EFFECTS OF VITAMIN D SUPPLEMENTATION AND FLOOR SPACE ON PIG PERFORMANCE

by

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B.S., Texas Tech University, 2010
M.S., Kansas State University, 2012

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Animal Sciences and Industry

College of Agriculture

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Abstract

Three experiments using 2,385 pre-weaned pigs, growing pigs, and sows were performed in addition to a meta-analysis and industry survey. Experiment 1 tested the effects of sow vitamin D supplementation from vitamin D_3 (low, medium, or high) or $25OHD_3$ (same IU equivalency as the medium level of vitamin D_3) on maternal performance, neonatal pig bone and muscle characteristics, subsequent pre-weaned pig performance and serum $25OHD_3$ with only differences in serum $25OHD_3$ being impacted. In the second experiment a subsample of pigs weaned from the maternal portion of the study were used in a split-plot design and fed 2 different forms of vitamin D in the nursery and growth performance was evaluated until the pigs reached market weight. Overall, the nursery vitamin D treatments did not impact growth; however, pigs from sows fed the medium level of vitamin D_3 performed better after weaning compared to pigs from sows fed the low or the high level of vitamin D_3, and serum $25OHD_3$ was altered based on maternal and nursery vitamin D supplementation. In the third experiment, finishing pigs were initially provided 2 different floor space allowances (0.64 or 0.91 m^2) and pigs initially provided 0.64 m^2 were subject to 1 of 3 marketing strategies which removed the heaviest pigs from the pen in order to provide additional floor space to the pigs remaining in the pen. Overall, pigs initially provided more floor space had improved ADG and ADFI, but increasing the number of marketing events increased ADG of the pigs remaining in the pen following market events. The meta-analysis suggested that a multi-term empirical model using random effects to account for known error and weighted observations to account for heterogeneous experimental designs and replication provided models that best fit the database. Also, the meta-analysis concluded that floor space allowance does influence ADG, ADFI, and G:F and BW of the pig can alter the floor space response. Finally, the vitamin and trace mineral survey suggested that a wide range of supplementation practices are used in the swine industry but most production systems supplement micronutrients above the basal requirement estimates of the animals.

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supplementation practices are used in the swine industry but most production systems supplement micronutrients above the basal requirement estimates of the animals.

Table of Contents

List of Figures

List of Tables

Preface

This dissertation is original work completed by the author, J. R. Flohr. Chapters 1 through 4 were formatted for publication according to the required standards of the Journal of Animal Science. Chapter 5 was formatted for publication according to the required standards of the Journal of Swine Health and Production.

Chapter 1 - Evaluating the impact of maternal vitamin D supplementation on sow performance, serum vitamin metabolites, neonatal muscle and bone characteristics, and subsequent pre-weaning pig performance

ABSTRACT

In Exp. 1, a total of 56 gestating sows (PIC 1050; 35 d post-insemination) were used in 30-d trial to determine the serum $25OHD_3$ response to titrated concentrations of dietary vitamin D_3. At initiation, sows were randomly allotted to 1 of 7 dietary D_3 treatments (200, 800, 1,600, 3,200, 6,400, 12,800, or 25,600 of D_3 per kg of complete diet) with 8 sows per treatment. Increasing D_3 increased (quadratic; $P < 0.001$) serum $25OHD_3$ with the response depicted by the prediction equation: Serum $25OHD_3$, ng/mL = 35.1746 + (0.002353 × dietary D_3, IU/d) - (0.0000000156 × dietary D_3, IU/d^2). In Exp. 2, 112 sows and their litters were used to determine the effects of dietary vitamin D regimen on sow performance, subsequent pre-weaning pig performance, neonatal pig bone and muscle characteristics, and serum vitamin metabolites. Sows were allotted to 1 of 4 dietary treatments: 800 IU, 2,000 IU, or 9,600 IU of D_3 per kg of the diet, or 2,000 IU of $25OHD_3$ (Hy-D, DSM Nutritional Products Inc, Parsippany, NJ) per kg of the diet. There were 25 to 27 sows per treatment. Increasing dietary D_3 increased (linear, $P = 0.001$) serum $25OHD_3$ of sows on d 100 of gestation, at farrowing, and at weaning. Also increasing D_3 in sow diets increased piglet serum $25OHD_3$ at birth (linear, $P = 0.001$) and weaning (quadratic, $P = 0.033$). Sows fed 2,000 IU of $25OHD_3$/kg had intermediate ($P < 0.004$) serum $25OHD_3$

concentrations on d 100 of gestation, at farrowing, and at weaning compared with sows fed 2,000 IU of D_3/kg and sows fed 9,600 IU of D_3/kg. Piglets from sows fed 2,000 IU of 25OHD_3/kg had greater serum 25OHD_3 compared to piglets from sows fed 2,000 IU of D_3/kg; but at weaning, serum 25OHD_3 concentrations were similar. Also, piglets from sows fed 9,600 IU of D_3/kg had greater (P = 0.011) serum 25OHD_3 at birth and weaning compared to piglets from sows fed 2,000 IU of 25OHD_3/kg. Maternal performance, litter characteristics, neonatal bone ash content, and neonatal muscle fiber characteristics were largely unaffected by the dietary vitamin D treatments. Overall, D_3 and 25OHD_3 are both useful at increasing serum 25OHD_3 concentrations, but more D_3 (on an IU basis) is needed to achieve similar serum 25OHD_3 responses compared to feeding 25OHD_3. Interestingly, concentration of maternal vitamin D supplementation in lactation impacted milk transfer of the vitamin more so than form of the vitamin as evidence of the weaned pig serum 25OHD_3 concentrations.

Key words: 25OHD_3, sow nutrition, vitamin D

INTRODUCTION

The most common form of dietary vitamin D supplemented in livestock nutrition is cholecalciferol (vitamin D_3). Research examining dietary supplementation of a synthetically produced 25OHD_3 (Hy-D, DSM Nutritional Products North America, Parsippany, NJ) has shown increased serum 25OHD_3 when both vitamin D_3 and 25OHD_3 were supplemented in diets at 2,000 IU of vitamin D (Lauridsen et al., 2010). This is because 25OHD_3 enters the blood stream quicker since it does not require the first hydroxylation step for metabolism.

Research examining the role of vitamin D in skeletal muscle development concluded that vitamin D is involved in myogenic signaling pathways and the in utero alterations were evident in postnatal skeletal muscle growth (Endo et al., 2003). A study in gestating first parity gilts concluded that when supplementing either 2,500 IU of vitamin D_3, or 500 IU of vitamin D_3 and 2,000 IU of $25OHD_3$ in the diet (both treatments having similar IU equivalency) that maternal and fetal serum $25OHD_3$ were increased with dietary $25OHD_3$ supplementation (Coffey et al., 2012). Additionally, the authors concluded that reproductive performance of gilts was improved with $25OHD_3$ supplementation. Interestingly, Hines et al. (2013) found alterations in fetal muscle characteristics in fetuses from gilts fed the $25OHD_3$ compared to fetuses from gilts fed vitamin D_3. If these improvements in fetal muscle development characteristics in swine lead to improvements in postnatal performance they will result in increased profitability of swine producers.

Therefore the objectives were to: 1) determine a feeding level of vitamin D_3 that would result in a similar serum $25OHD_3$ response as that observed from feeding 2,000 IU/kg of $25OHD_3$ in gestating sows, and 2) evaluate the influence of varying levels of vitamin D_3 or $25OHD_3$ supplementation (above the basal requirement level) on sow performance, serum vitamin metabolites, subsequent pig performance, and neonatal muscle and bone characteristics.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. These experiments were conducted at the K-State Swine Teaching and Research Facility in Manhattan, KS, and were conducted from January through December of 2014. Both the gestation and farrowing barns were totally enclosed,

environmentally controlled, and mechanically ventilated buildings. In gestation, sows were housed in gestation stalls (2.1 × 0.6-m). The farrowing barn contained 29 farrowing crates (2.1 × 0.6-m for the sow and 2.1 × 1.0-m for the pigs) that were each equipped with a single feeder and nipple waterer. Temperature in the farrowing house was maintained at a minimum of 21° C, and supplemental heat was provided to piglets with heat lamps. Gestation and lactation sow diets were prepared at the Kansas State University O. H. Kruse Feed Mill (Manhattan, Kansas). All diets were formulated to meet or exceed nutrient requirement estimates (NRC, 2012).

In Exp. 1, a total of 56 sows (PIC 1050) from 2 consecutive breeding groups were used in a 30-d study to determine the serum $25OHD_3$ response to varying concentrations of dietary vitamin D_3. The study began 35-d post insemination and after sows were confirmed pregnant. At initiation, the sows were randomly allotted to 1 of 7 dietary treatments receiving 200, 800, 1,600, 3,200, 6,400, 12,800, or 25,600 IU vitamin D_3/kg of complete diet. There were 8 sows per treatment. The gestation diets were common corn-soybean meal-based diets formulated to contain 0.56% standardized ileal digestible (SID) Lys and 0.82% Ca (Table 1-1). All sows were fed once daily (at 0800) and received 2.5 kg of feed. Prior to receiving their daily meal, sows were bled on d 0 and 30 of the trial via jugular venipuncture to collect serum for $25OHD_3$ analysis. Results from this study were then used to develop a prediction equation used to determine the dietary vitamin D_3 concentration needed to achieve a serum $25OHD_3$ response in gestating sows similar to levels previously reported in the literature (Weber et al., 2014) for females fed 2,000 IU of $25OHD_3$/ kg of the complete diet as their sole source of vitamin D.

In Exp. 2, a total of 112 sows (PIC 1050) from 4 consecutive farrowing groups and their litters were used in the study. Following breeding, sows were randomly assigned to 1 of 4 dietary vitamin D treatments receiving: 800 IU, 2,000 IU, or 9,600 IU of vitamin D_3/kg of complete diet,

or 2,000 IU of 25OHD$_3$/kg of complete diet. The treatment of 800 IU of vitamin D$_3$/kg was selected since it represents the basal requirement of the sow (NRC, 2012). The treatment of 2,000 IU of vitamin D$_3$/kg was used to directly compare to feeding 2,000 IU of 25OHD$_3$ at the same international unit equivalency. The treatment of 9,600 vitamin D$_3$/kg was determined following the results found in Exp. 1 and was predicted to have mean serum 25OHD$_3$ values that would be similar to the treatment fed 2,000 IU of 25OHD$_3$/kg. There were 28 sows per treatment and 6 to 8 replications per farrowing group. During d 0 through 110 of gestation, sows were fed once daily at 0800 and received 2.5 kg/d of the gestation diets. On d 110, sows were moved to the farrowing house and were housed in farrowing stalls. After farrowing, sows were fed lactation diets. Gestation and lactation diets were formulated to contain 0.56% and 1.07% SID Lys, respectively. Farrowing crate feeders were equipped with an electronic feeding system (Gestal Solo; JYGA Technologies, Quebec, Canada) which used a built-in feeding curve based on parity to feed individual sows. The feeding curves were monitored and adjusted daily for individual sows to allow for ad libitum feed intake while reducing feed wastage. Lactation feed intake was confirmed by measuring feed disappearance on d 7, 14, and 21 (weaning). Sow BW was measured at breeding, d 110 of gestation, within 24 h of farrowing, and at weaning to determine gestation BW gain and lactation weight loss. Back fat measurements were collected when sows arrived in the farrowing house and at weaning to determine BF loss. Sows were bled on d 0 and 100 of gestation, within 24 h after farrowing, and at weaning (d 21) to determine serum 25OHD$_3$, vitamin D$_3$, vitamin A (retinol), and vitamin E (α-tocopherol).

Within 24 h of parturition, all piglets were weighed and ear notched for identification. The male pig closest to the average BW of the litter was euthanized to collect bone and muscle samples for neonatal bone ash content and neonatal muscle immunohistochemistry

measurements. The male and female piglets next closest to the average BW of the litter were bled via jugular venipuncture within 24 h of birth and again at weaning to determine pre-weaned piglet serum $25OHD_3$, vitamin D_3, vitamin A (retinol), and vitamin E (α-tocopherol). Mummified and stillborn pigs were recorded to calculate total born. Although minimal, cross-fostering was conducted within vitamin D dietary treatments within 48 h after farrowing to help standardize litter size. Pigs were weighed after fostering to measure fostered litter weight. At weaning, piglet weights and piglet counts were recorded to determine individual and litter weight gains, along with survivability.

Feed preparation and vitamin D analysis

To achieve the dietary vitamin D_3 concentrations, a premix was made containing a vitamin D_3 supplement (Rovimix D_3, 500,000 IU/g; DSM Nutritional Products North America, Parsippany, NJ). This supplement was mixed into a rice hull carrier to form the premix and was added to the control diet by replacing corn. The vitamin D premix was the only source of added vitamin D within the diets, as other vitamin premixes did not contain vitamin D. For diets formulated to contain 2,000 IU $25OHD_3$/kg, 390 g of $25OHD_3$ (Hy-D, DSM Nutritional Products North America, Parsippany, NJ) was added per tonne of the diet in order to reach desired finished feed concentrations. Complete diet samples from Exp. 1 and 2 were analyzed for vitamin D_3 and $25OHD_3$ concentrations by DSM Nutritional Products North America (Parsippany, NJ) using a combination HPLC and mass spectrometry analytical technique (Schadt et al., 2012).

Serum 25-hydroxycholecalciferol, vitamin D_3, α-tocopherol, and retinol

All blood samples were collected via jugular venipuncture using 25-mm × 20 gauge needles and 10-mL blood collection tubes containing a gel separator. Six hours after collection,

blood was centrifuged (1,600 × g for 25 min at 2° C) and serum was harvested and stored at -20° C until analysis. All serum $25OHD_3$ testing for Exp. 1 was performed by Heartland Assays Inc. (Ames, IA) using a previously described RIA (Hollis et al., 1993). All vitamin metabolite testing ($25OHD_3$, vitamin D_3, α-tocopherol, and retinol) from Exp. 2 was conducted by the DSM Nutritional Laboratory (Kaiseraugst, Switzerland). The analyses were performed using a liquid chromatography/electrospray ionization tandem mass spectrometry technique with multiple reaction monitoring similar to the methods described by Capote et al. (2007). The lowest detectable limit was 5.00 ng/mL for $25OHD_3$, 1.00 ng/mL for vitamin D_3, 250 ng/mL for α-tocopherol, and 25 ng/mL for retinol. Some samples were below the detectable limit for serum vitamin D_3 concentration; therefore, the percentage of animals with serum concentrations above the detectable limit are reported herein along with the mean concentration of serum vitamin D_3 associated with those animals.

Necropsies, bone and tissue sampling, bone ash procedure

Necropsies were performed onsite and in compliance with the university standard operating procedures. Pigs were euthanized using CO_2 gas administered via a Euthanex® AgPro™ system (Nutriquest, Mason City, IA). Right femurs and second ribs were collected to determine percentage bone ash, and whole muscle cross sections of the longissimus thoracis (2 cm section over the 5 and 6 ribs caudal to the trapezius) and the semitendinosus (2 cm section medial to the insertion and origin) were collected for immunohistochemistry. Bones were boiled for 60 min and adhering tissue was removed. Then the bones were dried at 100°C for 7-d. After drying, the bones were ashed in a muffle furnace at 600°C for 24-h.

Immunohistochemistry

After dissecting the whole muscle cross sections, the cross sections were blotted using blotting paper to measure whole muscle cross sectional area. Then the cross sections were embedded in Optimal Cutting Temperature (OCT) tissue embedding media (Fisher Scientific, Pittsburgh, PA), frozen by submersion in supercooled isopentane, and stored at -80°C until analysis. For each muscle sample, two 10-μm cryosections were collected on positively charged slides (MidSci) and muscle fibers were immunostained with antibodies validated by Town et al. (2004) for the detection of primary and secondary muscle fibers and merged with the methods of Paulk et al. (2014) to simultaneously identify muscle fiber cross sectional area. Briefly, nonspecific antigen-binding sites were inhibited by incubating cryosections in 5% horse serum and 0.2% TritonX-100 (Fisher scientific) in phosphate-buffered saline (PBS) for 30 min. All sections were incubated with the following primary antibodies in blocking solution for 60 min: 1:500 α-dystrophin (Thermos Scientific, Waltham, MA); 1:10 supernatant myosin heavy-chain, slow IgG2b (BA-D5, Developmental Studies Hybridoma Bank, University of Iowa, Iowa City, IA); and 1:10 supernatant myosin heavy-chain type 2A, IgG1 (SC-71, Developmental Studies Hybridoma Bank). After incubation, sections were washed with PBS 3 times for 5 min, followed by incubation in the following secondary antibodies (1:1,000) in blocking solution for 30min: Alexa-Fluor 488 goat anti-mouse IgG1 for SC-71 (Invitrogen, San Diego, CA); Alexa-Fluor 633 goat anti-mouse IgG2b for BA-D5 (Invitrogen); and Alexa-Fluor 594 goat anti-rabbit H&L for α-dystrophin (Invitrogen). In addition, 1:1000 Hoechst Dye 33342 (Invitrogen) was utilized to identify all fiber-associated nuclei. Finally, sections were washed for 3 5-min periods in PBS, and then covered with 5 μL of 9:1 glycerol in PBS, then coverslipped for imaging.

Cryosections were imaged using a Nikon Eclipse T1-U inverted microscope with 20× working distance magnification (Nikon Instruments Inc., Melville, NY). Four representative photomicrographs per section were captured using a Nikon DS-QiMc digital camera (Nikon Instruments, Inc.) calibrated to the 20 × objective. For myosin heavy-chain fiber-type data collection, a minimum of 2 photomicrographs per section (minimum of 500 fibers per animal) were analyzed for isoform distribution with NIS-Elements Imaging Software (Basic Research, 3.3; Nikon Instruments Inc.). Fibers that were positively stained for the BA-D5 antibody were counted as primary muscle fibers and the fibers that positively stained for SC-71 were labelled as secondary fibers. Total muscle fiber number was calculated by dividing the whole muscle cross sectional area by the average cross sectional area of all muscle fibers. To calculate the total number of primary muscle fibers per muscle section, the percentage of primary muscle fibers was multiplied by the total number of muscle fibers. Similarly, the total number of secondary muscle fibers was calculated by multiplying the percentage of secondary fibers by the total number of muscle fibers.

Statistical analysis

All data was analyzed as a generalized randomized complete block design using the GLIMMIX procedure of SAS (SAS Institute, Inc., Cary, NC). Maternal performance data was analyzed with sow as the experimental unit, maternal treatment as a fixed effect, and farrowing group as a random effect. Responses not normally distributed were analyzed with a negative binomial distribution (Total born and number after cross-fostering), a binomial distribution (stillborns, mummies, number born alive), or a beta distribution (bone ash). Pre-planned comparisons consisted of: (1) linear and quadratic polynomials for increasing vitamin D_3 (Exp. 1 and 2), (2) 800 IU vitamin D_3 vs. 2,000 IU 25OHD_3 (Exp. 2), (3) 2,000 IU vitamin D_3 vs. 2,000

IU $25OHD_3$ (Exp. 2), and (4) 9,600 IU vitamin D_3 vs. 2,000 IU $25OHD_3$ (Exp. 2). The IML procedure of SAS was used to generate unequally spaced orthogonal contrast coefficients for dietary vitamin D_3 treatments in Exp. 1 and 2. Repeated measures analysis was performed on serum vitamin metabolite responses and day of collection was included as a fixed effect to determine serum changes to dietary treatments over time. Results were considered significant at $P \leq 0.05$ and a tendency at $P \leq 0.10$.

RESULTS AND DISCUSSION

Supplementation of dietary vitamin D is required for swine reared in environmentally controlled production facilities due to the lack of exposure to direct sunlight needed for the endogenous conversion of 7-dehydrocholesterol to vitamin D_3 in the skin. Previously documented cases of vitamin D being absent from premixes fed to pigs (Feedstuffs, 2010) has led to a resurgence of interest in the animal's requirement for vitamin D to safeguard from potential deficiency. Additionally, recent genomic data, which has shown the presence of the vitamin D receptor in many soft tissues not associated with normal Ca and P homeostasis (Norman and Bouillon, 2010) and has led to increased efforts to understand vitamin D's role in other normal bodily processes. The aim of the current study was to evaluate maternal vitamin D supplementation as either vitamin D_3 (at varying levels) or $25OHD_3$ on sow and subsequent pig response criteria.

Exp. 1

Although there is no published accepted standard for vitamin D recovery in animal feeds, analysis showed diets were within 25% of their formulated targets (Table 1-2. Analyzed dietary

vitamin D_3 in the complete diets, Exp. 1[1] which would be consistent with the acceptable analytical variation and recovery of other vitamins previously discussed by AAFCO (2015).

Gestating sows fed increasing vitamin D_3 had increased (quadratic, $P = 0.001$; Table 1-3) serum $25OHD_3$ concentrations. This data was used to develop an equation to predict the serum $25OHD_3$ response to increasing vitamin D_3 supplementation in gestating females. The equation was: Serum $25OHD_3$, ng/mL = 35.1746 + (0.002353 × dietary vitamin D_3, IU/d) - (0.0000000156 × dietary vitamin D_3, IU/d^2; Figure 1-1). The corresponding coefficient of variation (r^2) for this fitted prediction equation was 0.852 suggesting a high correlation of dietary vitamin D_3 supplementation to serum $25OHD_3$ which was expected since the sole source of vitamin D for commercially reared swine is from the diet. To our knowledge, this is the first study to develop a prediction equation based on dietary vitamin D intake in swine. This information was used to predict a vitamin D_3 supplementation rate needed to achieve serum $25OHD_3$ results similar to that of sows fed a known amount of $25OHD_3$. Previous literature examining the serum $25OHD_3$ response of sows fed 2,000 IU/kg of $25OHD_3$ (Weber et al., 2014) in gestation concluded that the range of serum $25OHD_3$ response appeared to be between 50 and 90 ng/mL depending on time of sampling (gestation or lactation) and parity of the female. This range was supported by Lauridsen et al. (2010) who reported a mean serum $25OHD_3$ concentration of approximately 85 ng/mL for sows fed 2,000 IU of $25OHD_3$/kg of the diet. Additionally, Coffey et al. (2012) observed serum $25OHD_3$ concentrations approximately 80 to 90 ng/mL for first parity gestating gilts fed diets containing 2,000 IU of $25OHD_3$/kg along with 500 IU of vitamin D_3/kg. In this preliminary experiment, we did not examine serum $25OHD_3$ concentrations from sows fed 2,000 IU of $25OHD_3$/kg due to the breadth of data supporting a response at approximately 70 to 80 ng/mL in the sow. Based on the prediction equation

developed herein, similar results could be achieved by supplementing between 17,000 and 29,000 IU of vitamin D_3/d. In order to ensure the supplementation rate was high enough to elicit a serum response, a targeted feeding level of 9,600 IU of vitamin D_3 per kg of complete feed (12 to 14 times the NRC, 2012 vitamin D requirement and approximately 24,000 IU/d) was selected as the highest level of vitamin D_3 supplementation for Exp. 2.

Exp. 2

Proximate analysis of gestation and lactation diets fed in Exp. 2 (Table 1-4) showed similar CP and P concentrations to formulated levels. Analyzed Ca concentrations were more variable, but all values were above the requirements of the sow. Analysis showed diets were within 10% of their formulated targets which would be within the acceptable analytical variation and recovery of other vitamins (AAFCO, 2015).

Sow performance and litter characteristics

Vitamin D treatment did not affect gestation BW gain (Table 1-5). Increasing vitamin D_3 increased (quadratic, $P = 0.011$) lactation ADFI and decreased (quadratic, $P = 0.003$) BW loss during lactation. This was due to sows having greater lactation ADFI when fed diets with 2,000 IU of vitamin D_3/kg compared with sows fed 800 or 9,600 IU of vitamin D_3/kg. Also, sows consuming diets with 9,600 IU vitamin D_3/kg tended ($P = 0.088$) to have lower lactation feed intake compared with sows fed diets with 2,000 IU of 25OHD_3. Total daily vitamin D intake during lactation was approximately 4,300, 11,800, and 50,600 IU/d for sows fed diets containing 800, 2,000, and 9,600 IU of vitamin D_3/kg, respectively, and approximately 11,300 IU/d for sows fed diets containing 2,000 IU of 25OHD_3/kg. The current study observed no impact of vitamin D treatment on litter characteristics or piglet BW at birth or weaning. The results herein suggest little to no influence of maternal vitamin D treatment above basal requirement on sow

performance. Flohr et al. (2014) also concluded that varying vitamin D_3 supplementation rates (1,500 to 6,000 IU/kg of the diet) had no influence on sow performance or litter characteristics. However, Lauridsen et al. (2010) observed reductions in stillborns from sows fed 1,400 or 2,000 IU of vitamin D/kg of the diet compared with sows fed 200 or 800 IU of vitamin D/kg of the diet. Weber et al. (2014) observed increases in the birth and weaning weight of pigs from sows fed 2,000 IU of $25OHD_3$ compared with pigs from sows fed 2,000 IU of vitamin D_3. They hypothesized that this was the result of improvements in the intrauterine development of the embryos. Coffey et al. (2012) observed an increase in the number of developed fetuses in the reproductive tracts of first service gilts when supplemented $25OHD_3$ rather than vitamin D_3 at the same IU equivalency. Although some significant differences have been observed with different vitamin D supplementation strategies, the lack of consistency in measured responses across studies makes it difficult to determine whether vitamin D supplementation (above basal NRC, 2012 requirement) truly impacts maternal performance. Ultimately, commercial scale studies with large sample sizes will be needed to increase sensitivity and reduce the experimental error associated with sow reproduction measurements to evaluate dietary supplementation of vitamin D above the current requirement.

Sow serum $25OHD_3$, vitamin D_3, α-tocopherol, and retinol

A treatment × day interaction ($P = 0.001$; Table 1-6) for serum $25OHD_3$ of sows was observed because sow serum $25OHD_3$ was similar on d 0 of gestation regardless of dietary vitamin D treatment, but increasing vitamin D_3 increased (linear, $P < 0.001$) serum $25OHD_3$ on d 100 of gestation, after farrowing, and at weaning. Also, sows fed diets with 800 or 2,000 IU of vitamin D_3/kg had less serum $25OHD_3$ on d 100 of gestation ($P = 0.001$), after farrowing ($P = 0.001$), and at weaning ($P = 0.001$) compared to sows fed 2,000 IU of $25OHD_3$/kg. Sows fed the

diets with 9,600 IU of vitamin D_3/kg had greater serum 25OHD_3 concentrations on d 100 of gestation ($P = 0.001$), after farrowing ($P = 0.004$), and at weaning ($P = 0.001$) compared with sows fed 25OHD_3. Lauridsen et al. (2010), Coffey et al. (2012), and Weber et al. (2014) have all discussed similar responses when comparing the supplementation of 25OHD_3 and vitamin D_3 at the same IU equivalency. It is clear that 25OHD_3 provides a greater serum 25OHD_3 response in sows. Although the exact reason for this improved response is not completely clear, Bar et al. (1980) demonstrated that 25OHD_3 is absorbed more efficiently than vitamin D_3 in the upper portion of the intestine of young broiler chicks. Another potential reason may be due to the post absorptive transport of the different forms. Because 25OHD_3 is the circulating form of the vitamin which binds with the vitamin D binding protein in the bloodstream, it does not require the hydroxylation step of metabolism in the liver. On the other hand, vitamin D_3 must enter the bloodstream as a part of a chylomicron (Clinton, 2013). Lipoprotein lipases in adipose tissue can interact with circulating chylomicrons to store a portion of their lipids and consequently the vitamin D_3 transported within them. This suggests that a portion of the vitamin D_3 that is absorbed may be stored in adipose tissue rather than being transported to the liver for hydroxylation. The serum 25OHD_3 concentrations achieved in gestation from supplementing 25OHD_3 were less than the reports of previous researchers (Lauridsen et al, 2010; Coffey et al., 2012; Weber et al., 2014), this may be due to the time of sampling and duration of feeding in which Weber et al. (2014) discussed as potential influencers of the serum response. Also, Laurdisen et al. (2010) summarized results using only the main effect of dietary treatment on serum 25OHD_3 concentrations from sows fed 2,000 IU of 25OHD_3/kg rather than reporting the interactive means of time × dietary treatment which may led to an inflated serum concentration due to increased vitamin intake during the lactation period. The increases in serum 25OHD_3 with

increasing vitamin D_3 agrees with previous data from Flohr et al. (2014). To our knowledge, this is the first study that has shown a level of vitamin D_3 supplementation that has elicited a serum response above feeding 2,000 IU of 25OHD_3/kg.

