RESEARCHREPORT

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ENVIRONMENT

Title: Feeding amino acids to reduce air emissions and the carbon footprint of swine production – **NPB #12-119**

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Industry summary

Reduced crude protein (CP) diets with synthetic amino acid (AA) supplementation has proven to be an effect way to reduce ammonia (NH_3) emissions from swine housing. However, there are very limited comprehensive feed-through-field studies to quantify gas emissions and carbon footprint changes that occur as a result of the feeding strategy. This study investigated air emissions and nutrient balance from swine housing, manure storage, and field applications using a reduced CP diet mitigation strategy.

Seventy-two pigs in 12 experimental rooms (6 pigs/room) were fed standard (18.5% to 12.2% CP over the grow-finish period, 6 rooms) or reduced CP diets (17.5% to 11.0% CP over the grow-finish period, 6 rooms) over the course of 5 feeding phases (107 d, total). The reduced CP diets were formulated to NRC 2012 nutrient recommendations. Diets contained similar energy and lysine contents within each feeding phase. During the animal growth period, animal performance and air emissions were monitored. Results showed that diet did not alter average daily gain (ADG; 1.013 kg/d-pig), average daily feed intake (ADFI; 2.714 kg/d-pig), or feed conversion ratio (FCR; 2.735 kg feed/kg gain). Feeding the reduced CP diet resulted in lower NH_3 emissions (33% over the 107-d feeding period). The percent NH_3 emission reduction observed for each percentage unit reduction in diet CP content was 47.9%, 53.2%, 26.8%, 26.5% and 51.6% during phases 1 through 5, respectively. No other gases were affected by the dietary treatments.

Manure was collected during the animal growth period and compiled to represent a single sample of manure for each diet treatment across the grow-finish period. Manure was placed in barrels, covered and air flow moved across the barrels for 90 days. During that time, barrels were stirred every hour and air emissions were collected. As a result of feeding the standard CP diet, room NH_3 concentration and NH_3 emissions were double that observed when the reduced CP diet was offered. No other gases were affected by the dietary treatments.

Post storage, manure was land applied to a soil surface and air emissions monitored. No differences in NH_3, nitrous oxide or methane emissions were observed.

These findings illustrate that feeding reduced CP diets that are formulated based on NRC 2012 recommendations provides an effective tool for reducing NH_3 emissions from swine housing compared to recent industry formulations. Once manure is moved to long-term storage and applied to fields, diet effects on the volatilization of gases may be different from that observed during housing. Losses during land application were low compared to housing and storage and no diet differences were observed suggesting that land application may not be the best place to target efforts to reduce ammonia emissions. Furthermore, diet strategies that produce large differences in ammonia emissions do not necessarily result in observed differences in nitrous oxide emissions.

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Keywords: Air emissions, amino acid, footprint, swine

Scientific abstract

A study was conducted to investigate the feed-through-field impacts of feeding a reduced crude protein diet to grow-finish pigs. Seventy-two pigs in 12 experimental rooms (6 pigs/room) were fed standard (18.5% to 12.2% CP over the grow-finish period, 6 rooms) or reduced CP diets (17.5% to 11.0% CP over the grow-finish period, 6 rooms) over the course of 5 feeding phases (107 d, total). Diets contained similar energy and lysine contents within each feeding phase. During the animal growth period, animal performance and air emissions were monitored. Manure collected during the 107-d feeding period was pooled by diet, across phases, and moved to incubate in storage containers equipped with stirrers. Air flowed across the manure surface continually for a 90-2 storage period (1.2 L/min) and headspace air was measured. Stored manure was then land applied to a soil surface in 208 L barrels at an application rate equivalent to 180 lb N/acre (570 g manure applied) and emissions measured for 7 d with continuous airflow across the soil surface (1.2 L/min).Results showed that diet did not alter average daily gain (ADG; 1.013 kg/d-pig), average daily feed intake (ADFI; 2.714 kg/d-pig), or feed conversion ratio (FCR; 2.735 kg feed/kg gain) ($P>0.05$). Dietary treatments had no effect on manure excretion rate or total solids concentration across feeding phases ($P > 0.05$). The manure concentrations of N and NH_4^+-N when removed from housing did not differ among pigs fed the different diets across phases. Dietary treatments and phases had significant effects on NH_3 emissions ($P<0.05$). Feeding the reduced CP diet resulted in lower NH_3 concentrations (ppm) and emissions (mg/d) (1471 vs. 2174 mg over the 107-d feeding period; $P<0.05$). The percent NH_3 emission reduction observed for each percentage unit reduction in diet CP content was 47.9%, 53.2%, 26.8%, 26.5% and 51.6% during phases 1 through 5, respectively. As a result of the 90-d storage period, average daily ammonia emissions from barrels containing manure from pigs fed the standard CP diets were double that from barrels containing the reduced CP diet manure (0.51 g/d vs. 0.24 g/d; $P<0.01$). No other gases were different. Average daily emissions emissions over the 7-d period that followed land application of the stored manures demonstrated no treatment differences for any gases. Using a feed-through-field approach for considering nutrient losses is that we demonstrated that over 40% more N is lost in the form of ammonia emissions during housing and manure storage as a result of feeding the standard CP diet. However, diet strategies that produce large differences in ammonia emissions do not necessarily result in observed differences in nitrous oxide emissions.

Introduction

Reduced crude protein (CP) diets with synthetic amino acid (AA) supplementation has proven to be an effect way to reduce ammonia (NH3) emissions from swine housing. However, there are very limited comprehensive feed-through-field studies to quantify gas emissions and carbon footprint changes that occur as a result of the feeding strategy. This study investigated air emissions and nutrient balance from swine housing, manure storage, and field applications using a reduced CP diet mitigation strategy.

Objectives

i. Quantify air or greenhouse gas (GHG) emissions (nitrous oxide, methane as well as ammonia, though not a GHG) from swine housing following feeding of diets containing different amounts of synthetic amino acids (AA). These diets have previously demonstrated differences in ammonia emissions. Because nitrogen excretion is the precursor to emissions of both ammonia and nitrous oxide we may see diet effects on nitrous oxide emissions from rooms as well.

ii. Measure air emissions during storage of manure collected from these pigs. Emissions measured will include methane, ammonia and nitrous oxide.

iii. Determine air emissions from manures following land application of those manures. Following land application excreted manure nitrogen can still be emitted as ammonia and/or nitrous oxide. Nitrous oxide emissions are more likely to occur following land application of manure than from animal housing. Compared to nitrous oxide emissions from manure storage, emissions following land application may be greater, less than or similar, depending in large part on soil condition (soil moisture, soil temperature). Availability of manure nitrogen likely influences the extent to which ammonia and nitrous oxides emissions occur following land application of manures.

iv. Integrate the data from the first 3 objectives to develop a systematic accounting of gaseous losses throughout a swine grow-finish operation. This will provide a farm-level assessment of the effect of 3 diets on emissions from feed-through-field. Economic differences between the diet approaches will be documented and included in the assessment.

