Cattle Feedlot Soil Moisture and Manure Content: I. Impacts on Greenhouse Gases, Odor Compounds, Nitrogen Losses, and Dust

Daniel N. Miller* and Elaine D. Berry

ABSTRACT

Beef cattle feedlots face serious environmental challenges associated with manure management, including greenhouse gas, odor, NH_3, and dust emissions. Conditions affecting emissions are poorly characterized, but likely relate to the variability of feedlot surface moisture and manure contents, which affect microbial processes. Odor compounds, greenhouse gases, nitrogen losses, and dust potential were monitored at six moisture contents (0.11, 0.25, 0.43, 0.67, 1.00, and 1.50 g H_2O g^{-1} dry matter [DM]) in three artificial feedlot soil mixtures containing 50, 250, and 750 g manure kg^{-1} total (manure + soil) DM over a two-week period. Moisture addition produced three microbial metabolisms: inactive, aerobic, and fermentative at low, moderate, and high moisture, respectively. Manure content acted to modulate the effect of moisture and enhanced some microbial processes. Greenhouse gas (CO_2, N_2O, and CH_4) emissions were dynamic at moderate to high moisture. Malodorous volatile fatty acid (VFA) compounds did not accumulate in any treatments, but their persistence and volatility varied depending on pH and aerobic metabolism. Starch was the dominant substrate fueling both aerobic and fermentative metabolism. Nitrogen losses were observed in all metabolically active treatments; however, there was evidence for limited microbial nitrogen uptake. Finally, potential dust production was observed below defined moisture thresholds, which were related to manure content of the soil. Managing feedlot surface moisture within a narrow moisture range (0.2–0.4 g H_2O g^{-1} DM) and minimizing the accumulation of manure produced the optimum conditions that minimized the environmental impact from cattle feedlot production.

Recently, cattle feedlot production systems have received attention for the environmental challenges associated with manure accumulation, storage, and disposal (National Research Council, 2003). Chief among these issues are odor, NH_3, dust, greenhouse gas (GHG), and pathogen emissions from the feedlot environment. Typical feedlot systems involve multiple pens (up to several hundred) equipped with watering and feeding sites with each pen holding dozens of animals for several months. Thus, manure management is a particularly challenging issue.

A standard feedlot management objective is to maintain a 2.5- to 5.0-cm layer of well-compacted manure above the mineral soil to enhance drainage, limit seepage, and decrease stress-related leg injuries in cattle. Excess manure is then scraped off the surface between cattle production cycles, usually once or twice a year. Manure enrichment, compaction, and moisture contents all vary considerably across the pen surface and with time during the production cycle (Woodbury et al., 2001) and depend predominantly on the location of feed and water sources. Thus, treating the pen surface as a single, homogenous source oversimplifies its complexity and hinders the development of methods that minimize feedlot emissions.

Odor, NH_3, dust, GHG, and pathogen emissions will be related to one another due to similar formation and transport processes. For instance, odor compounds and GHGs are the byproducts of microbial activities (Mackie et al., 1998) utilizing the substrates found in the manure (Miller and Varel, 2003). Ammonia emissions show a close relationship to odor (McGinn et al., 2003) and are also affected to some degree by microbial activities; the conversion of urea in urine to NH_4^+ is catalyzed by the enzyme urease in the feedlot surface (Muck and Richards, 1980; Varel et al., 1999). Environmental conditions, such as temperature, moisture, and manure content, will influence microbial activities and can directly modify gaseous flux rate and dust formation. Manipulating the feedlot surface moisture through sprinkler irrigation rate or varying stocking density to maintain the moisture content within a 20 to 41% (total mass basis) range has been recommended to control dust at cattle feedlots (Auvermann and Romanillos, 2000; Sweeten et al., 1988; Sweeten, 1998). Modifying cattle behavior relative to feeding schedule may also limit dust emissions (Wilson et al., 2002). Clarifying the effects that temperature, moisture, and manure content have on odor, NH_3, dust, and GHG emissions over a range of values would be a critical component establishing cattle feedlot practices that minimize environmental impact.

Although our knowledge of factors influencing individual emissions is expanding, the broad context of multiple emissions and their interactions, from a systems perspective, is lacking. Moisture content and the potential for dust or odor emission have been recognized, but not thoroughly described. Secondary effects of moisture manipulation for dust or odor control on feedlot surface soil N losses, GHG production, and pathogen persistence have not been investigated. The objective of this initial study was to quantify the effect of feedlot surface moisture in three manure and soil mixtures on odor production, dust potential, GHG emissions, and soil N losses under defined laboratory conditions. A companion study (Berry and Miller, 2005) reports the effect of manure and moisture content on pathogenic bacteria and indicator microorganisms.

USDA-ARS, U.S. Meat Animal Research Center, P.O. Box 166, Clay Center, NE 68933-0166. Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA and does not imply approval to the exclusion of other products that may be suitable. Received 18 Mar. 2004. *Corresponding author (miller@email.marc.usda.gov).

Published in J. Environ. Qual. 34:644–655 (2005).

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: DM, dry matter; FSM, feedlot surface mixture; GHG, greenhouse gas; MT, moisture threshold; OM, organic matter; VFA, volatile fatty acid; VFA_{COOH}, volatile fatty acid (protonated form).

MATERIALS AND METHODS

Soil and Manure Collection

Feedlot manure and soil samples were collected at the 6000 head capacity, open-air beef cattle feedlot at the USDA-ARS, U.S. Meat Animal Research Center located in south-central Nebraska. The feedlot was constructed on Hastings silt-loam soils (fine, smectitic, mesic Udic Argiustolls). The soil sample was collected from the surface soil (top 2 cm) in a feedlot drainage ditch and sieved through a screen (4 mm), whereas the manure samples (fresh, noncrusted) were collected from a nearby pen. Heifers in this pen were fed 7.63 kg dry matter (DM) animal^{-1} daily on a diet that contained 76.25% high moisture corn, 19.25% corn silage, and 4.50% liquid supplement (described in Miller and Varel, 2001) on a DM basis. The manure and soil stocks were dried for 2 d at 37°C with daily turning in aluminum pans. Since the manure was still too moist, half was dried for an additional day at 80°C, recombined with the remaining manure, and then ground (6 mm, Model 4732; Hobart Corp., Troy, OH). The DM and organic matter (OM) contents of the manure were determined before each of the three experiments. Dry matter was determined after drying overnight at 105°C, and OM was determined after loss-on-ignition at 425°C overnight (Nelson and Sommers, 1996). The final moisture contents of soil and manure stock were $<$0.1 g H_2O g^{-1} DM.

Pan Incubations

Three feedlot surface mixtures (FSM) containing dried manure (5, 25, and 75% manure on a DM basis with dried soil accounting for the remaining DM) were evaluated. The manure levels contained 99, 235, and 590 g OM kg^{-1} DM, respectively, similar to observed feedlot OM values (Woodbury et al., 2001). Incubations were conducted in plastic pans (18 cm long $\times$ 12.5 cm wide $\times$ 8.5 cm deep). Six target moisture levels of 0.11, 0.25, 0.43, 0.67, 1.00, or 1.50 g H_2O g^{-1} dry FSM were tested. Pans contained 360, 320, 280, 240, 200, or 160 g dry FSM with 1 g of powdered urea added per kilogram of dry FSM. In the 25% manure level incubation, all pans inadvertently received varying amounts of urea, which was mixed into the H_2O, and not the FSM, before incubation. Water was mixed into each of the pans to reach a final mass of 400 g. The depth of moistened FSM in the pans was roughly 4 cm, and the bulk density varied from 270 to 1200 kg m^{-3}, similar to observed feedlot values (Woodbury et al., 2001). Three replicate pans were prepared for each manure and moisture content. These were then incubated at room temperature (18–22°C) for a period of two weeks under mosquito netting to avoid possible transport of pathogens by insects in the incubation room. To maintain the FSM target moisture content, additional water was thoroughly mixed into the FSM daily based on the mass loss from the previous day. Gas samples for H_2, O_2, CO, CH_4, N_2O, and CO_2 were collected on Days 0, 1, 2, 3, 7, and 14 in 3-mL syringes 1 h after sealing each of the pans with lids (headspace volume = 1.4–1.7 L) equipped with rubber septa. (Uniform gas emissions were observed in initial incubations at 10-min intervals over 1 h.) Background air samples from the incubation room were also collected in syringes. Immediately following the collection of gas samples, FSM moisture content was adjusted to the target moisture content. Three, 2-g (wet wt.) FSM samples were collected from each pan for dry and organic matter, KCl-extractable N content, and odor compounds and fermentation products and either immediately processed (DM, OM, and N content) or frozen (odor compounds and fermentation products) for subsequent analysis. A fourth 4-g FSM sample was also collected for pH and microbial substrates and was frozen after pH determination.