For serum vitamin D_3, maternal vitamin D treatment did not affect the percentage of sows exhibiting serum concentrations above the detectable limit on d 0 or 100 of gestation, or at farrowing. However, at weaning greater percentages of sows fed vitamin D_3 ($P < 0.001$) had serum vitamin D_3 concentrations above the detectable limit. Increasing vitamin D_3 increased serum vitamin D_3 on d 100 of gestation (linear, $P = 0.001$), after farrowing (linear, $P = 0.001$), and at weaning (quadratic, $P = 0.035$). Also, sows fed the diets with 2,000 or 9,600 IU of vitamin D_3/kg had greater serum vitamin D_3 concentrations on d 100 of gestation ($P < 0.006$), after farrowing ($P < 0.020$), and at weaning ($P = 0.001$) compared with sows fed 25OHD_3. Sows fed diets containing 800 IU of vitamin D_3/kg tended to have greater ($P = 0.063$) serum vitamin D_3 concentrations at weaning compared to sows fed diets with 2,000 IU of 25OHD_3. Serum vitamin D_3 is typically much more variable compared with 25OHD_3 since it will increase rapidly after exposure (either in the diet or through the skin) and will be cleared from circulation by the liver or storage tissue within hours. Also, the vitamin D binding protein, which accompanies vitamin D metabolites in circulation, has a much lower affinity for vitamin D_3 compared to 25OHD_3 (IOM, 2011). In the current study, it is understandable that increasing dietary vitamin D_3 led to increased serum concentrations of the nutrient. Additionally, due to less vitamin D_3 exposure of sows fed 25OHD_3 it is justified that their serum vitamin D_3 was lower as compared to sows fed vitamin D_3.

There was a tendency ($P = 0.052$) for a treatment × day interaction for sow serum α-tocopherol concentrations because serum α-tocopherol was similar across maternal treatments on

d 0 of gestation and after farrowing, but on d 100 of gestation increasing vitamin D_3 supplementation decreased (quadratic, $P = 0.007$) serum α-tocopherol concentrations. Additionally, on d 100 of gestation, serum α-tocopherol tended ($P < 0.081$) to be greater for sows fed 800 or 9,600 IU of vitamin D_3/kg compared with sows fed 2,000 IU of 25OHD_3/kg. These differences observed in serum α-tocopherol were unexpected since all diets were formulated to contain similar concentrations of vitamin E (66 IU/kg of the diet) resulting in a daily intake of 165 IU of vitamin E/d. Additionally, there is no previous data that has evaluated a vitamin E and vitamin D interaction in livestock diets. However, Goncalves et al. (2015) concluded that there is the potential for common absorption pathways for vitamin D and E since increasing vitamin D uptake resulted in decreased vitamin E uptake in Caco-2 in vitro cells. At weaning, there was a tendency (quadratic, $P = 0.077$) for sows fed increasing vitamin D_3 to have increasing serum α-tocopherol. This tendency for increased serum α-tocopherol may be the result of increased lactation feed intake observed for sows fed 2,000 IU of vitamin D_3/kg. Based on lactation feed intake, sows consuming diets with 2,000 IU of vitamin D_3/kg had vitamin E intakes of approximately 390 IU/d compared to sows fed either 800 or 9,600 IU of vitamin D_3/kg with vitamin E intakes of approximately 350 IU/d.

A treatment × day interaction ($P = 0.001$) for sow serum retinol was observed because serum retinol was similar regardless of maternal vitamin D treatment on d 0 and 100 of gestation; however, after farrowing sows fed 9,600 IU of vitamin D_3/kg tended ($P = 0.089$) to have less serum retinol compared to sows fed 2,000 IU of 25OHD_3/kg. In addition, sows fed increasing levels of vitamin D_3 had increased (quadratic, $P = 0.001$) serum retinol concentrations at weaning. Sows fed diets with 2,000 IU of vitamin D_3/kg had greater ($P = 0.006$) serum retinol compared to sows fed 2,000 IU of 25OHD_3/kg at weaning. Again, this increase in serum retinol

at weaning was likely the result of increased vitamin A intake for sows fed the diets with 2,000 IU of vitamin D_3/kg due to the increase in lactation feed intake. Sows consuming diets with 2,000 IU of vitamin D_3 were consuming approximately 6,500 IU of vitamin A/d compared to sows fed 800 IU of vitamin D_3/kg (approximate vitamin A intake of 5,900 IU/d), sows fed 9,600 IU of vitamin D_3/kg (approximate vitamin A intake of 5,800 IU/d), and sows fed 2,000 IU of 25OHD_3/kg (approximate vitamin A intake of 6,225 IU/d). Little information has been reported on the interactions of vitamin A and vitamin D in previous literature. Abawi and Sullivan (1989) concluded that supplying higher supplemental levels of vitamin D helped improve performance in broilers supplemented high levels of vitamin A and E. Also, Payne and Manston (1967) concluded that increasing the supplementation of vitamin A with high supplementation of vitamin D may reduce the chance of vitamin D toxicity.

Piglet serum 25OHD_3, vitamin D_3, α-tocopherol, retinol, and neonatal percentage bone ash

For piglet serum 25OHD_3, there was a treatment × day interaction (P = 0.001;

	Maternal vitamin D, IU/kg					Probability, P <				
	Vitamin D_3			25OHD_3		Vitamin D_3		800 D_3 vs. 2,000 25OHD_3	2,000 D_3 vs. 2,000 25OHD_3	9,600 D_3 vs. 2,000 25OHD_3
	800	2,000	9,600	2,000	SEM[3]	Linear	Quadratic			
Pre-weaned pig serum vitamin metabolites										
25OHD_3, ng/mL[4]										
Birth	2.0	2.2	5.5	3.5	0.43	0.001	0.548	0.004	0.011	0.001
Weaning	4.3	7.0	16.3	6.1	0.43	0.001	0.033	0.001	0.101	0.001
Vitamin D_3[5]										
Birth										
Detectable samples, %	0.0	0.0	54.2	0.0	5.61	0.001	0.299	0.999	0.999	0.001

Serum vitamin D_3, ng/mL	---	---	1.7	---	0.45	---	---	---	---	---
Weaning										
Detectable samples, %	0.0	41.7	100	4.2	5.61	0.001	0.001	0.582	0.001	0.001
Serum vitamin D_3, ng/mL	---	1.4	5.7	2.1	1.24	---	---	---	---	---
α-tocopherol, mg/L										
Birth	2,718	2,494	2,190	2,662	395.9	0.319	0.757	0.912	0.741	0.342
Weaning	5,331	4,584	5,379	4,844	380.2	0.439	0.107	0.326	0.601	0.286
Retinol, ng/mL[6]										
Birth	108	80	93	106	9.6	0.714	0.031	0.909	0.038	0.288
Weaning	254	266	268	255	9.6	0.395	0.384	0.924	0.381	0.305
Bone ash content, %										
2nd rib	53.7	55.7	54.0	54.0	3.11	0.753	0.265	0.863	0.358	0.973
Femur	46.1	45.6	45.5	46.4	0.53	0.519	0.566	0.681	0.285	0.246

[1] A total of 112 sows and litters were used to determine the effects of supplemental vitamin D from varying levels of vitamin D_3 or from synthetic 25OHD_3 on maternal performance, subsequent pig performance, sow and piglet serum vitamin metabolites, neonatal bone mineralization and piglet muscle development.

[2] Means represent the average serum metabolite from 48 randomly selected litters (two pigs per litter were bled for serum analysis) within treatments and the same litters within each day were analyzed. One pig per litter (n = 104) was euthanized for bone ash percentage determination.

[3] Standard error of the means representing the within sampling day variation. Because the same number of treatments were analyzed for each day the variance estimates were the same.

[4] A treatment × day interaction ($P = 0.001$) was observed for serum 25OHD_3.

[5] The assay for serum vitamin D_3 had a lower detectable limit of 1.00 ng/mL. Samples below the detectable limit (n = 144 out of 192) were not used in the statistical analysis. Detectable sample represents the percentage of samples above the detectable limit and the mean serum vitamin D_3 was calculated using only samples above the detectable limit.

[6] A tendency ($P = 0.065$) for a treatment × day interaction was observed for serum retinol.

) because increasing maternal dietary vitamin D_3 increased (linear, $P < 0.001$) piglet serum 25OHD_3 at birth and at weaning (quadratic, $P = 0.033$) with a greater magnitude of increase occurring at weaning. This observation agrees with reports from Flohr et al. (2014), who found that increasing maternal vitamin D_3 supplementation from 1,500 to 6,000 IU/kg of the diet

increased subsequent piglet serum 25OHD$_3$ throughout lactation. Also in the current study, piglets from sows fed 25OHD$_3$ had greater ($P < 0.011$) serum 25OHD$_3$ compared with piglets from sows fed 800 or 2,000 IU of vitamin D$_3$/kg at birth; however, at weaning, piglets from sows fed 2,000 IU of 25OHD$_3$/kg had similar serum 25OHD$_3$ compared with piglets from sows fed the 2,000 of vitamin D$_3$/kg and greater ($P = 0.001$) serum 25OHD$_3$ concentrations compared to piglets from sows fed 800 IU of vitamin D$_3$/kg. Additionally, piglets from sows fed 9,600 IU of vitamin D$_3$/kg had increased ($P = 0.001$) serum 25OHD$_3$ at birth and weaning compared with piglets from sows fed 2,000 IU of 25OHD$_3$/kg.

Previous reports from Coffey et al. (2012) and Witschi et al. (2011) have discussed increases in serum 25OHD$_3$ concentrations in fetuses (d 90 of gestation) and piglets from sows supplemented dietary 25OHD$_3$ compared with those from sows supplemented with dietary vitamin D$_3$ at the same IU equivalency. Goff et al. (1984) demonstrated that 25OHD$_3$ of the neonate is largely correlated to the 25OHD$_3$ status of the sow at birth and 25OHD$_3$ has clearly been demonstrated as the vitamin D metabolite associated with transplacental transfer (Haddad et al., 1971). The current data would agree with previous reports and is the first to show a maternal dietary vitamin D$_3$ supplementation rate that provided a larger serum 25OHD$_3$ response in piglets compared with piglets from sows supplemented 50 μg of 25OHD$_3$. Human research has shown that the transfer of vitamin D metabolites into breast milk is limited (Hollis and Wagner, 2004). Flohr et al. (2014) concluded that increasing supplementation of vitamin D$_3$ led to increasing milk vitamin D$_3$ concentrations throughout a 21-d lactation period when milk samples were taken immediately after parturition (colostrum), on d 10, and at weaning. Clements and Fraser (1988) reported that vitamin D$_3$ was the predominant vitamin D constituent in colostrum of rats, but vitamin D$_3$ concentrations declined after a few days and 25OHD$_3$ becomes the predominant

metabolite in milk. The current study would suggest that form of dietary vitamin D supplementation ($25OHD_3$ or vitamin D_3) did not impact milk vitamin D concentrations since feeding either 2,000 IU of vitamin D_3 or $25OHD_3$ resulted in similar piglet serum $25OHD_3$ concentrations at weaning. Witschi et al. (2011) observed increased serum $25OHD_3$ of piglets from sows fed $25OHD_3$ compared to piglets from sows fed vitamin D_3 at the same IU equivalency, but their results were confounded with creep feed diets that were provided to suckling pigs starting on the third week of lactation with pigs being weaned at 5 wk of age. The data herein suggests that the level of maternal dietary vitamin D supplementation is more impactful on milk transfer of the vitamin rather than form (either vitamin D_3 or $25OHD_3$) of the vitamin, when pigs were weaned at approximately 21-d of age and creep feed was not provided prior to weaning.

A majority of piglet serum vitamin D_3 samples were below the laboratory detectable limit of 1.00 ng/mL, which was expected because of the quick clearance of vitamin D_3 from circulation. Samples below that threshold (144 out of 192) were not included in the statistical analysis; therefore, the results were summarized as the percentage of samples that were above the lowest detectable limit and then the average serum concentration of the detectable samples was calculated. Only 54.2% of pigs from sows fed 9,600 IU of vitamin D_3/kg exhibited serum vitamin D_3 concentrations above the detectable limit with mean serum concentrations of 1.7 ng/mL. Increasing maternal dietary vitamin D_3 increased (quadratic, $P = 0.001$) the percentage of pigs with serum vitamin D_3 concentrations above the detectable limit, and greater percentages of pigs from sows fed 2,000 or 9,600 IU of vitamin D_3/kg had serum vitamin D_3 concentrations ($P < 0.001$) above the detectable limit compared to pigs from sows fed 2,000 IU of $25OHD_3$/kg.

Piglet serum α-tocopherol was similar after birth and at weaning regardless of vitamin D maternal treatment. A tendency ($P = 0.065$) for a treatment × day interaction for piglet serum retinol was observed because at birth piglet serum retinol was reduced (quadratic, $P = 0.031$) with increasing maternal vitamin D_3, and piglets from sows fed diets with a medium level of vitamin D_3 had lower ($P = 0.038$) serum retinol compared with piglets from sows fed $25OHD_3$; however, by weaning, serum retinol was similar regardless of maternal vitamin D treatment. These differences in serum retinol in piglets at birth were unexpected and may be due to piglets from sows fed the medium level of vitamin D_3 having lower serum retinol in later gestation although it is unclear why this would have occurred.

Percentage bone ash for second ribs and femurs from pigs euthanized after birth were similar regardless of vitamin D treatment. Similarly, Flohr et al. (2014) observed no impact of increasing maternal vitamin D_3 concentration (1,500 to 6,000 IU/kg of the diet) on the bone ash percentage of neonates when maternal vitamin D_3 is above the animal's requirement. Alternatively, Rortvedt and Crenshaw (2012) clearly demonstrated the impact of maternal vitamin D deficiency on subsequent pig kyphosis; however, visual impacts of maternal deficiency were not observed until after weaning. A previous study with rat (Johnson et al., 1996) fetuses detected VDRs within fetal tissues prior to ossification alluding to the functional role of vitamin D in the proliferation and differentiation of chondrocytes in skeletal tissue. In the current study, the maternal vitamin D supplementation concentrations were well above those needed to induce a vitamin D deficiency in sows.

Neonatal muscle characteristics

Previous research by Hines et al. (2013) concluded that replacing 80% (2,000 IU of the total 2,500 IU/kg of the diet) of the vitamin D_3 supplemented to gestating gilts with $25OHD_3$

increased the maternal vitamin D status, and in turn altered fetal muscle development. The authors observed an increase in the number of skeletal muscle fibers and Pax7+ myoblasts in the longissimus muscle (LM) muscle of fetuses collected on d 90 of gestation. Additionally, after isolating and culturing myoblasts from the semitendinosus muscle, the satellite cells from fetuses of gilts supplemented $25OHD_3$ had a higher proportion of cells in the proliferation stage 96 h post plating which suggests increased hyperplasia of myoblasts. These conclusions suggest that vitamin D status of the dam can alter fetal skeletal muscle development with positive changes resulting from the use of $25OHD_3$ compared to vitamin D_3 itself. Previous work in poultry has elicited similar results (Giuliani and Boland, 1984) and has shown that exogenous addition of 1, 25 OH_2D_3 to primary cultures of embryonic chick myoblasts stimulated proliferation and differentiation. In the current study, a subsample of pigs were euthanized in order to obtain longissimus thoracis (LT) and semitendinosus (ST) whole muscle cross sections for immunohistochemistry to characterize potential development differences among maternal vitamin D treatments. Although Pax7+ myoblasts within muscles were not quantified in the current study, we hypothesized that neonatal muscle samples of pigs born from sows fed the $25OHD_3$ compared to those fed the 800 or 2,000 IU of vitamin D_3/kg would have an increased number of muscle fibers. Additionally, if vitamin D status were the reason for the change in fetal muscle fiber numbers, then muscle samples from pigs born of sows fed 9,600 IU of vitamin D_3/kg should be similar to the fiber numbers from muscles of pigs born for sows fed 2,000 IU of $25OHD_3$/kg of diet.

Results from the current study showed that whole muscle area of the LT and ST were similar (

Table 1-8. The effect of maternal dietary vitamin D supplementation on neonatal muscle immunohistochemistry, Exp. 2[1]

	Maternal vitamin D, IU/kg		Probability, *P* <

	Vitamin D_3			25OHD$_3$		Vitamin D_3		800 D_3 vs. 2,000 25OHD$_3$	2,000 D_3 vs. 2,000 25OHD$_3$	9,600 D_3 vs. 2,000 25OHD$_3$
	800	2,000	9,600	2,000	SEM	Linear	Quadratic			
Item										
Litters sampled, n	25	27	25	27						
Longissimus Thoracis										
Whole muscle area (mm^2)[2]	117.3	113.7	113.5	111	13.98	0.795	0.749	0.543	0.792	0.810
Average fiber CSA, (μm^2)[3]	101.1	106.4	96.8	109.8	9.56	0.291	0.362	0.200	0.609	0.057
Average primary fiber CSA, (μm^2)[4]	191.5	209.7	197.7	213.4	11.47	0.946	0.254	0.173	0.813	0.325
Average secondary fiber CSA, (μm^2)[5]	95.8	99.8	91.0	102.9	9.52	0.272	0.450	0.276	0.632	0.070
Total fiber number (1×10^6)[6]	1.2	1.1	1.3	1.1	0.18	0.540	0.296	0.235	0.823	0.177
Total primary fibers (1×10^4)[7]	6.8	6.9	6.5	8.5	1.06	0.776	0.924	0.234	0.254	0.158
Total secondary fibers (1×10^6)[8]	1.8	1.1	1.2	1.0	0.17	0.502	0.270	0.169	0.716	0.117
Secondary:primary[9]	18.0	16.5	18.8	15.7	1.63	0.289	0.238	0.112	0.577	0.035
Semitendinosus										
Whole muscle area (mm^2)[2]	60.0	64.3	61.6	62.0	7.30	0.985	0.460	0.730	0.695	0.939
Average fiber CSA, (μm^2)[3]	135.4	139.7	128.8	140.4	10.89	0.409	0.633	0.671	0.954	0.303
Average primary fiber CSA, (μm^2)[4]	185.4	198.7	171.8	202.9	12.47	0.142	0.279	0.243	0.767	0.031
Average secondary fiber CSA, (μm^2)[5]	131.7	135.8	125.7	136.2	10.59	0.449	0.656	0.700	0.968	0.349
Total fiber number (1×10^5)[6]	4.7	4.6	4.8	4.7	0.54	0.771	0.799	0.949	0.875	0.810
Total primary fibers (1×10^4)[7]	3.5	3.5	3.4	3.6	0.54	0.822	0.923	0.905	0.957	0.766
Total secondary fibers (1×10^5)[8]	4.4	4.3	4.5	4.4	0.51	0.739	0.775	0.932	0.871	0.773

Secondary:primary[9]	15.5	19.7	16.9	18.1	3.83	0.943	0.312	0.544	0.688	0.769

[1]A total of 112 sows and their subsequent litters were used to evaluate the effects of maternal vitamin D supplementation on fetal muscle development. One pig per litter (the male piglet closest to the mean BW within 24 h of birth), for all litters larger than 6 pigs, was euthanized for muscle fiber identification.
[2] Cross-sectional area (mm^2) of the whole muscle.
[3] Average cross-sectional area (μm^2) of all muscle fibers.
[4] Average cross-sectional area (μm^2) of a representative sample of primary muscle fibers.
[5] Average cross-sectional area (μm^2) of a representative sample of secondary muscle fibers.
[6] Total muscle fiber number is calculated as the whole muscle area divided by the average muscle fiber cross-sectional area of all muscle fibers.
[7] Total primary muscle fiber number was calculated as the percentage of primary fibers × total fiber number.
[8] Total secondary muscle fiber number was calculated as the percentage of secondary fibers × total fiber number.
[9] The average number of secondary muscle fibers per primary muscle fiber.

) regardless of maternal vitamin D treatment. Maternal vitamin D treatment did not influence ST average muscle fiber cross sectional area (CSA), but LT average muscle fiber CSA tended ($P = 0.057$) to be greater for piglets from sows fed 25OHD_3 compared with piglets from sows fed 9,600 IU of vitamin D_3/kg. Average primary muscle fiber CSA was similar for the LT regardless of maternal vitamin D treatment; however, primary muscle fiber CSA for the ST was greater ($P = 0.031$) for piglets from sows fed 25OHD_3 compared with piglets from sows fed 9,600 IU of vitamin D_3/kg. Secondary muscle fiber CSA for the ST was not influenced by maternal vitamin D treatments, but LT secondary muscle fiber CSA tended to be greater ($P = 0.070$) for piglets from sows fed 25OHD_3 compared with piglets from sows fed 9,600 IU of vitamin D_3/kg. Total fiber number, primary fiber number, and secondary fiber number for LT and ST muscles were not influenced by maternal dietary vitamin D treatment. The LT secondary to primary fiber ratio was less ($P = 0.035$) for piglets from sows fed 25OHD_3 compared with piglets from sows fed 9,600 IU of vitamin D_3/kg; however, maternal dietary vitamin D treatment did not influence ST secondary to primary muscle fiber ratio.

The results herein would contradict those previously reported by Hines et al. (2013) in the sense that total muscle fiber numbers were not different among maternal vitamin D

treatments. The current data suggests little to no impact of the maternal vitamin D treatments on neonatal muscle characteristics except for increases in the hypertrophic growth of the primary muscle fibers of the ST and the secondary muscle fibers of the LT for pigs from sows fed $25OHD_3$ compared to pigs from sows fed 9,600 IU of vitamin D_3/kg. More research is needed to help elucidate whether there are distinct impacts of maternal vitamin D supplementation from vitamin D_3 or $25OHD_3$ on fetal muscle development and at what levels of the vitamin are optimal.

Conclusion

Overall, the results of this study indicate that supplementing increasing levels of maternal vitamin D_3 to sows can increase sow and piglet serum $25OHD_3$. Additionally, when supplementing $25OHD_3$ and vitamin D_3 at the same IU equivalency, serum $25OHD_3$ of sows and piglets at birth will be increased for sows fed $25OHD_3$. It appears that maternal dietary vitamin D level impacted weaned pig serum $25OHD_3$ more so than the form (vitamin D_3 or $25OHD_3$) of vitamin D. This is likely due to increased vitamin D in milk as a result of an increased level of the maternal dietary supplementation rather than the vitamin D form. Maternal vitamin D treatment (above the basal requirement) had minimal impact on sow performance, neonatal percentage bone ash, or neonatal muscle development characteristics.

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TABLES AND FIGURES

Table 1-1. Sow diet composition (as-fed basis)[1]

	Gestation[2]	Lactation
Ingredient, %		
Corn	80.28	62.99
Soybean meal, 46.5% CP	15.62	30.21
Choice white grease	---	2.50
Monocalcium phosphate	1.48	1.48
Calcium carbonate	1.15	1.05
Sodium chloride	0.50	0.50
L-Lysine HCl	---	0.20
DL-Methionine	---	0.05
L-Threonine	0.03	0.08
Phytase[3]	0.02	0.02
Trace mineral premix[4]	0.15	0.15
Vitamin premix[5]	0.75	0.75
Vitamin D premix[6]	0.02	0.02
TOTAL	100.00	100.00
Calculated analysis		
SID[7] amino acids, %		
Lys	0.56	1.07
Met & Cys:Lys	76	56
Thr:Lys	80	64
Trp:Lys	24	20
NE, Mcal/kg	2.47	2.51
SID Lys:NE, g/Mcal	2.27	4.26
CP, %	14.1	19.9
Ca,%	0.82	0.83
P, %	0.64	0.70
Available P, %	0.47	0.49
STTD P, %	0.49	0.53
Ca:P	1.28	1.19
Vitamin A, IU/kg	1,102	1,102
Vitamin E, IU/kg	66.1	66.1

[1] In Exp. 1, a total of 56 gestating sows were used to determine the serum $25OHD_3$ response from feeding titrated concentrations of vitamin D_3. In Exp. 2, a total of 112 sows and litters were used to determine the effects of supplemental vitamin D from varying levels of vitamin D_3 or from synthetic $25OHD_3$ on maternal performance, subsequent pig performance, sow and piglet $25OHD_3$, neonatal bone mineralization, and piglet muscle development.
[2] Gestation diets for Exp. 1 and 2 were similar in composition.
[3] Ronozyme Hi-Phos, DSM, Parsippany, NJ. Provided 476 phytase units (FTU/kg) of diet with an expected release of 0.10% phytate P.
[4] Provided 11,000 ppm Cu, 198 ppm I, 73,413 ppm Fe, 22,046 ppm Mn, 198 ppm Se, and 74,413 ppm Zn per kg of premix.
[5] Provided 3,527,392 IU vit. A, 26,455 IU vit. E, 1,764 mg vit. K, 15 mg vit. B_{12}, 33,069 mg niacin, 11,023 mg pantothenic acid, 3,307 mg riboflavin, 661 mg folic acid, 882 mg pyridoxine, 220,460 mg choline, 19,842 mg carnitine, and 79 mg chromium per kg of premix.
[6] Vitamin D premix was mixed to contain 4,409,240 IU of vitamin D_3/kg of premix by blending vitamin D_3 (Rovimix D: DSM Nutritional Products, Parsippany, NJ) with rice hulls. Premix replaced a percentage of corn to achieve the desired treatment vitamin D_3 concentrations in Exp. 1 and 2. For diets containing $25OHD_3$, the vitamin D premix was not included and Hy-D (DSM Nutritional Products, Parsippany, NJ) was added into the diet, replacing a percentage of corn, at 0.37 kg/tonne to achieve the desired concentration of 50 μg of $25OHD_3$/kg of the diet.

[7] Standardized ileal digestible.

Table 1-2. Analyzed dietary vitamin D_3 in the complete diets, Exp. 1[1]

	Vitamin D_3, IU/kg						
	200	800	1,600	3,200	6,400	12,800	25,600
Formulated	200	800	1,600	3,200	6,400	12,800	25,600
Analyzed	194	714	1,600	2,440	6,116	13,049	24,540
% of claim	96.7	89.3	100.0	76.3	95.6	101.9	95.9

[1] Samples were collected and pooled together then shipped to a DSM Nutritional Products laboratory (Parsippany, NJ) for analysis. Means represent the average analyzed value of two samples.

Table 1-3. Effects of titrated dietary vitamin D_3 on serum $25OHD_3$ in gestating sows, Exp. 1[1]

	Vitamin D_3, IU/kg								Probability, $P <$ Vitamin D_3	
	200	800	1,600	3,200	6,400	12,800	25,600	SEM	Linear	Quadratic
Serum $25OHD_3$, ng/mL										
d 0	46.1	40.3	46.0	43.8	46.3	48.2	43.9	6.47	0.826	0.318
d 30	37.2	35.9	46.1	51.9	73.8	91.1	122.4	6.62	0.001	0.001

[1] A total of 56 gestating sows were used in a 30-d trial to determine the serum $25OHD_3$ response from feeding titrated concentrations of vitamin D_3. There were 8 sows per treatment, and sows were fed 2.5 kg/d.