Materials and Methods

Housing study (objective #1)

The experiment was conducted at the Animal Air Quality Facility at Michigan State University (AAQRF). Seventy-two pigs in 12 experimental rooms (6 pigs/room) were fed standard (18.5% to 12.2% CP over the grow-finish period, 6 rooms) or reduced CP diets (17.5% to 11.0% CP over the grow-finish period, 6 rooms) over the course of 5 feeding phases (107 d, total). Gases (NH3, N2O, H2S, CH4, NMTHC and CO2) and ventilation rates were measured continuously from the rooms. The reduced CP diets were adequately supplemented with all limiting AA.

The AAQRF consists of 12 animal rooms (each 2.59 m wide × 3.97 m long × 2.14 m high) with interchangeable penning and watering systems. At the beginning of the project, 72 crossbred barrows were allocated to 12 rooms (6 pig/room), initial body weight = 21.6 kg (Table 1). At the end of the phase 2, one pig was removed from each room. Pigs were confined in a raised-deck pen (1.5 m wide × 3.1 m long) with a plastic-coated woven wire floor. Floor-space allowance was in line with commercial practice at 0.775 m^2/pig and 0.930 m2/pig for phases 1 and 2 and phases 3 through 5, respectively. Each room was individually heated and cooled, using only fresh, outside air and exhausting all of the air to the outside (no recycling). Room temperatures were adjusted weekly, based on the average body weight of the barrows within the room, to remain within the thermoneutral zone of the animals (Table 1). Fluorescent lighting was programmed to turn on at 0600 h and turn off at 2000 h. All pigs in each room were weighed as a group weekly and at the start and end of each phase. Pigs were provided ad libitum access to feed and water. Swinging nipple waterers were located above the middle of the pens and a 1-hole feeder was located at one end. Daily feed was added to feeders and recorded, and feeder height was adjusted to prevent feed wastage. Weekly feeders were cleaned and the remaining feed mass was recorded. Diet samples were collected daily and pooled at the end of each feeding phase for analyses.

Galvanized steel manure collection pans (1.52 m wide × 3.05 m long × 0.2 m high) were placed underneath the flooring of each pen to collect urine, feces, and wasted feed and water. The manure pans were cleaned completely at the start of each phase. In addition, collection pans were partially cleaned semiweekly within each phase to prevent overflow of the pans. Before removal, manure was mixed thoroughly in the pan. Removed manure was weighed and mass recorded. A homogenous subsample was collected each time during manure cleaning and stored in a freezer (0 ^{o}C). All subsamples were thawed and combined into a composite phase sample for compositional analyses.

Table 1. Experimental animal and management

Phase	**Phase 1**	**Phase 2**	**Phase 3**	**Phase 4**	**Phase 5**
Phase length (d)	33	25	19	21	9
Starting/ending pig age (d)	60-92	93-117	118-136	137-157	158-166
Pig (#/room)	6	6	5	5	5
Floor-space allowance (m^2/pig)	0.775	0.775	0.930	0.930	0.930
Starting average BW (kg)	21	52	75	94	113
Average room temperature (^{o}C)	22.7	21.4	20.2	20.3	20.0
Average room relative humidity (%)	58.8	55.7	55.5	40.6	34.8
Lighting schedules	0600 h – 2000 h				
Feed/water routine check	0500 h and 1800 h				
BW collection frequency	Weekly and at each phase start and end				
Manure sampling	Semiweekly and at each phase end				

Diets

Half of 12 rooms were randomly selected to receive 1 of 2 feeding strategies (standard CP diet and a low CP diet), resulting in 6 replicates per treatment. Within each feeding strategy, diets were formulated that corresponded to 5 feeding phases. Supplemental AA were added to the low CP diet such that the AA needs of the pigs were achieved with concomitant reduction in dietary N (Table 2). Diets contained similar energy and lysine contents within each feeding phase. The CP contents in phase 1 were 18.6% and 17.5% for standard and low CP diets, respectively. Diet CP content was progressively deceased through each feeding phase (Table 2).

Gaseous Concentrations and Ventilation Measurements

Gaseous concentration monitoring of each room and background air occurred in a sequential manner through software control (LabVIEW, National Instruments Corp., Austin, TX). Each of the 12 rooms was sampled for a 15-min, the sampling line was purged for the first 10 min, and then data were saved for 5 min. Ammonia (NH3) was measured using a chemiluminescence NH3 analyzer (Model 17C, Thermo Fisher, Franklin, MA; detection limit of 0.001 ppm), which is a combination NH3 converter and NO-NO2-NOx analyzer. Methane (CH4) was measured using a 55i CH4-NMTHC analyzer (Thermo Fisher, Franklin, MA; CH4: range = 0 to 100 ppm; detection limit = 0.05 ppm). Nitrous oxide (N2O) was measured using an Innova 1412 photoacoustic analyzer (Lumasense Technologies, Ballerup, Denmark; range = 0 to 50000 ppm; detection limit = 0.03 ppm at 50,000 ppm range). Carbon dioxide (CO2) was measured using an X-Stream infrared analyzer (Emerson Electric Co., St Louis, MO; 5.1 ppm detection limit at 1,000 ppm range).

Airflow rates into each room were continuously measured using 15.24-cm orifice plates in the incoming ductwork of each room. Differential pressure transducers (Setra Model 239, Boxborough, MA) measured the pressure drop across orifice plates. Using calibration curves, airflow estimates were determined and automatically recorded every 30 sec. The temperature of each room was programmed based on the room temperature setting. Temperature and humidity of each room, measured using a CS500 Temperature and relative humidity probe (Campbell Scientific, Inc.; Logan, UT), were continuously monitored and recorded. In the event that the temperature fell outside of the specified range, an alarm system placed a series of phone calls to alert laboratory personnel.

Gas emission rates were calculated as the product of ventilation rates and concentration differences between exhaust and background air.

Chemical Analyses

Feed and excreta N content was determined using the Kjeldahl method (AOAC Method 928.08, 2000) . Feed amino acid content was analyzed by the University of Missouri Agriculture Experiment Station Laboratory using HPLC methods (AOAC Method 982.30, 2006). Feed energy and mineral content (Ca, P, Mg, K, Na, S, Cu, Zn, Fe, Mn, Mo) were analyzed using bomb calorimetry and microwave digestion followed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS), respectively (Dairy One Inc.; Ithaca, NY). Manure P and K contents were analyzed by Dairy One (Dairy One Inc.; Ithaca, NY) using a Foss NIR System Model 6500 with Win ISI II v1.5 (AOAC Method 941.04, 1984; AOAC Method 2001.11, 2005). Manure NH4-N content was measured by distillation (AOAC 2000, Method 928.08; Dairy One Inc.; Ithaca, NY).