Sample Analysis

Sample DM and OM contents were determined according to Nelson and Sommers (1996). The pH was determined using a PHM 83 pH meter (Radiometer, Copenhagen, Denmark) after mixing the 4-g sample with 10 mL of H_2O and an equilibration of 5 min. After pH determination, that particular sample was made alkali by the addition of 2 *M* NaOH (2 mL), freeze-dried, and ground to a fine powder using a mortar and pestle. Crude protein in the dried sample was calculated by multiplying the N content, determined using a CN-2000 carbon and nitrogen analyzer (LECO, St. Joseph, MI), by 6.25. Starch content in the dried sample was determined by hydrolyzing the starch during a 2-h digestion with amyloglucosidase and measuring dextrose using a Model 2700 autoanalyzer (Yellow Springs Instrument Company, Yellow Springs, OH). Total polysaccharide was determined using the phenol–sulfuric acid assay described by Daniels et al. (1994), with nonstarch polysaccharide calculated as the difference between total polysaccharide and starch. Loss of a particular substrate was deemed significant if the average substrate contents at the beginning and end of incubation differed ($P < 0.05$).

Inorganic N (NH_4^+, NO_2^-, and NO_3^-) and urea were extracted from each fresh sample by the addition of 8 mL of 2 *M* KCl and vigorous shaking for 1 h at room temperature (Mulvaney, 1996). After centrifugation at 10 000 $\times$ *g* for 5 min, 2 mL of supernatant was transferred to another tube, acidified by the addition of 5 μL of concentrated H_2SO_4, and stored at 4°C until analysis. Urea and NH_4^+ in the extracts were analyzed using a Technicon (Tarrytown, NY) autoanalyzer by a modification of the carbamido–diacetyl reaction and indophenol blue methods, respectively, as previously described (Varel et al., 1999). The Technicon autoanalyzer was also used for NO_3^- and NO_2^- analysis by copperized cadmium reduction of NO_3^- to NO_2^- followed by NO_2^- quantification using the Griess–Illosvay reaction (Bundy and Meisinger, 1994).

Headspace gas samples were analyzed for H_2, O_2, CO, CH_4, N_2O, and CO_2 content using an 8610C gas chromatograph (SRI Instruments, Torrance, CA) equipped with helium ionization and thermal conductivity detectors. The instrument was configured for multiple gas analysis according to the manufacturer's specification using a 10-port gas sampling valve with 1-mL injection loop, a 91-cm-long column (3-mm i.d.) packed with silica gel, and a 91-cm-long column (3-mm i.d.) packed with molecular sieve 5A. Gases were separated using He gas (241 KPa or 35 psi) during a 6.2-min run with the silica gel column experiencing a ramping temperature cycle (initial temperature = 45°C, initial time = 2 min, first temperature ramp = 30°C min^{-1} to 110°C, second temperature ramp = 10°C min^{-1} to 120°C, hold at 120°C for 1 min) and the molecular sieve column submerged in an ice water bath. Three gas standard mixes (Scotty Specialty Gases, Plumsteadville, PA) were used nondiluted and diluted in air to produce a range of gas concentrations. Conversion of CH_4 and N_2O into CO_2 equivalents was accomplished by multiplying the respective emissions by 23 and 296 according to a 100-yr time horizon (Intergovernmental Panel on Climate Change, 2001) similar to the method described by Hao et al. (2001, 2004) for feedlot manure compost.

Odorous compounds were extracted from the frozen soil samples by adjusting the H_2O content to 3 g H_2O per g DM, vigorously shaking the sample for 15 min, and then centrifuging (5 min at 10 000 $\times$ *g*). A YSI 2700 analyzer was used to quantify H_2O-extractable glucose monomer (a distinct carbo-

hydrate fraction differing from the particulate starch fraction) and L-lactate in the extract using the immobilized glucose oxidase and L-lactate oxidase enzyme methods, respectively. The persistence of free glucose monomer is a good marker for an inactive microbial community. Alcohols (C_2 to C_6, including isobutanol), VFA (C_2 to C_8, including isobutyrate, isovalerate, and isocaproate), and aromatic ring containing compounds (phenol, ρ-cresol, 4-ethyl phenol, indole, skatole, benzoate, phenylacetate, and phenylpropionate) in the extract were quantified using a Hewlett-Packard 6890 gas chromatograph (Agilent Technologies, Palo Alto, CA) equipped with flame ionization and mass selective detectors. Liquid extract (0.5 mL) was mixed in a 2-mL vial with ethyl butyrate internal standard (1 m*M* final concentration) and 50 μL of 3 *M* HCl and crimp-capped, and a 2-μL volume was injected by autoinjector into a split/splitless inlet (5:1 split) operated at 275°C. Compounds were then separated on a 30-m × 0.25-mm-i.d. (0.25-μm phase) HP-INNOWax column (Agilent Technologies) using a ramped flow (initial flow and time = 0.5 mL min^{-1} for 0.5 min, ramped flow = 20 mL min^{-2} to 2.5 mL min^{-1}) and ramped temperature (initial temperature and time = 50°C for 1 min, first temperature ramp = 30°C min^{-1} to 170°C, second temperature ramp = 15°C min^{-1} to 230°C, third temperature ramp = 5°C min^{-1} to 235°C, final time = 1 min) program and quantified by flame ionization detector (250°C) relative to standard compound mixes. The identities of the compounds were confirmed by mass spectroscopy as previously described (Miller and Varel, 2001). The content of highly volatile, protonated volatile fatty acids (VFA_{COOH}) was calculated using total VFA concentration, the pH of the sample, and the acid ionization constant for acetic acid (pK_a = 4.745) using the following equation:

$$VFA_{COOH} = (10^{-pH} \times VFA)/(10^{-pKa} + 10^{-pH}) \quad [1]$$

All VFA was treated as acetic acid to simplify the calculation. The pK_a values for the other dominant VFAs, propionic acid and butyric acid, are 4.873 and 4.81, respectively. This equation was derived from acid ionization ($K_a = [H^+][A^-]/[HA]$) and pH ($pH = -\log[H^+]$) equations.

The dust potential of each FSM was determined over a range of moisture contents using a two-speed blender (Model 51BL31; Waring Commercial, Torrington, CT), which was modified to produce and collect airborne dust samples as described by Miller and Woodbury (2003). Dust potential measurements were conducted in triplicate according to protocol.

Statistical Analyses

Data were analyzed as a split-plot in time using the general linear model (GLM) procedure of the SAS statistical software package (SAS Institute, 2001). The unit of observation was the pan (n = 54; three replicate pans per manure content × moisture level). The model included effects of manure content (5, 25, and 75%), moisture level, incubation day, pan (manure content × moisture level), manure content × moisture level, manure content × incubation day, and manure content × moisture level × incubation day. Manure content, moisture level, and manure content × moisture level were tested against the mean square of pan (manure content × moisture level). Differences between least-square means were tested with a protected t test. Net accumulation or net loss was determined using two sample paired t tests.

Data for dust potential versus moisture content experiments are presented as the least squares means calculated using the GLM procedure of SAS. For each manure–soil mix sample, data for dust potential versus moisture content were fitted using the NLIN procedure of SAS with the following equation:

$$\text{dust potential} = \text{dust}_{max} \times 10^{-(MC/10)}/[10^{-(MC/10)} + 10^{-(MT/10)}] \quad [2]$$

where MC is moisture content (g H_2O kg^{-1} DM); $dust_{max}$ is maximum dust potential; and MT is threshold moisture (i.e., the MC at which dust potential = 0.5 × $dust_{max}$). Both $dust_{max}$ and MT were determined through an iterative process. The NLIN procedure of SAS was also used to describe the relationship between MT and OM content of the manure–soil mixes and of soil and feedlot surface samples from an earlier study (Miller and Woodbury, 2003) with the following equation:

$$MT = A \times \exp(B \times OM) \quad [3]$$

Both constants A and B were determined through an iterative process.

RESULTS

Moisture Content, pH, Lactic Acid, and Glucose Monomer

Evaporative losses from the pans varied from 2.1 to 24.2 g d^{-1}. These losses were related to moisture level and manure contents ($P < 0.001$). For manure level, there was no consistent pattern for moisture loss with increasing manure content; the 5, 25, and 75% manure FSMs differed ($P < 0.001$), losing 11.2, 20.7, and 8.9 g H_2O d^{-1}, respectively. Daily moisture loss differed ($P < 0.001$) by moisture level with progressively greater moisture losses with increasing moisture content. Mean moisture loss differed between the 0.11, 0.25, and 0.43 to 1.50 g H_2O g^{-1} dry FSM moisture levels with losses of 6.0, 12.1, and 15.9 g H_2O d^{-1}, respectively, for these three categories. No differences ($P > 0.153$) were detected between the 0.43 to 1.50 g H_2O g^{-1} dry FSM moisture levels.

