increased during the hot months due to less compaction of the bedded pack. The depth of the bedded pack was higher during the hot months, which may indicate less trampling by livestock. Producers observed cattle lying on the concrete area surrounding the bedded pack instead of on the bedded pack area during hot months. The T and C area of the pen were cooler and had higher moisture content at this time, which allowed for heat loss through evaporation and conduction (table 2).

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 more 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 NH_3 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; Mitlöhner 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 NH_3 concentrations from the bedded

Table 5. Differences in environmental conditions between the inside and outside of the beef deep-bedded mono-slope facilities during cold, moderate, and hot seasons.[a]

	Temperature (°C)		Relative Humidity (%)		THI[b]	
Season	Inside	Outside	Inside	Outside	Inside	Outside
Cold[c]	-2.8 x,A	-6.5 y,A	73.2	72.0	31.2 x,A	24.9 y,A
Moderate[d]	11.7 x,B	10.8 y,B	68.3	68.5	53.8 B	52.9 B
Hot[e]	23.9 x,C	22.9 y,C	70.3	66.8	72.1 x,C	69.8 y,C

[a] N = 4726 and included data from both barns. Outside temperature and relative humidity sensors were located at the barn site on an external support 3 m above the ground. Inside sensors were positioned inside the mono-slope facility 3.3 m above the feedlot surface on the north side of an I-beam located in the middle of the pen. Different lowercase letters within a row and different uppercase letters within a column indicate a significant seasonal difference for variable ($p < 0.01$).

[b] Temperature humidity index calculated as $THI = 0.81t_{db} + RH\ (t_{db} - 14.4) + 46.4$, where t_{db} is the dry bulb temperature (°C), and RH is relative humidity expressed as a decimal (Thom, 1959).

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

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

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

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 NH_3 (Voorburg and Kroodsma, 1992), and increases the mineralization of organic N (Voorburg and Kroodsma, 1992), which contribute to more NH_3 production and a higher NH_3 emission rate (Voorburg and Kroodsma, 1992; Jeppsson, 1999). Conditions that promote rapid drying of the pen surface also encourage NH_3 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 NH_3 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 NH_3 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 NH_3 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 NH_3 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 NH_3 volatilization. Therefore, it is likely that, in the current study, the increase in bedded pack temperature contributed to the increased NH_3 concentration in air samples collected from the bedded pack surface of the mono-slope barns.

Moisture content also influences NH_3 emissions. In dry soil, the transport of NH_4^+ ions from the soil surface down to the deep soil horizon is restricted; hence, increased losses of nitrogen occur as NH_3 emissions from the soil (Liu et al., 2007). Sherwood et al. (2007) reported an increase in NH_3 losses from the surface of open feedlots when the moisture content of the soil was decreased. Liu et al. (2007) measured NH_3 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 NH_3 volatilization (Liu et al., 2007). Water acts a solvent to transport NH_4^+ away from the soil surface (Liu et al., 2007). The drier bedded pack during the hot months may have contributed to higher concentration of NH_3 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 NH_4^+ ions and NH_3 in manure. If the pH value is decreased, then the equilibrium is displaced toward NH_4^+ and less NH_3 is formed (Kirchmann and Witter, 1989). The pH of the bedded packs in the two barns studied was poorly correlated to NH_3 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 NH_3 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 ($r^2 \leq 0.24$).

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

Table 6. Effect of bedding management on pack characteristics of beef deep-bedded mono-slope facilities.[a]

	Deep-Bedded Management[b]	Shallow-Bedded Management[c]
Pack moisture (%)	63.1 ±0.6 a	67.2 ±0.6 b
Pack temperature (°C)	21.2 ±0.6 a	18.4 ±0.5 b
Total VFA (mmol g^{-1})	73.8 ±10.4 a	142.0 ±10.5 b
Straight-chain VFA (mmol g^{-1})	71.7 ±10.1 a	138.2 ±10.1 b
Branch-chain VFA (mmol g^{-1})	2.1 ±0.4 a	3.8 ±0.4 b
Aromatics (mmol g^{-1})	2.6 ±0.4 a	4.4 ±0.4 b
Volatile solids (%)	83.8 ±0.2	87.1 ±0.2

[a] N = 168 and included data from one pen in barn A for April, June, and August 2009. Values are least square means with standard errors. Different letters within a row indicate a significant difference ($p \leq 0.01$).