Global Warming Potentials (GWP)

Global Warming Potential (GWP) is a simple and commonly used estimator of the warming effects of different long-lived greenhouse gases, and it is expressed in terms of emissions of CO2. Because GWP is always expressed relative to CO2, CO2’s GWP is 1. Methane (CH4) has a GWP of 24 over a 100 year period, meaning that the emission of 1 unit of CH4 is the same as the emission of 24 units of CO2 over a 100 year period. Nitrous oxide (N2O) has a GWP of 298 over a 100 year period (IPCC, 2007).

Statistical Analyses

The PROC Mixed procedure of SAS (SAS Institute, 2012) was used to analyze experimental data to determine any significant differences. Dietary treatments and phases were fixed factors, and room was random factor. The Kenward-Roger procedure was applied for calculating the

Table 2. Ingredient and nutrient composition of standard CP and low CP diets, as fed.

Ingredient	Phase[1] 1		Phase 2		Phase 3		Phase 4		Phase 5	
	Standard	Low	Standard	Low	Standard	Low	Standard	Low	Standard	Low
Corn, yellow dent	66.88	70.91	9.20	72.91	71.08	74.56	72.89	76.74	74.53	78.93
Soybean meal, dehull, sol.extr	24.51	20.20	20.39	16.47	16.29	12.41	12.18	7.83	8.10	3.31
Wheat middlings	5.00	5.00	7.50	7.50	10.00	10.00	12.50	12.50	15.00	15.00
Limestone	0.80	0.81	1.16	1.18	1.05	1.08	1.08	1.08	1.02	1.05
Calcium phosphate (monocalcium)	1.51	1.54	0.50	0.55	0.43	0.48	0.27	0.34	0.25	0.29
Soybean oil	0.50	0.50	0.51	0.45	0.43	0.55	0.33	0.52	0.28	0.27
Sodium chloride	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Trace minerals and vitamins	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
L-Lysine·HCl	0.22	0.36	0.20	0.32	0.19	0.31	0.21	0.35	0.26	0.41
L-Threonine	0.04	0.10	0.03	0.08	0.03	0.09	0.04	0.10	0.06	0.13
DL-Methionine	0.02	0.04	0.01	0.03	-	0.01	-	0.01	-	0.01
L-Cysteine	0.02	0.03	-	0.01	-	0.01	-	0.01	-	0.01
L-Tryptophan	-	0.01	-	-	-	-	-	-	-	-
L-Isoleucine	-	-	-	-	-	-	-	-	-	0.04
L-Valine	-	-	-	-	-	-	-	-	-	0.02
Composition, analyzed, %										
CP	18.5	17.5	16.5	15.6	15.2	13.9	14.0	12.3	12.2	11.0
DM	88.1	87.8	89	88.9	88.8	88.5	88.2	88.3	88.3	88.3
TDN	84	83	84	84	83	84	83	83	83	84
Ca	0.79	0.89	0.73	0.76	0.66	0.7	0.69	0.65	0.36	0.51
P	0.9	0.93	0.59	0.56	0.57	0.57	0.57	0.58	0.31	0.46
Amino acid										
Lysine	1.12	1.15	1.00	1.04	0.87	0.87	0.78	0.86	0.77	0.72
Available Lysine	1.04	1.07	0.97	1.01	0.84	0.84	0.75	0.83	0.74	0.70
Methionine	0.30	0.28	0.30	0.30	0.23	0.24	0.22	0.21	0.19	0.19
Tryptophan	0.22	0.24	0.20	0.19	0.19	0.17	0.15	0.16	0.16	0.16
Threonine	0.68	0.70	0.63	0.65	0.55	0.52	0.52	0.54	0.50	0.48
Isoleucine	0.73	0.67	0.69	0.64	0.59	0.56	0.55	0.46	0.45	0.38
Leucine	1.56	1.48	1.49	1.41	1.39	1.31	1.29	1.15	1.17	1.05
Valine	0.79	0.73	0.78	0.71	0.72	0.68	0.62	0.55	0.63	0.55
Composition, calculated, %										
CP, total	18.24	16.72	16.83	15.43	15.41	14.01	14.02	12.46	12.66	11.00
CP, SID	15.47	14.14	14.20	12.98	12.93	11.71	11.68	10.33	10.48	9.04
Amino acid, SID										
Arg	1.06	0.93	0.96	0.84	0.86	0.74	0.75	0.63	0.65	0.51
His	0.43	0.39	0.40	0.36	0.37	0.33	0.33	0.29	0.30	0.25
Ile	0.64	0.57	0.58	0.51	0.51	0.45	0.45	0.38	0.39	0.34
Leu	1.38	1.28	1.29	1.20	1.19	1.10	1.10	0.99	1.00	0.89
Lys	0.97	0.97	0.86	0.86	0.76	0.76	0.68	0.69	0.63	0.63
Met	0.28	0.28	0.25	0.25	0.22	0.22	0.21	0.20	0.19	0.18
Total Sulfur	0.55	0.55	0.49	0.49	0.45	0.44	0.42	0.40	0.39	0.37
Phe	0.77	0.69	0.70	0.63	0.63	0.56	0.57	0.49	0.50	0.41
Total Aromatic	1.26	1.13	1.15	1.03	1.03	0.91	0.92	0.78	0.80	0.66
Thr	0.59	0.59	0.53	0.53	0.48	0.48	0.44	0.44	0.41	0.41

Trp	0.19	0.17	0.17	0.15	0.15	0.13	0.13	0.12	0.11	0.11
Val	0.71	0.64	0.65	0.59	0.60	0.53	0.54	0.46	0.48	0.42
NEg (Mcal/Lb, DM)	0.65	0.64	0.64	0.65	0.64	0.65	0.64	0.64	0.64	0.65
ME	3281	3286	3298	3298	3293	3301	3286	3300	3280	3286
SID Lysine/ME	2.95	2.96	2.61	2.61	2.31	2.30	2.08	2.08	1.93	1.93
Fermentable fiber	11.61	10.82	11.17	10.46	10.71	9.99	10.24	9.43	9.77	8.89
P, total	0.72	0.71	0.51	0.50	0.49	0.48	0.46	0.45	0.45	0.44
P, STTD	0.46	0.45	0.27	0.27	0.25	0.25	0.23	0.23	0.22	0.22
Ca, total	0.64	0.64	0.59	0.59	0.53	0.54	0.50	0.50	0.47	0.47

[1] Phase 1 from pig age 60 d to 92 d; initial BW = 21 kg; Phase 2 from pig age 93 d to 117 d; initial BW = 52 kg; Phase 3 from pig age 118 d to 136 d; initial BW = 75 kg; Phase 4 from pig age 137 d to 157 d; initial BW = 94 kg; Phase 5 from pig age 158 d to 166 d; initial BW = 113 kg.

denominator degrees of freedom. Tukey adjustment was used for multiple comparisons. Significant differences among least squares means were declared at $P < 0.05$.