The pH of the FSM varied with time between moisture and manure levels (Fig. 1). High moisture content combined with intermediate to high levels of manure content promoted acid accumulation and resulted in the pH decline. In the 25% manure level incubations, pH declined in treatments at 0.67 g H_2O g^{-1} dry FSM and higher. At the 75% manure level, only the 1.50 g H_2O g^{-1} dry FSM moisture level treatment showed a marked decline in pH. Lactic acid, a nonvolatile product of microbial metabolism, accumulated in all of the incubation pans except at the 0.11 g H_2O g^{-1} dry FSM moisture level (all manure levels) and at the 0.25 g H_2O g^{-1} dry FSM moisture level at the 75% manure level (Fig. 1). Lactic acid also accumulated in pans at moderate moisture levels (0.25–1.50, 0.25–0.43, and 0.43–0.67 g H_2O g^{-1} dry FSM moisture levels at the 5, 25, and 75% manure level, respectively), but no pH decline was observed. In the lowest moisture treatments, the pH remained unchanged or increased slightly during the incubation.

The concentration of glucose monomer rapidly decreased to zero in nearly all incubations. Three incubations, which proved an exception to this pattern, were observed. Glucose monomer present on Day 0 persisted at the 0.11 g H_2O g^{-1} dry FSM moisture level in the 25 and 75% manure incubations and at the 0.25 g H_2O g^{-1} dry FSM moisture level in the 75% manure incubation. In the 75% manure incubations where glucose monomer

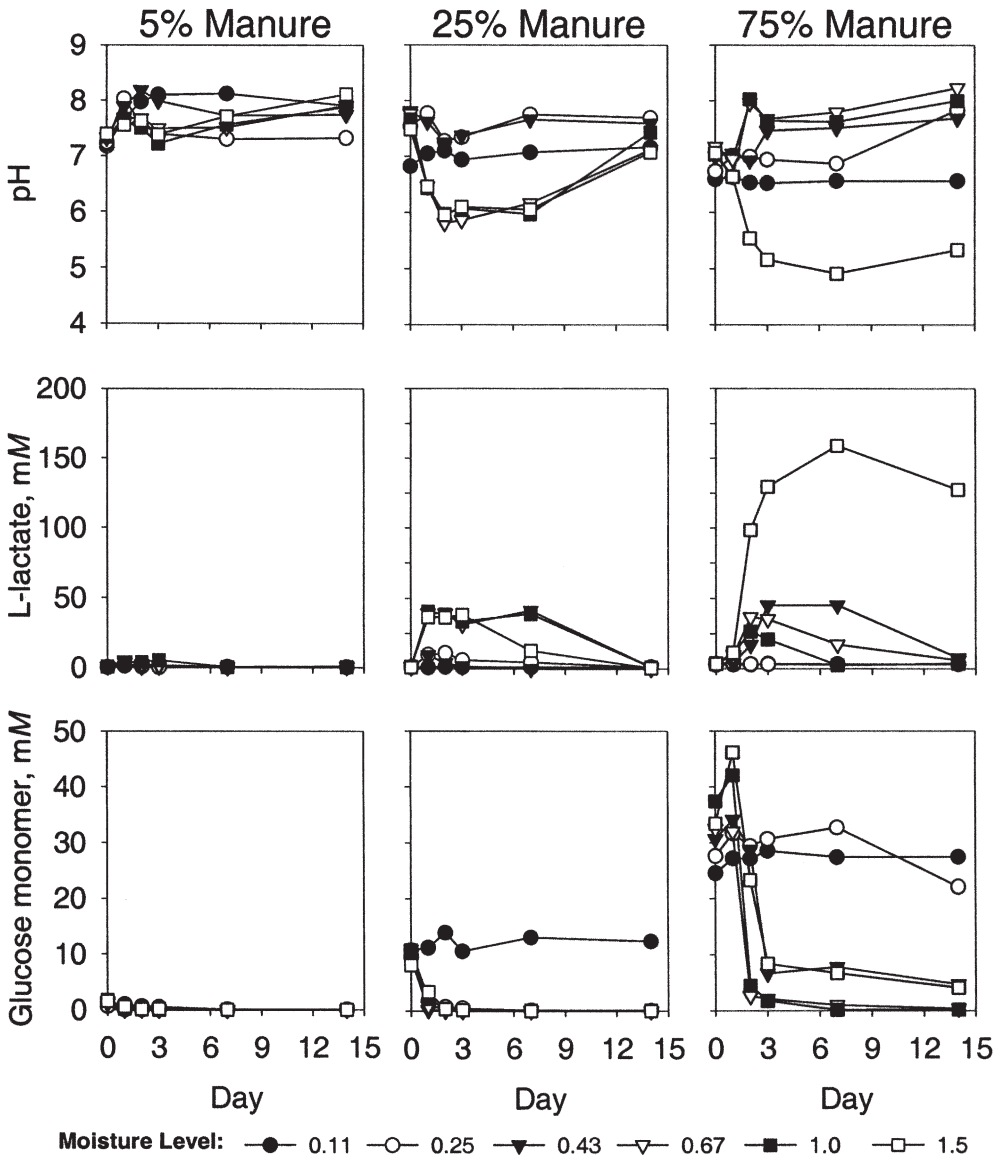

Fig. 1. Effect of manure and moisture level (g H_2O g^{-1} dry feedlot soil mixture [FSM]) on pH, L-lactate accumulation, and the persistence of glucose monomer. The standard errors of the least squares mean (n = 3) for pH, L-lactate, and glucose monomer are 0.04, 2.40, and 0.84, respectively.

concentrations declined, significant declines of glucose monomer did not occur until Day 2 or 3, whereas significant losses occurred on Day 1 in the 5 and 25% manure incubations.

Gas Fluxes and Greenhouse Gas Emissions

Gas fluxes into and out of the incubation pans differed with manure and moisture level ($P < 0.001$). The hourly consumption of O_2 and the emission of CO_2 were closely correlated (r = 0.974), and regression analysis for all manure and moisture levels estimated that for every mole of CO_2 that was emitted from the FSM, 1.8 mol atmospheric O_2 fluxed into the FSM. The largest fluxes were observed at moderate moisture levels (0.25–0.43 g H_2O g^{-1} dry FSM) in the 25% manure level incubation and at higher moisture levels in the 75% manure level incubation. Despite low O_2 and CO_2 fluxes in the 5% manure level incubation, fluxes of O_2 into the FSM were greater ($P < 0.05$) on Days 2 and 3 in the 0.25 g H_2O g^{-1} dry FSM moisture level pans and on Day 1 in the 0.43 g H_2O g^{-1} dry FSM moisture level pans compared with fluxes on Day 0. Lower O_2 and CO_2 fluxes were observed at both moisture extremes for all three manure levels.

The highest fluxes of CH_4 and N_2O were observed at the lower manure levels, 5 and 25% (Fig. 2). Methane emissions were only observed on Day 14 and were preceded by H_2 emissions (45–735 nmol cm^{-2} of FSM surface during the 1-h period) on previous sampling days. A brief pulse of N_2O was observed on Days 2 and 3 in the 5 and 25% manure level at moisture levels of ≥0.43 g H_2O g^{-1} dry FSM. The magnitude of the N_2O pulse was

inversely related to the manure level. Emission of CO from the FSM was not detected.

The relative contribution of CO_2, CH_4, or N_2O toward the GHG equivalents emitted during the two-week period varied depending on the manure and moisture level (Fig. 3). The two-week emission of total CO_2 equivalents increased ($P < 0.05$) with manure content going from the 5% to the 25 or 75% manure levels. However, the emission of total CO_2 equivalents did not differ between 25 and 75% manure levels. Although CO_2 was an important fraction of the total CO_2 equivalents, the short pulse of N_2O in the 5 and 25% manure levels comprised up to 82% of the CO_2 equivalents emitted during the incubation period depending on the moisture level. Methane accounted for only a small fraction (up to 3%) of the CO_2 equivalents emitted in these incubations. The impact of N_2O and CH_4 decreased with increasing manure content.