Table 1-4. Analyzed sow diet composition from Exp. 2[1]

	Maternal vitamin D supplementation, IU/kg			
	Vitamin D_3			$25OHD_3$
	800	2,000	9,600	2,000
Formulated gestation diets				
CP, %	14.1	14.1	14.1	14.1
Ca, %	0.82	0.82	0.82	0.82
P, %	0.64	0.64	0.64	0.64
Vitamin D_3, IU/kg	800	2,000	9,600	---
$25OHD_3$, IU/kg	---	---	---	2,000
Analyzed gestation diets				
CP, %	15.0	15.2	14.8	14.8
Ca, %	1.01	0.86	0.87	1.06
P, %	0.62	0.62	0.64	0.63
Vitamin D_3, IU/kg	730	2,000	9,057	---
$25OHD_3$, µg/kg	---	---	---	1,840
Vitamin D, % of formulated	91.2	100.0	94.3	92.7
Formulated lactation diets				
CP, %	19.9	19.9	19.9	19.9
Ca, %	0.83	0.83	0.83	0.83
P, %	0.70	0.70	0.70	0.70
Vitamin D_3, IU/kg	800	2,000	9,600	---
$25OHD_3$, IU/kg	---	---	---	2,000
Analyzed lactation diets				
CP, %	19.3	20.1	19.5	19.5
Ca, %	1.05	1.10	0.94	0.94
P, %	0.65	0.66	0.67	0.70
Vitamin D_3, IU/kg	906	1,986	9,310	---
$25OHD_3$, IU/kg	---	---	---	1,814
Vitamin D, % of formulated	113.1	99.3	97.0	90.7

[1] Samples were collected and pooled together then shipped to DSM Nutritional Products laboratory (Parsippany, NJ) for vitamin D analysis and to a commercial laboratory (Ward laboratories, Kearney, NE) for proximate analysis. Means represent the average analyzed value of two samples.

Table 1-5. The effects of maternal dietary vitamin D supplementation on sow and pre-weaned pig performance, Exp. 2[1]

	Maternal vitamin D, IU/kg					Probability, *P* <				
	Vitamin D_3			$25OHD_3$		Vitamin D_3		800 D_3 vs. 2,000 $25OHD_3$	2,000 D_3 vs. 2,000 $25OHD_3$	9,600 D_3 vs. 2,000 $25OHD_3$
	800	2,000	9,600	2,000	SEM	Linear	Quadratic			
Sows, n	27	28	25	28	---	---	---	---	---	---
Parity	2.2	2.2	2.1	2.2	0.30	0.807	0.822	0.914	0.963	0.775
Lactation ADFI, kg	5.36	5.88	5.27	5.65	0.199	0.137	0.011	0.184	0.294	0.088
Sow BW, kg										
Gestation										
d 0	193.2	190.8	190.4	192.0	9.55	0.835	0.835	0.905	0.908	0.876
d 110	234.7	226.1	233.7	233.9	7.85	0.721	0.232	0.923	0.293	0.980
BW gain, kg	41.4	35.4	43.9	42.0	3.74	0.330	0.190	0.901	0.191	0.771
Lactation										
d 0	229.3	222.3	226.6	231.2	7.31	0.909	0.348	0.800	0.231	0.547
d 21	221.2	221.8	220.5	227.0	6.94	0.889	0.926	0.452	0.494	0.406
BW loss, kg	-8.1	-0.6	-6.1	-4.2	2.44	0.677	0.003	0.129	0.153	0.464
Sow BF, mm										
Farrowing	14.3	13.5	14.9	14.1	0.72	0.245	0.305	0.796	0.539	0.343
Weaning	12.7	12.5	13.3	12.6	0.63	0.303	0.661	0.868	0.892	0.339
Lactation BF loss	-1.6	-1.1	-1.6	-1.5	0.58	0.734	0.395	0.876	0.516	0.883
Litter characteristics										
Total born, n	13.93	12.96	12.96	13.57	0.718	0.584	0.573	0.783	0.645	0.652
Born alive, %	91.0	94.5	93.2	93.4	1.48	0.763	0.329	0.428	0.651	0.929
Stillborn, %	7.7	4.1	6.2	6.1	1.38	0.956	0.294	0.534	0.447	0.958
Mummies, %	1.3	1.4	0.6	0.5	0.61	0.497	0.854	0.466	0.454	0.899
Total after foster, n	12.00	11.29	11.53	11.76	0.706	0.824	0.457	0.797	0.606	0.810
Number weaned	10.70	10.21	10.20	10.54	0.639	0.761	0.698	0.880	0.773	0.770
Survivability, %	89.5	90.8	88.8	88.9	2.27	0.573	0.524	0.809	0.426	0.972
Piglet BW, kg										
Birth	1.43	1.41	1.44	1.42	0.052	0.816	0.842	0.989	0.989	0.770
Weaning	6.48	6.76	6.55	6.40	0.237	0.882	0.349	0.231	0.231	0.622

[1] A total of 112 sows and litters were used to determine the effects of supplemental vitamin D from varying levels of vitamin D_3 or from synthetic $25OHD_3$ on maternal performance, subsequent pig performance, sow and piglet serum vitamin metabolites, neonatal bone mineralization and piglet muscle development.. Three sows (one from the 800 IU/kg treatment and 2 from the 9,600 IU/kg treatment) were removed due to farrowing complications. One sow from the treatment fed 9,600 IU/kg was removed from the dataset due to a late-term abortion.

Table 1-6. The effects of maternal dietary vitamin D supplementation on sow serum metabolites, Exp. 2[1,2]

	Maternal vitamin D, IU/kg					Probability, *P* <				
	Vitamin D_3			25OHD_3		Vitamin D_3		800 D_3 vs. 2,000 25OHD_3	2,000 D_3 vs. 2,000 25OHD_3	9,600 D_3 vs. 2,000 25OHD_3
	800	2,000	9,600	2,000	SEM[3]	Linear	Quadratic			
Sow serum vitamin metabolites										
25OHD_3, ng/mL[4]										
d 0 of gestation	44.6	43.9	41.1	45.9	3.54	0.405	0.957	0.768	0.650	0.278
d 100 of gestation	27.6	29.2	82.5	59.5		0.001	0.157	0.001	0.001	0.001
Farrowing	25.1	26.1	68.2	55.4		0.001	0.241	0.001	0.001	0.004
Weaning	34.6	50.9	110.6	94.6		0.001	0.153	0.001	0.001	0.001
Vitamin D_3, ng/mL[5]										
d 0 of gestation										
Detectable samples, %	100.0	100.0	100.0	100.0	4.74	0.999	0.999	0.999	0.999	0.999
Serum D_3, ng/mL	7.6	7.5	7.1	7.6	0.926	0.677	0.965	0.954	0.877	0.646
d 100 of gestation										
Detectable samples, %	100.0	100.0	100.0	100.0		0.999	0.999	0.999	0.999	0.999
Serum D_3, ng/mL	3.5	5.2	26.6	1.9	0.926	0.001	0.217	0.188	0.006	0.001
Farrowing										
Detectable samples, %	100.0	100.0	100.0	91.7		0.999	0.999	0.216	0.216	0.216
Serum D_3, ng/mL	3.0	4.7	19.5	1.8	0.961	0.001	0.645	0.357	0.020	0.001
Weaning										
Detectable samples, %	91.7	100.0	100.0	58.3		0.387	0.255	0.001	0.001	0.001
Serum D_3, ng/mL	4.5	10.9	33.7	1.8	1.17	0.001	0.035	0.063	0.001	0.001
α-tocopherol, mg/L[6]										
d 0 of gestation	2,187	2,063	1,979	2,099	131.1	0.275	0.545	0.601	0.830	0.473
d 100 of gestation	2,096	1,668	2,112	1,803		0.211	0.007	0.081	0.420	0.066
Farrowing	1,247	1,054	1,219	1,329		0.748	0.231	0.622	0.102	0.508
Weaning	2,338	2,611	2,295	2,358		0.305	0.077	0.905	0.132	0.705
Retinol, ng/mL[7]										
d 0 of gestation	285	294	254	279	17.6	0.113	0.569	0.833	0.565	0.301
d 100 of gestation	231	210	237	225		0.492	0.353	0.807	0.554	0.604
Farrowing	128	165	149	192		0.593	0.713	0.177	0.291	0.089
Weaning	299	393	337	325		0.957	0.001	0.299	0.006	0.625

[1] A total of 112 sows and litters were used to determine the effects of supplemental vitamin D from varying levels of vitamin D_3 or from synthetic 25OHD_3 on maternal performance, subsequent pig performance, sow and piglet serum vitamin metabolites, neonatal bone mineralization and piglet muscle development.
[2] Means represent the average serum metabolite from 12 randomly selected sows within treatment and day combinations.
[3] Standard error of the means representing the within sampling day variation. Because the same number of treatments were analyzed for each day the variance estimates were the same.

[4] A treatment × day interaction ($P = 0.001$) was observed for serum $25OHD_3$.
[5] The assay for serum vitamin D_3 had a lower detectable limit of 1.00 ng/mL. Samples below the detectable limit (n = 144 out of 192) were not used in the statistical analysis. Detectable samples represent the percentage of samples above the detectable limit and the mean serum vitamin D_3 was calculated using only samples above the detectable limit.
[6] A tendency ($P = 0.052$) for a treatment × day interaction was observed for serum α-tocopherol.
[7] A treatment × day interaction ($P = 0.035$) was observed for serum retinol.

Table 1-7. The effect of maternal dietary vitamin D supplementation on pre-weaned pig serum vitamin metabolites and neonatal bone ash, Exp. 2[1,2]

	Maternal vitamin D, IU/kg					Probability, *P* <				
	Vitamin D_3			$25OHD_3$		Vitamin D_3		800 D_3 vs. 2,000 $25OHD_3$	2,000 D_3 vs. 2,000 $25OHD_3$	9,600 D_3 vs. 2,000 $25OHD_3$
	800	2,000	9,600	2,000	SEM[3]	Linear	Quadratic			
Pre-weaned pig serum vitamin metabolites										
$25OHD_3$, ng/mL[4]										
Birth	2.0	2.2	5.5	3.5	0.43	0.001	0.548	0.004	0.011	0.001
Weaning	4.3	7.0	16.3	6.1	0.43	0.001	0.033	0.001	0.101	0.001
Vitamin D_3[5]										
Birth										
Detectable samples, %	0.0	0.0	54.2	0.0	5.61	0.001	0.299	0.999	0.999	0.001
Serum vitamin D_3, ng/mL	---	---	1.7	---	0.45	---	---	---	---	---
Weaning										
Detectable samples, %	0.0	41.7	100	4.2	5.61	0.001	0.001	0.582	0.001	0.001
Serum vitamin D_3, ng/mL	---	1.4	5.7	2.1	1.24	---	---	---	---	---
α-tocopherol, mg/L										
Birth	2,718	2,494	2,190	2,662	395.9	0.319	0.757	0.912	0.741	0.342
Weaning	5,331	4,584	5,379	4,844	380.2	0.439	0.107	0.326	0.601	0.286
Retinol, ng/mL[6]										
Birth	108	80	93	106	9.6	0.714	0.031	0.909	0.038	0.288
Weaning	254	266	268	255	9.6	0.395	0.384	0.924	0.381	0.305
Bone ash content, %										
2nd rib	53.7	55.7	54.0	54.0	3.11	0.753	0.265	0.863	0.358	0.973
Femur	46.1	45.6	45.5	46.4	0.53	0.519	0.566	0.681	0.285	0.246

[1] A total of 112 sows and litters were used to determine the effects of supplemental vitamin D from varying levels of vitamin D_3 or from synthetic $25OHD_3$ on maternal performance, subsequent pig performance, sow and piglet serum vitamin metabolites, neonatal bone mineralization and piglet muscle development.
[2] Means represent the average serum metabolite from 48 randomly selected litters (two pigs per litter were bled for serum analysis) within treatments and the same litters within each day were analyzed. One pig per litter (n = 104) was euthanized for bone ash percentage determination.
[3] Standard error of the means representing the within sampling day variation. Because the same number of treatments were analyzed for each day the variance estimates were the same.
[4] A treatment × day interaction ($P = 0.001$) was observed for serum $25OHD_3$.
[5] The assay for serum vitamin D_3 had a lower detectable limit of 1.00 ng/mL. Samples below the detectable limit (n = 144 out of 192) were not used in the statistical analysis. Detectable sample represents the percentage of samples above the detectable limit and the mean serum vitamin D_3 was calculated using only samples above the detectable limit.
[6] A tendency ($P = 0.065$) for a treatment × day interaction was observed for serum retinol.

Table 1-8. The effect of maternal dietary vitamin D supplementation on neonatal muscle immunohistochemistry, Exp. 2[1]

	Maternal vitamin D, IU/kg					Probability, *P* <				
	Vitamin D_3			25OHD_3		Vitamin D_3		800 D_3 vs. 2,000 25OHD_3	2,000 D_3 vs. 2,000 25OHD_3	9,600 D_3 vs. 2,000 25OHD_3
	800	2,000	9,600	2,000	SEM	Linear	Quadratic			
Item										
Litters sampled, n	25	27	25	27						
Longissimus Thoracis										
Whole muscle area (mm^2)[2]	117.3	113.7	113.5	111	13.98	0.795	0.749	0.543	0.792	0.810
Average fiber CSA, (μm^2)[3]	101.1	106.4	96.8	109.8	9.56	0.291	0.362	0.200	0.609	0.057
Average primary fiber CSA, (μm^2)[4]	191.5	209.7	197.7	213.4	11.47	0.946	0.254	0.173	0.813	0.325
Average secondary fiber CSA, (μm^2)[5]	95.8	99.8	91.0	102.9	9.52	0.272	0.450	0.276	0.632	0.070
Total fiber number (1×10^6)[6]	1.2	1.1	1.3	1.1	0.18	0.540	0.296	0.235	0.823	0.177
Total primary fibers (1×10^4)[7]	6.8	6.9	6.5	8.5	1.06	0.776	0.924	0.234	0.254	0.158
Total secondary fibers (1×10^6)[8]	1.8	1.1	1.2	1.0	0.17	0.502	0.270	0.169	0.716	0.117
Secondary:primary[9]	18.0	16.5	18.8	15.7	1.63	0.289	0.238	0.112	0.577	0.035
Semitendinosus										
Whole muscle area (mm^2)[2]	60.0	64.3	61.6	62.0	7.30	0.985	0.460	0.730	0.695	0.939
Average fiber CSA, (μm^2)[3]	135.4	139.7	128.8	140.4	10.89	0.409	0.633	0.671	0.954	0.303
Average primary fiber CSA, (μm^2)[4]	185.4	198.7	171.8	202.9	12.47	0.142	0.279	0.243	0.767	0.031
Average secondary fiber CSA, (μm^2)[5]	131.7	135.8	125.7	136.2	10.59	0.449	0.656	0.700	0.968	0.349
Total fiber number (1×10^5)[6]	4.7	4.6	4.8	4.7	0.54	0.771	0.799	0.949	0.875	0.810
Total primary fibers (1×10^4)[7]	3.5	3.5	3.4	3.6	0.54	0.822	0.923	0.905	0.957	0.766
Total secondary fibers (1×10^5)[8]	4.4	4.3	4.5	4.4	0.51	0.739	0.775	0.932	0.871	0.773
Secondary:primary[9]	15.5	19.7	16.9	18.1	3.83	0.943	0.312	0.544	0.688	0.769

[1]A total of 112 sows and their subsequent litters were used to evaluate the effects of maternal vitamin D supplementation on fetal muscle development. One pig per litter (the male piglet closest to the mean BW within 24 h of birth), for all litters larger than 6 pigs, was euthanized for muscle fiber identification.

[2] Cross-sectional area (mm^2) of the whole muscle.

[3] Average cross-sectional area (μm^2) of all muscle fibers.

[4] Average cross-sectional area (μm^2) of a representative sample of primary muscle fibers.

[5] Average cross-sectional area (μm^2) of a representative sample of secondary muscle fibers.

[6] Total muscle fiber number is calculated as the whole muscle area divided by the average muscle fiber cross-sectional area of all muscle fibers.

[7] Total primary muscle fiber number was calculated as the percentage of primary fibers × total fiber number.

[8] Total secondary muscle fiber number was calculated as the percentage of secondary fibers × total fiber number.

[9] The average number of secondary muscle fibers per primary muscle fiber.

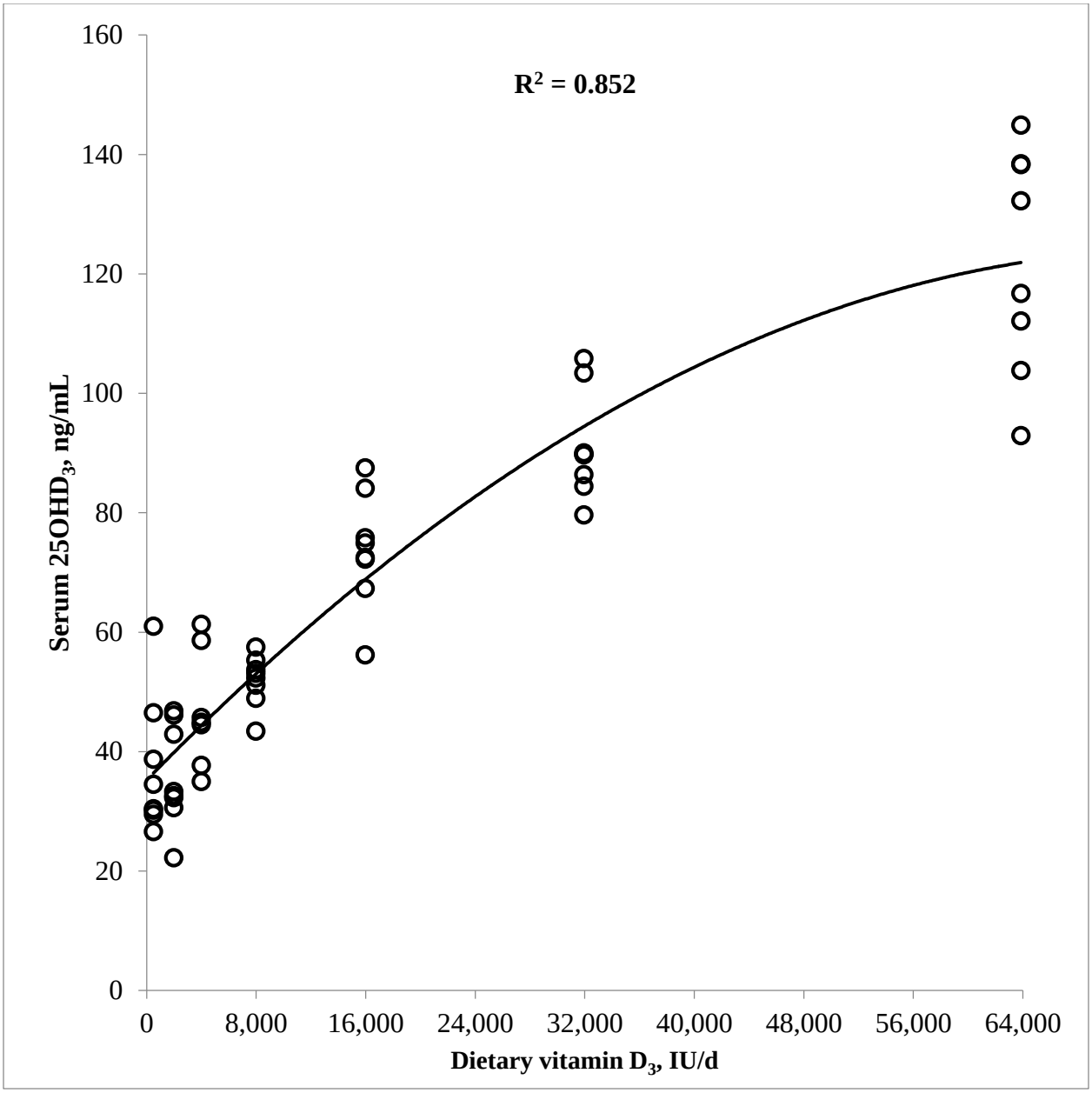

Figure 1-1. Plot of predicted serum 25OHD$_3$ response to daily vitamin D$_3$ intake of gestating sows (Exp. 1) based on the observed serum 25OHD$_3$. The equation used for predated values was: serum 25OHD$_3$, ng/mL = 35.1746 + (0.002353 × dietary vitamin D$_3$, IU/d) – (0.0000000156 × dietary vitamin D$_3$, IU/d^2

Chapter 2 - Evaluating the effects of dietary maternal vitamin D supplementation and nursery vitamin D dietary regimen on the subsequent growth performance and carcass characteristics of growing pigs

ABSTRACT

A of subsample of 448 growing pigs (PIC 327 × 1050) weaned from 52 sows fed varying dietary vitamin D regimens were used in a split-plot design to determine the influence of maternal and nursery dietary vitamin D on growth performance. Sows were previously administered diets containing vitamin D as vitamin D_3 (800, 2,000, or 9,600 IU/kg) or as $25OHD_3$ (2,000 IU/kg; DSM Nutritional Products Inc). Once weaned, pigs were allotted to pens in based on previous maternal vitamin D treatment, and then pens were randomly assigned to 1 of 2 nursery vitamin D dietary regimens (2,000 IU of vitamin D_3/kg, or 2,000 IU $25OHD_3$/kg). Pigs remained on nursery vitamin D treatments for 35-d then they were provided common finishing diets until market (135 kg). Growing pig serum $25OHD_3$ suggested that maternal dietary vitamin D influenced ($P < 0.001$ at weaning) serum concentrations early after weaning, but nursery vitamin D regimen had a larger impact ($P < 0.001$, d 17 and 35 post-weaning) during the late nursery portion of the study. Overall growth performance was not influenced by nursery vitamin D dietary treatments. Overall from d 0 to 35 in the nursery, pigs from sows fed increasing vitamin D_3 had increased (quadratic, $P < 0.003$) ADG and ADFI, but G:F was similar regardless of maternal vitamin D regimen. Also, pigs from sows fed 2,000 IU of $25OHD_3$ had

increased (P = 0.002) ADG compared to pigs weaned from sows fed 800 IU of vitamin D_3. Throughout finishing (d 35 post-weaning until 135 kg), ADG was increased (quadratic, P = 0.005) and G:F was improved (quadratic, P = 0.049) with increasing maternal dietary vitamin D_3. Also, pigs from sows fed 2,000 IU of 25OHD_3 had increased (P = 0.002) ADG compared to pigs weaned from sows fed 800 IU of vitamin D_3. Carcass data was collected from another subsample population separate from that used for the growth performance portion of the study and a total of 642 carcasses from sows fed the varying dietary vitamin D treatment were used. Live BW of pigs at marketing and HCW were heavier (P < 0.030) for pigs from sows previously fed 25OHD_3 compared to pigs from sows fed 9,600 IU of vitamin D_3. Overall, pigs from sows fed the 2,000 IU of vitamin D_3 grew faster after weaning compared to pigs from sows fed the 800 or 9,600 IU of vitamin D_3. Pigs from sows fed 25OHD_3 hag greater ADG compared to pigs from sows fed 800 IU of vitamin D_3 and they had increased final BW and HCW compared to pigs from sows fed 9,600 IU of vitamin D_3.

Key words: 25OHD_3, growth, finishing pig, nursery pig, vitamin D

INTRODUCTION

Studies evaluating maternal dietary manipulation have determined that fetal muscle development in swine can be altered based on nutritional strategies (Dwyer et al., 1994; Musser et al., 2004). Dwyer et al. (1993) concluded that differences in the total number of muscle fibers at birth, resulting from fetal muscle development, were positively correlated with postnatal growth potential. Additionally, previous research in mice has demonstrated that vitamin D plays

a role in fetal muscle development. Endo et al. (2003) concluded that skeletal muscle in knock-out mice without the vitamin D receptor (VDR) gene had approximately 20% smaller muscle fiber diameters at 3 wk of age compared to wild type mice.

Hines et al. (2013) evaluated feeding $25OHD_3$ or vitamin D_3 to bred gilts and observed alterations in fetal muscle characteristics for fetuses from gilts fed the $25OHD_3$ compared to fetuses from gilts fed vitamin D_3 when fed at concentrations above the basal requirement estimate (NRC, 2012). There was an increase in the number of muscle fibers and an increase in the number of Pax7+ myoblasts within the longissimus muscle. These alterations would suggest the potential for increased postnatal growth performance. Weber et al. (2014) observed increases in piglet BW at birth and weaning when dams were supplemented 2,000 IU of $25OHD_3$/kg compared to piglets from dams supplemented 2,000 IU of vitamin D_3/kg. However, no previous research has evaluated whether pigs from dams supplemented varying forms or concentrations of vitamin D have improved postnatal growth after weaning or the impacts of maternal vitamin D on carcass characteristics.

Therefore, the objective of the experiments herein were to: 1) determine the vitamin D status of pigs within a subsample population from dams fed varying vitamin D regimens and 2) evaluate the influence of maternal vitamin D status and nursery dietary vitamin D regimen on growth performance and carcass characteristics.

MATERIALS AND METHODS

Experimental procedures and animal care were approved by the Kansas State University Institutional Animal Care and Use Committee. These experiments were conducted at the K-State Swine Teaching and Research Facility in Manhattan, KS, from September of 2014 to May of

2015. Nursery and finishing diets were prepared at the Kansas State University O. H. Kruse Feed Mill (Manhattan, KS). All diets were formulated to meet or exceed nutrient requirement estimates (NRC, 2012).

All nursery and finishing facilities were totally enclosed, environmentally controlled, and mechanically ventilated buildings. Pigs in the first weaning group were housed in nursery pens that were 1.22 × 1.52 m with a 4-hole dry self-feeder and a single nipple waterer to provide ad libitum access to feed and water. Pens had wire mesh flooring and allowed 0.28 m^2/pig. On d 55 after weaning, pigs were moved to the finishing barn into pens that were 1.52 × 3.05 m with totally slatted concrete flooring. Each pen was equipped with a 2-hole dry self-feeder and 2 nipple waterers to provide ad libitum access to feed and water. Pigs in the second weaning group were housed in nursery pens that were 1.52 × 1.52 m with tri-bar flooring. Each pen was equipped with a 3-hole dry self-feeder and a nipple waterer to allow for ad libitum access to feed and water. These pigs were moved to the finishing pens (2.44 × 3.05 m) with totally slatted flooring. Each pen was equipped with a 2-hole dry self-feeder and bowl waterer to allow ad libitum access to feed and water. Feed was delivered to each pen individually by a robotic feeding system (FeedPro; Feedlogic Corp., Wilmar, MN).

A total of 448 pigs (PIC 327 × 1050, Hendersonville, TN) from 52 litters from 2 consecutive weaned pig groups (approximately 50% of pigs weaned from the maternal trial discussed by Flohr et al., 2015) were used as a subsample of the weaned pig population in a 4 × 2 split-plot design to determine the effects of maternal vitamin D treatment and nursery dietary vitamin D regimen on growth performance. Sows were previously administered 1 of 4 maternal dietary vitamin D treatments receiving either vitamin D_3 (800, 2,000, or 9,600 IU/kg of diet) or 25OHD_3 (2,000 IU/kg of diet; Hy-D, DSM Nutritional Products North America, Parsippany, NJ)

throughout gestation and lactation as discussed by Flohr et al. (2015). At weaning, pigs were allotted to pens based on their previously administered maternal vitamin D regimen. Pens were then randomly assigned to the nursery regimen of feeding diets containing either 2,000 IU vitamin D_3 or 2,000 IU 25OHD_3/kg. There were 7 pigs per pen and 4 pens per treatment in the first wean group, and 4 pigs per pen and 8 or 9 pens per treatment in the second wean group. Dietary vitamin D regimens remained consistent in three consecutive nursery diets which were fed from d 0 to 10, d 10 to 21, and d 21 to 35 for phases 1, 2, and 3, respectively. The nursery diets were formulated to contain 1.40, 1.34, and 1.22% standardized ileal digestible (SID) Lysine (Table 2-1) for phase 1, 2, and 3, respectively. Phase 1 nursery diets were pelleted and all other diets were in meal form. Pigs and feeders were weighed on d 0, 10, 21, and 35 to determine ADG, ADFI, and G:F.