Manure storage study (objective #2)

The experiment was conducted at the AAQRF. Manure collected from the housing study (objective #1) was pooled by diet. From the pooled manure, 6 aliquots (32.4 kg or 71.4 lb) were placed into 30 gal barrels (6 barrels per diet). A lid was placed onto each barrel and manure was stored for 90 days. No new additions of manure were made to the barrel following study start. This differs from what occur in a swine barn manure pit but was practiced in order to quantify the percent of total N stored that would be emitted from the storage. Lids were constructed to allow airflow across the surface of each barrel at a rate of approximately 1.2 L/min. In addition, barrels were automatically stirred for 15 min of each hour using a Dewalt 18v drill equipped with a stir paddle. Beginning and ending excreta N content was determined using the Kjeldahl method (AOAC Method 928.08, 2000).

Gaseous Concentrations and Ventilation Measurements

Gaseous concentration monitoring of each barrel and background air occurred in a sequential manner through software control (LabVIEW, National Instruments Corp., Austin, TX) using the same procedures and instruments as described above for Objective #1. Airflow rates into each barrel were checked twice weekly using a flow meter. Flow rates were determined based on a pump setting that was not changed throughout the study. The room temperature where barrels were stored was not controlled but was measured continuously using a CS500 Temperature and relative humidity probe (Campbell Scientific, Inc.; Logan, UT), and recorded. Gas emission rates were calculated as the product of ventilation rates and concentration differences between exhaust and background air.

Statistical Analyses

The PROC Mixed procedure of SAS (SAS Institute, 2012) was used to analyze experimental data to determine any significant differences. Dietary treatment was a fixed factor and barrel was random factor. Emissions were summed over the treatment period to provide a single, cumulative emission value for each barrel. The Kenward-Roger procedure was applied for calculating the denominator degrees of freedom. Tukey adjustment was used for multiple comparisons. Significant differences among least squares means were declared at $P < 0.05$.

Soil application study (objective #3)

Post-storage, manure was applied to a soil surface in 55 gal (208 L) barrels similar to those used for manure storage. Manure represented excretion from pigs fed either the standard crude protein diets or the reduced crude protein diets. Gravel was added to barrels (18 in). Topsoil (9.5 in) was added on top of the gravel and compacted. Final headspace was 6.75 in. Soil was wetted to achieve a starting soil moisture of 17.25%. To the surface of each barrel, 570 g of manure was applied. A lid was placed onto each barrel and manure was stored for 7 days. No new additions of manure were made to the soil surface following study start. Lids were constructed to allow airflow across the surface of each barrel at a rate of approximately 1.2 L/min. Beginning N content of the manure was determined using the Kjeldahl method (AOAC Method 928.08, 2000). Due to the need to scrape manure off the soil surface, thereby contaminating manure with soil, no analyses of the manure were conducted at the end of the study period.

Gaseous Concentrations and Ventilation Measurements

Gaseous concentration monitoring of each barrel and background air occurred in a sequential manner through software control (LabVIEW, National Instruments Corp., Austin, TX) using the same procedures and instruments as described above for Objective #1. Airflow rates into each barrel were checked twice weekly using a flow meter. Flow rates were determined based on a pump setting that was not changed throughout the study. The room temperature where barrels were stored was measured using a CS500 Temperature and relative humidity probe (Campbell Scientific, Inc.; Logan, UT), and recorded. Gas emission rates were calculated as the product of ventilation rates and concentration differences between exhaust and background air.

Statistical Analyses

The PROC Mixed procedure of SAS (SAS Institute, 2012) was used to analyze experimental data to determine any significant differences. Dietary treatment was a fixed factor. The Kenward-Roger procedure was applied for calculating the denominator degrees of freedom. Tukey adjustment was used for multiple comparisons. Significant differences among least squares means were declared at $P < 0.05$.

Results and Discussion

Housing study (objective #1)

Pig Performance. Dietary treatment had no statistical significant effect on average daily gain (ADG; 1.013 kg/d-pig), average daily feed intake (ADFI; 2.714 kg/d-pig), or feed conversion ratio (FCR; 2.735 kg feed/kg gain) ($P > 0.05$, Table 3). Pigs had higher ADG during phase 2 and they consumed more feed as they aged. Pigs had highest FCR during phases 2 and 3, and as they reached to market body weight (120 kg) FCR declined indicating less efficient conversion of feed to weight gain (Table 3). In this study, the reduced protein diets were adequately supplemented with all limiting AA and did not limit pig growth.

Table 3. Least squares means for body weight gain, feed intake, and feed conversion of pigs fed a standard or reduced CP diet.

	ADG (kg/d-pig)	ADFI (kg/d-pig)	FCR (kg feed/kg gain)
Diet			
Standard CP diet	1.008	2.709	2.756
Red CP diet	1.019	2.719	2.714
SE	0.018	0.036	0.073
Phase[1]			
1	0.945^a	1.822^a	1.933^a
2	1.126^b	2.338^b	2.079^a
3	1.042^{ab}	2.993^c	2.927^b
4	1.007^a	3.141^d	3.133^b
5	0.949^a	3.276^e	3.602^c
SE	0.037	0.041	0.120
Type 3 Tests of Fixed Effects (P-values)			
Diet	0.68	0.86	0.69
Phase	0.01	<0.01	<0.01
Diet*Phase	0.39	0.42	0.37

[1] Phase 1 from pig age 60 d to 92 d; initial BW = 21 kg; Phase 2 from pig age 93 d to 117 d; initial BW = 52 kg; Phase 3 from pig age 118 d to 136 d; initial BW = 75 kg; Phase 4 from pig age 137 d to 158 d; initial BW = 94 kg; Phase 5 from pig age 159 d to 166 d; initial BW = 113 kg.

[a-d] Significant differences within a column at $P < 0.05$.