[b] A bedded pack was allowed to accumulate in the center of the pen while cattle were in barn. The area around the pack was scraped and removed, and fresh bedding was added to the pack once weekly.

[c] All bedding and manure were completely removed every three weeks. Fresh bedding was added as needed, but no bedded pack was allowed to accumulate.

Table 7. Nutrient composition of manure from beef deep-bedded mono-slope facilities.[a]

	Barn A, Pen 13	Barn A, Pen 14	Barn B, Pen 1	Barn B, Pen 4
Dry matter (%)	16.9 ±0.45	16.3 ±0.49	16.4 ±0.32	18.0 ±0.33
Total (g kg^{-1})	23.6 ±0.49	23.5 ±0.57	22.0 ±0.37	21.2 ±0.27
Total P (g kg^{-1})	6.7 ±0.19	7.1 ±0.19	7.5 ±0.25	7.1 ±0.29
Total K (g kg^{-1})	16.9 ±0.44	15.5 ±0.43	19.9 ±0.57	21.1 ±0.66
Total S (g kg^{-1})	6.65 ±0.26	5.9 ±0.31	5.6 ±0.20	5.6 ±0.20
Volatile solids (%)	83.8 ±0.19	84.6 ±0.20	78.6 ±0.18	79.1 ±0.18

[a] N = 1062 and included data from both barns. Total N, total P, total K, total S, and volatile solids expressed on a dry-matter basis. Values presented are least square means with standard errors.

Table 8. *E. coli* O157:H7 prevalence in bedding/manure from beef deep-bedded mono-slope facilities.

Sampling Period (2009)	Barn A, Pen 13		Barn A, Pen 14		Barn B, Pen 1		Barn B, Pen 4
	Positive/total samples[a]	% Positive[b]	Positive/total samples[a]	% Positive[b]	Positive/total samples[a]	% Positive[b]	Positive/total samples[a]
March	ns	ns	0/38	0 x,A	44/56	78.6 y,A	1/56
April	0/56	0 x,A	1/56	1.8 x,A	48/56	85.7 y,A	19/56
June	9/56	16.1 x,B	50/56	89.3 y,B	2/56	3.6 x,B	36/56
August	46/56	82.1 x,C	2/56	3.6 y,A	53/56	94.6 x,A	27/56
October	0/56	0 x,A	2/56	3.6 y,A	51/56	91.1 x,A	27/56

[a] Values indicate the number of positive samples / the total number of samples; ns = not sampled.
[b] Different lowercase letters within a row and different uppercase letters within a column indicate a significant difference ($p \leq 0.01$).

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 NH_3 emissions compared to deep-bedded management, making it an effective management tool during hot months when NH_3 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 $\log_{10}$ CFU per g of bedding/manure material, with an average level of 6.38 $\log_{10}$ CFU per g of material. Similar to steady-state NH_3 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 NH_3 concentration on the pen surface of BDMF. Areas with a high NH_3 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 NH_3 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 NH_3 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

Aarnink, A. J. A., M. J. M. Wagemans, and A. Keen. 1993. Factors affecting ammonia emission from housing for weaned piglets. In *Proc. Nitrogen Flow in Pig Production and Environmental Consequences*, 286-294. M. W. A. Verstegen, L. A. den Hartog, G. J. M. van Kempen, and J. H. M. Metz, eds. Wageningen, The Netherlands: Pudoc Scientific Publishers.

Aneja, V. P., B. P. Malik, Q. Tong, D. Kang, and J. H. Overton. 2001. Measurement and modeling of ammonia emissions at waste treatment lagoon-atmospheric interface. *Water, Air, and Soil Pollution: Focus* 1(5-6): 177-188.

APHIS. 2001. *Escherichia coli* O157 in United States feedlots. Washington, D.C.: USDA Animal and Plant Health Inspection Service. Available at: www.aphis.usda.gov/animal_health/nahms/feedlot/downloads/feedlot99/Feedlot99_is_Ecoli.pdf. Accessed 30 July 2010.

Arthur, T. M., J. E. Keen, J. M. Bosilevac, D. M. Brichta-Harhay, N. Kalchayanand, S. D. Shackelford, T. L. Wheeler, X. Nou, and M. Koohmaraie. 2009. Longitudinal study of *Escherichia coli* O157:H7 in a beef cattle feedlot and role of high-level shedders in hide contamination. *Appl. Environ. Microbiol.* 75(20): 6515-6523.