After d 35 post-weaning, pigs were switched to a common growing pig diet (Phase 4) and then were transported to the finishing facility approximately 55 d after weaning. Pigs remained penned by maternal and dietary nursery treatments in the finisher; however, because the pen sizes changed from the nursery to the finisher, pigs were remixed within treatments and were allotted to finishing pens. In finishing, all pigs received common diets formulated to contain 827, 690, and 551 IU of vitamin D_3/kg for phase 4, 5, and 6, respectively. Pigs were weighed and feed disappearance was calculated every 28 d until marketing (135 kg).

Feed preparation and vitamin D analysis

To achieve the dietary vitamin D_3 concentrations, a premix was made containing a vitamin D_3 supplement (Rovimix D_3, 500,000 IU/g; DSM Nutritional Products North America, Parsippany, NJ). This supplement was mixed with a rice hull carrier to form the premix and was added to the control diet by replacing corn. The vitamin D premix was the only source of added

vitamin D within the diets, as other vitamin premixes did not contain vitamin D. For diets formulated to contain 2,000 IU of $25OHD_3$/kg, 390 g of $25OHD_3$ (Hy-D, DSM Nutritional Products North America, Parsippany, NJ) was added per tonne of the diet in order to provide 2,000 IU of $25OHD_3$/kg. Complete nursery diet samples were analyzed for vitamin D_3 and $25OHD_3$ concentrations by DSM Nutritional Products (Parsippany, NJ) using a combination HPLC and mass spectrometry analytical technique (Schadt et al., 2012).

Serum 25-Hydroxycholecalciferol, vitamin D_3, α-tocopherol, and retinol

One pig per pen (randomly selected) was bled via jugular venipuncture at weaning (d 21), d 17, 35, and 70 post-weaning to determine serum vitamin metabolites. All blood samples were collected via jugular venipuncture using 25-mm × 20 gauge needles and 10-mL blood collection tubes containing a gel separator. Six h after collection, blood was centrifuged (1,600 × g for 25 min at 2° C) and serum was harvested and stored at -20° C until analysis. All vitamin metabolite testing ($25OHD_3$, vitamin D_3, α-tocopherol, and retinol) was conducted by the DSM Nutritional Laboratory (Kaiseraugst, Switzerland). The analyses were performed using a liquid chromatography/electrospray ionization tandem mass spectrometry technique with multiple reaction monitoring similar to the methods described by Capote et al. (2007). The lowest detectable limit for $25OHD_3$ was 5.00 ng/mL, for vitamin D_3 it was 1.00 ng/mL, for α-tocopherol it was 250 ng/mL, and for retinol it was 25 ng/mL. Over half of the serum samples were below the detectable limit for serum vitamin D_3 concentration (n=130 out of 256 total samples); therefore, the percentage of animals with serum concentrations above the detectable limit are reported herein along with the mean concentration of serum vitamin D_3 associated with those animals.

Carcass Characteristics

Carcass data was collected from approximately 642 pigs or approximately 75% (3 of the 4 weaned pig groups) of the weaned progeny from the maternal portion of the study (Flohr et al, 2015). Pigs were individually weighed and tattooed for slaughter at a commercial abattoir (Triumph Foods, St. Joseph, MO). Hot carcass weights were measured immediately after evisceration and each carcass was evaluated for percentage carcass yield, backfat, and loin depth. Percentage carcass yield was calculated by dividing HCW by live weight obtained at the farm before transport to the abattoir. Fat depth and loin depth were measured with an optical probe (SFK; Herlev, Denmark) inserted between the 3rd and 4th ribs located anterior to the last rib at a distance approximately 7.1 cm from the dorsal midline.

Statistical Analysis

All growth data was analyzed as a split-plot design using the GLIMMIX procedure of SAS (SAS Institute, Inc., Cary, NC). Maternal vitamin D regimen acted as the whole plot unit and nursery vitamin D regimen acted as the split-plot unit. Pen was the experimental unit and weaning group was included in the model as a random effect. Contrast statements tested for maternal vitamin D treatments included: (1) increasing maternal vitamin D_3 linear and quadratic polynomials, and (2) 800 IU vitamin D_3 vs. 2,000 IU $25OHD_3$, (3) 2,000 IU vitamin D_3 vs. 2,000 IU $25OHD_3$, and (4) 9,600 IU vitamin D_3 vs. 2,000 IU $25OHD_3$. The IML procedure of SAS was used to generate unequally spaced orthogonal contrast coefficients for maternal dietary vitamin D_3 treatments. Due to unbalanced sample sizes for maternal treatments, a Tukey-Kramer multiple comparison adjustment was used for the maternal vitamin D pair-wise comparison tests. Repeated measures analysis was performed on the serum vitamin metabolite responses and day of collection was included as a fixed effect to determine serum changes to dietary treatments

over time. For carcass data, maternal vitamin D treatment served as the fixed effect and weaning group acted as a random effect in the model. The percentage carcass yield was analyzed using a beta distribution. Results were considered significant at $P \leq 0.05$ and a tendency at $P \leq 0.10$.

RESULTS

Chemical analysis of experimental nursery diets confirmed that diets contained similar CP and P concentrations to that which they were formulated (Table 2-2. Analyzed nursery diet composition (as-fed basis)[1]). The Ca concentrations analyzed higher than formulated, but all diets were above the animals' requirement. Although there is no published accepted standard for vitamin D recovery in animal feeds, analysis showed nursery diets were within 25% of their formulated targets which would be consistent with the acceptable analytical variation and recovery of other vitamins previously discussed by AAFCO (2015).

Growth Performance

At weaning, BW of pigs subsampled for the nursery portion of the study increased (quadratic, $P = 0.001$; Table 2-3) with increasing maternal vitamin D_3. This was because pigs subsampled from sows fed the 2,000 IU of vitamin D_3/kg were heavier (6.8 kg) compared to pigs from sows fed either 800 (6.5 kg) or 9,600 (6.6 kg) IU of vitamin D_3/kg. In addition, pigs weaned from sows fed 800 IU of vitamin D_3/kg tended (P = 0.088) to have lighter BW at weaning compared to pigs weaned from sows fed 2,000 IU of 25OHD_3/kg. For the maternal portion of the study these numeric differences were not statistically significant but changing the experimental unit from sow to pen led to a significant difference in initial BW among vitamin D_3

treatments and a statistical tendency when comparing pig BW of pigs weaned from sows fed 800 IU of vitamin D_3/kg compared to pigs weaned from sows fed 2,000 IU of 25OHD_3/kg.

No nursery × maternal vitamin D interactions were observed for growth performance in the nursery or finishing portion of the growth study. Thus, only the main effects of maternal vitamin D treatment and nursery vitamin D treatments are reported herein.

Nursery dietary vitamin D regimen had no influence (Table 2-4) on pig growth throughout the nursery or finishing portion of the study. From d 0 to 35 in the nursery, increasing maternal vitamin D_3 increased (quadratic, $P < 0.003$) ADG and ADFI, but G:F was similar regardless of maternal vitamin D regimen. Pigs weaned from sows fed 800 IU of vitamin D_3/kg had lower ($P = 0.002$) ADG and tended ($P = 0.066$) to have less ADFI compared to pigs weaned from sows fed 2,000 IU of 25OHD_3/kg. Final BW at the end of the nursery period (d 35) was increased (quadratic, $P = 0.001$) with increased maternal vitamin D_3. This was because pigs from sows fed 2,000 IU of vitamin D_3/kg had heavier BW at the end of the nursery compared with pigs from sows fed 800 or 9,600 IU of vitamin D_3/kg. In addition, pigs from sows fed 800 IU of vitamin D_3/kg had lighter ($P = 0.001$) final BW at the end of the nursery period compared to pigs fed 2,000 IU of 25OHD_3/kg. Overall finisher ADG increased (quadratic, $P = 0.005$) with increased maternal vitamin D_3 which also led to increased (quadratic, $P = 0.006$) final BW. Similar to nursery growth, this was due to pigs from sows fed 2,000 IU of vitamin D_3/kg having increased ADG and improved G:F compared to pigs from sows fed 800 or 9,600 IU of vitamin D_3/kg. Also, pigs from sows fed 800 IU of vitamin D_3/kg had lower ($P = 0.004$) ADG and lighter ($P = 0.003$) final BW compared to pigs from sows fed 2,000 IU of 25OHD_3/kg. Feed efficiency was improved (quadratic, $P = 0.049$) with increasing maternal vitamin D_3.

Growing Pig serum 25OHD$_3$, vitamin D$_3$, α-tocopherol, and retinol

No three-way maternal × nursery × day interactions were observed for serum vitamin metabolite responses. Thus, only the main effects of maternal and nursery vitamin D regimens are reported herein.

A maternal treatment × day ($P < 0.001$; Table 2-5) interaction was observed for growing pig serum 25OHD$_3$ because changes in serum concentrations over time were dependent on the maternal dietary treatments. At weaning, increasing maternal dietary vitamin D$_3$ increased (linear, $P = 0.001$) serum 25OHD$_3$, and (quadratic, $P = 0.037$) serum retinol, but it decreased (linear, $P = 0.037$) serum α-tocopherol. In addition, pigs from sows 9,600 IU of vitamin D$_3$/kg had increased ($P < 0.001$) serum 25OHD$_3$ compared to pigs from sows fed 2,000 IU of 25OHD$_3$/kg. Pigs from sows fed 800 IU of vitamin D3/kg had increased ($P = 0.001$) serum α-tocopherol compared to pigs from sows fed 2,000 IU of 25OHD$_3$/kg. Also, increasing maternal dietary vitamin D$_3$ supplementation led to an increased (quadratic, $P = 0.023$) percentage of pigs exhibiting serum vitamin D$_3$ concentrations above the detectable limit with a decreasing (quadratic, $P = 0.001$) mean vitamin D$_3$ concentration. On d 17 after weaning, increasing maternal vitamin D$_3$ increased (quadratic; $P = 0.023$) serum retinol, and tended (quadratic, $P = 0.063$) to increase serum 25OHD$_3$. Additionally, increasing maternal vitamin D$_3$ supplementation tended (linear, $P = 0.082$) to decrease piglet serum vitamin D$_3$ concentrations although the percentage of pigs exhibiting serum concentrations above the detectable limit was not affected by maternal vitamin D dietary treatment. By d 35 post-weaning, increasing maternal vitamin D$_3$ supplementation increased (quadratic, $P = 0.006$) serum 25OHD$_3$ and tended (quadratic, $P = 0.063$) to increase serum retinol. Also, pigs from sows fed 2,000 IU of vitamin D$_3$/kg had increased ($P < 0.002$) serum 25OHD$_3$ compared with pigs from sows fed 2,000 IU of

25OHD$_3$/kg. By d 70 after weaning, maternal dietary vitamin D treatment had no influence on growing pig serum vitamin metabolites.

A nursery × day ($P < 0.001$; **Error! Reference source not found.**) interaction was observed for growing pig serum 25OHD$_3$ because changes over time were different based on nursery vitamin D regimen. At weaning, pigs moved to pens fed vitamin D$_3$ had less ($P = 0.015$) serum α-tocopherol concentrations compared to pigs moved to pens fed 25OHD$_3$. Also, pigs moved to pens fed vitamin D$_3$ tended ($P = 0.099$) to have greater mean serum vitamin D$_3$ concentrations although the percentage of pigs exhibiting concentrations above the detectable limit was not influenced by nursery treatment. On d 17 and 35 in the nursery, pigs fed vitamin D$_3$ had greater ($P < 0.001$) percentages of pigs exhibiting serum vitamin D$_3$ concentrations above the detectable limit; however, they also had decreased serum 25OHD$_3$ ($P = 0.001$) concentrations compared to pigs fed 25OHD$_3$. By d 70 (35-d post nursery vitamin D treatments), serum vitamin metabolites were not influenced by nursery dietary vitamin D regimens.

Carcass Characteristics

Pigs from sows fed 2,000 IU of 25OHD$_3$/kg had heavier ($P < 0.047$; Table 2-7) final live BW and HCW compared to pigs from sows fed 9,600 IU of vitamin D$_3$/kg. Carcass yield percentage increased (quadratic, $P = 0.003$) with increasing maternal dietary vitamin D$_3$ supplementation. Loin depth (linear, $P = 0.047$) and BF thickness (quadratic, $P = 0.031$) decreased with increasing maternal dietary vitamin D$_3$ supplementation.

DISCUSSION

The impact of maternal imprinting on postnatal performance of progeny has led to an increased interest in understanding how maternal nutrition can impact subsequent progeny growth. Mahan and Vallet (1997) concluded that the understanding of vitamin and mineral transport in utero was still very much in its infancy almost two decades ago. Research specifically focused on vitamin D's transport and function in utero has been more researched than some other vitamins and trace minerals.

Haddad et al. (1971) illustrated using pregnant rats that both vitamin D_3 and $25OHD_3$ are capable of being transported transplacentally to the fetus and concluded that maternal and fetal ratios of vitamin D_3 and $25OHD_3$ were similar as soon as 1 h after administration. Clements and Fraser (1998) determined that supplementing vitamin D deficient pregnant rats resulted in the increased in utero presence of vitamin D metabolites, predominately of which were $25OHD_3$ and $24,25OH_2D_3$. The active form of the vitamin ($1,25OH_2D_3$) must be derived from fetal sources but little to no data is available about how the active form is metabolized in the fetus. However, Johnson et al. (1996) and Endo et al. (2003) have both illustrated the presence of vitamin D nuclear receptors (VDRs) within fetal bone and muscle tissues. This suggests that the active $1,25OH_2D_3$ metabolite plays a role in the fetal development of these tissues. In fact, Endo et al. (2003) demonstrated that the absence of the VDR in mice led to aberrant expression of myogenic transcription factors (Myf5, myogenin, and E2A) in hind leg muscle. High expression of these factors in utero could lead to precocious cell differentiation and impaired cell proliferation leaving a smaller myoblast cell pool for postnatal muscle development and hypertrophic growth. Most of this research has been conducted with deficient animals; however, previous work in swine by Hines et al. (2013) concluded that differences in fetal muscle fiber number and Pax7+ cells within the longissimus of fetuses from bred gilts fed 2,500 IU of vitamin D/kg of the diet as

100% vitamin D_3 or as 80% 25OHD_3 and 20% vitamin D_3. Their conclusion was that the increases in maternal 25OHD_3 concentrations (vitamin D status) were the reason for the improvements in fetal muscle development. Other researchers have observed similar increases in the serum 25OHD_3 response of growing pigs and sows fed 25OHD_3 compared to feeding similar international unit equivalency concentrations of vitamin D_3. The aforementioned conclusions from previous research led to our hypothesis that by altering the maternal vitamin D status of the sow, it could lead to alterations in fetal muscle development and, subsequently, changes in postnatal growth. The aim of the study herein was to evaluate the postnatal growth of pigs from sows fed the varying dietary vitamin D supplementation treatments and determine whether growth was impacted by maternal dietary vitamin D treatment and/or by subsequent nursery dietary vitamin D treatments.

Nursery and finishing growth herein was not influenced by nursery vitamin D supplementation which would be consistent with conclusions reported by Wahlstrom and Stolte (1958), Combs et al. (1966) and Flohr et al. (2014a) who have all evaluated supplementing dietary vitamin D_3 when all other nutrient concentrations were adequate. Rohrvedt and Crenshaw (2012) demonstrated a reduction in the growth of nursery pigs weaned from sows deficient in vitamin D, only when nursery diets were formulated to be marginal (80% of NRC [1998]) in Ca and P. When diets were replete with the nutrients (120% of NRC [1998]), performance was restored. This suggests that unless pigs are faced with a nutritional deficiency of vitamin D, Ca, or P, vitamin D supplementation will not affect growth rate.

Interestingly, in the study herein, maternal vitamin D influenced post-weaning growth, but not in the way that we had hypothesized based on previous conclusions drawn from Hines et al. (2013) and Weber et al. (2014). In the current study, it appeared that the only consistent

impact on growth performance was that pigs from sows fed 2,000 IU of vitamin D_3/kg had increased ADG and ADFI in the nursery and improved ADG and G:F in finishing. Considering that performance of pigs from sows fed 2,000 IU of $25OHD_3$ was similar to that of pigs from sows fed 2,000 IU of vitamin D_3/kg, the conclusion would be that form of maternal vitamin D (vitamin D_3 or $25OHD_3$) does not influence post-weaning growth; however, it appeared that the level of the vitamin supplemented did result in growth differences. The data herein suggests that 2,000 IU of vitamin D/kg of the diet was useful in achieving the highest growth rates compared to feeding 800 or 9,600 IU of vitamin D_3/kg. Also, pigs weaned from sows fed 2,000 IU of vitamin D_3/kg had numerically heavier weaning BW (although not statistically significant in the sow portion of the study [Flohr et al., 2015]) compared to pigs from sows fed 800 or 9,600 IU of vitamin D_3/kg. Pluske and Dong (1998) showed that the growth of suckling pig is predominately limited by the amount of milk produced by the sow. In addition, the amount of feed intake during lactation can impact total milk production and subsequent litter weaning weight (Eissen et al., 2003). Due to the increase in lactation ADFI observed for sows fed diets with 2,000 IU of vitamin D_3/kg discussed by Flohr et al. (2015), it is plausible to think that lactation feed intake may have been a larger reason for the numeric increase in weaning weights of pigs rather than maternal vitamin D treatment. There is no previous evidence to support that maternal vitamin D treatment would have impacted lactation feed intake except for the case of toxicity which has been described to cause lethargy and anorexia (NRC, 1987); however, signs of these symptoms were not observed during the lactation portion of the study. Ultimately, the results herein suggest that maternal dietary vitamin D treatment impacted nursery performance which disagrees with results from Flohr et al. (2014b) who observed no impact of maternal vitamin D_3 treatment or

nursery vitamin D_3 treatment on nursery performance of pigs weaned from sows supplemented between 1,500 to 6,000 IU of vitamin D_3/kg of the diet.

The maternal and nursery vitamin D treatment impacts on growing pig serum $25OHD_3$ in this study were largely expected. Most previous reports (Lauridsen et al., 2010; Witschi et al., 2011; Coffey et al., 2012; Weber et al., 2014) have all shown that supplementation of $25OHD_3$ at the same international unit equivalency of vitamin D_3 will result in an increased serum $25OHD_3$ response. Also, increasing maternal vitamin D_3 supplementation has shown to lead to an increase in subsequent pig serum $25OHD_3$ (Flohr et al., 2014b) which was consistent with results from the current study. However, pigs weaned from sows fed 2,000 IU of $25OHD_3$/kg had similar serum $25OHD_3$ concentrations as pigs weaned from sows 2,000 IU of vitamin D_3/kg (which were formulated to be at the same international unit equivalency of the vitamin); but, levels were less than that of pigs from sows 9,600 IU of vitamin D_3/kg. This shows that for milk transfer of the vitamin (which was the lone source of the nutrient prior to weaning) the level of maternal dietary vitamin D was more impactful than the form dietary of vitamin D. Additionally, Flohr et al. (2014b) concluded that serum $25OHD_3$ of weaned pigs was no longer impacted by maternal vitamin D_3 supplementation as soon as 21-d post-weaning. However, maternal vitamin D treatment impacted serum $25OHD_3$ of growing pigs up to 35-d post-weaning in the current study. This may be largely in part due to the increase in ADFI of pigs weaned from sows fed the medium level of vitamin D_3 which would have increased total vitamin D intake.

Serum vitamin D_3 concentrations responded as expected in growing pigs based on maternal and nursery vitamin D treatments. Particularly, supplementing $25OHD_3$, maternally or in the nursery diet, led to decreased serum vitamin D_3 concentrations in the growing pig. This would be expected because the demand for transport of vitamin D_3 to tissue for storage, or to the

liver for metabolism would be lessened if the animal is not exposed to that specific metabolite. However, it is difficult to infer much about the animal's vitamin D status from serum vitamin D_3 concentrations since circulating levels will increase quickly after a meal and then clear circulation within hours after absorption (Clinton, 2013).

Little research has examined metabolic interactions of vitamin D with vitamin A and vitamin E. It was hypothesized that differences among serum retinol and α-tocopherol based on maternal or nursery vitamin D treatment would be minimal and largely that was true. Interestingly, increased growing pig serum retinol after weaning was observed for pigs from sows fed 2,000 IU of vitamin D_3/kg compared to pigs from sows 800 or 9,600 IU of vitamin D_3/kg. This may be the result of the increased lactation ADFI for sows fed diets containing 2,000 IU of vitamin D_3/kg compared to sows fed diets containing 800 or 9,600 IU of vitamin D_3/kg. Daily vitamin A intake would have been approximately 650 IU/d greater for sows fed diets containing 2,000 IU of vitamin D_3/kg compared to sows fed diets containing 800 or 9,600 IU of vitamin D_3/kg.

The carcass data herein showed that pigs from sows fed 2,000 IU of 25OHD_3/kg had increased final BW and HCW compared to pigs from sows fed 9,600 IU of vitamin D_3/kg. Ultimately, this result was unexpected and to our knowledge is the first data associating subsequent pig carcass data to maternal dietary vitamin D supplementation. Increases in carcass yield and decreases in BF of pigs from sows fed 2,000 IU of vitamin D_3/kg compared to pigs from sows fed 800 or 9,600 IU of vitamin D_3/kg compliment the growth data herein suggesting pigs from sows fed 2,000 IU of vitamin D_3 had both improved post-weaning growth and carcass characteristics. However it is still unclear whether these responses were the result of maternal

vitamin D treatments or numeric differences in weaning weight of pigs weaned from sows fed the medium level of vitamin D.

In conclusion, serum $25OHD_3$ of growing pigs is influenced by maternal dietary vitamin D treatment early after weaning, but afterwards it is largely dependent on nursery dietary vitamin D supplementation. Growing pigs fed $25OHD_3$ in the nursery had increased serum $25OHD_3$ compared to pigs fed vitamin D_3 at the same international unit equivalency, but by 35-d post nursery treatment serum levels were similar regardless of nursery vitamin D source. Also in this study, pigs from sows fed 2,000 IU of vitamin D_3/kg had increased ADG and ADFI in the nursery, increased ADG and G:F in finishing, and increased percentage carcass yield and decreased BF compared to pigs from sows fed 800 or 9,600 IU of vitamin D_3/kg. These results show benefit to supplementing maternal vitamin D_3 at 2,000 IU/kg of the diet compared to 800 or 9,600 IU/kg of the diet. In addition, ADG was improved for pigs weaned from sows fed 2,000 IU of $25OHD_3$/kg compared to pigs weaned from sows fed 800 IU of vitamin D_3/kg, and carcass data suggested that pigs weaned from sows fed 2,000 IU of $25OHD_3$/kg had increased final BW and HCW compared to pigs from sows fed 9,600 IU/kg. However, it is unclear from the current study whether this was in fact due to the maternal vitamin D treatments or because of numeric differences in BW of pigs at weaning. More research examining potential relationships of maternal vitamin D supplementation and subsequent pig growth and carcass characteristics is needed to elucidate if there are potential benefits of maternal vitamin D supplementation strategies besides those currently employed in commercial sow diets.

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TABLES AND FIGURES

Table 2-1. Nursery and finishing diet composition (as-fed basis)[1]

	Nursery diets[2]			Finishing diets[3]		
	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Ingredient, %						
Corn	35.68	46.01	56.39	71.50	78.44	82.86
Soybean meal, 46.5% CP	22.09	20.37	24.27	25.71	19.20	14.93
Corn DDGS[4]	5.00	15.00	15.00	---	---	---
Fish meal	5.00	5.00	---	---	---	---
Spray dried whey	25.00	10.00	---	---	---	---
Choice white grease	3.00	---	---	---	---	---
Monocalcium phosphate, 21.5% P	0.15	0.23	0.88	0.55	0.33	0.30
Calcium carbonate	1.05	1.13	1.35	1.13	1.10	1.08
Sodium chloride	0.30	0.30	0.35	0.35	0.35	0.35
L-Lys HCl	0.40	0.45	0.50	0.31	0.25	0.22
DL-Met	0.20	0.14	0.13	0.06	0.02	---
L-Thr	0.17	0.16	0.17	0.09	0.05	0.05
L-Trp	0.04	0.05	0.04	---	---	---
L-Val	0.09	0.03	0.03	---	---	---
Choline chloride, 60%	0.04	---	---	---	---	---
Zinc oxide	0.39	0.25	---	---	---	---
Medication[5]	1.00	0.50	0.50	---	---	---
Phytase[6]	0.02	0.02	0.02	0.02	0.02	0.02
Trace mineral premix[7]	0.15	0.15	0.15	0.15	0.13	0.10
Vitamin premix[8]	0.25	0.25	0.25	0.15	0.13	0.10
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis						
SID[9] amino acids, %						
Lys	1.40	1.34	1.22	1.05	0.85	0.72
Met & Cys:Lys	57	57	57	55	56	59
Thr:Lys	63	63	63	61	61	64
Trp:Lys	19	19	19	18	18	18
Val:Lys	68	68	68	69	73	76
NE, Mcal/kg	2.58	2.43	2.40	2.47	2.51	2.54
SID Lys:NE, g/Mcal	5.43	5.51	5.08	4.25	3.39	2.83
CP,%	21.6	22.6	21.0	18.5	15.9	14.2
Ca,%	0.86	0.81	0.74	0.62	0.55	0.52
P, %	0.63	0.62	0.60	0.49	0.41	0.39
Available P, %	0.51	0.47	0.42	0.29	0.23	0.22
STTD P, %	0.43	0.41	0.36	0.34	0.28	0.27
Ca:P	1.36	1.30	1.23	1.28	1.34	1.35

[1] A total of 448 pigs from 52 litters in 2 farrowing groups were used in a 35-d nursery trial. There were a total of 7 pigs per pen and 4 pens per treatment in the first weaning group and there were 4 pigs per pen and either 8 or 9 pens per treatment in the second weaning group.

[2] Phase 1 diets were fed from d 0 (weaning) until d 10, phase 2 diets were fed from d 10 to d 21, and phase 3 diets were fed from day 21 to 35. Experimental treatments were made by adding either a vitamin D_3 premix (4,409,240 IU/kg of premix) in the diet replacing corn or 0.33 kg/ton of $25OHD_3$ (Hy-D; DSM Nutritional Products North America, Parsippany, NJ) was added to the diet by replacing corn.

[3] Common finishing diets were fed from approximately 23 to 55 kg, 55 to 93 kg, and 93 kg until market for phase 4, 5, and 6, respectively. Common finishing diets were formulated to contain 827, 690, and 551 IU of vitamin D_3 per kg of complete diet for phase 4, 5, and 6, respectively.

[4] Dried distillers grains with solubles.
[5] Mecadox 2.5, Phibro Animal Health, Ridgefiled Park, NJ. Provided 44 mg/kg of carbadox in phase 1 nursery diets and 22 mg/kg of carbadox in phase 2 and 3 diets, respectively.
[6] Ronozyme Hi-Phos, DSM, Parsippany, NJ. Provided 476 phytase units (FTU/kg) of diet with an expected release of 0.10% phytate P.
[7] Provided 11,000 ppm Cu, 198 ppm I, 73,413 ppm Fe, 22,046 ppm Mn, 198 ppm Se, and 74,413 ppm Zn per kg of premix.
[8] Provided 3,527,392 IU vit. A, 17,637 IU vit. E, 1,764 mg vit. K, 15 mg vit. B_{12}, 33,069 mg niacin, 11,023 mg pantothenic acid, and 3,307 mg riboflavin per kg of premix.
[9] Standardized ileal digestible.