Excreta Composition. The manure excretion rate (kg/day-pig), total solid (%), manure N (%), manure NH_4^+-N (%), manure P (%), and manure K (%) are shown in Table 4. Dietary treatments had no effect on manure excretion rate or total solids concentration across feeding phases ($P > 0.05$; Table 4). The generally greater manure excretion (kg/day-pig) during phases 1-3 may be due to greater wasting of water as evidenced by <5% solids content of manure was during those phases. The concentrations of N and NH_4^+-N did not differ among pigs fed the different diets across phases (Table 4). However, phase effects were observed that reduced CP diets results in decreased NH_4^+ in fresh and stored manure (Sutton et al., 1999), which contrasts the findings of the current study. The findings of the current study reflect N remaining after storage in housing ranging from 9 to 33 d, during which some NH_3 volatilization had occurred perhaps contributing to little difference in manure N content when removed from housing. Manure P and K content was not affected by diet ($P > 0.05$) and their concentrations increased as pigs grew ($P < 0.05$) (Table 4).

Table 4. Least squares means of excretion characteristics of manure from grow-finish pigs fed either a standard CP diet or a reduced CP diet over 5 feeding phases.

	Manure excretion rate (kg/day-pig)	Total solids (%)	Manure N (%, wet)	Manure NH_4^+-N (%, wet)	Manure P (%, wet)	Manure K (%, wet)
Main effect means						
Diet						
Standard CP	7.93	4.07	0.34	0.20	0.096	0.18
Red CP	7.91	4.41	0.34	0.18	0.098	0.16
SE	0.61	0.40	0.03	0.01	0.007	0.01
Phase[1]						
1	8.08^{b}	1.65^{a}	0.20^{a}	0.09^{a}	0.074^{b}	0.12^{a}
2	9.79^{d}	2.95^{b}	0.26^{b}	0.16^{b}	0.058^{a}	0.14^{b}
3	8.28^{bc}	3.73^{c}	0.30^{c}	0.22^{c}	0.089^{c}	0.18^{c}
4	7.06^{ab}	5.72^{d}	0.44^{d}	0.24^{cd}	0.120^{d}	0.20^{d}
5	6.39^{a}	7.16^{e}	0.49^{d}	0.25^{d}	0.143^{e}	0.21^{d}
SE	0.51	0.36	0.02	0.01	0.006	0.01
Type 3 Tests of Fixed Effects (P-value)						
Diet	0.98	0.56	0.95	0.11	0.83	0.30
Phase	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Diet*Phase	0.62	0.29	0.27	0.85	0.65	0.93

[1] Phase 1 from pig age 60 d to 92 d; initial BW = 21 kg; Phase 2 from pig age 93 d to 117 d; initial BW = 52 kg; Phase 3 from pig age 118 d to 136 d; initial BW = 75 kg; Phase 4 from pig age 137 d to 158 d; initial BW = 94 kg; Phase 5 from pig age 159 d to 166 d; initial BW = 113 kg.

$^{a\text{-}d}$ Significant differences within a column at $P < 0.05$.

Air Quality. Over the course of the 107-d experimental period air entering the rooms had an average temperature of 18.5 ^{o}C, relative humidity of 80%, and background gas concentrations as follows: NH_3, 0.28 ppm; N_2O, 0.46 ppm; CO_2, 513 ppm; O_2, 21%; H_2S, 0.01 ppm; CH_4, 2.51 ppm, and NMTHC, 0.03 ppm. Mean room ventilation rates and temperatures for each feeding phase are shown in Figure 1. Temperature setpoints in rooms decreased as pig body weight increased so as to remain in the recommended thermal conditions for growing-finishing swine (National Pork Board, 2003).

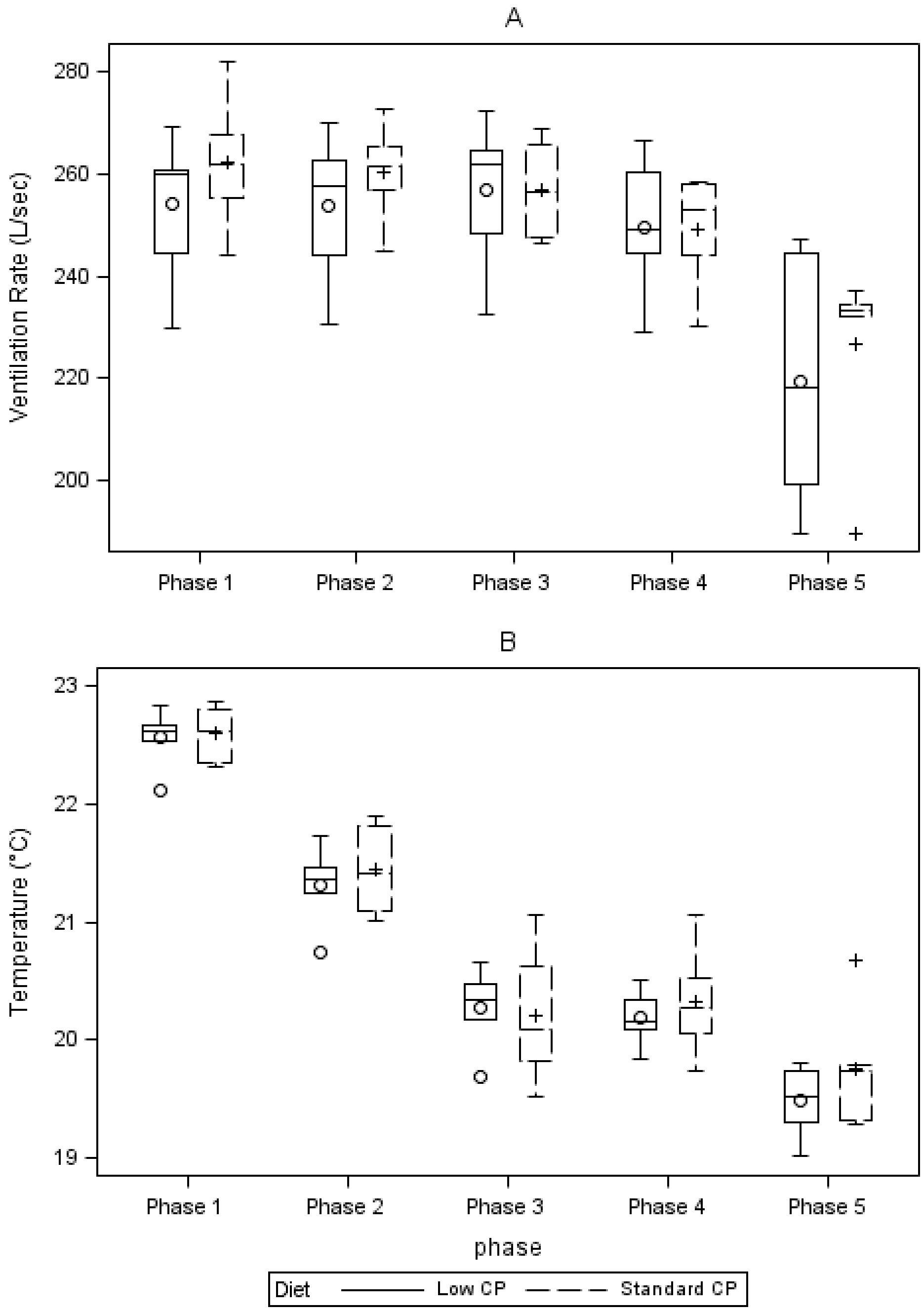

Figure 1. Room ventilation rates and temperature during different feeding phases when grow-finish pigs were fed standard CP diets or low CP diets. Note: the bottom and top of each box are the 25th and 75th percentiles, the line near the middle of the box is the 50th percentile (median), and the diamond is the mean; The whiskers represent the lowest datum with 1.5 interquartile range (IQR) of the lower quartile and the highest datum with 1.5 IQR of the upper quartile; data points (small circles) that are not included between the whiskers are potential outliers).