ASABE Standards. 2005. D384.2: Manure production and characteristics. St. Joseph, Mich.: ASABE.

Barkocy-Gallagher, G. A., T. M. Arthur, M. Rivera-Betancourt, X. Nou, S. D. Shackelford, T. L. Wheeler, and M. Koohmaraie. 2003. Seasonal prevalence of Shiga toxin-producing *Escherichia coli*, including O157:H7 and non-O157 serotypes, and *Salmonella* in commercial beef processing plants. *J. Food Prot.* 66(11): 1978-1986.

Berry, E. D., J. E. Wells, T. M. Arthur, B. L. Woodbury, J. A. Nienaber, T. M. Brown-Brandl, and R. A. Eigenberg. 2010. Soil vs. pond ash surfacing of feedlot pens: Occurrence of *Escherichia coli* O157:H7 in cattle and persistence in manure. *J. Food Prot.* 73(7): 1269-1277.

Brosh, A., Y. Aharoni, A. A. Degen, D. Wright, and B. Young. 1998. Effects of solar radiation, dietary energy, and time of feeding on thermoregulatory responses and energy balance in cattle in a hot environment. *J. Animal Sci.* 76(10): 2671-2677.

Cole, N. A., R. N. Clark, R. W. Todd, C. R. Richardson, A. Gueye, L. W. Greene, and K. McBride. 2005. Influence of dietary crude protein concentration and source on potential ammonia emissions from beef cattle manure. *J. Animal Sci.* 83(3): 722-731.

Cole, N. A., R. W. Todd, D. B. Parker, and M. B. Rhodes. 2007. Challenges in using flux chambers to measure ammonia emissions from simulated feedlot pen surfaces and retention ponds. In *Proc Intl. Symp. Air Qual. Waste Mgmt.* St. Joseph, Mich.: ASABE.

Doran, B., R. Euken, and M. Spiehs. 2010. Hoops and mono-slopes: What we have learned about management and performance. In *Feedlot Forum 2010*. Ames, Iowa: Iowa State University, Iowa Beef Center.

Ebeling, A. M., L. G. Bundy, J. M. Powell, and T. W. Andraski. 2002. Dairy diet phosphorus effects on phosphorus losses in runoff and land-applied manure. *SSSA J.* 66(1): 284-291.

Eigenberg, R. A., and T. M. Brown-Brandl. 2009. Shade material evaluation using a cattle response model and meteorological instrumentation. *Intl. J. Biometeorol.* 53(6): 501-507.

Ernst, J. W., and H. F. Massey. 1960. The effects of several factors on volatilization of ammonia formed from urea in the soil. *SSSA J.* 24(2): 87-90.

Flesch. T. K., J. D. Wilson, L. A. Harper, R. W. Todd, and N. A. Cole. 2007. Determining ammonia emissions from a cattle feedlot with an inverse dispersion technique. *Agric. Forest Meteorol.* 144(1-2): 139-155.

Jacobson, L. D., D. R. Schmidt, J. K. Lake, and V. J. Johnson. 2003. Ammonia, hydrogen sulfide, odor, and PM_{10} emissions from deep-bedded hoop and curtain-sided pig finishing barns in Minnesota. In *Proc. Conf. Air Pollution from Agricultural Operations III*, 283-291. Robert Burns, ed. ASAE Pub. No. 701P1403. St. Joseph, Mich.: ASAE.

Jacobson, L. D, B. P. Hetchler, L. J. Johnston, and V. J. Johnson. 2004. Gas and PM emissions from deep-bedded and slatted floor farrowing buildings. ASAE/CSAE Meeting Paper No. 044155. St. Joseph, Mich.: ASAE/CSAE.

Jeppsson, K. H. 1999. Volatilization of ammonia in deep-litter systems with different bedding materials for young cattle. *J. Agric. Eng. Res.* 73(1): 49-57.

Kirchmann, H., and E. Witter. 1989. Ammonia volatilization during aerobic and anaerobic manure decomposition. *Plant and Soil* 115(1): 35-41.