Table 2-2. Analyzed nursery diet composition (as-fed basis)[1]

	Nursery diets					
	Phase 1		Phase 2		Phase 3	
Item	D_3	$25OHD_3$	D_3	$25OHD_3$	D_3	$25OHD_3$
Formulated						
CP, %	21.6	21.6	22.6	22.6	21	21
Ca, %	0.86	0.86	0.81	0.81	0.74	0.74
P, %	0.63	0.63	0.62	0.62	0.60	0.60
Vitamin D_3, IU/kg	2,000	---	2,000	---	2,000	---
$25(OH)D_3$, IU/kg	---	2,000	---	2,000	---	2,000
Analyzed[2]						
CP, %	21.8	22.4	24.2	23.2	23.1	22.4
Ca, %	1.04	1.04	1.03	1.02	0.80	0.9
P, %	0.65	0.64	0.71	0.70	0.61	0.61
Vitamin D_3, IU/kg	2,240	---	1,700	---	2,110	---
$25(OH)D_3$, IU/kg	---	1,580	---	1,500	---	1,540
% of formulated	112	79	85	75	106	77

[1] Means represent the average of two pooled samples.
[2] Crude protein, Ca, and P was determined at Ward laboratories (Kearney, NE). Vitamin D_3 and $25OHD_3$ analysis was performed by DSM Nutrition Products (Parsippany, NJ).

Table 2-3. Main effects of maternal vitamin D regimen on the performance of growing pigs[1]

	Maternal Vitamin D, IU/kg					Probability, *P* <				
	Vitamin D_3			25OHD_3		Vitamin D_3		800 D_3 vs. 2,000 25OHD_3	2,000 D_3 vs. 2,000 25OHD_3	9,600 D_3 vs. 2,000 25OHD_3
Item	800	2,000	9,600	2,000	SEM	Linear	Quadratic			
Nursery growth[2]										
d 0 to 35										
ADG, kg	0.42	0.44	0.43	0.45	0.016	0.729	0.003	0.002	0.917	0.105
ADFI, kg	0.65	0.70	0.67	0.69	0.024	0.853	0.002	0.066	0.929	0.437
G:F	0.638	0.632	0.639	0.647	0.0062	0.708	0.407	0.709	0.236	0.709
Finishing growth[3]										
d 35 to Market										
ADG, kg	0.93	0.96	0.94	0.96	0.010	0.602	0.005	0.004	0.916	0.220
ADFI, kg	2.56	2.59	2.57	2.63	0.024	0.981	0.492	0.216	0.558	0.327
G:F	0.368	0.377	0.374	0.373	0.0062	0.610	0.049	0.701	0.740	0.997
Average BW, kg										
d 0	6.5	6.8	6.6	6.6	0.06	0.566	0.001	0.088	0.371	0.985
d 35	21.1	22.3	21.8	22.3	0.52	0.555	0.001	0.001	0.997	0.141
Market	132.6	136.5	134.9	137.5	2.95	0.480	0.006	0.003	0.866	0.240

[1] A total of 448 pigs from 52 litters in 2 farrowing groups were used in a 35 d nursery trial. The treatment structure was a split-plot design with maternal treatment as the whole-plot unit and nursery treatment as the split-plot unit.

[2]For nursery performance pen was the experimental unit. Random effect of group was used in the statistical model. There were a total of 7 pigs per pen and 8 pens per treatment in group 1 and there were 4 pigs per pen and either 16 or 17 pens per treatment.

[3] For finishing performance pen was the experimental unit. Random effect of group was used in the statistical model. There were a total of 5 to 8 pigs per pen and 19 finishing pens per treatment.

Table 2-4. Main effects of nursery dietary vitamin D regimen on the performance of growing pigs[1]

	Nursery source[2]			Probability, $P <$
Item	Vitamin D_3	$25OHD_3$	SEM	Nursery
Nursery growth[3]				
d 0 to 35				
ADG, kg	0.44	0.43	0.015	0.482
ADFI, kg	0.68	0.67	0.023	0.137
G:F	0.635	0.643	0.0041	0.224
Finishing growth[4]				
d 35 to Market				
ADG, kg	0.95	0.95	0.008	0.577
ADFI, kg	2.57	2.61	0.017	0.126
G:F	0.374	0.369	0.0057	0.453
Average BW, kg				
d 0	6.6	6.6	0.05	0.922
d 35	21.9	21.8	0.49	0.537
Market	135.3	135.4	2.86	0.911

[1] A total of 448 pigs from 52 litters in 2 farrowing groups were used in a 35 d nursery trial. The treatment structure was a split-plot design with maternal treatment as the whole-plot unit and nursery treatment as the split-plot unit.

[2] Subsequent nursery treatments consisted of supplementing vitamin D in phase 1, 2, and 3 diets from either vitamin D_3 (2,000 IU/kg) or from $25OHD_3$ (2,000 IU/kg).

[3]For nursery performance pen was the experimental unit. Random effect of group was used in the statistical model. There were a total of 7 pigs per pen and 16 pens per treatment in group 1 and there were 4 pigs per pen and 33 pens per treatment.

[4] For finishing performance pen was the experimental unit. Random effect of group was used in the statistical model. There were a total of 5 to 8 pigs per pen and 38 finishing pens per treatment.

Table 2-5. Main effects of maternal dietary vitamin D regimen on growing pig serum metabolites[1]

	Maternal Vitamin D, IU/kg					Probability, $P <$				
	Vitamin D_3			$25OHD_3$		Vitamin D_3		800 D_3 vs.	2,000 D_3	9,600 D_3
Item	800	2,000	9,600	2,000	SEM	Linear	Quadratic	2,000 $25OHD_3$	vs. 2,000 $25OHD_3$	vs. 2,000 $25OHD_3$
Growing pig serum vitamin metabolites										
$25OHD_3$, ng/mL[2]										
Weaning	5.4	7.1	16.6	5.5	1.15	0.001	0.871	0.925	0.300	0.001
d 17	22.7	25.9	25.0	23.6	1.24	0.466	0.063	0.581	0.163	0.398
d 35	26.4	30.8	26.8	25.5	1.29	0.366	0.006	0.556	0.002	0.452
d 70	18.3	15.7	16.1	16.5	1.54	0.497	0.257	0.403	0.686	0.816
Vitamin D_3[3]										
Weaning										
Detectable samples, %	6.3	32.4	83.3	0.0	5.19	0.001	0.023	0.395	0.001	0.001
Mean, ng/mL	7.3	1.2	5.6	---	0.24	0.369	0.001	---	---	---
d 17										
Detectable samples, %	43.8	43.8	50.0	50.0	5.66	0.367	0.907	0.420	0.420	0.999
Mean, ng/mL	3.3	3.8	2.7	3.0	0.41	0.082	0.266	0.505	0.114	0.614
d 35										
Detectable samples, %	43.8	50.0	50.0	50.0	5.91	0.593	0.459	0.420	0.999	0.999
Mean, ng/mL	3.5	3.5	3.6	3.8	0.40	0.888	0.920	0.590	0.521	0.641
d 70										
Detectable samples, %	100.0	100.0	100.0	100.0	7.06	0.999	0.999	0.999	0.999	0.999
Mean, ng/mL	3.2	3.1	3.1	2.6	0.33	0.855	0.784	0.191	0.312	0.277
α-tocopherol, mg/L[4]										
Weaning	5,304	4,769	4,591	4,331	197.5	0.037	0.086	0.001	0.101	0.340
d 17	982	829	804	924	207.4	0.641	0.629	0.837	0.738	0.679
d 35	1,521	1,401	1,242	1,291	216.4	0.374	0.758	0.417	0.698	0.869
d 70	1,799	1,566	1,784	1,631	258.8	0.796	0.498	0.632	0.856	0.646
Retinol, ng/mL[5]										
Weaning	254	301	286	283	19.9	0.464	0.037	0.176	0.427	0.907
d 17	366	419	397	413	21.0	0.599	0.023	0.038	0.795	0.491
d 35	389	435	431	421	21.6	0.242	0.063	0.158	0.553	0.667
d 70	379	393	373	360	24.8	0.635	0.585	0.507	0.250	0.631

[1] A total of 448 pigs from 52 litters in 2 farrowing groups were used in a 35 d nursery trial and followed through finishing. The treatment structure was a split-plot design with maternal treatment as the whole-plot unit and nursery treatment as the split-plot unit.
[2] A maternal × day ($P < 0.001$) interaction was observed for growing pig serum $25OHD_3$ concentrations.

[3] The assay for serum vitamin D_3 had a lower detectable limit of 1.00 ng/mL. Samples below the detectable limit (n = 130 out of 256) were not used in the statistical analysis. Detectable sample represents the percentage of samples above the detectable limit and the mean serum vitamin D_3 was calculated using only samples above the detectable limit.
[4] A day effect ($P < 0.001$) was observed for growing pig serum α-tocopherol concentrations.
[5] A day effect ($P < 0.001$) was observed for growing pig serum retinol concentrations.

Table 2-6. Main effects of nursery dietary vitamin D regimen on growing pig serum vitamin metabolites[1]

	Nursery source[2]			Probability, $P <$
Item	Vitamin D_3	25OHD_3	SEM	Nursery
Growing pig serum vitamin metabolites				
25OHD_3, ng/mL[3]				
Weaning	9.3	8.0	0.84	0.229
d 17	11.3	37.3	0.89	0.001
d 35	16.1	38.7	0.91	0.001
d 70	16.8	16.6	1.10	0.889
Vitamin D_3, ng/mL[4]				
Weaning				
Detectable samples, %	33.3	27.0	4.65	0.335
Mean, ng/mL	4.9	4.0	0.44	0.099
d 17				
Detectable samples, %	93.8	0.0	5.01	0.001
Mean, ng/mL	3.2	---	0.27	---
d 35				
Detectable samples, %	96.9	0.0	5.10	0.001
Mean, ng/mL	3.6	---	0.28	---
d 70				
Detectable samples, %	100.0	100.0	5.95	0.999
Mean, ng/mL	3.0	3.1	0.33	0.823
α-tocopherol, mg/L[5]				
Weaning	4,512	4,984	137.7	0.015
d 17	902	868	144.5	0.868
d 35	1,404	1,324	147.7	0.695
d 70	1,680	1,710	1.77.9	0.901
Retinol, ng/mL[6]				
Weaning	284	278	16.7	0.663
d 17	408	390	17.2	0.260
d 35	423	415	17.4	0.660
d 70	373	379	19.6	0.800

[1] A total of 448 pigs from 52 litters in 2 farrowing groups were used in a 35 d nursery trial and followed through finishing. The treatment structure was a split-plot design with maternal treatment as the whole-plot unit and nursery treatment as the split-plot unit.

[2] Subsequent nursery treatments consisted of supplementing vitamin D in phase 1, 2, and 3 diets from either vitamin D_3 (2,000 IU/kg) or from 25OHD_3 (2,000 IU/kg).

[3] A nursery × day ($P < 0.001$) interaction was observed for growing pig serum 25OHD_3 concentrations.

[4] The assay for serum vitamin D_3 had a lower detectable limit of 1.00 ng/mL. Samples below the detectable limit (n = 130 out of 256) were not used in the statistical analysis. Positive sample represents the percentage of samples above the detectable limit and the mean serum vitamin D_3 was calculated using only samples above the detectable limit.

[5] A day effect ($P < 0.001$) was observed for growing pig serum α-tocopherol concentrations.

[6] A day effect ($P < 0.001$) was observed for growing pig serum retinol concentrations.

Table 2-7. The effect of maternal dietary vitamin D regimen on subsequent pig carcass characteristics[1]

	Maternal vitamin D, IU/kg					Probability, *P* <				
	Vitamin D_3			$25OHD_3$		Vitamin D_3		800 D_3 vs. 2,000 $25OHD_3$	2,000 D_3 vs. 2,000 $25OHD_3$	9,600 D_3 vs. 2,000 $25OHD_3$
Item	800	2,000	9,600	2,000	SEM	Linear	Quadratic			
Live weight, kg	134.8	135.5	133.8	137.1	3.17	0.264	0.534	0.266	0.574	0.047
HCW, kg	99.8	100.7	98.9	101.6	3.35	0.155	0.288	0.276	0.830	0.037
Yield, %	73.9	74.3	73.8	74.0	0.76	0.077	0.002	0.521	0.339	0.298
Loin Depth, mm^3	60.2	60.6	58.9	59.4	4.06	0.037	0.470	0.743	0.457	0.905
BF, mm^3	20.8	19.7	20.3	20.0	0.91	0.923	0.031	0.407	0.898	0.941

[1] Means represent data collected from 642 finishing pigs within 3 consecutive finishing groups. Group and finishing treatment within group were used as random effects.

[2] Maternal vitamin D_3 concentrations of 800, 2,000, and 9,600 IU vitamin D_3 per kg of complete diet were fed for low, medium, and treatments, respectively, and 50 μg of $25OHD_3$ /kg of the complete diet for the maternal $25OHD_3$ treatment.

[3] Hot carcass weight was used as a covariate in the statistical model.

Chapter 3 - Evaluating the removal of pigs from a group and subsequent floor space allowance on the growth performance of heavy weight finishing pigs[1]

ABSTRACT

A total of 1,092 finishing pigs (initially 36.3 kg) were used in a 117-d study to evaluate the impact of initial floor space allowance and removal strategy on the growth of finishing pigs up to 140 kg. There were 4 experimental treatments with 14 pens per treatment. The first treatment stocked pigs at 0.91 m^2 (15 pigs/pen) throughout the duration of the study. The other 3 treatments initially stocked pigs at 0.65 m^2 (21 pigs/pen) and were subject to one of 3 removal strategies. The second treatment (*2:2:2*) removed the 2 heaviest pigs from pens on d 64, 76, and 95 which coincided with times that floor space allowance was predicted (Gonyou et al., 2006) to become limiting. Treatment 3 (*2:4*) removed the 2 heaviest pigs on d 76 and the 4 heaviest pigs on d 105. Treatment 4 (*6*) removed the heaviest 6 pigs on d 105. All pigs remaining in pens after removals were fed to d 117. Overall (d 0 to 117), pigs initially provided 0.91 m^2 of floor space had increased ($P < 0.05$) ADG compared to pigs in pens on the *2:4* or *6* removal strategy, but ADG was not different compared with pigs on the *2:2:2* removal strategy. In addition the current study illustrates that the prediction equation developed by Gonyou et al. (2006) are useful predictors of the impact of floor space allowance on growth rate of finishing pigs but may

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underestimate the true impact of space restriction. Total BW gain per pen was greater ($P < 0.05$) for pens initially stocked at 0.65 m^2 compared to pens initially stocked at 0.91 m^2. Feed usage per pen was less ($P < 0.05$) for pens initially stocked at 0.91 m^2 compared to pens initially providing 0.65 m^2 of floor space and on removal strategies; but feed usage per pig was greater ($P < 0.05$) for pigs initially stocked at 0.91 m^2 compared to pigs initially stocked at 0.65 m^2 and on removal strategies. Feed usage, on a pig or pen basis, was less ($P < 0.05$) for pigs on the *2:2:2* removal strategy compared to pigs on the *2:4* or the *6* removal strategy. Income over feed and facility cost (IOFFC) was less ($P < 0.05$) for pigs initially provided 0.91m^2 compared to pigs initially provided 0.65 m^2 and on removal strategies. Also, IOFFC was less ($P < 0.05$) for pigs on the *2:2:2* compared to the *2:4* and *6* removal strategy. In conclusion, increasing the floor space allowance or the time points at which pigs are removed from the pen improved the growth of pigs remaining in the pen; however, IOFFC may be reduced due to fewer pigs marketed from each pen (pigs stocked at 0.91 m^2 throughout the study) or from reducing total weight produced (*2:2:2* removal strategy).

Key words: Finishing pig, floor space, late finishing, removals

INTRODUCTION

Reducing the variation in BW of pigs marketed to commercial abattoirs is a ubiquitous goal of swine producers because of the economic incentives tied to marketing animals within a specified weight range. One common practice is to market the heaviest pigs in a group prior to

marketing the entire group. This provides additional time for lighter weight pigs that remain to reach a more desirable BW.

Following the removal of pigs from a group, increased growth of the pigs remaining is typically observed (Woodworth et al., 2000; Jacela et al., 2009). DeDecker et al. (2005) concluded that the improved growth performance of pigs was the result of increased feed intake from increased pen resources that were provided after pigs within the group were removed. One resource that has clearly been shown to impact growth of finishing pigs is floor space allowance (Gehlbach et al., 1966; Jensen et al., 1973; Moser et al., 1985). Gonyou et al. (2006) developed floor space prediction equations for ADG and ADFI based on a review of published literature. A decade later it is still recognized as the most commonly used predictor of finishing pig growth based on floor space allowance due to its use of a percentage change in ADG and ADFI which is easily translated across a wide variety of genetic, health, and environmental scenarios which can impact growth. Interestingly, these prediction equations were developed using previously published research that evaluated the influence of floor space allowance on pigs up to approximately 110 kg, which is well below current BW targets for finishing pigs.

The objectives of this study were to evaluate initial stocking density and marketing removal strategies on the growth of pigs remaining in the pen until market and the economic implications of the experimental treatments. Additionally, this study was designed to help validate whether the use of the prediction equations proposed by Gonyou et al. (2006) were applicable for heavier weight finishing pigs.

MATERIALS AND METHODS

This experiment was conducted in a commercial wean to finish facility in central Iowa. This study was approved by and conducted in accordance with the guidelines of the Kansas State University Institutional Animal Care and Use Committee.

Experimental design

The experiment was conducted as a generalized randomized block design with seven replicates. Four experimental treatments were compared: 1) Control, initial floor space allowance of 0.91 m^2 (15 pigs/pen) with no pigs removed from pens and was designed to provide enough space for pigs to be above their predicted requirement until 140 kg; 2) initial floor space allowance of 0.65 m^2 with the 2 heaviest pigs removed when average BW was high enough to drop the *k* coefficient below its predicted optimal threshold (0.0336; as calculated by the equation: k = floor space, $m^2/BW^{0.67}$) proposed by Gonyou et al. (2006) with the average weights targeted being 83 (0.65 m^2), 97 (0.72 m^2), and 114 (0.80 m^2) kg, respectively, which corresponded to removals conducted on d 64, 76, and 95 of the study; referred to as the (*2:2:2*) strategy; 3) initial floor space allowance of 0.65 m^2 with the 2 heaviest pigs removed at an average BW of 109 kg and the 4 heaviest pigs removed when average BW reached 127 kg with removals conducted on d 76 and 105; referred to as the (*2:4*) strategy; and 4) initial floor space allowance of 0.65 m^2 with the 6 heaviest pigs removed when average BW reached 127 kg which correlated to d 105 of the study which was referred to as the (*6*) strategy. Table 3-1 provides a timeline of marketing events that occurred by experimental treatment throughout the length of the study. Prior to initiation of the study, all pens were stocked with 21 pigs (0.65 m^2). Pens were blocked by gender and were randomly allotted to treatments within each block. The number of pigs per pen was adjusted after allotment to experimental treatments to reflect the desired initial

stocking density. Pigs were removed from pens assigned to treatment 1 in order to maintain similar initial BW and initial SD while adjusting group size down to 15 pigs per pen.

Animals

A total of 1,092 crossbred pigs (PIC 359 × Genetiporc F25; PIC, Hendersonville, TN; initial BW of 36.3 ± 1.2 kg) in 56 split-sex pens (barrows and gilts) were used in a 117-d study. Pigs were initially allotted to treatments approximately 10 wk post-weaning.

Diets and housing

The study was conducted in an insulated, tunnel-ventilated wean-to-finish barn. Pens contained fully slatted concrete floors and were 5.75 m × 2.50 m (length × width). In case of a pig removal due to illness or death, pen gates were adjusted to maintain the desired floor space allowance. The only changes in floor space that occurred were the changes consistent with the experimental removal strategies.

Pigs were given ad libitum access to feed and water throughout the study. Pigs were fed common corn and soybean-meal based diets that contained 20% dried distillers grains with solubles and 3% added fat (Table 3-2). Diets were fed in 4 sequential phases from approximately 36 to 59, 59 to 82, 82 to 100, and 100 to 140 kg. Diets were formulated to meet or exceed NRC (2012) recommendations for the nutrient requirements of finishing pigs. The diets were formulated to contain 1.10, 0.90, 0.80, and 0.70% standardized ileal digestible Lys in phases 1 through 4, respectively. Each pen was equipped with a 4-hole (SDI; Alexandria, SD) stainless steel dry self-feeder with feed pan dimensions of 127 × 18 × 15 cm (length × width × height). In order to help maintain similar linear feeder space across initial floor space allowances, one feeder hole in pens stocked at 0.91 m^2 (15 pigs/pen; treatment 1) was blocked. This provided

approximately 6.0 or 5.8 linear cm of trough space/pig for pens initially stocked at 0.91 or 0.65 m^2, respectively. All pens contained 1 pan waterer (53 × 20 cm).

Growth measurements

All pigs were individually weighed at initiation of the study (d 0) and again on d 64, 76, 95, 105, and 117. Pen weights were also collected on the aforementioned days along with d 21 and 42. Individual weight information was used to identify the heaviest pigs in the pen to market on removal days, to calculate the variation of BW with pens throughout the study, and to evaluate ADG of pigs within pens when categorized into the lightest, medium, or heavy thirds of the pen. Pen weights along with feed disappearance were used to calculate ADG, ADFI, and G:F during each period.

Economic calculations

Total weight gain per pen was calculated by subtracting the total pen weight on d 0 from the sum of BW from pigs marketed from the pen. The total weight gain per pig was calculated using the total weight gain per pen divided by the number of pigs marketed per pen. Revenue was calculated using a low ($0.99/kg) and high ($1.32/kg) base carcass price, then individual HCW for each pig marketed was calculated using a fixed yield percentage of 75%. To account for premiums and discounts associated with varying individual HCW the following equation was used: \$/Cwt, kg = (0.0001169532 × HCW, kg^3) – (0.0516996146 × HCW, kg^2) + (6.6397162094 × HCW, kg) – 257.58240. The premium/discount calculation was added to the base price to determine revenue/pig. The individual revenue per pig was summed for the number of pigs in a pen to calculate the revenue per pen. A low ($220.46/tonne) and high ($286.60/tonne) feed cost were used to calculate feed cost per pen and per pig based on the observed feed intake. Finally,

to calculate the income over feed and facility cost (IOFFC) the total feed cost and facility cost (assumed to be \$0.11/0.69 m^2/d) were subtracted from the total revenue.

Statistical analyses

Pig performance data was analyzed as a generalized randomized block design using the MIXED procedure of SAS (SAS Inst., Inc., Cary, NC) with pen as the experimental unit and gender as the blocking factor. Treatment means were analyzed using the LSMEANS statement and protected pairwise comparisons were performed using the Tukey-Kramer multiple comparison adjustment. A pre-planned CONTRAST statement was used to compare the means of pigs initially provided 0.91 m^2 of floor space vs. pigs initially provided 0.65m^2 of floor space. Mortality and morbidity was not a normally distributed response; therefore, the GLIMMIX procedure with binomial distribution was used to evaluate treatment means. For BW categorization information, the RANK procedure of SAS was used to rank pigs within the pen into the lightest, medium, and heaviest thirds of the pen prior to each weigh period. The assigned rank was then used as a fixed effect in the model to evaluate the interactive and main effects of experimental treatment and BW category on ADG within each period. Resutls were considered significant at $P < 0.05$ and a tendency at $P < 0.10$.

RESULTS AND DISCUSSION

Growth performance

There were no gender by treatment interactions; therefore, only the main effects of gender and treatment will be discussed. The lack of interaction agrees with other researchers (Hugh and Reimer, 1967; Jensen et al., 1973; Hamilton et al., 2003; Peterson, 2004) who have

also tested the potential for a gender × floor space interaction and did not observe a difference in response to floor space allowances between barrows and gilts.

From d 0 to 64, barrows had increased ($P < 0.001$; Table 3-3) ADG and ADFI compared to gilts, but G:F was similar. Barrows and gilts had similar ADG from d 64 to 76; however, barrows had increased ($P < 0.001$) ADFI and poorer ($P < 0.001$) G:F during this period. From d 76 to 95, barrows tended ($P < 0.098$) to have lower ADG and increased ($P = 0.068$) ADFI compared to gilts which resulted in poorer ($P = 0.007$) G:F. Barrows had increased ($P = 0.018$) ADFI from d 95 to 105; although, ADG and G:F were similar between genders. During the final period (d 105 to 117), barrows had lower ($P < 0.001$) ADG and ($P < 0.001$) G:F than gilts, but ADFI was not different. Overall (d 0 to 117), barrows had increased ($P < 0.002$) ADG and ADFI, and poorer ($P < 0.001$) G:F compared to gilts. The differences in performance of gilts and barrows are similar to the differences in lean tissue deposition and maturity curves among genders discussed by Cline and Richert (2001).

Initial BW on d 0 was similar across treatments (Table 3-4). One objective of this study was to use the information to validate whether the ADG and ADFI prediction equations developed by Gonyou et al. (2006) were applicable to heavy weight finishing pigs. The allometric principle of these equations suggests that as BW increases the pig's space requirement increases at a rate of $BW^{0.67}$. This geometric principle was first applied to swine by Petherick and Baxter (1981) who found that as large white × landrace pigs grew, their length and height increased at a rate of $BW^{0.33}$; thereby, increasing the animal's surface area by the proportion of $BW^{0.67}$. Gonyou et al. (2006) predicted a broken-line requirement for space (based on the allometric measurement of k = floor space, $m^2/BW, kg^{0.67}$) where $k = 0.0336$ and is the optimal point where maximum ADG and ADFI are achieved, but when space is provided below that

value pigs have reduced ADG and ADFI. The treatments in the current study were designed to test this hypothesis. In treatment 1, pigs initially stocked at 0.91 m^2 should not have been limited on space, based on the prediction equations, up to 140 kg. Additionally, for pigs stocked at 0.65 m^2, if the 2 heaviest pigs are marketed when average BW reaches 83, 97, and 114 kg (*2:2:2*) then the pigs remaining in the pen should also achieve maximum ADG and ADFI. Meanwhile, the pigs initially stocked at 0.65 m^2 and marketed using more common industry practices of two removal points (*2:4* removal strategy) or a single removal point (*6* removal strategy) will still have limited ADG and ADFI until the final marketing event occurs. Then for the final period (d 105 to 117), after all removal events have taken place, pigs remaining in pens initially provided 0.65 m^2 (*2:2:2, 2:4, 6*) should have enough space for ADG and ADFI to be similar to pigs initially stocked at 0.91 m^2.

From d 0 to 64, pigs initially provided 0.91 m^2 of floor space had greater ($P < 0.003$; Table 3-4) ADG and ADFI compared to pigs initially provided 0.65 m^2 of floor space, regardless of removal strategy but G:F was not different between treatments. On d 64, the mean BW of pigs provided 0.91 m^2 of floor space was heavier ($P < 0.05$) compared to pigs initially provided 0.65 m^2 of floor space and on the *2:4* removal strategy.

The objective was to remove the first 2 heaviest pigs from pens on the *2:2:2* removal strategy when BW reached 83 kg. However, pigs were not removed until d 64 when average BW was 92 kg; therefore, a depression in ADG and ADFI was expected for pigs from 83 to 92 kg, and that is illustrated by the calculated *k* coefficients listed in Table 3-6. The predicted reduction by Gonyou et al. (2006) in ADG and ADFI for this period was 1.4 and 4.9%, respectively. But the observed reduction in ADG and ADFI, between treatment pigs provided 0.91 m^2 and 0.65 m^2, was 3.4 and 5.1%, respectively. This suggests that the predicted outcomes were

underestimated for ADG. Potter et al. (2010) reported similar findings when finishing pigs were stocked at 22, 24, 26, or 28 pigs per pen. However, the authors contributed the larger than predicted reduction in ADG, to be from reduced trough space which was confounded with the different group sizes. However, Thomas et al. (2015) concluded the same findings when evaluating floor space allowance effects on finishing pigs. The researchers controlled feeder space by adjusting gates to achieve floor space treatments, rather than group size. In both the aforementioned studies, reductions occurred prior to pigs reaching the calculated BW needed to reduce the coefficient *k* below the "critical threshold" expected to reduce ADG. That would mean the breakpoint estimated by Gonyou et al. (2006) needed for maximal ADG is underestimated at $k = 0.0336$. The results reported from d 0 to 64 herein would draw the same conclusion; however, since the heaviest pigs on the *2:2:2* marketing strategy were removed and marketed after the time point when average BW was 83 kg (needed to keep $k \geq 0.0336$), it is unclear whether the higher than expected reduction in ADG is due to the critical threshold of 0.0336 underestimating the true threshold of the pig's space requirement, or if the slope associated with the linear reduction in ADG, below the critical point, is underestimating the reduction in ADG when pigs were limited on floor space.