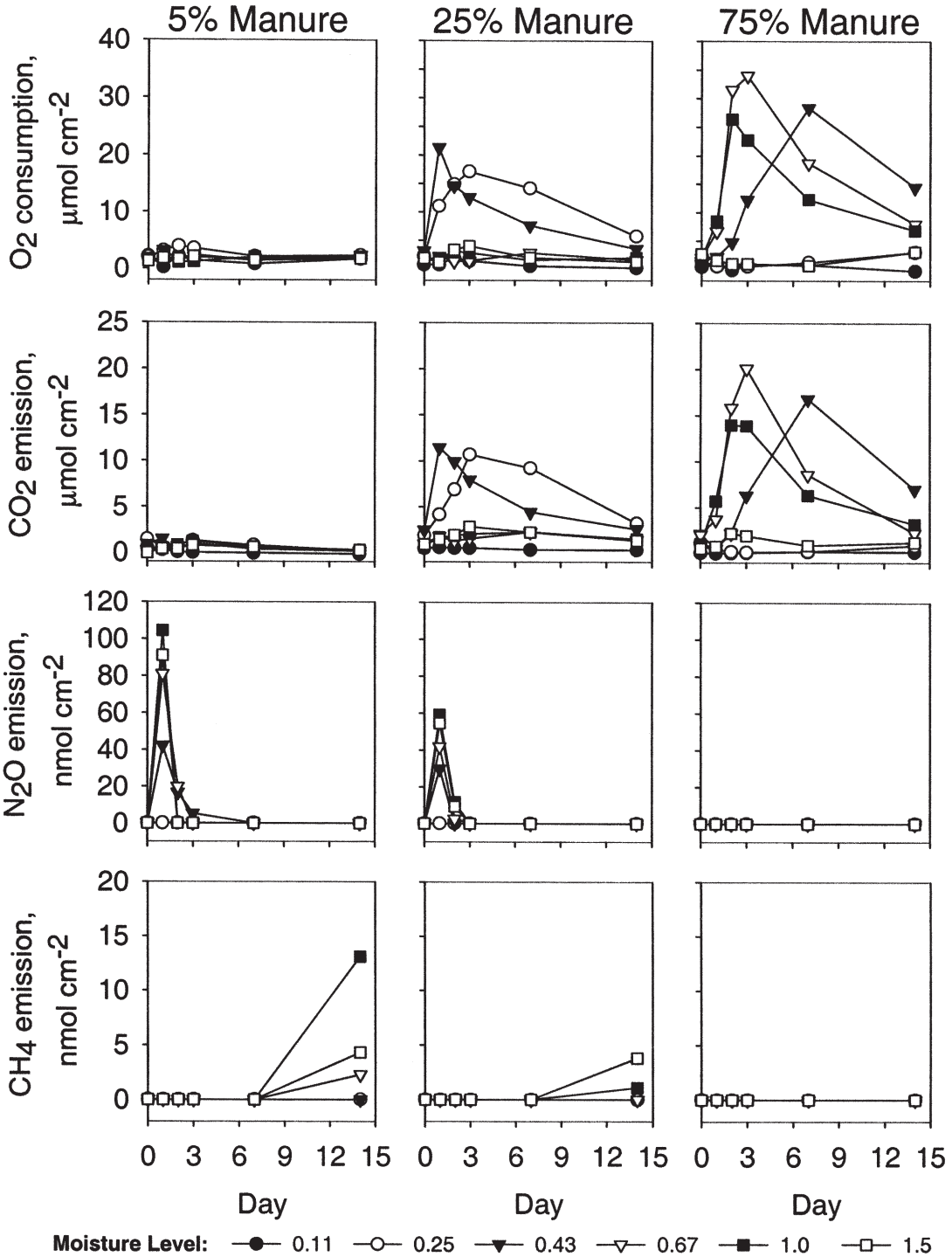

Fig. 2. Effect of manure and moisture level (g H_2O g^{-1} dry feedlot soil mixture [FSM]) on hourly consumption of O_2 and emission of CO_2, N_2O, and CH_4. The standard errors of the least squares mean ($n = 3$) for O_2, CO_2, N_2O, and CH_4 are 0.52, 0.17, 4.6, and 0.56, respectively.

Odor Compound Content and Volatility

Initial VFA content in the manure pans increased with increasing manure level (Fig. 4) confirming that the manure drying process before incubation did not eliminate the endogenous VFA from the fresh manure. The total VFA content did not increase substantially (<2.5-fold over initial concentrations) at any time during the course of the two-week incubation for any of the moisture or manure contents evaluated. However, significant VFA losses (>75% of the initial VFA content) were observed at low moisture contents (0.11–0.43 g H_2O g^{-1} dry FSM) at the 5% manure level, moderate moisture contents (0.25–0.43 g H_2O g^{-1} dry FSM) at the 25% manure level, and moderate to high moisture contents (0.43–1.00 g H_2O g^{-1} dry FSM) at the 75% manure level. When FSM pH was used to determine the concentration of highly volatile, protonated volatile fatty acids (VFA_{COOH}) in the FSM, four combinations of manure and moisture (0.67–1.50 g H_2O g^{-1} dry FSM at the 25% manure level and 1.50 g H_2O g^{-1} dry FSM at the 75% manure level) transiently accumulated from 63- to 167-fold higher concentration of VFA_{COOH} (Fig. 4).

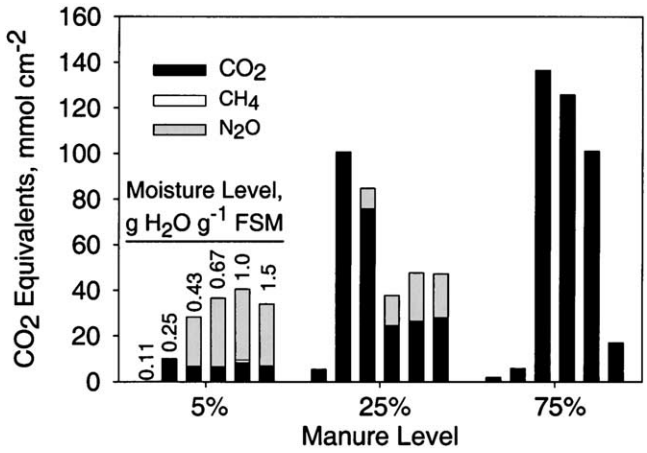

Fig. 3. The two-week integrated emission of CO_2 equivalents reflecting the contribution of individual greenhouse gases CO_2, CH_4, and N_2O. Methane and N_2O equivalents were scaled to CO_2 using scaling factors of 23 and 296, respectively (Intergovernmental Panel on Climate Change, 2001). The standard errors of the least squares mean (n = 3) for CO_2, CH_4, and N_2O are 0.17, 0.01, and 0.92, respectively. FSM, feedlot soil mixture.

Microbial Substrates

Organic nitrogen, expressed as crude protein, varied with manure and moisture level during the incubation (Fig. 5). Crude protein decreased (P = 0.042) in only one incubation (0.43 g H_2O g^{-1} dry FSM at the 5% manure level), but there was a tendency ($P < 0.1$) for crude protein to decrease at moderate moisture levels (0.25–0.67 g H_2O g^{-1} dry FSM) in the 5% manure incubations. At higher manure contents, crude protein either remained unchanged or increased ($P < 0.05$) during the incubation. This is particularly notable at the 75% manure level in the moderate to high moisture content incubations (0.43–1.00 g H_2O g^{-1} dry FSM).

Noticeable starch losses were observed in the 25 and 75% manure level pans (Fig. 5), except in the driest incubations (0.11 g H_2O g^{-1} dry FSM at the 25% manure level and 0.11–0.25 g H_2O g^{-1} dry FSM at the 75% ma-

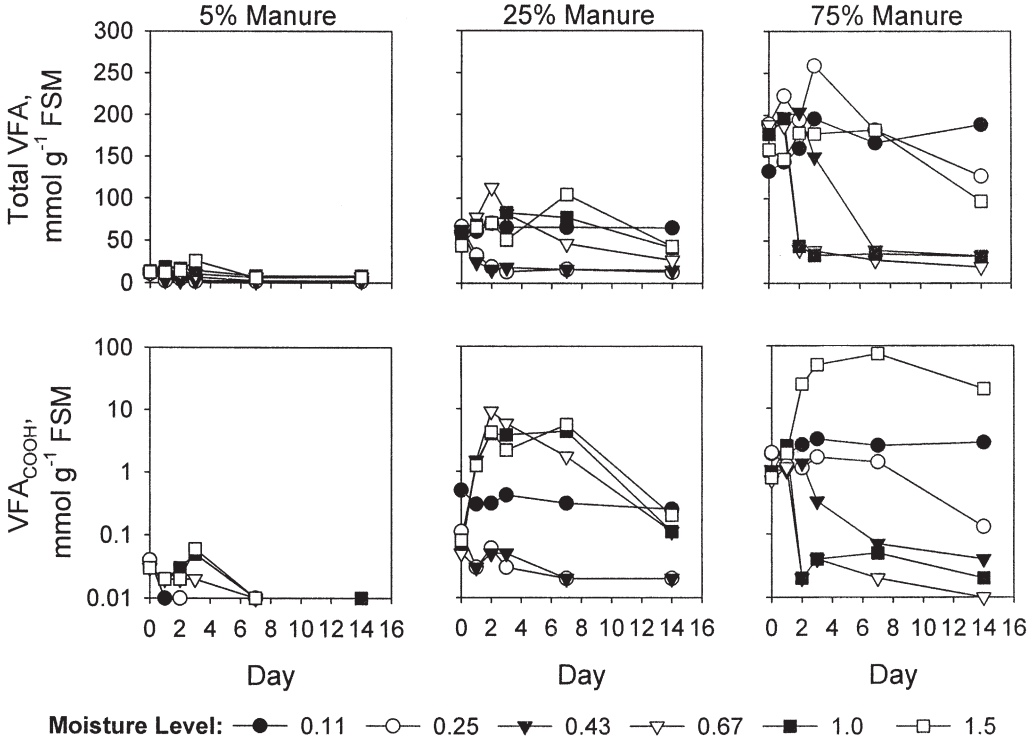

Fig. 4. Effect of manure and moisture level (g H_2O g^{-1} dry feedlot soil mixture [FSM]) on total volatile fatty acid (VFA) and protonated volatile fatty acid (VFA_{COOH}) contents of the FSM. The standard errors of the least squares mean (n = 3) for total VFA and VFA_{COOH} are 6.5 and 1.0, respectively.