NH_3 and N_2O Emissions. Dietary treatments and phases had significant effects on NH_3 emissions (Table 5). For both dietary treatments, the emission rates increased from phase 1 through phase 3, then leveled off or decreased during phases 4 and 5. The interaction between phase and treatment were significant ($P < 0.05$**Error! Reference source not found.**), indicating dietary effects were phase dependent. Although feeding the reduced

CP diet resulted in lower NH_3 concentrations (ppm) and emissions (mg/d), neither NH_3 concentrations nor emissions as a function of per animal count (g/d-pig) or N intake (g NH_3/kg of N consumed) was influenced by diet during phase 1. During phases 2 through 5, feeding the low CP diet resulted in lower NH_3 emissions ($P < 0.05$).

The current study demonstrates that reducing crude protein reduces NH_3 emissions. In the current study the percent NH_3 emission reduction observed for each percentage unit reduction in diet CP content was 47.9%, 53.2%, 26.8%, 26.5% and 51.6% during phases 1 through 5, respectively.

Table 5. Least squares means of ammonia emissions from grow-finish pigs fed either a standard CP diet or a reduced CP diet over 5 feeding phases.

	Standard CP diet					Red CP diet				
Phase[1]	1	2	3	4	5	1	2	3	4	5
Concentration (ppm)	0.56	1.38^{a}	2.71^{a}	2.72^{a}	2.45^{a}	0.39	0.94^{b}	1.83^{b}	1.60^{b}	1.33^{b}
Emissions (g/d-pig)	1.05	2.61^{a}	8.28^{a}	8.09^{a}	6.82^{a}	0.55	1.36^{b}	5.39^{b}	4.45^{b}	2.60^{b}
Emissions (g/d-AU[2])	1.32^{a}	17.10^{a}	42.10^{a}	33.50^{a}	25.00^{a}	6.99^{b}	9.19^{b}	27.90^{b}	18.70^{b}	9.72^{b}
Emission (g-NH_3/kg of N consumed)	19.6	41.9	116.5^{a}	116.0^{a}	106.0^{a}	10.8	23.7	79.6^{b}	71.6^{b}	45.3^{b}

Type 3 tests of fixed effects

	Concentration (ppm)	Emissions (g/day-pig)	Emissions (g/day-AU)	Emission (g-NH3/kg of N consumed)
Diet	<0.01	<0.01	<0.01	<0.01
Phase	<0.01	<0.01	<0.01	<0.01
Diet*Phase	<0.01	<0.01	<0.01	<0.01

[1] Phase 1 from pig age 60 d to 92 d; initial BW = 21 kg; Phase 2 from pig age 93 d to 117 d; initial BW = 52 kg; Phase 3 from pig age 118 d to 136 d; initial BW = 75 kg; Phase 4 from pig age 137 d to 158 d; initial BW = 94 kg; Phase 5 from pig age 159 d to 166 d; initial BW = 113 kg.

[2] AU = animal unit is equivalent to 454 kg live weight.

[a-b] Significant differences between diet treatments within a row and feeding phase (simple effects) at $P < 0.05$ (e.g. standard CP diet in phase 2 vs. low CP diet in phase 2 is significant different).

A diet effect was observed for N_2O emissions expressed as a function of pig count and animal unit ($P > 0.05$; Table 6). A strong phase effect was observed for emissions, with increasing emissions from phase 1 to phase 4 followed by decreased emissions during phase 5. This is due in part to the exhaust air from rooms having similar N_2O concentrations as air entering the rooms during phases 1 through 3, which resulted in very low (even negative) emission rates. The interactions between phase and treatment for concentration and emissions were not significant ($P > 0.05$, Table6). Among possible N emissions (NH_3, N_2O, NO, NO_2 and N_2), NO and NO_2 emissions were negligible in our study, and N_2 gas was not measured. As the second most important N-containing gas, N_2O was less than 1% of total N-NH3 + N-N_2O emitted during phases 1 through 3, and represented approximately 4% of total N-NH_3 + N- N_2O during phases 4 and 5.

Table 6. Least squares means of nitrous oxide emissions from grow-finish pigs fed either a standard CP diet or a reduced CP diet over 5 feeding phases.

	Concentration (ppm)	Emissions (g/d-pig)	Emissions (g/d-AU[2])	Emissions (g-N$_2$O/ kg of N consumed)
Main effect means				
Diet				
Standard CP diet	0.471	0.077^{y}	0.340^{y}	1.140
Reduced CP diet	0.470	0.059^{x}	0.218^{x}	0.976
SE	0.0015	0.0046	0.027	0.074
Phase[1]				
1	0.321^{a}	0.0078^{ab}	0.096^{a}	0.136^{abc}
2	0.449^{b}	-0.0168^{a}	-0.112^{b}	-0.283^{b}
3	0.523^{d}	0.0243^{b}	0.122^{a}	0.347^{c}
4	0.501^{c}	0.205^{d}	0.854^{d}	3.128^{e}
5	0.558^{e}	0.118^{c}	0.435^{c}	1.960^{d}
SE	0.0019	0.011	0.06	0.182
Type 3 Tests of Fixed Effects (P-value)				
Diet	0.55	0.02	0.01	0.15
Phase	<0.01	<0.01	<0.01	<0.01
Diet*Phase	0.93	0.87	0.36	0.60

[1] Phase 1 from pig age 60 d to 92 d; initial BW = 21 kg; Phase 2 from pig age 93 d to 117 d; initial BW = 52 kg; Phase 3 from pig age 118 d to 136 d; initial BW = 75 kg; Phase 4 from pig age 137 d to 158 d; initial BW = 94 kg; Phase 5 from pig age 159 d to 166 d; initial BW = 113 kg.

[2] AU = animal unit is equivalent to 454 kg liveweight.

[a-d] Significant differences within a column at $P < 0.05$.

Methane Emissions. No diet effect was observed for CH$_4$ ($P > 0.05$; Table 8). The CH$_4$ emissions were generally higher during the finish phases (phases 3 through 5) than grower phases (phases 1 through 2). The interactions between phase and treatment for concentration and emissions were not significant for CH$_4$.