From d 64 to 76, pigs on the *2:4* removal strategy had decreased ($P < 0.05$) ADG compared to pigs initially provided 0.91 m^2 of floor space and pigs initially provided 0.65 m^2 of floor space on the *2:2:2* removal strategy. This was expected since pigs on the *2:4* and *6* removal strategy were still stocked at 0.65 m^2 which was below their predicted space requirement. Additionally, ADFI was higher ($P < 0.05$) for pigs initially provided 0.91 m^2 of floor space compared to pigs initially provided 0.65m^2 of floor space regardless of removal strategy. Pigs remaining in pens on the *2:2:2* removal strategy had increased ($P < 0.05$) ADFI compared to

pigs on the *2:4* removal strategy. Feed efficiency was also increased ($P < 0.05$) for pigs on the *2:2:2* removal strategy compared to pigs on the *2:4* removal strategy. On d 76, mean BW of pigs provided 0.91 m^2 of floor space was heavier ($P < 0.05$) than pigs on the *2:2:2* or the *2:4* removal strategy. The fact that pigs remaining in pens on the *2:2:2* removal strategy had similar ADG, during this period, as pigs provided 0.91 m^2 of floor space suggests that relieving stocking pressure and providing additional floor space resulted in improvements in gain. Interestingly, by the end of the period their calculated *k* coefficient (0.323) was still below their predicted need, but it did not seem to affect their gain. Also, ADFI of pigs remaining in pens on the *2:2:2* removal strategy was improved compared to pigs on the *2:4* removal strategy suggesting that providing additional floor space to the pigs remaining in the pen changed their feeding behavior. This has been previously reported by Augspurger et al. (2000), who found that removing pigs from pens caused changes in feeding behavior to be more like that of pigs in intact pens of the same group size. But in the current study, pigs remaining in pens on the *2:2:2* removal strategy did not consume as much as pigs initially provided 0.91 m^2 of floor space. This may be due to the fact that the heaviest pigs were removed from the pen on d 64, which reduced the voluntary feed intake of the pigs remaining below that of pigs in intact pens provided 0.91 m^2 of floor space.

From d 76 to 95, pigs initially provided 0.91 m^2 of floor space had increased ($P < 0.05$) ADG compared to pig on the *2:4* or the *6* removal strategies. Additionally, pigs provided 0.91 m^2 of floor space had increased ($P < 0.05$) ADFI compared to pigs initially provided 0.65 m^2 regardless of the removal strategy. Feed efficiency was similar regardless of treatment. During this period, it was expected that pigs remaining in pens on the *2:4* removal strategy would have improved ADG and ADFI compared to pigs on the *6* removal strategy, but that was not

observed. Although they were still below their predicted space requirement to reach maximal ADG and ADFI, these pigs performed similarly to those on the 6 removal strategy who had less space (*k* coefficient 0.0326 vs. 0.0291 for pigs on the *2:4* and *6* removal strategy, respectively). On d 95, pigs provided 0.91 m^2 had heavier ($P < 0.05$) mean BW compared to pigs initially provided 0.65 m^2 regardless of removal strategy.

From d 95 to 105, pigs remaining in pens on the *2:2:2* removal strategy tended ($P < 0.10$) to have increased ADG compared to pigs on the *6* removal strategy. Average daily feed intake was greater ($P < 0.05$) for pigs initially provided 0.91 m^2 or on the *2:2:2* removal strategy compared to pigs on the *6* removal strategy. Feed efficiency was similar regardless of experimental treatment. The importance of space for late finishing pigs was most evident during this period where pigs on the *6* removal strategy, who were still stocked at 0.65 m^2, had greatly decreased ADG and ADFI compared to the other treatments. On d 105, average BW of pigs provided 0.91 m^2 of floor space was heavier ($P < 0$ .05) compared to pigs initially provided 0.65 m^2 regardless of removal strategy.

During the final period from d 105 to 117, after all removal strategies were completed; ADG and ADFI were similar regardless of treatment. This suggests that removing pigs and providing additional floor space was useful in recapturing ADG and ADFI back to levels similar to that of pigs maintained with adequate floor space. Feed efficiency tended ($P < 0.10$) to be higher for pigs remaining in pens on the *2:4* and *6* removal strategies compared to pigs initially provided 0.91 m^2 of floor space. That is not surprising considering that the mean BW of pigs provided 0.91 m^2 of floor space was heavier ($P < 0.05$) on d 117 compared to pigs initially provided 0.65 m^2 of floor space regardless of removal strategy.

Over the entire length of the study from d 0 to 117, pigs provided 0.91 m^2 of floor space had greater ($P < 0.05$) ADG compared to pigs on the *2:4* and *6* removal strategies. Also, pigs on the *2:2:2* removal strategy had increased ($P < 0.05$) ADG compared to pigs on *6* removal strategy. Pigs provided 0.91 m^2 had greater ($P < 0.05$) ADFI compared to pigs initially provided 0.65 m^2 regardless of removal strategy. Pigs on the *2:2:2* removal strategy had improved ($P < 0.05$) G:F compared to pigs initially provided 0.91 m^2 of floor space or pigs on the *6* removal strategy. Additionally, pigs on the *2:4* removal strategy had improved ($P < 0.05$) G:F compared to pigs initially provided 0.91 m^2 of floor space. Pigs initially provided 0.91 m^2 of floor space had heavier ($P < 0.05$) average BW at removal compared to pigs initially provided 0.65 m^2 regardless of removal strategy. Also, pigs on the *2:2:2* removal strategy had lighter ($P < 0.05$) average BW at removal compared to pigs on the *6* removal strategy.

Growth performance results from the current study agree with previous research examining the impact of removals on finishing pig growth performance (Woodworth et al., 2000; DeDecker et al., 2005; Jacela et al., 2009), in the sense that removing heavy weight pen mates from a pen results in the remaining pigs having increased ADG and ADFI compared to pigs in intact pens. Interestingly, Bates and Newcomb (1997) and Woodworth et al. (2000) observed no impact of pig removal on the G:F of those animals remaining. Alternatively, DeDecker et al. (2005) observed an improvement in feed efficiency for pigs remaining in pens after the removals were conducted. Also, Jacela et al. (2009) observed improved feed efficiency for pigs remaining in pens after removals occurred compared to intact pens. Chapple (1993) hypothesized that the improvements in performance of pigs in smaller group sizes may be due to biological and hormonal changes which increase protein deposition and correspondingly feed efficiency compared to commercially reared pigs in larger group environments. However, in the case of

most removal studies, the heaviest pigs are the animals removed; therefore, it suggests that the difference in BW of the pigs remaining in the pen, after removals occur, may be the driver of the differences in feed efficiency that are observed. In the present study, overall G:F was poorer for pens initially provided 0.91 m^2 of floor space compared to pens on the *2:2:2* removal strategy. This difference could be attributed to the lower average BW of the pigs remaining in pens on the *2:2:2* removal strategy after removals occurred. If the feed efficiency estimates were adjusted to account for final BW, there would likely be much smaller differences in the G:F measurements across treatments.

The specific source of the improvements in ADG and ADFI following pig removals is still debatable. It has been said that the additional resources that become present after pig removals may be the leading factor. The most notable resources that increase are floor space, feeder space, and water space. Based on previous research, floor space appears to be the most definite factor that affects growth rate (Moser et al., 1985; Hamilton, 2003; Potter at al., 2010). However, some studies have confounded the effects of floor space and feeder space because they alter group size to achieve the desired floor space treatments rather than pen size and the feeder or trough space are not controlled with the varying number of pigs within a pen. Therefore, it makes it harder to interpret the results and attribute the response to a single source. However, the current study reduced feeder space for pigs initially provided 0.91 m^2 of floor space in order to more closely mimic the trough space in pens initially provided 0.65 m^2. The available trough space in the current trial was between 5.8 and 6.0 cm/pig. Previous research by Myers et al. (2012) found that trough space of 4.45 cm/pig was adequate for maximum growth; therefore, the trough space in the current study should have been enough to mitigate a trough space effect on the growth performance of the pigs across initial floor space treatments.

Research examining the effects of water space (pigs per waterer) on growth is limited. The MWPS (1991) recommends one water space per 10 weaned pigs or 15 growing pigs. However, this recommendation makes no mention of different waterer forms that are available. A study by Brumm and Shelton (1986) reported an increase in the variation of weight gain as the number of weaned pigs per nipple waterer increased from 8 to 16. Brumm (2001) suggests that the number of allowable pigs per waterer increases as pigs grow and can adapt to social stress. Landero et al. (2014) observed an improvement in ADG, ADFI and G:F when providing an additional cup waterer to pens of pigs only receiving water from 2 wet/dry feeder spaces. In the current study, water space was not adjusted which may have altered the response to removals but water pans were used which may have allowed more than one pig access to water at a time.

Based on the available resources for the pigs within the study and the previous literature, it suggests that the increased floor space for pigs remaining after removals is the most important source of the improved growth rates. Additionally, Scroggs et al. (2002) measured physiological and behavioral responses among pigs in pens that remained intact compared to pigs in pens after removals occurred and found no detectable differences among responses. This suggests that physiological and biological differences did not result from the removal process which also strengthens the argument that floor space is the dominate contributor to growth improvements.

Based on the current study and the growth data from d 0 to 64, it appeared that prediction equations for ADG and ADFI developed by Gonyou et al. (2006) for varying groups sizes of finishing pigs on slatted floors slightly underestimated either the threshold of *k* need to achieve maximum ADG and ADFI, or the slope of the linear reduction in ADG and ADFI when the animal is below their critical space threshold. This would support the conclusions of Potter et al. (2010) and Thomas et al. (2015) who observed reductions in ADG and ADFI prior to $k = 0.0336$.

However, because the performance of pigs initially provided 0.91 m^2 and those pigs on the *2:2:2* removal strategy were similar over the entire study (d 0 to 117), and because growth was similar from d 105 to 117 across all treatments, it suggests the concept of an allometric requirement is valid and useful as a predictor of floor space needs of heavier BW pigs.

Within pen BW variation

On d 0, the within pen BW variation was similar (Table 3-7) across treatments. On d 64, prior to removing the heaviest 2 pigs from treatment 2, within pen BW variation was similar across treatments, but after the removals occurred, the within pen BW variation of pigs remaining in pens on the *2:2:2* removal strategy was less ($P < 0.05$) than pens initially provided 0.91 m^2 of floor space. On d 76, prior to removing the 2 heaviest pigs from pens on the *2:2:2* or the *2:4* removal strategies, within pen BW variation was less ($P < 0.05$) for pens on the *2:2:2* removal strategy compared to pens initially providing 0.91 m^2 of floor space. After the removals occurred, BW CV numerically reduced for pigs remaining in pens on the *2:2:2* and *2:4* removal strategies, but only the *2:2:2* removal strategy CV was significantly less ($P < 0.05$) than that of pigs in pens initially provided 0.91 m^2 of floor space. On d 95 prior to removals, the *2:2:2* removal strategy pens had less ($P < 0.05$) within pen variation compared to pigs on the *6* removal strategy and pigs initially provided 0.91 m^2 of floor space. After removals occurred on d 95, pigs remaining in pens on the *2:2:2* removal strategy had less ($P < 0.05$) within pen BW variation than pigs initially provided 0.91 m^2 of floor space, or pigs on the *2:4* and *6* removal strategies. By d 105, prior to removals, pigs remaining in pens on the *2:2:2* removal strategy had less ($P < 0.05$) within pen BW variation compared to pigs initially provided 0.91 m^2 of floor space or pigs on the *6* removal strategy. After removals occurred, all treatments initially provided 0.65 m^2 had less ($P < 0.05$) within pen BW variation compared to pigs initially provided 0.91 m^2 of floor

space. This was still evident on d 117, where within pen variation was greater ($P < 0.05$) for pens initially providing 0.91 m^2 of floor space compared to pens initially providing 0.65 m^2 of floor space.

DeDecker et al. (2005) concluded that BW variation within pen was reduced with the removal of the heaviest pigs, but the rate of reduction was dependent on the number of pigs removed and the time of measure after removals. Previous work by DeDecker et al. (2002) concluded that removing the heaviest 25% of the pen reduced within pen BW variation, but by 21-d post removal the BW variation was similar regardless of removal strategy. In the current study, it appeared that removing 2 pigs per pen or approximately 10% of the pen was successful at reducing within pen BW variation and the reductions in variation were still evident up to 19 d after the removals occurred. Interestingly, after removing two pigs from pens on the *2:4* removal strategy on d 76, within pen variation was not reduced enough to be different from pens initially providing 0.91 m^2 of floor space or pens on the *6* removal strategy (treatments without removals) and this suggests that as BW increases more pigs must be removed in order to significantly drop the weight variation. Regardless, after all 6 pigs were removed from pens (approximately 30% of the pen) on treatments initially provided 0.65 m^2 of floor space the BW variation within the pen was reduced below that of intact pens initially provided 0.91 m^2. This information would agree with the previous reports of DeDecker et al. (2005) that within pen BW variation is reduced when the heaviest pigs in a pen are removed but the degree of reduction is dependent on the number of pigs removed and their BW at time of removal.

BW categories within pen

From d 0 to 64, there was a BW category × treatment interaction ($P = 0.048$; Table 3-8) for ADG. This was due to a greater ADG in the heavy weight pigs initially provided 0.91 m^2 of

floor space compared to heavy weight pigs initially provided 0.65 m^2 of floor space whereas, growth rate of the light and medium BW pigs were similar across initial floor space treatments. From a space standpoint it would be sensible to hypothesize that the heavier pigs in the pen would become limited on floor space before the lighter weight pigs. The dataset from the first growth period (d 0 to 64) supports that hypothesis. To our knowledge this is the first dataset to describe this type of interaction. From d 64 to 76, individual pig weights suggested no BW category × treatment interaction; however, light weight pigs had lower ($P < 0.001$) ADG compared to medium and heavy weight pigs. From d 76 to 95, there was a tendency for a BW group × treatment interaction ($P = 0.085$) mainly being the result of light weight pigs in pens on the *2:4* removal strategy having lower ADG than light weight pigs initially provided 0.91 m^2 of floor space or light weight pigs on the *2:2:2* removal strategy . No interaction of BW group × treatment or main effect of BW group was observed from d 95 to 105, but from d 105 to 117 there was a tendency for a BW group × treatment interaction ($P = 0.099$) because light weight pigs provided 0.91 m^2 of initial floor space had lower ADG compared to light weight pigs on other floor space and removal strategy treatments. Also, there was a BW group effect ($P = 0.026$) from d 105 to 117 because medium BW pigs had the greatest ADG compared to light and heavy weight pigs within pens regardless of treatment.

Economic implications

Total BW gain per pen was less ($P < 0.05$; Table 3-9) for pens initially providing 0.91 m^2 of floor space per pig compared to pens initially providing 0.65 m^2 of floor space per pig. This was expected because there were fewer pigs per pen in pens initially providing 0.91 m^2 of floor space. Alternatively, total weight gain per pig was greater ($P < 0.05$) for pigs initially provided 0.91 m^2 of floor space compared to pigs initially provided 0.65 m^2 of floor space. Additionally,

pigs on the *2:2:2* removal strategy had less ($P < 0.05$) weight gain than pigs on the *6* removal strategy. Similar to weight gain, revenue expressed on a pen basis was less ($P < 0.05$) for pens initially providing 0.91 m^2 of floor space due to fewer pigs in the pen; however, when expressing the revenue on a pig basis, it was greater for pigs initially provided 0.91 m^2 of floor space compared to pigs initially provided 0.65 m^2 of floor space. Pigs on the *2:2:2* removal strategy had less ($P < 0.05$) revenue, either on a pen or pig basis, than pigs on the *2:4* and *6* removal strategies. Feed usage and feed cost per pen were less ($P < 0.05$) for pens initially providing 0.91 m^2 of floor space compared to pens initially providing 0.65 m^2 of floor space; however, per pig feed usage and feed cost were greater ($P < 0.05$) for pigs initially provided 0.91 m^2 of floor space compared to pigs initially provided 0.65 m^2 of floor space. Pigs in pens on the *2:2:2* removal strategy had less ($P < 0.05$) feed usage and reduced feed cost, either on a pen or pig basis, than pigs on the *2:4* and *6* removal strategies. Interestingly, there was a tendency ($P < 0.10$) for pigs in pens on the *2:4* removal strategy to have less feed usage and feed cost than pigs on the *6* removal strategy. Income over feed and facility cost was the least ($P < 0.05$), either on a pen or pig basis, for pigs initially provided 0.91 m^2 of floor space. Pigs on the *2:2:2* removal strategy had less ($P < 0.05$) IOFFC when revenue was high and feed cost was low compared to pigs on the *2:4* and *6* removal strategies.

Powell et al. (1993) developed an economic model to determine the optimal stocking density for growing and finishing pigs and concluded that providing floor space below the requirement of pigs needed to achieve maximal ADG and ADFI is the most economic. The current study agrees with the previous work of Powell et al. (1993) in the sense that providing enough space for pigs to achieve their maximum ADG is not the most economic. But the use of removal strategies is beneficial to increase profitability. DeDecker et al. (2005) and Jacela et al.

(2009) both observed reductions in feed usage when removal strategies were utilized and the same conclusion was derived from the present trial. Additionally, utilizing removal strategies reduces weight discounts associated with marketing pigs outside the specified packer weight range (Jacela et al., 2009). The study herein, also illustrates that performing removals in order to provide the floor space allowance needed to reach maximum ADG (*2:2:2*), is still not economical because the weight of pigs that were removed are lighter than the specified packer weight range. The economic scenarios conclude that using the *2:4* and *6* marketing strategies were the most economic and as feed cost increases and revenue decreases then the feed savings from the *2:4* marketing strategy were more profitable; alternatively, if revenue increases keeping pigs within pens longer is more cost effective. Therefore, this study would conclude that improvements in ADG and ADFI can be achieved by pigs remaining in the pen following planned removals; however, it is important to consider the economic implications of removals strategies in order to determine the most profitable strategy. In addition the current study illustrates that the prediction equations developed by Gonyou et al. (2006) are useful predictors of the impact of floor space allowance on growth of finishing pigs but may underestimate the true impact of space restriction.

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TABLES AND FIGURES

Table 3-1. Removal strategies based on experimental treatments[1]

	Initial floor space, m^2 and removal strategy[2]			
	0.91	0.65	0.65	0.65
Number of pigs removed from the pen[3]	none	*2:2:2*	*2:4*	*6*
d 0	0 (15)	0 (21)	0 (21)	0 (21)
d 64	0 (15)	2 (19)	0 (21)	0 (21)
d 76	0 (15)	2 (17)	2 (19)	0 (21)
d 95	0 (15)	2 (15)	0 (19)	0 (21)
d 105	0 (15)	0 (15)	4 (15)	6 (15)
d 117	15 (0)	15 (0)	15 (0)	15 (0)

[1] A total of 1,092 pigs (PIC 359 × Genetiporc F25 females; initial BW = 36.3 kg) were used in a 117-d study to determine the influence of initial floor space allowance and removal strategy on growth performance. There were either 15 or 21 pigs per pen and 14 pens (7 barrow and 7 gilt pens) per treatment.

[2] Pigs initially provided 0.65 m^2 of floor space were removed using three different strategies: *2:2:2* signifies pens where the 2 heaviest pigs on d 64, 76, and 95 were removed; *2:4* represents pens where the heaviest 2 pigs were removed on d 76 and the 4 heaviest pigs were removed on d 105; and *6* represents pens where the heaviest 6 pigs were removed on d 105.

[3] Values in parentheses represent the calculated number of pigs left following the experimental marketing strategies.

Table 3-2. Diet composition (as-fed basis)

	Dietary Phase and BW range, kg			
	1	2	3	4
Ingredient, %	36 to 59	59 to 82	82 to 100	100 to 140
Corn	55.22	59.62	61.54	63.39
Soybean meal, 46.5% CP	19.20	14.90	13.15	11.40
DDGS[1]	20.00	20.00	20.00	20.00
Fat[2]	3.50	3.50	3.43	3.35
Calcium carbonate	0.96	0.95	0.95	0.95
Sodium chloride	0.44	0.44	0.44	0.44
Lysine sulfate, 46.5% Lys	0.44	0.37	0.36	0.34
DL-Methionine	0.01	---	---	---
Phytase[3]	0.023	0.018	0.013	0.005
Copper sulfate	0.05	0.05	---	---
VTM premix[4]	0.15	0.15	0.12	0.12
Total	100.00	100.00	100.00	100.00
Calculated Analysis				
SID[5] amino acids, %				
Lys	1.10	0.90	0.80	0.70
TSAA:Lys	58	58	58	58
Thr:Lys	62	62	64	68
Trp:Lys	18	18	18	18
NE, Mcal/kg	2.61	2.64	2.65	2.66
SID Lys:NE, g/Mcal	4.21	3.41	3.02	2.63
Ca, %	0.46	0.46	0.44	0.43
P, %	0.40	0.40	0.38	0.37
Available P, %	0.28	0.27	0.25	0.21

[1] Dried distillers grains with solubles.

[2] The source of fat was an animal vegetable blend.

[3] Optiphos (HuvePharma, St. Louis, Mo) Provided 562, 438, 313, and 125 FTU/kg of diet releasing an estimated 0.11, 0.10, 0.07, and 0.04 % available P for phases 1, 2, 3, and 4, respectively.

[4] VTM= Vitamin and trace mineral premix. The premix provided 14,595 ppm Cu, 330 ppm I, 162,018 ppm Fe, 44,555 ppm Mn, 440 ppm Se, 162,018 ppm Zn, and 573 ppm Co per kg of premix. The premix also provided 2,943,168 IU vit. A, 738,548 IU vit. D_3, 14,698 IU vit. E, 1,470 mg vit. K, 2,205 mg riboflavin, 18,364 mg niacin, 11,023 mg pantothenic acid, and 14.70 mg vit. B_{12} per kg of premix.

[5] Standardized ileal digestible.

Table 3-3. Main effects of gender on the growth of finishing pigs[1,2]

	Gender			Probability, *P* <
	Barrow	Gilt	SEM	Gender
d 0 to 64				
ADG, kg	0.90	0.83	0.007	0.001
ADFI, kg	2.16	1.95	0.020	0.001
G:F	0.419	0.425	0.003	0.138
d 64 to 76				
ADG, kg	0.99	1.01	0.013	0.309
ADFI, kg	3.07	2.84	0.023	0.001
G:F	0.322	0.356	0.004	0.001
d 76 to 95				
ADG, kg	0.94	0.98	0.019	0.098
ADFI, kg	2.99	2.93	0.026	0.068
G:F	0.314	0.340	0.006	0.007
d 95 to 105				
ADG, kg	0.85	0.86	0.032	0.849
ADFI, kg	2.99	2.88	0.033	0.018
G:F	0.283	0.298	0.010	0.294
d 105 to 117				
ADG, kg	0.85	0.95	0.020	0.001
ADFI, kg	3.12	3.01	0.046	0.103
G:F	0.273	0.319	0.006	0.001
d 0 to 117				
ADG, kg	0.91	0.88	0.005	0.002
ADFI, kg	2.52	2.35	0.016	0.001
G:F	0.360	0.375	0.002	0.001

[1] A total of 1,092 pigs (PIC 359 × Genetiporc F25 females; initial BW = 36.3 kg) were used in a 117-d study to determine the influence of initial floor space allowance and marketing strategy on growth performance. There were either 15 or 21 pigs per pen and 28 pens per gender.
[2] No treatment × gender interactions were observed for growth performance.

Table 3-4. The effects of initial floor space and removal strategy on the growth of finishing pigs[1,2]

	Initial floor space, m^2 and marketing strategy[3]					
	0.91	0.65	0.65	0.65		Probability, *P* <
	none	*2:2:2*	*2:4*	*6*	SEM	Initial space[4]
d 0 to 64						
Pigs per pen, n	15	21	21	21		
ADG, kg	0.89[a]	0.86[a,b]	0.85[b]	0.85[b]	0.010	0.003
ADFI, kg	2.14[a]	2.03[b]	2.02[b]	2.03[b]	0.028	0.001
G:F	0.418	0.426	0.424	0.419	0.004	0.178
d 64 to 76[5]						
Pigs per pen, n	15	19	21	21		
ADG, kg	1.03[a]	1.04[a]	0.94[b]	0.98[a,b]	0.019	0.040
ADFI, kg	3.10[a]	2.96[b]	2.84[c]	2.91[b,c]	0.032	0.001
G:F	0.334[a,b]	0.352[b]	0.332[a]	0.337[a,b]	0.005	0.310
d 76 to 95[5]						
Pigs per pen, n	15	17	19	21		
ADG, kg	1.03[a]	0.97[a,b]	0.93[b]	0.92[b]	0.027	0.005
ADFI, kg	3.16[a]	2.94[b]	2.87[b]	2.88[b]	0.037	0.001
G:F	0.326	0.332	0.323	0.320	0.008	0.938
d 95 to 105[5]						
Pigs per pen, n	15	15	19	21		
ADG, kg	0.86[x,y]	0.92[x]	0.89[x,y]	0.75[y]	0.046	0.890
ADFI, kg	3.03[a]	3.02[a]	2.93[a,b]	2.76[b]	0.046	0.024
G:F	0.283	0.305	0.305	0.270	0.014	0.545
d 105 to 117[5]						
Pigs per pen, n	15	15	15	15		
ADG, kg	0.88	0.90	0.92	0.91	0.028	0.340
ADFI, kg	3.20	3.04	3.03	2.98	0.066	0.022
G:F	0.275[x]	0.299[x,y]	0.305[y]	0.304[y]	0.008	0.005
d 0 to 117						
ADG, kg	0.92[a]	0.90[a,b]	0.88[b,c]	0.87[c]	0.008	0.001
ADFI, kg	2.58[a]	2.40[b]	2.39[b]	2.39[b]	0.022	0.001
G:F	0.358[c]	0.377[a]	0.370[a,b]	0.364[b,c]	0.002	0.001

[1] A total of 1,092 pigs (PIC 359 × Genetiporc F25 females; initial BW = 36.3 kg) were used in a 117-d study to determine the influence of initial floor space allowance and removal strategy on growth performance. There were either 15 or 21 pigs per pen and 14 pens (7 barrow and 7 gilt pens) per treatment at the start of the trial.

[2] Different superscripts [(a,b,c)] within row, $P < 0.05$. Differing superscripts [(x,y,z)] within row, $P < 0.10$.

[3] Pigs initially provided 0.65 m^2 of floor space were removed using three different strategies: *2:2:2* signifies pens where the 2 heaviest pigs on d 64, 76, and 95 were removed; *2:4* represents pens where the heaviest 2 pigs were removed on d 76 and the 4 heaviest pigs were removed on d 105; and *6* represents pens where the heaviest 6 pigs were removed on d 105.

[4] Initial floor space compares the mean of pigs initially provided 0.91 or 0.65 m^2.