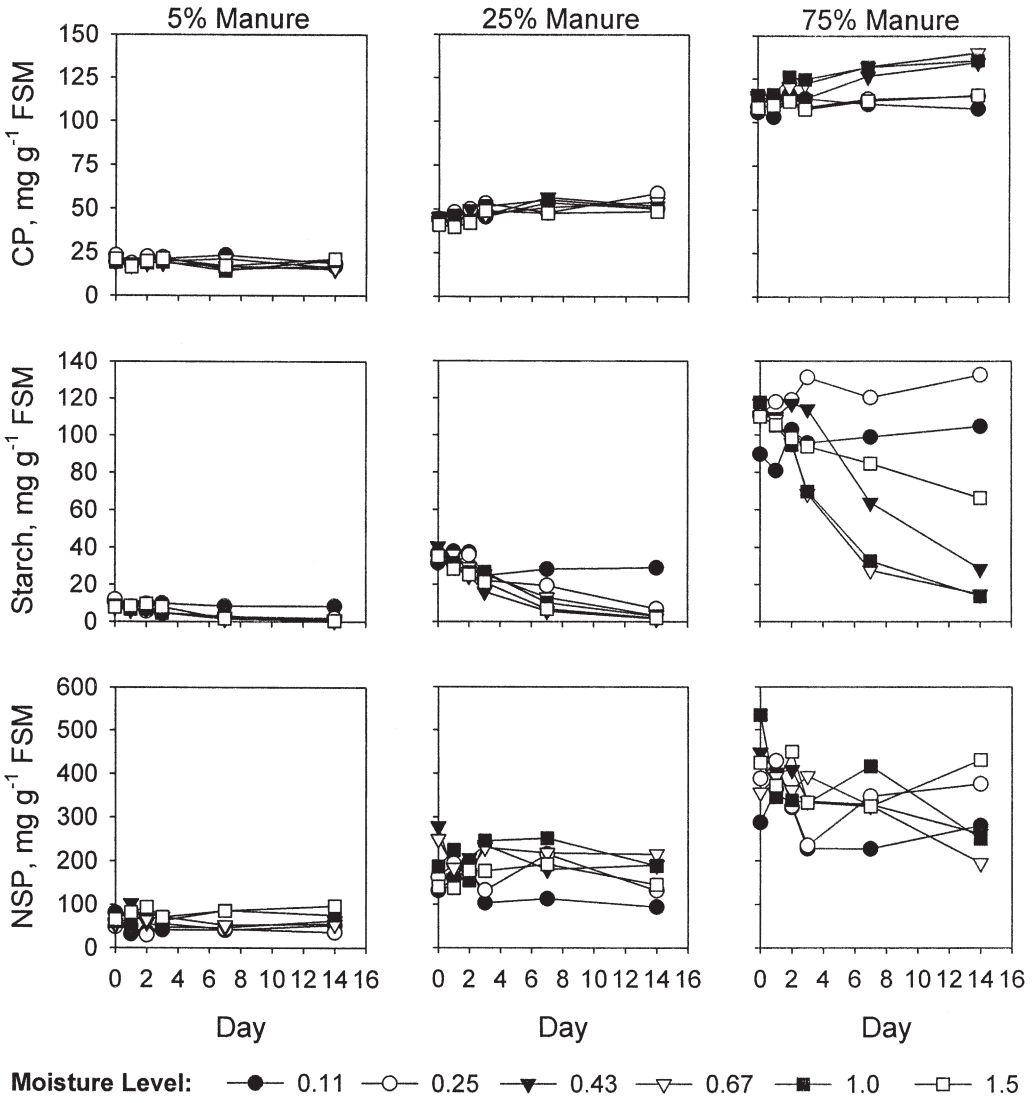

Fig. 5. Effect of manure and moisture level (g H_2O g^{-1} dry feedlot soil mixture [FSM]) on microbial substrate content of the FSM. The standard errors of the least squares mean (n = 3) for crude protein ([CP], organic N × 6.25), starch, and nonstarch polysaccharide (NSP) are 2.2, 3.1, and 42.9, respectively.

nure level), which did not decrease ($P > 0.5$). Assessing starch loss at the lowest manure level (5%) was problematic, because the starch content was already very low. Regardless of low starch content, there was a tendency ($P < 0.15$) for starch to be lost in the 5% manure level incubations at all moisture contents of ≥0.25 g H_2O g^{-1} dry FSM.

Loss of nonstarch polysaccharide was detected ($P < 0.01$) at 0.43 to 1.00 g H_2O g^{-1} dry FSM moisture levels in the 75% manure level incubation (Fig. 5). There was also a tendency toward nonstarch polysaccharide loss at the 0.43 g H_2O g^{-1} dry FSM moisture content in the 25% manure level incubation. Interestingly, the growth of coliforms, generic *E. coli*, and *E. coli* O157:H7 was also associated with these particular treatments where nonstarch polysaccharide may have been consumed (Berry and Miller, 2005). All other moisture and manure level combinations remained unchanged in nonstarch polysaccharide ($P > 0.535$).

Nitrogen Retention

Significant ($P < 0.05$) losses of total KCl-extractable N, the sum of urea, NH_4^+, NO_3^- and NO_2^- contents, were observed at 0.25 to 0.43 g H_2O g^{-1} dry FSM in the 25% manure incubations and at moisture contents of ≥0.25 g H_2O g^{-1} dry FSM in the 75% manure incubations (Fig. 6). The pooled standard error, however, was very large (25.3 μmol g^{-1} dry FSM) due to the large variation in initial urea concentrations at the 25% manure level incubation. Thus, our ability to determine the significance of extractable N losses from low-N pans was compromised. A two-sample paired t test was used to assess whether extractable N content decreased from Day 0 to Day 14 for each manure and moisture level combination. Extractable N content decreased ($P < 0.05$) in all manure and moisture contents except at the 0.11 g H_2O g^{-1} dry FSM moisture level in the 25 and 75% manure level incubations ($P \geq 0.125$), where urea, NH_4^+, and NO_3^- and NO_2^- persisted. In addition, the NO_3^- and

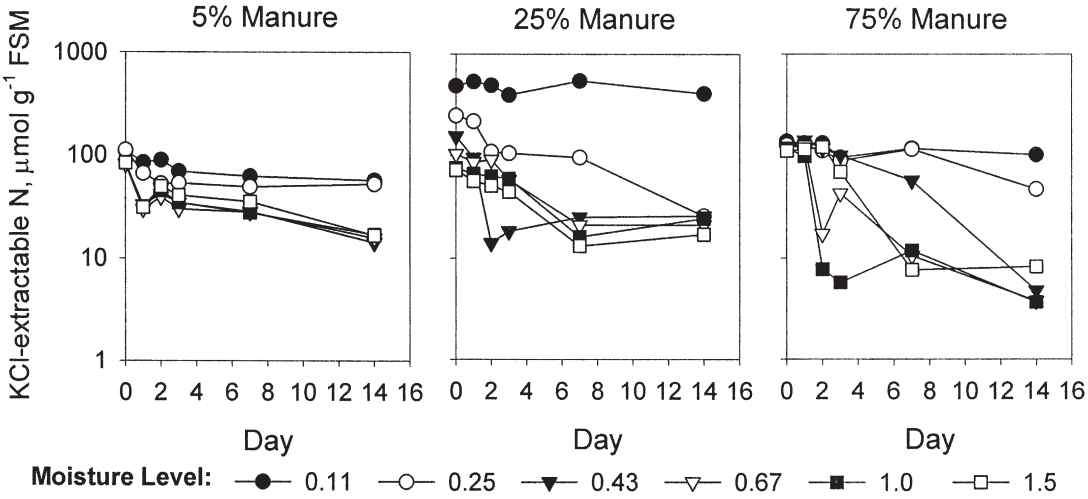

Fig. 6. Effect of manure and moisture level (g H_2O g^{-1} dry feedlot soil mixture [FSM]) on KCl-extractable N (urea, NH_4^+, and NO_3^- and NO_2^-) content of the FSM. The standard error of the least squares mean (n = 3) is 25.3.