Table 8. Least squares means of methane emissions from grow-finish pigs fed either a standard CP diet or a reduced CP diet over 5 feeding phases[1].

	Concentration (ppm)	Emissions (g/d-pig)	Emissions (g/d-AU[2])
Main effect means			
Diet			
Standard CP diet	3.668	3.169	15.57
Reduced CP diet	3.722	3.312	16.39
SE	0.044	0.164	0.838
Phase1			
1	2.546^{a}	0.658^{a}	8.305^{a}
2	3.470^{b}	1.662^{b}	11.00^{b}
3	3.894^{c}	4.789^{d}	24.61^{e}
4	4.144^{c}	4.943^{d}	20.64^{d}
5	4.421^{d}	4.149^{c}	15.36^{c}

SE	0.059	0.180	0.832
Type 3 Tests of Fixed Effects (P-value)			
Diet	0.41	0.55	0.50
Phase	<0.01	<0.01	<0.01
Diet*Phase	0.34	0.46	0.335

[1] Phase 1 from pig age 60 d to 92 d; initial BW = 21 kg; Phase 2 from pig age 93 d to 117 d; initial BW = 52 kg; Phase 3 from pig age 118 d to 136 d; initial BW = 75 kg; Phase 4 from pig age 137 d to 158 d; initial BW = 94 kg; Phase 5 from pig age 159 d to 166 d; initial BW = 113 kg.

[2] AU = animal unit is equivalent to 454 kg liveweight.

[a-d] Significant differences within a column at $P < 0.05$.

CO_2 emissions and calculated CO_2eq. A diet effect was not observed for CO_2 or CO_2eq concentrations or emissions ($P > 0.05$, Table 9). Similarly, interaction between phase and treatment was not significant for any variable. However, a phase effect was observed because CO_2 emissions increased from 537.4 g/d-pig during phase 1 to approximately 2000 g/d-pig during phases 3 through 5 ($P < 0.01$). The CO_2 emissions based on AU (g/d-AU) showed slightly different pattern compared to emissions based on pig count (g/d-pig) in that the highest emission rates were observed during phase 3.

When calculating the CO_2eq emissions, because N_2O and CH_4 emissions are low from swine housing, CO_2 was the most dominant greenhouse gases accounting for more than 90% of total CO_2eq. Given the feeding strategy employed in this study (reduced diet CP), coupled with low emissions of N_2O and CH_4 from housing, it is not unexpected that no differences in CO_2eq emissions were observed in the housing system. The potential for diet effects on CO_2eq emissions lies in the manure management part of the livestock system, particularly N_2O emissions that result following land application of manures containing different N content. Given the feeding strategy employed in this study (reduced diet CP), coupled with low emissions of N_2O and CH_4 from housing, it is not unexpected that no differences in CO_2eq emissions were observed in the housing system. The potential for diet effects on CO_2eq emissions lies in the manure management part of the livestock system, particularly N_2O emissions that result following land application of manures containing different N content. In this study, the manure N content did not differ as a result of dietary treatments fed to the pigs suggesting that no difference in a feed-through-field CO_2eq balance would be observed.

Table 9. Least squares means of CO_2 and CO_2eq concentrations and emissions from grow-finish pigs fed either a standard CP diet or a reduced CP diet over 5 feeding phases.

	Concentration (ppm)	Emissions (g/d-pig)		Emissions (g/d-AU)	
	CO_2	CO_2	CO_2eq	CO_2	CO_2eq
Main effect means					
Diet					
Standard CP diet	713.4	1461	1563	7531	8022
Reduced CP diet	706.9	1397	1498	7285	7760
SE	5.44	34.0	34.2	159	163
Phase					
1	585.5a	537.4a	556.2a	6774b	7010b
2	646.8b	745.9b	782.4b	4940a	5181a
3	690.0c	1886c	2013c	9681e	10333e
4	751.8d	2037d	2222d	8488d	9258d
5	876.8e	1941cd	2080c	7159c	7672c
SE	6.38	32.4	32.3	137	141
Type 3 Tests of Fixed Effects (P-value)					

Diet	0.42	0.21	0.20	0.30	0.27
Phase	<0.01	<0.01	<0.01	<0.01	<0.01
Diet*Phase	0.997	0.76	0.84	0.49	0.36

[1] Phase 1 from pig age 60 d to 92 d; initial BW = 21 kg; Phase 2 from pig age 93 d to 117 d; initial BW = 52 kg; Phase 3 from pig age 118 d to 136 d; initial BW = 75 kg; Phase 4 from pig age 137 d to 158 d; initial BW = 94 kg; Phase 5 from pig age 159 d to 166 d; initial BW = 113 kg.
[2] AU = animal unit is equivalent to 454 kg liveweight.
[a-d] Significant differences within a column at $P < 0.05$.

Manure storage study (objective #2)

As a result of feeding the standard CP diet, room ammonia concentration and ammonia emissions were double that observed when the reduced CP diet was offered (Figure 2). Manure collected from housing was pooled across phases and rooms and analyzed by diet. Analyses showed that the pooled manure N content was higher in manure from pigs fed the standard CP diet (Table 10) prior to long term storage. Note that more N was present, initially, in the barrels that stored the manure from pigs fed the standard CP diet (Table 10) however, ending concentrations of N showed that more N remained in the barrels containing manure from pigs fed the reduced CP diets. When expressed as a percent of N in the barrels, total N emitted over the storage period was less from barrels that stored manure from pigs fed the reduced CP diets (44% of TKN lost vs. 58% of TKN lost; Table 10).

Table 10. Total nitrogen content of manure from pigs fed standard or reduced crude protein (CP) diets prior to and following manure 90 d of storage.