Table 3-5. The effects of initial floor space and removal strategy on BW of finishing pigs[1,2]

	Initial floor space, m^2 and marketing strategy[3]					
	0.91	0.65	0.65	0.65		Probability, $P <$
	none	*2:2:2*	*2:4*	*6*	SEM	Initial floor space[4]
Avg BW of pen prior to removals, kg						
d 0	36.4	36.3	36.3	36.3	0.32	0.835
d 64	93.7^{a}	92.0^{a,b}	91.3^{b}	91.6^{a,b}	0.62	0.007
d 76	105.6^{a}	102.9^{b}	102.8^{b}	103.4^{a,b}	0.68	0.002
d 95	125.5^{a}	119.9^{b}	118.7^{b}	121.3^{b}	0.79	0.001
d 105	134.1^{a}	127.5^{b}	127.8^{b}	129.0^{b}	0.80	0.001
d 117	144.8^{a}	138.4^{b}	135.5^{b}	135.0^{b}	1.00	0.001
Avg BW of pigs removed, kg						
d 0	---	---	---	---	---	---
d 64	---	107.1	---	---	---	---
d 76	---	115.0	120.2	---	0.79	---
d 95	---	131.0	---	---	---	---
d 105	---	---	139.9	140.4	0.81	---
d 117	144.8^{a}	138.4^{b}	135.5^{b}	135.0^{b}	1.00	0.001
Avg BW of pigs remaining in pen after removals, kg						
d 0	---	---	---	---	---	---
d 64	---	90.3	---	---	---	---
d 76	---	100.9	101.4	---	0.63	---
d 95	---	118.3	---	---	---	---
d 105	---	---	124.4	124.1	0.89	---
d 117	---	---	---	---	---	---
Avg BW of pigs at time of removal, kg	144.8^{a}	132.3^{c}	134.9^{b,c}	136.6^{b}	0.87	0.001

[1] A total of 1,092 pigs (PIC 359 × Genetiporc F25 females; initial BW = 36.3 kg) were used in a 117-d study to determine the influence of initial floor space allowance and removal strategy on growth performance. There were either 15 or 21 pigs per pen and 14 pens (7 barrow and 7 gilt pens) per treatment at the start of the trial.

[2] Different superscripts (^{a,b,c}) within row, $P < 0.05$. Differing superscripts (^{x,y,z}) within row, $P < 0.10$.

[3] Pigs initially provided 0.65 m^2 of floor space were removed using three different strategies: *2:2:2* signifies pens where the 2 heaviest pigs on d 64, 76, and 95 were removed; *2:4* represents pens where the heaviest 2 pigs were removed on d 76 and the 4 heaviest pigs were removed on d 105; and *6* represents pens where the heaviest 6 pigs were removed on d 105.

[4] Initial floor space compares the mean of pigs initially provided 0.91 or 0.65 m^2.

Table 3-6. Calculated *k* coefficients based on floor space and removal strategy[1]

	Initial floor space, m^2 and marketing strategy[2]			
	0.91	0.65	0.65	0.65
	none	*2:2:2*	*2:4*	*6*
Calculated *k* coefficient[3,4,5]				
d 0	0.0819 (0.91)	0.0586 (0.65)	0.0586 (0.65)	0.0586 (0.65)
d 64				
Prior to removals	0.0434 (0.91)	**0.0314** (0.65)	**0.0316** (0.65)	**0.0315** (0.65)
After removals	---	0.0352 (0.72)	---	---
d 76				
Prior to removals	0.0401 (0.91)	**0.0323** (0.72)	**0.0292** (0.65)	**0.0291** (0.65)
After removals	---	0.0363 (0.80)	**0.0326** (0.72)	---
d 95				
Prior to removals	0.0357 (0.91)	**0.0324** (0.80)	**0.0293** (0.72)	**0.0261** (0.65)
After removals	---	0.0372 (0.91)	---	---
d 105				
Prior to removals	0.0342 (0.91)	0.0353 (0.91)	**0.0279** (0.72)	**0.0251** (0.65)
After removals	---	---	0.0359 (0.91)	0.0360 (0.91)
d 117	**0.0325** (0.91)	**0.0335** (0.91)	0.0339 (0.91)	0.0340 (0.91)

[1] A total of 1,092 pigs (PIC 359 × Genetiporc F25 females; initial BW = 36.3 kg) were used in a 117-d study to determine the influence of initial floor space allowance and removal strategy on growth performance. There were either 15 or 21 pigs per pen and 14 pens (7 barrow and 7 gilt pens) per treatment at the start of the trial.

[2] Pigs initially provided 0.65 m^2 of floor space were removed using three different strategies: *2:2:2* signifies pens where the 2 heaviest pigs on d 64, 76, and 95 were removed; 2:4 represents pens where the heaviest 2 pigs were removed on d 76 and the 4 heaviest pigs were removed on d 105; and 6 represents pens where the heaviest 6 pigs were removed on d 105.

[3] The constant coefficient *k* is calculated as: *k* = floor space, $m^2/BW^{0.67}$.

[4] Values in parentheses represent the floor space allowance (m^2) pigs remaining in pens were provided based on initial floor space and marketing strategy.

[5] Coefficients in bold represent values below the predicted critical threshold of *k* = 0.0336 predicted by Gonyou et al. (2006) as the required amount of space needed to maximize ADG and ADFI.

Table 3-7. The effects of initial floor space allowance and removal strategy on the within pen BW variation of finishing pigs[1,2]

	Initial floor space, m^2 and marketing strategy[3]					
	0.91	0.65	0.65	0.65		Probability, $P <$
	none	*2:2:2*	*2:4*	*6*	SEM	Initial floor space[4]
CV of within pen BW						
d 0	15.5	14.8	15.2	14.1	0.67	0.295
d 64						
Prior to removals	12.6	11.1	11.6	11.8	0.56	0.107
After removals	12.6[b]	10.0[a]	11.6[a,b]	11.8[a,b]	0.57	0.041
d 76						
Prior to removals	11.5[b]	9.1[a]	10.8[a,b]	11.1[a,b]	0.56	0.067
After removals	11.5[b]	8.5[a]	9.7[a,b]	11.1[b]	0.67	0.012
d 95						
Prior to removals	9.8[b]	7.7[a]	9.0[a,b]	9.3[b]	0.42	0.022
After removals	9.8[b]	7.1[a]	9.0[b]	9.3[b]	0.43	0.007
d 105						
Prior to removals	9.3[b]	6.9[a]	8.2[a,b]	8.7[b]	0.40	0.004
After removals	9.3[b]	6.9[a]	6.7[a]	7.0[a]	0.50	0.001
d 117	9.0[b]	6.5[a]	6.5[a]	6.8[a]	0.40	0.001
Morbidity and mortality[5], %	2.86	2.89	3.61	5.40	1.324	0.503

[1] A total of 1,092 pigs (PIC 359 × Genetiporc F25 females; initial BW = 36.3 kg) were used in a 117-d study to determine the influence of initial floor space allowance and removal strategy on growth performance. There were either 15 or 21 pigs per pen and 14 pens (7 barrow and 7 gilt pens) per treatment.

[2] Different superscripts [(a,b,c)] within row, $P < 0.05$.

[3] Pigs initially provided 0.65 m^2 of floor space were removed using three different strategies: *2:2:2* signifies pens where the 2 heaviest pigs on d 64, 76, and 95 were removed; *2:4* represents pens where the heaviest 2 pigs were removed on d 76 and the 4 heaviest pigs were removed on d 105; and 6 represents pens where the heaviest 6 pigs were removed on d 105.

[4] Initial floor space compares the mean of pigs initially provided 0.91 or 0.65 m^2.

[5] Morbidity and mortality were analyzed as a binomial distribution and were based on the actual number of pigs marketed divided by initial pen inventories.

Table 3-8. The effects of initial floor space and removal strategy on ADG of BW groups (light, medium, or heavy pigs within pens)[1]

Initial floor space, m^2	Marketing strategy[2]	BW group	d 0 to 64	d 64 to 76	d 76 to 95	d 95 to 105	d 105 to 117
0.91	---	Light	0.82	0.98	1.00	0.88	0.81
0.91	---	Medium	0.88	1.03	0.98	0.93	0.94
0.91	---	Heavy	0.97	1.02	1.02	0.87	0.87
No. of pigs per pen			15	15	15	15	15
0.65	*2:2:2*	Light	0.81	1.03	0.98	0.90	0.92
0.65	*2:2:2*	Medium	0.87	1.02	1.00	0.93	0.93
0.65	*2:2:2*	Heavy	0.91	1.06	0.99	0.95	0.90
No. of pigs per pen			21	19	17	15	15
0.65	*2:4*	Light	0.82	0.89	0.88	0.84	0.92
0.65	*2:4*	Medium	0.84	0.94	0.94	0.86	0.94
0.65	*2:4*	Heavy	0.91	0.97	0.96	0.87	0.94
No. of pigs per pen			21	21	19	19	15
0.65	*6*	Light	0.80	0.91	0.93	0.76	0.94
0.65	*6*	Medium	0.86	0.96	0.95	0.74	0.94
0.65	*6*	Heavy	0.92	0.98	0.92	0.75	0.84
No. of pigs per pen			21	21	21	21	15
SEM			0.04	0.027	0.045	0.057	0.085
			Probability, *P* <				
Interaction							
Treatment × BW group			0.048	0.347	0.085	0.511	0.099
Main effects							
Treatment			0.022	0.001	0.064	0.085	0.602
BW group			0.001	0.001	0.055	0.665	0.026

[1] A total of 1,092 pigs (PIC 359 × Genetiporc F25 females; initial BW = 36.3 kg) were used in a 117-d study to determine the influence of initial floor space allowance and removal strategy on growth performance. There were either 15 or 21 pigs per pen and 14 pens (7 barrow and 7 gilt pens) per treatment.
[2] Pigs were ranked within pen as either: light, medium, or heavy weight prior to each growth period for evaluation.

[3] Pigs initially provided 0.65 m^2 of floor space were removed using three different strategies: *2:2:2* signifies pens where the 2 heaviest pigs on d 64, 76, and 95 were removed; *2:4* represents pens where the heaviest 2 pigs were removed on d 76 and the 4 heaviest pigs were removed on d 105; and *6* represents pens where the heaviest 6 pigs were removed on d 105.

Table 3-9. The effects of initial floor space and removal strategy on economic parameters[1,2]

	Initial floor space, m^2 and marketing strategy[3]					
	0.91	0.65	0.65	0.65		Probability, $P <$
	none	*2:2:2*	*2:4*	*6*	SEM	Initial floor space[4]
Total weight gain, kg/pen	1,603[b]	2,032[a]	2,077[a]	2,083[a]	27.4	0.001
Total weight gain, kg/pig[4]	110.1[a]	99.8[c]	103.1[b,c]	104.7[b]	0.93	0.001
Revenue[5]						
Low, $/pen	1,705[c]	2,177[b]	2,247[a]	2,281[a]	10.6	0.001
High, $/pen	2,243[c]	2,844[b]	2,931[a]	2,977[a]	15.2	0.001
Low, $/pig[6]	113.69[a]	103.65[c]	106.98[b]	108.64[b]	0.51	0.001
High, $/pig[6]	149.55[a]	135.45[c]	139.57[b]	141.78[b]	0.74	0.001
Feed usage, kg/pen	4,537[c]	5,349[a]	5,566[b,x]	5,730[b,y]	46.1	0.001
Feed usage, kg/pig	307.7[a]	269.5[c]	282.8[b,x]	292.4[b,y]	2.75	0.001
Feed Cost[7]						
Low, $/pen	1,000[c]	1,179[b]	1,227[a,x]	1,263[a,y]	10.2	0.001
High, $/pen	1,300[c]	1,533[b]	1,595[a,x]	1,642[a,y]	13.2	0.001
Low, $/pig[8]	66.69[a]	56.16[c]	58.43[b,x]	60.16[b,y]	0.51	0.001
High, $/pig[8]	86.70[a]	73.01[c]	75.97[b,x]	78.21[b,y]	0.67	0.001
IOFFC, $/pen[9]						
Low Rev-High Feed	152.15[b]	390.75[a]	398.57[a]	386.45[a]	10.51	0.001
Low Rev-Low Feed	452.25[b]	744.50[a]	766.71[a]	765.45[a]	8.94	0.001
High Rev-High Feed	690.15[b]	1,058.59[a]	1,083.06[a]	1,082.37[a]	11.93	0.001
High Rev-Low Feed	990.15[c]	1,412.38[b]	1,451.19[a,b]	1,461.37[a]	11.48	0.001
IOFFC, $/pig[9]						
Low Rev-High Feed	10.14[b]	18.60[a]	18.98[a]	18.40[a]	0.56	0.001
Low Rev-Low Feed	30.15[b]	35.45[a]	36.51[a]	36.45[a]	0.47	0.001
High Rev-High Feed	46.00[b]	50.41[a]	51.57[a]	51.54[a]	0.62	0.001
High Rev-Low Feed	66.01[c]	67.26[b,c]	69.10[a,b]	69.59[a]	0.58	0.001

[1] A total of 1,092 pigs (PIC 359 × Genetiporc F25 females; initial BW = 36.3 kg) were used in a 117-d study to determine the influence of initial floor space allowance and removal strategy on growth performance. There were either 15 or 21 pigs per pen and 14 pens (7 barrow and 7 gilt pens) per treatment.

[2] Different superscripts [(a,b,c)] within row, $P < 0.05$. Differing superscripts [(x,y,z)] within row, $P < 0.10$.

[3] Pigs initially stocked at 0.65 m^2 were removed using three different strategies: *2:2:2* signifies pens where the 2 heaviest pigs on d 64, 76, and 95 were removed; *2:4* represents pens where the heaviest 2 pigs were removed on d 76 and the 4 heaviest pigs were removed on d 105; and *6* represents pens where the heaviest 6 pigs were removed on d 105.

[4] Refers to the total weight gain per pig marketed.

[5] Revenue was based on a low ($0.99/kg) or high ($1.32/kg) base price. To mimic premium and discounts associated with specific carcass weights a fixed yield of 75% was used to calculate HCW of pigs marketed, and the following regression equation was used to adjust premiums and discounts for varying HCW: Premium/discount, $/Cwt, kg=0.0001169532*$HCW^3$-0.0516996146*$HCW^2$+6.6397162094*HCW-257.58240.

[6] Revenue per pen divided by the initial placement of either 15 or 21 pigs per pen for pens initially stocked at 0.91 or 0.65 m^2, respectively.

[7] Based on average diet costs of $220.46/tonne for Low and $286.60/ tonne for High.

[8] Feed cost per pen divided by the initial placement of either 15 or 21 pigs per pen for pens initially stocked at 0.91 or 0.65 m^2, respectively.
[9] Income over feed and facility costs: calculated as revenue-feed cost-facility cost. A fixed facility cost of \$0.11/0.69 m^2/day was used to calculate facility costs.

Chapter 4 - Development of alternative equations to predict the influence of floor space on ADG, ADFI, and G:F of finishing pigs

ABSTRACT

Data from existing literature examining the influence of floor space allowance on the growth of pigs was used to develop prediction equations for ADG, ADFI, and G:F of finishing pigs. Two databases were used; the first included information from studies examining the influence of floor space allowance, and the second included the aforementioned papers along with papers examining the impact of floor space after pigs were removed from the pen. The first database included 27, 25, and 25 papers for ADG, ADFI, and G:F, respectively, and the second database contained 30, 28, and 28 papers for ADG, ADFI, and G:F, respectively. The predictor variables tested were floor space (m^2/pig), *k* (floor space/final $BW^{0.67}$), initial BW, final BW, feed space (pigs per feeder hole), water space (pigs per waterer), group size (pigs per pen), gender, floor type, and study length (d). The PROC MIXED procedure of SAS (SAS Institute, Inc., Cary, NC) was used to develop regression equations. Floor space treatments within each experiment were the experimental unit. The optimum equations to predict finishing ADG, ADFI, and G:F for the first database were: ADG, g =395.57+(15,727 × *k*)-(221,705 × k^2)-(3.6478 × initial BW, kg)+(2.209 × final BW, kg)+(67.6294 × *k* × initial BW, kg); ADFI, g =802.07+(20,121 × *k*)-(301,210 × k^2)-(1.5985 × initial BW, kg)+(11.8907 × final BW, kg)+(159.79 × *k* × initial BW, kg); G:F = predicted ADG/predicted ADFI. The optimum equations to predict ADG, ADFI, and G:F for the second database were: ADG, g =337.57+(16,468 × *k*)-(237,350 × k^2)-(3.1209 × initial BW, kg)+(2.569 × final BW, kg)+(71.6918 × *k* × initial BW,

kg); ADFI, g = 833.41+(24,785 × k)-(388,998 × k^2)-(3.0027 × initial BW, kg)+(11.246 × final BW, kg)+(187.61 × k × initial BW, kg); G:F =predicted ADG/predicted ADFI. Data from 3 separate experiments examining the effects of floor space allowance on growth performance were used to evaluate the efficacy of the prediction equations herein and previously developed prediction equations (Kornegay and Notter, 1984; Powell et al., 1993; and Gonyou et al., 2006). Predicted values from equations reported herein improved model evaluation statistics compared to Kornegay and Notter (1984), and Powell et al. (1993), and were comparable to predicted values by Gonyou et al. (2006) for full finishing growth periods and improved on Gonyou et al. (2006) over short periods and for mimicking marketing events. Therefore, the equations herein provide a good estimation of the impact of stocking density on finishing pig growth performance.

Key words: Finishing pig, Floor space, Prediction equations

INTRODUCTION

Determining ideal floor space for growing pigs is regarded by many as an enigmatic topic. On one hand, reducing floor space decreases gain and feed intake (Gehlbach et al., 1966; Gonyou and Stricklin, 1998), but on the other, it can increase production per unit of space (Powell et al., 1993). Because of the welfare and economic implications of floor space allowance, accurately predicting its impact on growth could help establish value per unit of floor space in order to optimize growth rate while still efficiently utilizing space.

Kornegay and Notter (1984) calculated the first empirical prediction equations for growing and finishing pigs; however, their database only contained finishing studies with pigs up to 93 kg. Powell et al. (1993) developed more recent prediction equations for pigs up to 114 kg. However, both sets of equations are outdated for current market weights. Gonyou et al. (2006) used non-linear statistical modeling to capture a broken line allometric based space requirement of pigs for ADG and ADFI. To date, these equations are viewed as the most applicable prediction equations due to their transformation of the data into percentage changes in ADG and ADFI as the unit of analysis. While this analysis allowed for the removal of study-to-study variation, it may have led to non-normally distributed error terms. Also, when the researchers collected information for their database, they only included experiments that contained at least one treatment above the *k* coefficient of 0.030 and at least one treatment below 0.030 which may have limited the amount of available literature in the database and may have potentially biased their results.

The objective of this study was to utilize data from the existing literature to establish alternative predictive equations for ADG, ADFI, and G:F of finishing pigs. In addition, 3 separate floor space allowance studies, not included in the databases, were used to evaluate the efficacy of the prediction equations developed herein.

MATERIALS AND METHODS

A literature review was conducted to compile studies that examined the effects of floor space allowance on ADG, ADFI, and G:F of finishing pigs. The literature search was conducted via the Kansas State University Libraries, utilizing the CABI search engine, and using the key

words “space requirement” or “floor space allowance” with “finishing pig” or “growing pig”. Data were derived from both refereed and non-refereed publications including theses, electronic publications and university publications. The final database resulted in publication dates from 1983 to 2014.

To be included in the final database, experiments had to meet the following criteria: 1) pigs used in the experiments had to have ad libitum access to feed and water; 2) the experiments provided information including study length, initial BW, final BW, ADG, ADFI, G:F, feeder space, water space, group size, and floor type; 3) Studies had to have reported SE or SD terms for treatment means. The initial screen yielded 37 publications. Papers were eliminated from the analysis for not allowing ad libitum access to feed and water (1 paper), experiments did not report means for either ADG, ADFI or G:F (1 paper), SE or SD terms associated with response criteria were not reported (3 papers), or information associated with feeder space, water space, or group size was not included (2 paper). The final database for studies examining the influence of floor space allowance resulted in 27 papers with 97 observations for ADG, and 25 papers with 92 observations for ADFI and G:F. The database for studies evaluating floor space allowance, before and after pig removals, resulted in 30 papers with 112 observations for ADG, and 28 papers with 107 observations for ADFI and G:F. Trials that were conducted in wean to finish facilities (Wolter et al., 2003) were not included in the databases because floor space treatments were conducted during the growing period immediately after weaning. Citations and descriptions of studies utilized in the database are presented in Table 4-1. Descriptive statistics describing the databases are presented in Table 4-2.

Papers that did not calculate study length (Moser et al., 1985; NCR-89, 1993; Brumm and NCR-89, 1996; Brumm and Miller, 1996; Brumm et al., 2001; Hamilton et al., 2003; Brumm,

2004) or final BW (McGlone and Newby, 1994; Ward et al, 1997; Edmonds et al., 1998; Gonyou and Stricklin, 1998; Matthews et al., 2001; Edmonds and Baker, 2003; Street and Gonyou, 2008) were included in the database and the missing information was calculated by using ADG, initial BW, and either study length or final BW. For papers that reported feed efficiency as F:G, an inverse proportion was calculated using ADG and ADFI values. To convert the related standard errors associated with the F:G information, the estimates were converted to a SD (SD=SE*√n) and then a CV (SD/mean) was calculated and a relative SD (CV*G:F) for the G:F proportion was then reconverted back to a SE (SD/√n=SE).

The coefficient *k* (*k* = floor space m^2/ $BW^{0.67}$) was calculated for all experimental units based on the final BW of the growth period and the associated floor space allowance. Growth performance over the entire study length for each experimental unit was used in the database except if floor space allowance was adjusted across phases. In these instances where individual phase performance was reported (Moser et al., 1985; Dritz et al., 1999; Hamilton et al., 2003), the growth periods associated with the floor space allowance provided were used.

Flooring type (partially slatted or fully slatted concrete) used in each study was also accounted for in the prediction models. For some studies, which may have had multiple group sizes (Gonyou and Stricklin, 1998; Street and Gonyou, 2008), the minimum group size was assigned to the treatment observation. Water space was calculated as the number of pigs per waterer within a pen. In studies where wet/dry feeders were used, each feeder space was also considered a waterer. For treatments where the group size varied within floor space treatment, the average water space was calculated and assigned to that treatment observation. Feeder space was calculated as the number of pigs per feeder hole. If a space treatment varied in the number of pigs per pen which altered the number of pigs per feeder hole, then an average feeder space value

was assigned to the treatment observation. Gender was also categorized as a potential predictor variable. There were 4 papers that presented floor space treatments for barrows and 4 papers that reported floor space treatments for gilts. All other papers either contained mixed gender pens (barrows and gilts) or reported main effect means without separating gender × floor space treatment interactions.

Equation evaluation experiments

Three separate experiments were used to evaluate the regression equations determined herein and previously discussed in literature. Data from these experiments were not included in the databases used to develop the equations. The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments.

The first two experiments were conducted by Thomas et al. (2015). Briefly, in Exp. 1 a total of 189 pigs in 21 pens (9 pigs per pen) were provided 0.65, 0.74, or 0.84 m^2 for 66-d and there were 7 replications per treatment. In Exp. 2, a total of 216 pigs were used in a 77-d trial to evaluate the impact of 0.65, 0.74, and 0.84 m^2 of floor space allowance on growth performance. There were 9 pigs per pen and 8 pens per treatment. Both Exp. 1 and 2 were conducted in environmentally-controlled tunnel ventilated barns with fully slatted flooring. Each pen contained one cup waterer and one single sided 2-hole dry self-feeder (Farmweld, Teutopolis, IL; provided 7.9 cm/pig trough space) to allow *ad libitum* access to feed and water. All pens used in Exp. 1 and 2 contained both barrows and gilts. All pigs received corn and soybean meal-based diets fed in three dietary phases formulated to 0.85, 0.72, and 0.65 % SID Lys and fed from d 0 to 28, 28 to 56, and d 56 to the end of the study, respectively.

The third experiment was conducted by Flohr et al. (2015) using a total of 1,092 finishing pigs in a 123-d study to examine floor space allowance and pig removal strategies on growth.

Pens were allotted to initial floor space treatments of either 0.65 or 0.91 m^2 which were consistent with either 21 or 15 pigs per pen. There were 14 pens (7 barrow pens and 7 gilt pens) that were allotted to the floor space treatment of 0.91 m^2, meanwhile 42 pens were stocked at 21 pigs per pen for a floor space allowance of 0.65 m^2. Of the 42 pens initially stocked at 21 pigs per pen, 3 separate pig removal strategies were initiated. The first, was to remove the 2 heaviest pigs per pen when average pen BW reduced *k* to the threshold of 0.0336 described by Gonyou et al. (2006) as the threshold where reduced ADG and ADFI are observed. These removals were performed on d 64, 76, and 95. The second removal strategy was to remove the 2 heaviest pigs when treatment mean BW reached 109 kg (d 76), and then remove the 4 heaviest pigs when treatment mean BW reached 127 kg (d 105). Finally, the last strategy was to remove the 6 heaviest pigs from pens when the treatment mean BW reached 127 kg (d 105). There were 14 pens (7 gilt pens and 7 barrow pens) per treatment. All pigs that remained in pens after planned removals occurred were marketed on d 117. Gates were adjusted to maintain constant floor space treatments as pigs were removed from pens for illness or death. The finishing barn was an environmentally-controlled, tunnel-ventilated facility with fully-slatted flooring. Pens provided 13.5 m^2 floor space and were equipped with 1 pan waterer and a 4-hole dry self-feeder (SDI, Alexandria, SD) to allow *ad libitum* access to feed and water. Pigs were fed a corn and soybean-meal diet that contained 20% dried distillers grains with solubles and 3% added fat. Pigs were fed in 4 sequential dietary phases from approximately 36 to 59, 59 to 82, 82 to 100, and 100 to 140 kg with diets formulated to 1.10, 0.90, 0.80, and 0.70% standardized ileal digestible Lys in phases 1 to 4, respectively. Pens of pigs and feeders were weighed on d 21, 42, 64, 76, 95, and 105 of the study to calculate ADG, ADFI, and G:F. Individual pig weights were also collected on d 0, 64, 76, 95, and 105.

Growth performance for the individual floor space treatments in Exp. 1 and 2 were used to validate prediction equations for both databases examined herein. Growth performance from pigs stocked at 0.91 m^2 and those stocked at 0.65 m^2 until d 105 of Exp. 3 were used in the first database without pig removal studies. However, in order to examine the second database that included pig removal studies, growth performance during periods following pig removals from specific treatments were used rather than the entire 105-d period used to evaluate the first database. Those periods used were from d 64 to 76 (pigs stocked at 0.65, 0.71 after removing 2 pigs, and 0.91 m^2), d 76 to 95 (pigs stocked at 0.65, 0.71 after removing 2 pigs, 0.79 after removing 4 pigs, and 0.91 m^2), and d 95 to 105 (pigs stocked at 0.65, 0.71 after removing 2 pigs, 0.90 after removing 6 pigs, and 0.91 m^2).

To accommodate the variation between the baseline predicted and actual performance, the difference between predicted and actual growth performance of pigs stocked at the highest floor space allowance was used to adjust the intercept of the prediction equations within each experiment or each period within Exp. 3 comparisons.

Statistical analyses for model development

The PROC MIXED procedure of SAS (SAS Institute, Inc., Cary, NC) was used to develop regression equations to separately predict ADG and ADFI for finishing pigs based on the two separate databases. The method of maximum likelihood (ML) was used in the model selection to evaluate significance of fixed effect terms. Once the optimal ADG and ADFI models were determined, then the G:F model was developed to determine the fit of a G:F model to estimate the impact of floor space on feed efficiency.

The floor space treatment applied within each experiment was the experimental unit for modeling the equations and random effects of decade, paper within decade, and experiment

within paper × decade interactions were used. Decade was included as a random effect to account for random error associated with the increases in growth rate over time (Knap, 2009). Paper within decade was used to account for random error observed between papers within the same decade. Experiment within paper × decade interactions was used to account for random error observed from experiment to experiment within each paper × decade interaction. The error between decades, papers within decades, and experiments within paper × decade interactions were partitioned using the repeated statement. Covariance parameter estimates were different, emphasizing the use of these random effects in the model selection process.