Liu, G. D., Y. C. Li, and K. Alva. 2007. Moisture quotients for ammonia volatilization from four soils in potato production regions. *Water Air Soil Pollution* 183(1-4): 115-127.

Liu, Z., L. Wang, and D. B. Beasley. 2006. A review of emission models of ammonia released from broiler houses. ASABE Paper No. 064101. St. Joseph, Mich.: ASABE.

Lockyer, D. R., and D. C. Whitehead. 1990. Volatilization of ammonia from cattle urine applied to grassland. *Soil Biol. Biochem.* 22(8): 1137-1142.

Mackie, R. I. 1994. Microbial production of odor components. In *Proc. Intl. Roundtable on Swine Odor Control*, 18-19. Ames, Iowa: Iowa State University.

Mackie, R. I., P. G. Stroot, and V. H. Varel. 1998. Biochemical identification and biological origin of key odor components in livestock waste. *J. Animal Sci.* 76(5): 1331-1342.

Mader, T. L., J. M. Dahlquist, G. L. Hahn, and J. B. Gaughan. 1999. Shade and wind barrier effects on summer-time feedlot cattle performance. *J. Animal Sci.* 77(8): 2065-2072.

Miller, D. N., and V. H. Varel. 2001. In vitro study of the biochemical origin and production limits of odorous compounds in cattle feedlots. *J. Animal Sci.* 79(12): 2949-2956.

Miller, D. N., and B. L. Woodbury. 2006. A solid-phase microextraction chamber method for analysis of manure volatiles. *J. Environ. Qual.* 35(6): 2383-2394.

Misselbrook, T. H., B. F. Pain, and D. M. Headon. 1998. Estimates of ammonia emission from dairy cow collecting yards. *J. Agric. Eng. Res.* 71(2): 127-135.

Mitlöhner, J., L. Morrow, J. W. Dailley, S. C. Wilson, M. L. Galyean, M. F. Miller, and J. J. McGlone. 2001. Shade and water misting effects on behavior, physiology, performance, and carcass traits of heat-stressed feedlot cattle. *J. Animal Sci.* 79(9): 2327-2335.

Morse, D., H. Head, C. Wilcox, H. Van Horn, C. Hissem, and B. Harris Jr. 1992. Effects of concentration of dietary phosphorus on amount and route of excretion. *J. Dairy Sci.* 75(11): 3039-3049.

Mulvaney, M. J., K. A. Cummins, C. W. Wood, B. H. Wood, and P. J. Tyler. 2008. Ammonia emissions from field-simulated cattle defecation and urination. *J. Environ. Qual.* 37(6): 2022-2027.

NRAES. 1999. *Field Guide to On-Farm Composting.* NRAES-114. M. Dougherty, ed. Ithaca, N.Y.: Natural Resource Agricultural and Engineering Service.

O'Neill, D. H., and V. R. Phillips. 1992. A review of the control of odour nuisance from livestock buildings: Part 3. Properties of the odorous substances which have been identified in livestock waste or in the air around them. *J. Agric. Eng. Res.* 53: 23-50.

Paton, A. W., and J. C. Paton. 1998. Detection and characterization of Shiga toxigenic *Escherichia coli* by using multiplex PCR assays for stx_1, stx_2, *eaeA*, enterohemorrhagic *E. coli hlyA*, $rfbO_{111}$, and rfb_{O157}. *J. Clin. Microbiol.* 36(2): 598-602.

Rappert, S., and R. Muller. 2005. Odor compounds in waste gas emissions from agricultural operations and food industries. *Waste Mgmt.* 25(9): 887-907.

Sherwood, D. M., G. E. Erickson, and T. J. Klopfenstein. 2006. Nitrogen mass balance and cattle performance of steers fed clinoptilolite zeolite clay. In *2006 Nebraska Beef Cattle Report*, 90-91. Lincoln, Neb.: University of Nebraska, Institute of Agriculture and Natural Resources.

Sherwood, D. M., G. E. Erickson, T. J. Klopfenstein, D. D. Schulte, and R. R. Stowell. 2007. Feedlot surface conditions and ammonia emissions. In *2007 Nebraska Beef Cattle Report*, 50-51. Lincoln, Neb.: University of Nebraska, Institute of Agriculture and Natural Resources.