NO_2^- component of KCl-extractable N also persisted in the 0.25 g H_2O g^{-1} dry FSM in the 5 and 75% manure incubations. Nitrate and nitrite increased ($P < 0.04$) in two of those incubations by 5.3 μmol N g^{-1} dry FSM in the 0.25 g H_2O g^{-1} dry FSM (5% manure incubation) and 1.0 μmol N g^{-1} dry FSM in the 0.11 g H_2O g^{-1} dry FSM (25% manure incubation).

Dust Potential

All FSM tested produced dust at very low moisture contents (Fig. 7a). As moisture content was incrementally raised, a threshold was reached where dust potential rapidly declined with only a small increase in moisture content. Above this threshold, no dust potential was observed. Equation [2] was iteratively fitted to the data for each FSM and calculated the maximum dust potential (y intercept) and the moisture threshold (MT). Each FSM possessed a unique MT ($P < 0.05$) that increased as the OM content increased. Furthermore, MT provided a valuable measure of the moisture required by the FSM to control potential dust emissions. Integrating these results with the data of a previous study (Miller and Woodbury, 2003) helped to refine the model (Eq. [3]) predicting MT from OM (Fig. 7b). Based on the moisture threshold equation, FSM composed entirely of dried manure (92% organic matter content) would require a moisture content of 0.35 g H_2O g^{-1} of DM to control dust.

DISCUSSION

Effects of Manure and Moisture Content

The variation in moisture and manure content examined in these incubations directly affected soil properties and indirectly affected microbial processes, both of which influenced odor compound formation, N loss, GHG emission, and the potential for dust emission. Moisture content directly affected the cohesiveness of the surface material by binding together manure and soil particles to limit dust potential. Based on our findings, we predicted that to achieve dust control in high-manure environments, a feedlot surface soil required 0.35 g H_2O g^{-1} dry soil. For comparison, this value expressed as 26% moisture on a total mass basis is well within the range of values (20–41%) recommended to control dust at cattle feedlots (Auvermann and Romanillos, 2000; Sweeten et al., 1988; Sweeten, 1998). Conditions of low moisture also enhanced the persistence of odorous (VFA) and nitrogenous compounds (NH_4^+, urea, and NO_3^- and NO_2^-), which were less likely to volatilize, convert to more volatile forms, or to hydrolyze by tightly binding to the soil particles at very low moisture (roughly <0.1 g H_2O g^{-1} DM). Unfortunately, this could provide an alternate method of transport via dust-associated emission. We speculate that the addition of moisture, on the other hand, would provide a liquid phase enhancing volatilization of VFA and NH_3 from the FSM. Excess moisture negatively impacted gaseous fluxes by limiting the diffusion of gaseous compounds into and out of the FSM.

An indirect effect of moisture was its impact on microbial metabolism, a well-established principal in soil microbiology (Parr et al., 1981). Three classes of metabolism (inactive, aerobic, and fermentative) can be inferred based on the accumulation, loss, or persistence of key microbial substrates and metabolites in the artificial feedlot soils (Table 1). Temporary lactic acid accumulation, persistence of glucose monomer, and declining KCl-extractable N and starch contents provided evidence for the general metabolic state (active vs. inactive) of the microorganisms except in the most extreme case of lowest manure (5%) and moisture contents (0.11 g H_2O g^{-1} of FSM) where the consumption of glucose monomer was very slow and lactic acid, starch content, and extractable N did not change. Declining N contents, as measured in these experiments, could be attributed to one or a combination of several processes, including NH_3 volatilization, microbial N immobilization, or nitrification–denitrification, that require a metabolically active microbial community or functional urease enzymes in the case of NH_3 volatilization (Hutchinson et al., 1982).

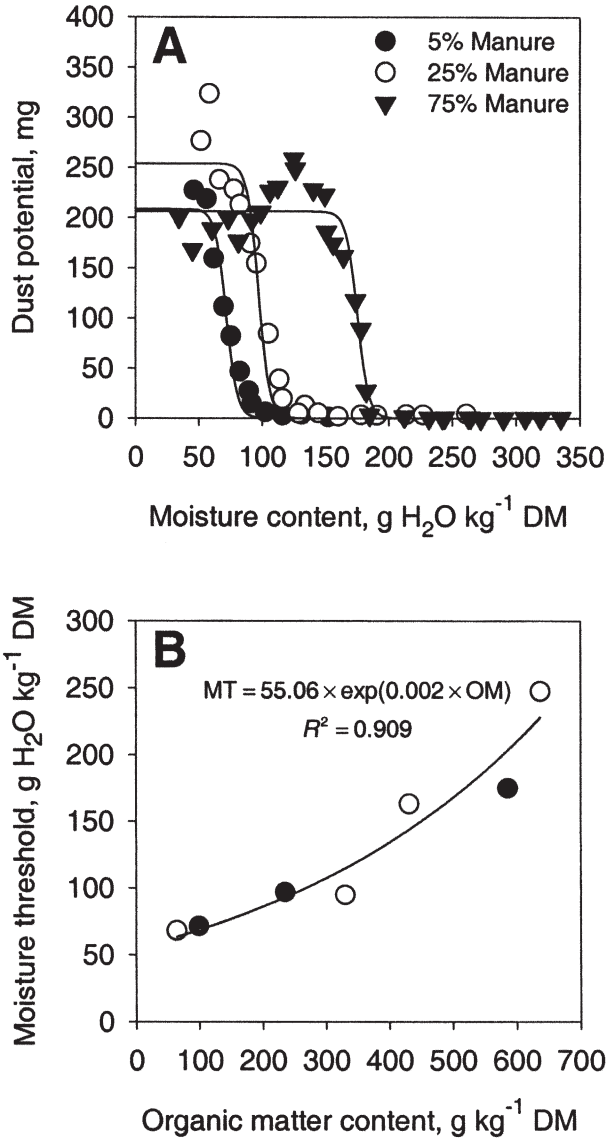

Fig. 7. The dust potential of the three feedlot soil mixtures (FSM) with increasing moisture content (A) and the relationship between the moisture threshold (MT) and organic matter (OM) content (B). The standard error of the least squares mean (n = 3) for dust potential (A) is 10.3. Open circles in (B) are data from four areas within a cattle feedlot pen as reported in Miller and Woodbury (2003), whereas filled circles are data points calculated from the three FSM. The term DM is dry matter.

Starch losses associated with the "active" metabolic state were consistent with earlier cattle feedlot manure slurry studies (Miller and Varel, 2001, 2002) identifying starch as the primary substrate, rather than protein, which is a major microbial substrate in swine manure slurry incubations (Miller and Varel, 2003). Thus, the link between fecal starch content and odors originally proposed by Watts and Tucker (1993) is supported by our results.

Large pH declines and gaseous fluxes were used to further classify whether metabolically active incubations experienced predominantly aerobic or fermentative metabolism. Fermentative metabolism was characterized by a measurable efflux of CH_4 or a large decline in FSM pH attributable to lactic acid accumulation, which is typical of fermentative metabolism. Thus, a consequence of lactic acid accumulation was an increased content of highly volatile VFA_{COOH}, which was consistent with personal observations of offensive odor associated with the high moisture pans. Aerobic metabolism was inferred by the large influx of O_2, a rapid loss of VFA, the absence of CH_4 emission and acidification, and a smaller, transient accumulation of lactic acid. It is likely that a high rate of HCO_3^- production and subsequent CO_2 emission in the aerobic incubations helped to mitigate acidification by consuming H^+:

$$HCO_3^- + H^+ \rightarrow H_2O + CO_2 \quad [4]$$

Aerobic consumption of VFA, increased emission of VFA, or a combination of both could account for the loss of VFA in the aerobic incubations.

Manure content affected FSM processes in two ways. First, the manure modulated the effect of moisture by requiring more moisture at higher manure contents to elicit conditions observed at lower manure contents. The relationship between dust potential, MT, and OM content most directly illustrated this point. With increasing manure content, more moisture was required to reduce dust potential. A similar pattern was observed in the pan incubations in the subtle shift of a variety of processes including glucose consumption, lactic acid production, O_2 and CO_2 fluxes, pH declines, nitrogen persistence, and starch consumption (Table 1). The likely mechanism involves a shift in the soil water matric potential, which is closely tied to the potential for microbial activity (Paul and Clark, 1996). Increasing manure content likely decreased the availability of water for microbial processes.