Manure treatment	Manure N content prior to storage, % TKN[1]	Manure N content following 90 days of storage, % TKN	Percent of TKN lost during storage
Standard CP diet	9.65	4.09	57.6
Reduced CP diet	8.86	4.92	44.4

[1] TKN – total Kjeldahl nitrogen

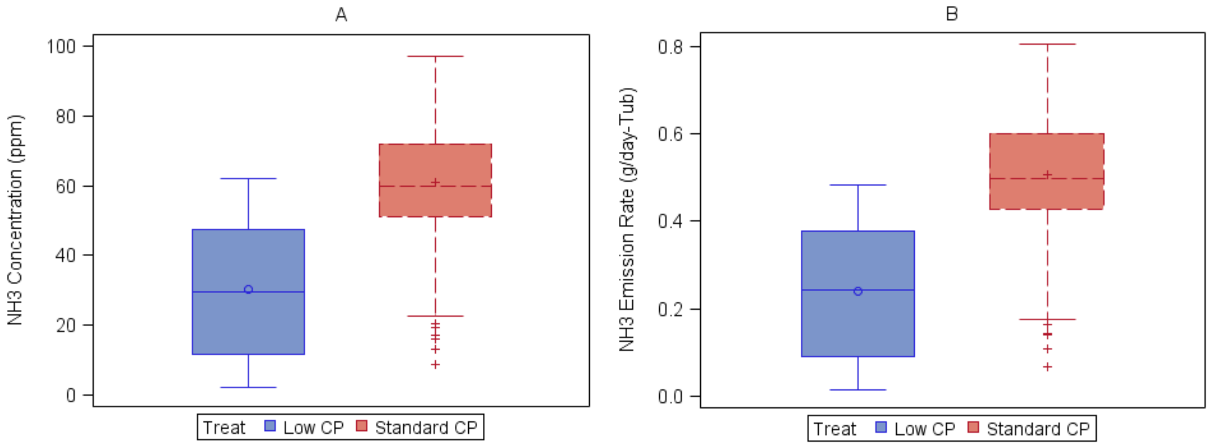

Figure 2. Ammonia concentration and ammonia emissions resulting from feeding either a standard CP diet or a reduced CP diet to pigs from growing through finishing.

No significant differences in other gases were observed though a trend was observed for differences in N_2O emissions (Table 11). Data were re-analyzed to consider day of storage as a random term (looked at daily emissions rather than a single, cumulative emission value for each barrel). While Day was a significant effect, no Day × Diet effect was observed therefore data are not shown. Based on observed emissions and lack of treatment effect for greenhouse gas emissions, no difference in carbon balance would be calculated. However, ammonia may contribute to potential nitrous oxide emissions if deposited in soil at a geographic location outside of the farm boundary (dry or wet deposition). Therefore, the observations from this study, while not quantifiable in terms of a carbon balance, are noteworthy due to the magnitude of difference in ammonia emissions between the two feeding strategies.

Table 11. Least squares means of diet effect on emissions from manure storage (manure from grow-finish pigs fed either a standard CP diet or a reduced CP diet).

	Concentration (ppm)	Emissions (g/day)
NH_3		
Manure from standard diet	61.1	0.51
Manure from reduced CP diet	30.2	0.24
SE	5.0	0.04
N_2O		
Manure from standard diet	0.19	-0.0009
Manure from reduced CP diet	0.20	-0.0010
SE	0.004	0.00001
CH_4		

Manure from standard diet	3.75	-1.7×10^{-4}
Manure from reduced CP diet	3.76	-1.6×10^{-4}
SE	0.01	4.1×10^{-5}
CO_2		
Manure from standard diet	977	7.10
Manure from reduced CP diet	1110	10.2
SE	67.5	1.3
Type 3 Tests of Diet Effects (P-value)		
NH_3	<0.01	<0.01
N_2O	0.11	0.07
CH_4	0.77	0.81
CO_2	0.19	0.12

Soil application study (objective #3)

Following simulated land application of stored manures, no significant differences in any gases were observed (Table 12). Data were re-analyzed to consider day following application as a random term. While Day was a significant effect, no Day × Diet effect was observed therefore data are not shown. Based on observed emissions and lack of treatment effect for greenhouse gas emissions, no difference in carbon balance would be calculated. Lack of observation is likely due to no measurable difference (either not measureable with technology available or just not there). Soil moisture content, if increased, might have helped to demonstrate differences due to the formation of nitrous oxide under anaerobic conditions. However, the lack of effect for ammonia emissions following surface application suggest that most excess nitrogen in the manure from pigs fed the standard diet was lost during manure storage. In addition, the soil was conditioned to a moisture content suitable for manure application as this is the practice followed by the swine industry. As would be expected with no additional moisture addition and continual airflow across the surface, final soil moisture content at the end of the 7-d sample period was reduced to 13.91%.

Table 12. Least squares means of diet effect on emissions from manure soil application (manure from grow-finish pigs fed either a standard CP diet or a reduced CP diet).

	Concentration (ppm)	Emissions (g/day)
NH_3		
Manure from standard diet	1.62	0.038
Manure from reduced CP diet	1.86	0.045
SE	0.18	0.0049
N_2O		
Manure from standard diet	0.27	0.0018
Manure from reduced CP diet	0.27	0.0020
SE	0.003	0.0002
CH_4		
Manure from standard diet	5.96	0.027
Manure from reduced CP diet	5.53	0.015
SE	0.24	0.007
CO_2		
Manure from standard diet	817	11.8
Manure from reduced CP diet	789	9.45
SE	18.0	1.58
Type 3 Tests of Diet Effects (P-value)		
NH_3	0.36	0.36

N_2O	0.38	0.44
CH_4	0.23	0.22
CO_2	0.31	0.32

Conclusions

These findings illustrate that feeding reduced CP diets that are formulated based on NRC 2012 recommendations provides an effective tool for reducing NH_3 emissions from swine housing compared to recent industry formulations. No diet effects on pig performance were observed ($P > 0.05$). Feed conversion ratios (FCR) were 2.76 kg-feed/kg-gain and 2.71 kg-feed/kg-gain for standard and reduced CP diets, respectively. The change in NH_3 emissions for each percentage unit reduction of diet CP content that resulted from feeding the reduced CP diets compared with the standard CP diets corresponded to 47.9%, 53.2%, 26.8%, 26.5% and 51.6% during phases 1 through 5, respectively. No diet effects were observed for other gases (N_2O, CH_4, and CO_2) emissions. Once manure is moved to long-term storage and applied to fields, diet effects on the volatilization of gases may be different from that observed during housing. In this study, a diet effect on ammonia was observed during manure storage, only. As a result of feeding the standard CP diet, room ammonia concentration and ammonia emissions were double that observed when the reduced CP diet was offered. No differences in greenhouse gas emissions between diet treatments were observed during manure storage or following land application of manures. Because no changes in greenhouse gas emissions were observed during any phase of the study (housing, manure storage, or land application of manures) no difference between diets in the carbon footprint of pork production would be calculated if the boundary was drawn around the farm. If the effect of producing synthetic amino acids were compared to that of meeting nutrient requirements through feedstuffs were considered (setting boundaries well outside of the farm borders and outside the scope of this project) the findings may illustrate differences. The value in using a feed-through-field approach for considering nutrient losses is that we demonstrated that over 40% more N is lost in the form of ammonia emissions during housing and manure storage as a result of feeding the standard CP diet. However, losses during land application were low compared to housing and storage and no diet differences were observed suggesting that land application may not be the best place to target efforts to reduce ammonia emissions. Furthermore, diet strategies that produce large differences in ammonia emissions do not necessarily result in observed differences in nitrous oxide emissions.