Shurson, J., M. Whitney, and R. Nicolai. 1998. Nutritional manipulation of swine diets to reduce hydrogen sulfide emissions. In *Proc. 59th Minnesota Nutr. Conf. and IPC Tech. Symp.*, 219-240. St. Paul, Minn.: University of Minnesota Extension Service.

Smith, D., M. Blackford, S. Younts, R. Moxley, J. Gray, L. Hungerford, T. Milton, and T. Klopfenstein. 2001. Ecological relationships between the prevalence of cattle shedding *Escherichia coli* O157:H7 and characteristics of the cattle or conditions of the feedlot pen. *J. Food Prot.* 64(12): 1899-1903.

Thom, E. C. 1959. The discomfort index. *Weatherwise* 12(): 57-59.

Todd, R. W., N. A. Cole, R. N. Clark, T. K. Flesch, L. A. Harper, and B. H. Baek. 2008. Ammonia emissions from a beef cattle feedyard on the southern High Plains. *Atmos. Environ.* 42(28): 6797-6805.

Van Donkersgoed, J., T. Graham, and V. Gannon. 1999. The prevalence of verotoxins, *Escherichia coli* O157:H7, and Salmonella in the feces and rumen of cattle at processing. *Canadian Vet. J.* 40(5): 332-338.

Van Horn, H. H., G. L. Newton, and W. E. Kunkle. 1996. Ruminant nutrition from environmental perspective: Factors affecting whole-farm nutrient balance. *J. Animal Sci.* 74(12): 3082-3102.

Varel, V. H. 1997. Use of urease inhibitors to control nitrogen loss from livestock manure. *Biores. Tech.* 62(1-2): 11-17.

Vlek, P. L. G., and M. F. Carter. 1983. The effect of soil environment and fertilizer modifications on the rate of urea hydrolysis. *Soil Sci.* 136(1): 56-63.

Voorburg, J. H., and W. Kroodsma. 1992. Volatile emissions of housing systems for cattle. *Livestock Prod. Sci.* 31(1-2): 57-70.

Watson, M., A. Wolf, and N. Wolf. 2003. Total nitrogen. In *Recommended Methods of Manure Analysis*, 18-24. Publication No. A3769. Madison, Wisc.: University of Wisconsin Cooperative Extension.

Wells, J. E., S. D. Shackelford, E. D. Berry, N. Kalchayanand, M. N. Guerini, V. H. Varel, T. M. Arthur, J. M. Bosilevac, H. C. Freetly, T. L. Wheeler, C. L. Ferrell, and M. Koohmaraie. 2009. Prevalence and level of *Escherichia coli* O157:H7 in feces and on hides of feedlot steers fed diets with or without wet distillers grains with solubles. *J. Food Prot.* 72(8): 1624-1633.

Whitehead, D. C., and N. Raistrick. 1991. Effects of some environmental factors on ammonia volatilization from simulated livestock urine applied to soil. *Biol. Fertil. Soils* 11(4): 279-284.

Wolf, A., M. Watson, and N. Wolf. 2003. Digestion and dissolution methods for P, K, Ca, Mg, and trace elements. In *Recommended Methods of Manure Analysis*, 30-38. Publication No. A3769. Madison, Wisc.: University of Wisconsin Cooperative Extension.

Woodbury, B. L., D. N. Miller, R. A. Eigenberg, and J. A. Nienaber. 2006. An inexpensive laboratory and field chamber for manure volatile gas flux analysis. *Trans. ASABE* 49(3): 767-772.

Woodbury, B. L., R. A. Eigenberg, and J. A. Nienaber. 2007. Comparing soil and pond ash feedlot pen surfaces for environmental management. ASABE Paper No. 074070. St. Joseph, Mich.: ASABE.

Wu, Z., L. D. Satter, and R. Sojo. 2000. Milk production, reproductive performance, and fecal excretion of phosphorus by dairy cows fed three amounts of phosphorus. *J. Dairy Sci.* 83(5): 1028-1041.

Zahn, J. A., J. L. Hatfield, Y. S. Do, A. A. DiSpirito, D. A. Laird, and R. L. Pfeiffer. 1997. Characterization of volatile organic emissions and waste from a swine production facility. *J. Environ. Qual.* 26(6): 1687-1696.

Zhu, E. 2000. A review of microbiology in swine manure odour control. *Agric. Ecosystems and Environ.* 78(2): 93-106.