A second consequence of varying manure content was that increasing manure content modulated microbial processes by increasing the availability of microbial substrate and the subsequent buildup of inhibitory metabolic byproducts. The production of various GHGs exemplifies this point. At low manure contents under fermentative conditions, pH declined minimally, CH_4 was produced, and N_2O was the dominant GHG emission during the incubation period. The source of N_2O is likely attributable to either microbial denitrification or nitrification, both of which have been observed in feedlot surface soils (Woodbury et al., 2001). Incubation conditions likely favored a denitrifying mechanism because N_2O efflux was observed only at the highest moisture levels (fermentative) and not at moisture contents of $<$0.43 g H_2O g^{-1} dry FSM (aerobic conditions of high O_2 and CO_2 fluxes) that should have favored nitrification activity. The absence of N_2O emissions at the 75% manure level may reflect a robust demand by denitrifying bacteria for any electron acceptor including N_2O. Brown et al. (2000) attributed the lack of N_2O emission during the first week of dairy manure incubation to a similar mechanism; when the aerated crust of their manure incubations was inadvertently mixed into the anaerobic center of the incubation, any NO_3^- or N_2O produced in the crust was scavenged by denitrifying bacteria. Methane emissions were expected at highest moisture and

Table 1. Dominant microbial metabolism in the feedlot surface mixtures (FSM) based on pH decline (pH), lactic acid accumulation (lactate), persistence of glucose monomer (glucose), high oxygen consumption (O_2), or detectable methane efflux (CH_4).

	Manure content		
Moisture level	5%	25%	75%
g H_2O g^{-1} dry FSM			
0.11	aerobic (glucose†)	inactive (glucose)	inactive (glucose)
0.25	aerobic (lactate)	aerobic (lactate, O_2)	inactive (glucose)
0.43	aerobic (lactate)	aerobic (lactate, O_2)	aerobic (lactate, O_2)
0.67	fermentative (lactate, CH_4)	fermentative (pH, lactate)	aerobic (lactate, O_2)
1.00	fermentative (lactate, CH_4)	fermentative (pH, lactate, CH_4)	aerobic (lactate, O_2)
1.50	fermentative (lactate, CH_4)	fermentative (pH, lactate, CH_4)	fermentative (pH, lactate)

† Borderline determination, probably aerobic. Monomeric glucose declined very slowly relative to other moisture and manure levels, yet lactate did not accumulate.

manure contents, but the pH decline was large enough to inhibit methanogenesis, and CO_2 was the dominant GHG emission. Emissions of CH_4 and N_2O from feedlot manure compost (Hao et al., 2001, 2004) differed with our results, but are likely related to anaerobic conditions in the center of the compost pile. However, both FSM and compost emissions were dominated by non-CO_2 GHG (CH_4 and N_2O).

Increasing the manure content also affected N transformations in the FSM. Ammonia volatilization is a major route of N loss from cattle feedlots, with urea hydrolysis to NH_4^+ and its subsequent volatilization under conditions of alkaline pH a primary NH_3 emission source (Hutchinson et al., 1982). McGinn et al. (2002) measured initially large fluxes of NH_3 followed by much smaller fluxes from a high-moisture (1.7 g H_2O g^{-1} DM) mixture of cattle manure and bedding. Although NH_3 volatilization was not directly measured in our incubations, declining extractable N in the metabolically active incubations was consistent with the results of McGinn et al. (2002). However, a coupled nitrification–denitrification mechanism resulting in N_2 emission cannot be rejected. An alternative beneficial sink for NH_4^+ is N immobilization, which would increase the fertilizer value of the manure. Adams et al. (2004) found that incorporating more OM into feedlot surfaces decreased N losses from feedlot pens, presumably through increased N immobilization. Under aerobic conditions in high manure content incubations, there was clear evidence for N incorporation into the FSM OM fraction. Further research optimizing N immobilization in feedlot surface material relative to NH_3 emission will have significant impact and should be pursued.

As a source for potential odor compound production, manure-rich feedlot surfaces are undoubtedly much more troublesome than low manure surfaces. Volatile fatty acids are major end products produced during the anaerobic decomposition of cattle feedlot manure and arise primarily from incomplete starch decomposition (Miller and Varel, 2001, 2002). These compounds have also been linked to the malodor downwind from confined animal feeding operations (McGinn et al., 2003; Williams, 1984; Zhan et al., 2001). We expected VFA to increase in the fermentative incubations at higher manure contents, but the VFA content did not increase appreciably. Instead, the fraction of VFA_{COOH} increased due to declining FSM pH. Thus, the effect of decreasing pH on the forms of VFA may account for increased odor emission after rainfall events more so than an increase in VFA content alone (Watts et al., 1994).

Predominant Environmental Issues

Understanding the various consequences of the varying manure and moisture landscape and its impact on microbial activities provided useful insights into potential pen management avenues. The dominant microbial metabolisms aligned well with particular environmental concerns and emphasized the role of microorganisms in the feedlot environment (Fig. 8). Microbial inactivity

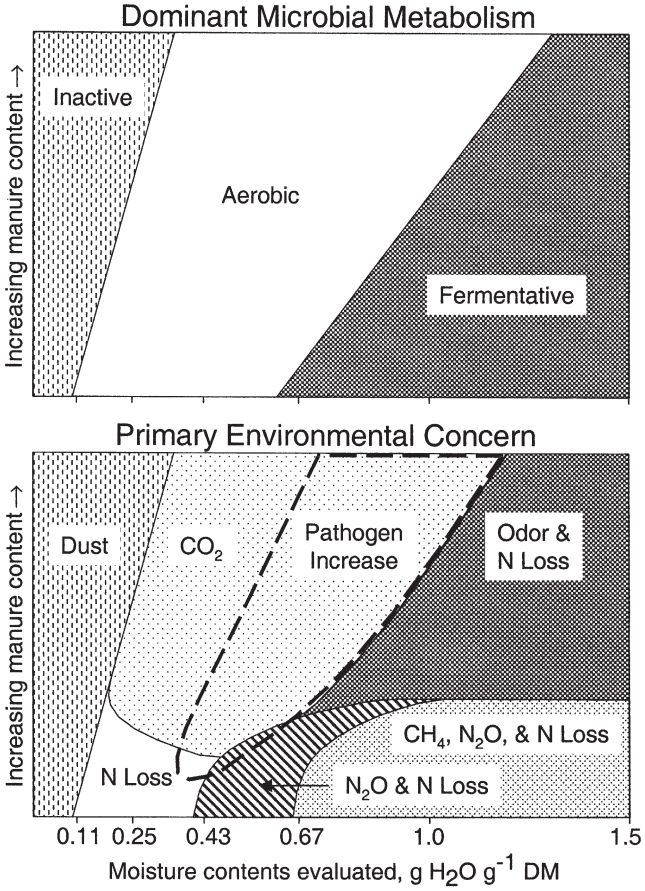

Fig. 8. Conceptual diagram of the dominant microbial metabolisms and primary environmental issues as they relate to manure and moisture content in cattle feedlot surfaces. The term N loss refers to a decline of KCl-extractable N. Information on pathogen growth is interpreted from Berry and Miller (2005). The term DM is dry matter.

and dust emission issues were related; low water availability inhibited microbial metabolism and urea hydrolysis, but also enhanced the formation of dust particles. Under conditions favoring aerobic metabolic activity, KCl-extractable N loss at low manure contents and CO_2 emission in high manure contents were the primary concerns. In an accompanying paper, pathogen persistence and in some cases pathogen growth was observed in aerobic treatments at higher moisture contents (Berry and Miller, 2005). Incorporating those observations into the conceptual model showed that not all aerobic activity was beneficial. Finally, fermentative conditions produced a variety of effects. The loss of KCl-extractable N was indicated at all manure levels under fermentative conditions, whereas there was a transition from GHG production to enhanced odor emission resulting from acid accumulation.

Does an optimum moisture and manure content exist for minimizing emissions from cattle feedlot surfaces? How much control do feedlot managers have over feedlot surface moisture and manure content, and more importantly, how much capital can be spent managing feedlot surface moisture and manure content? Given all the possible effects on microbial metabolism and associated environmental issues at all manure and moisture contents, it is difficult to assess the optimum conditions to minimize environmental impacts. Should issues at local (dust, pathogens, and odor) or global scales (NH_3 and GHG) take priority? A "least impact" approach is proposed to determine optimum manure and moisture levels. The environmental issues associated with inactive (dust) and fermentative metabolisms (odor, GHG, and N losses) appear to have the greatest impact. Not only is the practicality of managing feedlot moisture to halt microbial activity questionable, but dust-related health issues arise for cattle (MacVean et al., 1986). Considerable effort is already spent managing excess moisture (drainage and mounding) and manures (pen cleaning frequency). Clearly, managing the surface for modest manure content (<500 g organic matter kg^{-1} dry matter) and enough moisture to enhance aerobic activity (0.2–0.4 g H_2O g^{-1} of dry feedlot surface material), yet not enough to encourage pathogen growth, odors, or GHGs, is the least impact option. Tightly controlling the moisture content would avoid odor, pathogen, and dust issues, whereas limiting manure accumulation would act to minimize CO_2 emission and N loss. Application of soil water matric potential to more accurately monitor or control microbial activities should also be pursued. The reality of the feedlot pen, however, is that all identified metabolic activities and their associated environmental issues are likely to be present because manure and moisture distribution is heterogeneous and not easily controlled. Alternative pen designs to more evenly distribute manure and moisture should be considered to provide greater opportunity for emission control.

The results of these laboratory experiments illustrate that a wide range of environmental consequences are possible based on initial manure and moisture conditions. Thus, the conclusions drawn from laboratory incubations evaluating only a single set of moisture and manure conditions will not be applicable to the range of manure and moisture contents observed in cattle feedlot pens. The results of these experiments may be biased to some degree because the steps necessary to prepare dried manure (oven drying and grinding) and the incubation conditions (short incubation period, FSM depth and bulk density, sunlight effects, temperature variation) differ in subtle ways from feedlot conditions. However, as an initial investigation, the results of this study provide insights into the underlying microbial processes and relationships between emissions of concern and directions for future investigations.

CONCLUSIONS

Feedlot surfaces experience a wide range of manure and moisture contents, which affect the emissions of odor compounds, NH_3, GHGs, and dust. Potential dust production was directly attributable to moisture and manure content, whereas other emissions were the product of, or affected by, microbial metabolism. The range of moisture and manure contents tested produced three general microbial metabolisms, inactive, aerobic, and fermentative. Microbial metabolism was fueled by glucose and starch and affected emissions by changing the pH, producing malodorous fermentation end products and GHGs, and consuming free NH_3. Minimizing environmentally important emissions requires understanding the context of emissions, the underlying mechanisms, and the relationships between emissions.

ACKNOWLEDGMENTS

The authors acknowledge the secretarial assistance of Jackie Byrkit and the technical assistance of Ty Post. We would also like to thank Dr. Brent Auvermann and Dr. Bryan Woodbury for their thoughtful review of the manuscript.

REFERENCES

Adams, J.R., T.B. Farran, G.E. Erickson, T.J. Klopfenstein, C.N. Macken, and C.B. Wilson. 2004. Effect of organic matter addition to the pen surface and pen cleaning frequency on nitrogen mass balance in open feedlots. J. Anim. Sci. 82:2153–2163.

Auvermann, B.W., and A. Romanillos. 2000. Manipulating stocking density to manage fugitive dust emission from cattle feedyards. p. 61–70. *In* Proc. of the Innovative Technologies for Planning Animal Feeding Operations, Denver. USDA-ARS Central Great Plains Res. Stn., Akron, CO.

Berry, E.D., and D.N. Miller. 2005. Cattle feedlot soil moisture and manure content: II. Impact on *Escherichia coli* O157:H7. J. Environ. Qual. 34:656–663 (this issue).

Brown, H.A., C. Wagner-Riddle, and G.W. Thurtell. 2000. Nitrous oxide flux from solid dairy manure in storage as affected by water content and redox potential. J. Environ. Qual. 29:630–638.

Bundy, L.G., and J.J. Meisinger. 1994. Nitrogen availability indices. p. 951–984. *In* R.W. Weaver, J.S. Angle, and P.S. Bottomley (ed.) Methods of soil analysis. Part 2. SSSA Book Ser. 5. SSSA, Madison, WI.

Daniels, L., R.S. Hanson, and J.A. Phillips. 1994. Chemical analysis. p. 512–554. *In* P. Gerhardt, R.G.E. Murray, W.A. Wood, and N.R. Krieg (ed.) Methods of general and molecular bacteriology. Am. Soc. for Microbiol., Washington, DC.

Hao, X., C. Chang, and F.J. Larney. 2004. Carbon, nitrogen balances and greenhouse gas emission during cattle feedlot manure composting. J. Environ. Qual. 33:37–44.

Hao, X., C. Chang, F.J. Larney, and G.R. Travis. 2001. Greenhouse

gas emissions during cattle feedlot manure composting. J. Environ. Qual. 30:376–386.
Hutchinson, G.L., A.R. Mosier, and C.E. Andre. 1982. Ammonia and amine emission from a large cattle feedlot. J. Environ. Qual. 11: 288–293.
Intergovernmental Panel on Climate Change. 2001. Global climate change 2001: The scientific basis. Technical summary of the Working Group I, IPCC third assessment report (TAR) [Online]. Available at www.ipcc.ch/index.htm (verified 1 Sept. 2004). IPCC, Geneva.
Mackie, R.I., P.G. Stroot, and V.H. Varel. 1998. Biochemical identification and biological origin of key odor components in livestock waste. J. Anim. Sci. 76:1331–1342.
MacVean, D.W., D.K. Franzen, T.J. Keefe, and B.W. Bennett. 1986. Airborne particle concentration and meteorologic conditions associated with pneumonia incidence in feedlot cattle. J. Am. Vet. Res. 47:2676–2682.
McGinn, S.M., H.H. Janzen, and T. Coates. 2003. Atmospheric ammonia, volatile fatty acids, and other odorants near beef feedlots. J. Environ. Qual. 32:1173–1182.
McGinn, S.M., K.M. Koenig, and T. Coates. 2002. Effect of diet on odorant emissions from cattle manure. Can. J. Anim. Sci. 82:435–444.
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. Anim. Sci. 79:2949–2956.
Miller, D.N., and V.H. Varel. 2002. In vitro study of manure composition on the biochemical origins, composition, and accumulation of odorous compounds in cattle feedlots. J. Anim. Sci. 80:2214–2222.
Miller, D.N., and V.H. Varel. 2003. Swine manure composition affects the biochemical origins, composition, and accumulation of odorous compounds. J. Anim. Sci. 81:2131–2138.
Miller, D.N., and B.L. Woodbury. 2003. Simple protocols to determine dust potentials from cattle feedlot soil and surface samples. J. Environ. Qual. 32:1634–1640.
Muck, R.E., and B.K. Richards. 1980. Losses of manurial N in freestall barns. Agric. Manure 7:65–93.
Mulvaney, R.L. 1996. Nitrogen—Inorganic forms. p. 1123–1184. *In* D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI.
National Research Council. 2003. The scientific basis for estimation air emissions from animal feeding operations: Interim report. Ad hoc committee on air emissions from animal feeding operations, committee on animal nutrition. Natl. Res. Council, Natl. Acad. Press, Washington, DC.
Nelson, D.W., and L.E. Sommers. 1996. Total carbon, organic carbon, and organic matter. p. 961–1010. *In* D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI.
Parr, J.F., W.R. Gardner, and L.F. Elliott (ed.) 1981. Water potential relations in soil microbiology. SSSA, Madison, WI.
Paul, E.A., and F.E. Clark. 1996. Soil as a habitat for organisms and their reactions. p. 11–33. *In* Soil microbiology and biochemistry. 2nd ed. Academic Press, San Diego, CA.
SAS Institute. 2001. The SAS system for Windows. Release 8.2. SAS Inst., Cary, NC.
Sweeten, J.M. 1998. Cattle feedlot manure and wastewater management practices. p. 125–155. *In* J.L. Hatfield and B.A. Stewart (ed.) Animal waste utilization: Effective use of manure as a soil resource. Ann Arbor Press, Chelsea, MI.
Sweeten, J.M., C.B. Parnell, R.S. Etheredge, and D. Osborne. 1988. Dust emissions in cattle feedlots. p. 557–578. *In* J.L. Howard (ed.) Stress and disease in cattle, veterinary clinics of North America. Food animal practice. Vol. 4, no. 3. W.B. Saunders, Philadelphia.
Varel, V.H., J.A. Nienaber, and H.C. Freetly. 1999. Conservation of nitrogen in cattle feedlot waste with urease inhibitors. J. Anim. Sci. 77:1162–1168.
Watts, P.J., M. Jones, S.C. Lott, R.W. Tucker, and R.J. Smith. 1994. Feedlot odor emissions following heavy rainfall. Trans. ASAE 37: 629–636.
Watts, P.J., and R.W. Tucker. 1993. The effect of ration on waste management and odor control in feedlots. p. 117–129. *In* D.J. Farrell (ed.) Recent advances in animal nutrition in Australia. Univ. of Armidale, NSW, Australia.
Williams, A.G. 1984. Indicators of piggery slurry odour offensiveness. Agric. Wastes 10:15–36.
Wilson, S.C., J. Morrow-Tesch, D.C. Straus, J.D. Cooley, W.C. Wong, F.M. Mitlohner, and J.J. McGlone. 2002. Airborne microbial flora in a cattle feedlot. Appl. Environ. Microbiol. 68:3238–3242.
Woodbury, B.L., D.N. Miller, J.A. Nienaber, and R.A. Eigenberg. 2001. Seasonal and spatial variations of denitrifying enzyme activity in feedlot soil. Trans. ASAE 44:1635–1642.
Zhan, J.A., A.A. DiSpirito, Y.S. Do, B.E. Brooks, E.E. Cooper, and J.L. Hatfield. 2001. Correlation of human olfactory responses to airborne concentrations of malodorous volatile organic compounds emitted from swine effluent. J. Environ. Qual. 30:624–634.