To account for variance in experimental designs and replication across studies, weighted standard error and standard deviations were utilized in the model as discussed previously by St-Pierre (2001). Weighting the SE terms resulted in a reduced residual covariance estimate signifying their use for the model fitting process. When random effect terms were used in the model, Bayesian Information Criterion (BIC) was decreased further signifying the use of these parameters for the model fitting process. The statistical significance for inclusion of terms in the model was determined at $P < 0.10$. Further evaluation of models with significant terms was then conducted based on the BIC. A model comparison with a reduction in BIC of more than 2 was considered an improvement (Kass and Raftery, 1995). Throughout the selection process, studentized residuals plots were observed to determine if quadratic or interaction terms needed to be tested in the model. The model was determined using a step-wise selection procedure starting with manual forward selection through individual predictor variables.

The method of residual maximum likelihood (REML) was then used to obtain the estimate of the parameters for the candidate models. The adequacies of the candidate models were also examined by evaluating a histogram of the residuals for evidence of normality and

plotting residuals against predicted values of Y (ADG, ADFI, and G:F of finishing pigs within each set of databases; Kuehl, 2000 and St-Pierre, 2003). Actual values were plotted against predicted values to evaluate the line of equality and determine if there was bias in the estimation (Altman and Bland, 1983). Residual plots were also used to investigate outliers. Any residual greater than 3 standard deviations from the mean were deemed outliers for review. Outliers were reviewed to determine if they were biologically significant. As a result, 3 observations for Finishing ADG, ADFI, and G:F in both databases were removed from the analysis.

Statistical analyses for model validation

As a measure of model performance, the observed values from the model databases were regressed against the predicted values and statistical calculations were performed. These procedures were completed using the model evaluation system developed by Tedeschi (2006).

The coefficient of determination (r^2) was calculated to evaluate the precision of the model predicted values to the observed values, by describing the proportion of variance in the observed values described by the predicted values (Neter et al., 1996).

Mean bias was used to assess model accuracy and was computed by subtracting the mean of the observed values minus the mean of the predicted values (Cochran and Cox, 1957). The mean bias was expressed in g for ADG and ADFI. A positive mean bias would indicate an underestimation and a negative value indicate an overestimation by the prediction equation.

The bias correction factor (C_b) measures the accuracy of the model predicted values to the observed values by examining how far the regression line deviates from the slope of unity (45°; Lin, 1989). A range of 0 to 1 can be observed for the bias correction factor with a value of 1 indicating there is no deviation of the regression line from the line of unity.

The concordance correlation coefficient (CCC), also known as the reproducibility index, is used to simultaneously assess both precision and accuracy of the model by utilizing the correlation coefficient (r), mean bias, and the bias correction factor in its calculation (Lin, 1989). A value of 1 or -1 implies perfect concordance or disconcordance. While a value closer to zero denotes the absence of agreement between the variables.

Root mean square error of prediction (RMSEP) is used to measure the predictive accuracy of the model (Mitchell, 1997), by examining the variation between the observed values and model predicted values.

Model efficiency statistic (MEF) is interpreted as the proportion of variation explained by the line $Y = f(X_1,\ldots,X_p)$ (Loague and Green, 1991). A value of 1 would indicate a perfect fit and, if the MEF value is less than zero, the model predicted values are more variable than the observed values.

The coefficient of model determination is a ratio of the total variance of observed data to the squared of the difference between the model-predicted mean and mean of the observed data (Loague and Green, 1991). A ratio less than 1 suggests an over estimation of the total variance is observed in the model predicted values, and a value greater than one suggests an underestimation of the total variance by the predicted values.

RESULTS

The range of values that make up ADG, ADFI, and G:F for the finishing databases are presented in Table 4-2. These values depict the floor space, feeder space, water space, floor type, and study length from finishing pig experiments throughout the literature. They also portray the

range of growth performance and BW throughout experiments used to develop the models herein. When using the equations developed herein, the input variables should reside within these ranges. Model development processes were similar for both databases and finalized models contained the same predictor variables.

Average daily gain

For ADG models, increasing *k* appeared to increase ADG, and using *k* as a single predictor variable, for both databases, resulted in the lowest BIC value (1,033 and 1,221 for database 1 and 2, respectively; Table 4-3); therefore, it was the first predictor variable selected for the models. When examining the studentized residuals resulting from the models (ADG=*k*) clear quadratic trends were evident suggesting that increasing *k* increased ADG but at a diminishing rate; thus, k^2 was added to the models which were significant predictors ($P < 0.001$) of ADG and its inclusion lowered the BIC values (1,012 and 1,200 for database 1 and 2, respectively). Including final BW appeared to be useful in the models ($P = 0.054$ and 0.013 for database 1 and 2, respectively) because as final BW increased, ADG increased, it also lowered the BIC values (1,009 and 1,195 for database 1 and 2, respectively). Initial BW was included as a significant predictor ($P = 0.026$) in the first database which reduced a BIC value (1,005), and as initial BW increased ADG decreased. However, for the second database initial BW was not a significant predictor of ADG ($P = 0.233$), but after examining the residuals of models it appeared that for observations with heavier initial BW, as *k* increased, predicted values continued to underestimate ADG suggesting the need for a $k \times$ initial BW interactive term. Its inclusion increased ADG as *k* or as initial BW were increased, and it was useful ($P = 0.006$ for database 1 and $P < 0.001$ for database 2) as a predictor of ADG and resulted in models with the lowest BIC values. The BIC values resulting from these final multivariable models were improved (BIC =

999 and 1,183 for database 1 and 2, respectively; Table 4-4) compared to single term models which justifies their use to predict finishing ADG for the both sets of databases.

When examining the model fits to their databases (Table 4-5; Figure 4-1;Figure 4-2), it appeared the model had excellent fit with predicted values being only slightly over estimated with mean biases of -1.3 and -1.6 g/d for databases 1 and 2, respectively. The coefficients of determination (r^2 = 0.968 and 0.949 for database 1 and 2, respectively) suggested that almost than 97% and 95% of the variation observed in the actual values were explained by the model predicted values. This agrees with the MEF statistics (MEF = 0.967 and 0.948 for database 1 and 2, respectively) that almost 97% and 95% of the variation associated with the responses were explained by the fitted model predicted lines. Additionally, the bias correction factors (C_b = 0.999) were high suggesting the regression lines were closely related to the lines of unity, and the reproducibility indexes was also high (CCC = 0.983 and 0.989 for database 1 and 2, respectively) indicating strong agreement between the observed and model-predicted values. The coefficients of model determination were greater than 1 (CD = 1.08 and 1.13 for database 1 and 2, respectively) suggesting that the model predicted values underestimated the total variance in the observed values by approximately 8% and 13%. The RMSEP (20.08 and 28.68 g/d for database 1 and 2, respectively) indicated that in both databases over 93% of the error associated with the models were random error.

Average daily feed intake

For ADFI models, increasing *k* appeared to increase ADFI, and using *k* as a single predictor variable resulted in the lowest BIC values (1,175 and 1,391 for database 1 and 2, respectively); therefore, it was the first predictor variable selected for the models. When examining the studentized residuals resulting from the models, (ADFI= *k*), clear quadratic trends

were evident for *k* suggesting that increasing *k* increased ADFI but at a diminishing rate. Thus, k^2 was added to the models as a significant predictor ($P < 0.003$) which lowered the BIC values (1,168 and 1,383 for database 1 and 2, respectively). Final BW was then included as a significant ($P < 0.001$) predictor of ADFI, because ADFI increased within increasing final BW, and this reduced the BIC values (1,126 and 1,339 for database 1 and 2, respectively). Initial BW was also a predictor ($P = 0.056$ and 0.007 for database 1 and 2, respectively) of ADFI, because increasing initial BW decreased ADFI, which reduced the BIC values (1,123 and 1,332 for database 1 and 2, respectively). Finally, similar to ADG, the inclusion of a *k* × initial BW interaction ($P < 0.001$) reduced the BIC to their lowest values, and with its inclusion in the models, increasing *k* or initial BW resulted in an increased ADFI. The resulting multivariable models had improved BIC values (1,118 and 1,317 for database 1 and 2, respectively) compared to single term models, which justifies their use for predicting finishing pig ADFI.

When examining the model fits to their databases, it appeared the model predicted values were very close to actual values with mean biases of -0.21 and 0.06 g/d for database 1 and 2, respectively. The coefficients of determination ($r^2 = 0.981$ and 0.978 for database 1 and 2, respectively) suggested that approximately 98% of the variation observed in the actual values were explained by the model predicted values. This agrees with the MEF statistics (MEF = 0.981 and 978 for database 1 and 2, respectively) that approximately 98% of the variation associated with the responses were explained by the fitted model predicted lines. Additionally, the bias correction factors ($C_b = 0.999$) were high suggesting the regression lines were closely related to the lines of unity, and the reproducibility indexes were also high (CCC = 0.990) suggesting strong agreement between the observed and model-predicted values. The coefficients of model determination were greater than 1 (CD = 1.04) suggesting that the models predicted values

underestimated the total variance in the observed values by approximately 4%. The RMSEP was 50.5 and 59.2 g/d for database 1 and 2, respectively, and indicated that over 98% of the error of the models was random error.

Gain:feed ratio

For finishing G:F models, using the predicted ADG divided by the predicted ADFI for both databases resulted in models that produced BIC values of 636 and 758 for database 1 and 2, respectively. The 95% confidence interval on the coefficient for the predicted G:F was 0.9948 – 1.0030 for the first database, and 0.9949 – 1.0026 for the second database. In both cases, the coefficient of 1.00 was observed in the 95% confidence interval range which indicates predicted ADG/predicted ADFI was useful as a predictor of G:F for the corresponding databases. When evaluating the fit of the G:F models to their databases, the mean biases were -0.0006 and -0.0007 for database 1 and 2, respectively. The slight overestimations in G:F are due to the over estimations of ADG. The coefficients of determination (r^2 = 0.986 and 0.978 for database 1 and 2, respectively) suggested that approximately 98% of the variation observed in the actual values were explained by the model predicted values. This agrees with the MEF statistics (MEF = 0.986 and 0.977 for database 1 and 2, respectively) that almost 99% of the variation associated with the responses are explained by the fitted model predicted lines. Additionally, the bias correction factors (C_b = 0.999) were high suggesting the regression lines was closely related to the lines of unity, and the reproducibility index was also high (CCC = 0.993 and 0.988 for database 1 and 2, respectively) suggesting strong agreement between the observed and model-predicted values. The coefficients of model determination were greater than 1 (CD = 1.02 and 1.04 for database 1 and 2, respectively) suggesting that the model predicted underestimated the total variance in the

observed values. The RMSEP were 0.008 and 0.010 and both indicated that more than 96% of the models error was random error.

Evaluating prediction model fits to external data sets

After developing the prediction equations herein, their accuracy was evaluated using external datasets not within the current databases. The datasets that were used were Thomas et al. (2015) and Flohr et al. (2015). As part of the data validation, previously published prediction equations (Harper and Kornegay, 1983; Powell et al., 1993; and Gonyou et al., 2006) were compared as well. The equations were validated with two separate datasets; the first included data from Exp. 1 and 2 from Thomas et al. (2015), and the data from Flohr et al. (2015) from d 0 to 105 among treatments in which no pig removals occurred. The second validation dataset included the aforementioned data along with the growth performance of pigs following pig removals in the Flohr et al. (2015) study.

Results comparing the predicted values from previously developed equations and the equations discussed herein to the first external dataset are presented in Table 4-6. Coefficients of determination (r^2) suggested strong precision of all the equations, which is largely due to the intercept adjustments that were performed. However, MEF values from the ADG and ADFI models of Powell et al. (1993) and Harper and Kornegay (1983) along with the ADFI model of Gonyou et al. (2006) were lower than the corresponding r^2 values, suggesting those model predicted values explained less variation than the models developed herein. Mean biases for ADG were improved for the equations developed herein and for Gonyou et al. (2006) compared to Powell et al. (1993) and Harper and Kornegay (1983). Average daily feed intake model mean biases were largely (more than 35 g/d) over estimated by the Powell et al. (1993) and the Harper and Kornegay (1983) models; whereas, models herein overestimated ADFI values by 16 and 13

g/d for the models from the database 1 and 2, respectively. The smallest observed mean bias for ADFI models was observed from the Gonyou et al. (2006) model (-3 g/d). All C_b and CCC values were above 0.90 suggesting strong precision and accuracy of the models to the observed data; again, this is biased upward due to the use of the intercept adjustment that was applied to all equations. Root mean square error of prediction values suggest that the variance and bias were reduced the most using the models developed herein, whereas Gonyou et al. (2006) equations were intermediate, and the Powell et al. (1993) and Harper and Kornegay (1983) models resulted in the highest estimates for variance and bias. Coefficient of model determination ratios ranged from 0.91 to 1.05 for ADG models suggesting either slight overestimations or underestimations of the total variance. Although for ADFI models, equations from Gonyou et al. (2006) and from Harper and Kornegay (1983) resulted in low CD ratios (0.78 and 0.84, respectively) suggesting overestimations of the total variances in the observed data. Feed efficiency prediction equations developed herein were compared to the equation previously developed by Powell et al. (1993); however, Harper and Kornegay (1983) and Gonyou et al. (2006) did not provide a G:F prediction equation that could be evaluated. The G:F models developed herein and those by Powell et al. (1993) fit the observed datasets similarly.

Results comparing the predicted values from previously developed equations and the equations discussed herein to the second external dataset are presented in Table 4-7. In this evaluation, only the prediction equations developed from the second database (with pig removal studies) was evaluated and compared to the fit of other previously published prediction equations. Coefficients of determination (r^2) suggested moderate to strong precision of all the equations, which is largely due to the intercept adjustments that were performed. However, MEF values for the Powell et al. (1993) and Harper and Kornegay (1983) ADFI models were much

lower than corresponding r^2 values, suggesting the model predicted values explained less variation than the linear regression of the predicted values plotted against the observed values. Mean biases for ADG were similar across all equations. Average daily feed intake model mean biases were largely (more than 58 g/d) over estimated by the Powell et al. (1993) and the Harper and Kornegay (1983) model; whereas, models herein and from Gonyou et al. (2006) were slightly over estimated (5 to 8 g/d). All C_b and CCC values were above 0.71 suggesting strong precision and accuracy of the models to the observed data. Root mean square error of prediction values suggest that the variance and bias were reduced the most using the models developed herein and from Gonyou et al. (2006) equations; whereas, the Powell et al. (1993) and Harper and Kornegay (1983) models resulted in the highest RMSEP values. Coefficient of model determination ratios ranged were from 0.92 to 0.99 for previously published prediction equations for ADG and ADFI; however, values for the ADG model herein appeared to overestimate total variance (0.76) and for ADFI it appeared the model underestimated total variance (1.06). The G:F models developed herein and those by Powell et al. (1993) fit the observed datasets similarly.

DISCUSSION

Historically, floor space allowance has been expressed in the literature as the amount of space per pig. The difficulty with this approach is that as pigs grow, their requirement for space grows as well. To alleviate this challenge, the use of an allometric tool to convert the three-dimensional term of weight to a 2-dimensional measure of area was used as the expression of floor space: $A = k \times BW^{0.67}$. In this equation, A represents floor space allowance, *k* represents a

constant coefficient, and $BW^{0.67}$ represents the geometric conversion of weight to area assuming that as BW increases the animal's surface area requirement increases proportionately. The first to propose this method was Petherick and Baxter (1981) with others adopting it as a means to provide a consistent area of space as the animal grows. In fact, many space recommendations are based on *k* (European Community, 2001; AAFC, 1993). All models generated herein used *k* rather than floor space as a predictor variable, within the multivariable models, suggesting that the inference from final BW within the *k* calculation had additional value for fitting models to the databases compared to floor space allowance itself.

Shull (2010) discussed one discrepancy with the use of the allometric measurement *k*. Does the pig's requirement for space grow proportionately to $BW^{0.67}$? This assumption is based off of the geometric principle that increasing the volume of a cube results in a proportional increase in the surface area of each side. There is little research truly examining whether this function captures the true changes in the pig's space requirement as it increases in BW. The multivariable models herein would contest that assumption; therefore, we feel that we are providing an alternative way of expressing floor space requirement for maximal growth as a function of BW and *k* which more closely describes the biological response.

Kornegay and Notter (1983) were the first to use linear and curvilinear analysis to describe the impact of floor space allowance on growth criteria. Their empirical equations, developed for growing and finishing pigs, were single variable prediction models with floor space as the predictor variable in which increasing floor space improved performance parameters at a decreasing (quadratic) rate. The drawbacks to their prediction equations were that they did not account for BW influences on response criteria, and with the statistical capabilities of the time, their models were simple fixed effect models which did not account for known random

error terms that could have impacted responses. Another limitation from their data was that their heaviest observed BW was 93 kg which is much lower than current market weights.

The prediction equations developed herein were able to utilize more recent statistical software which allowed for the use of mixed linear models. This was beneficial to account for known random errors which could influenced the analyzed results, including changes in growth over time (decade to decade variation), paper to paper variation within the same time period, and experiment to experiment variation within the same paper. Also, the current analysis used weighted observations to account for differences in experimental design and replication across papers and experiments to help improve the precision of estimates and lower the residual error of the prediction models. Additionally, since the publication of Kornegay and Notter's prediction equations, more research has been conducted with finishing pigs at heavier weights providing more information on how BW alters the impact floor space allowance on growth.

Gonyou et al. (2006) developed linear broken-line space requirement curves based on the allometric coefficient *k*. The authors believed that instead of measuring the continuous variables ADG, ADFI, or G:F, quantifying the percentage reduction in these responses from reduced floor space allowance would be much more interpretable. Because of their transformation of the data to a percentage change as the response criteria, its ease of application across production environments has resulted in its wide acceptance as a standard for estimating the influence of floor space allowance on ADG and ADFI. The current models herein would disagree that the single use of the allometric coefficient *k* can account for the BW interactions with floor space allowance. And as a result, the multi-term models herein use initial and final BW along with a *k* × initial BW interaction as predictor terms for growth. This would mean that there are different

critical *k* thresholds (requirements) based on the BW range of finishing pigs that are being examined.

Also, when Gonyou et al (2006) included studies into their database, they only accepted studies in which at least one floor space treatment was above the *k* coefficient of 0.030 and at least one observation was below that same threshold. In total, the authors had 11 published papers that were used to estimate the space requirement of finishing pigs. However, the available database of peer-reviewed published literature available (at the time prior to publication of the prediction equations) included an additional 9 studies (NCR-89, 1993; Brumm and NCR-89, 1996; Edmonds et al., 1998; Hyun et al., 1998a; Hyun et al., 1998b; Brumm et al., 2001; Edmonds and Baker, 2003; Hamilton et al., 2003; Brumm, 2004). Due to the stringent *k* threshold to include studies, it may have biased their threshold response closer to $k = 0.030$ than the available literature would have suggested the true response to be. The models developed herein used a total of 92 and 112 observations in their respective databases which are more than 3 times the size of the database used by Gonyou et al. (2006) to predict ADG and ADFI.

The impact of floor space allowance on feed efficiency is a perplexing topic. There are several proposed mode of actions for the worsened feed efficiency caused by reduced floor space allowance. Chapple (1993) proposed that rearing pigs in groups reduces the capacity of the pig to deposit protein resulting in reduced feed intake and worsened feed utilization. Zhang et al., (2013) reported a linear reduction in N digestibility and BUN for 25 kg pigs stocked at 0.64, 0.48, and 0.38 m^2 for 36 d. Shull (2010) has implicated the potential for increased feed wastage and energy expenditures due to increased trips to the feeder caused by more interruptions during feeding. It may be that reducing floor space allowance leads to multiple behavioral changes that could impact growth and metabolism. Most researchers have not necessarily focused on the

impact of floor space allowance on feed efficiency because the response seems to be less than that of ADG and ADFI and more variable across studies.

Previous equations to estimate the impact of floor space allowance on feed efficiency were proposed by Harper and Kornegay (1983) and by Powell et al. (1993), but Gonyou et al. (2006) concluded that feed efficiency was not impacted by floor space allowance. Most papers conclude that there were no statistical differences in G:F with varying floor space allowance; however, most studies see increased final BW as floor space allowance is increased. So it begs to question; is the influence of floor space allowance on feed efficiency potentially veiled by changes in final BW between treatments? Of the papers utilized in the databases herein, 17 studies (Harper and Kornegay, 1983; Edwards et al., 1988; NCR-89, 1993; McGlone and Newby; 1994; Ward et al.,1997; Edmonds et al., 1998; Gonyou and Stricklin, 1998; Hyun et al., 1998a; Hyun et al., 1998b; Dritz et al., 1999; Matthews et al., 2001; Edmonds and Baker, 2003; Peterson, 2004; White et al., 2008; Street and Gonyou, 2008; Jacela et al., 2009; Shull, 2010; Potter et al., 2010) observed either numerically increased G:F or similar G:F for pigs that had heavier final BW when provided more floor space over a fixed time period. Although the response may not be to the same magnitude as ADG and ADFI, examining the available literature as a whole suggests that feed efficiency is impacted by floor space allowance.

Our decision to segregate the databases herein into a set of studies examining floor space allowance with or without pig removal studies was done based on the debate as to whether improvements in growth of pigs following removals from the pen are due solely to increased floor space allowance, or if this improvement is also due to other factors. Providing both sets of equations from the databases herein would allow users to choose which they believed to be more applicable for their situation. Results from Scroggs et al. (2002), and Ewbank and Meese (1971)

reported no changes in aggression or immune responses after removing pigs compared to intact pens of pigs with the same group size, indicating that the response is attributed to increased floor space allowance following the removals of pigs from the pen. Additionally, Augspurger et al. (2000) concluded that removing pigs from a pen changed feeding behavior of the pigs remaining to levels similar to that of pigs in an undisturbed pen with a similar group size.

Because of the lack of previous research to distinguish changes in behavior or activity among pigs in intact pens versus pigs remaining in a pen after contemporaries are removed, our belief is that the equations derived from the second database are more useful. This is because the studies performed with pig removals were typically performed at heavier BW ranges. This provided additional information to the model for growth rates of pigs at heavier BW than that of the database without pig removal studies. This is most evident when evaluating the predicted growth values in Figure 4-3 and Figure 4-4 which were derived from the prediction equations from each database developed herein. The figures depict the predicted ADG, ADFI, and G:F for pigs over three different BW ranges (20 to 80, 80 to 130, and 20 to 130 kg) based on the equations from each database. For lighter BW pigs (20 to 80 kg) and pigs over the entire finishing period (20 to 130 kg), predicted values are similar from both databases. Alternatively, predicted values for heavy BW range pigs (80 to 130 kg) differed between the two databases. The ADG values derived from the second database suggest that ADG increases more with additional floor space compared to predicted ADG values derived from the first database. Consequently, the predicted G:F values for heavy weight pigs are numerically higher from the second database compared to the first. The values derived from the second database are more similar to the commonly observed ADG and G:F of heavy weight pigs with modern genotypes reared in commercial finishing facilities.

Interestingly, the prediction equations herein did not find any other environmental factors (group size, feeder space, water space) as predictors of growth in the multivariable models. However, that does not mean that potential interactions with these factor and floor space allowance do not exist.

In fact, the amount of research examining the effects of water space (pigs per waterer) on growth is limited. The MWPS (1991) recommends one water space per 10 weaned pigs and for 15 growing pigs. However, this recommendation makes no mention of difference waterer forms that are available. A study by Brumm and Shelton (1986) reported an increase in the variation of weight gain as the number of weaned pigs per nipple water increased from 8 to 16. Brumm (2001) suggests that the number of allowable pigs per waterer increases as pigs grow and can adapt to social stress. Landero et al. (2014) observed an improvement in ADG, ADFI and G:F when providing an additional cup waterer to pens of pigs only receiving water from 2 wet/dry feeder spaces. This suggests the need for continued research effects on water space.

Also, within this analysis, feeder space was the vague term used to describe the number of pigs per feeder hole. Ideally, a more descriptive term to evaluate its role in the current models would have been preferred; however, the number of pigs per feeder hole was the only consistently reported value across papers included in the databases. Additional information regarding trough space per pig, along with feeder design would have helped describe potential feeder effects on growth performance. Wolter et al. 2003 observed a reduction in ADFI and ADG, along with an increase in G:F when trough space was limited from (2 versus 4 cm/pig) for wean to finish pigs for the first 14 wk post weaning. One paper in the current databases utilized wet/dry feeders which are recommended to accommodate more pigs/space than conventional dry feeders. Bergstrom et al. (2012) concluded that pigs fed from wet/dry feeders had increased

ADG and ADFI compared to pigs fed from conventional dry feeders. These differences based on feeder design and feed trough spaces justify the use of more descriptive and accurate terms in model selection than just feeder space itself. In the future, distinction among these feeder traits may help explain more of the variance and characterize its impact on finishing pig growth.

Application of prediction equations

Discrepancies in health status, genetics, and environment between farms could result in differences in the predicted values of equations herein and the actual growth rate. One method to adjust for these factors is to assume the shape and magnitude of the response are similar across these factors and adjust the intercept of the equations to provide farm-specific estimates. To do so, the actual growth rates of pigs stocked at a known floor space allowance at a known initial and final BW can be used to make the adjustment. The difference between the predicted and actual value of growth is then used to adjust the intercept of the equation. For instance, in Farm A, pigs from 50- to 110-kg stocked at a floor space of 0.65 m^2 demonstrated an ADG of 920 g/d and an ADFI of 2,490 g/d. Based on the stocking density of 0.65 m^2 and BW range of 50 to 100 kg, the predicted equations for ADG and ADFI herein from the second database with pig removal studies would predict values of 839 g/d for ADG and 2,570 g/d for ADFI. As a result, the ADG was 81 g/d higher than the predicted value and ADFI was 80 g/d lower than the predicted value. The intercepts for the equations can be adjusted by adding the difference (ADG: 337.57+81=418.57; ADFI: 833.41-80=753.41). These adjusted equations can then be used to model different economic scenarios based on floor space allowances.

In summary, floor space allowance is an important environmental factor that influences finishing pig growth. The regression equations herein provide good alternative estimates of ADG, ADFI, and G:F based on BW and *k* associated with finishing pigs provided varying floor

space allowances. Compared to previous equations, the models herein were developed using general linear mixed models from larger databases with additional information at heavier weights than previously reviewed. These growth predictions can be used to assess the economic value of floor space allowance for swine production.

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TABLES AND FIGURES

Table 4-1. Summary of papers used in the regression analyses to predict ADG, ADFI, and G:F from varying floor space allowances in finishing pigs

First author, year	Source type: J = journal T = thesis M = technical memo	Trials	Treatments	Gender[1]	Floor space allowances, m^2	Initial BW, kg	Final BW, kg[2]	k[3]
Harper and Kornegay, 1983	J	1	2	Mixed	0.43-0.78	22.7	91-98	0.021-0.036
Moser et al., 1985	J	2	Exp. 1: 3	Mixed	0.28-0.37	23.0	55.0	0.019-0.026
			Exp. 2: 3	Mixed	0.56-0.74	55.0	100	0.026-0.034
Edwards et al., 1988	J	1	4	Mixed	0.46-0.67	34.2	83-86	0.024-0.034
NCR-89, 1993	J	2	Exp. 1: 3	Mixed	0.56-0.93	52.8-52.9	114-115	0.024-0.039
			Exp. 2: 4	Mixed	0.56-1.11	54.2-54.9	96-102	0.026-0.050
McGlone and Newby, 1994	J	1	3	Mixed	0.56-0.74	59.0	100-103	0.026-0.032
Brumm, 1996[4]	J	1	3	Barrows	0.65-1.20	55.6	137-138	0.024-0.044
Brumm and Miller, 1996	J	3	Exp. 1: 2	Mixed	0.56-0.78	20.6	111	0.024-0.033
			Exp. 2: 2	Mixed	0.56-0.78	22.6	106-108	0.025-0.034
			Exp. 3: 2	Mixed	0.56-0.78	20.6	106	0.025-0.034
Ward et al., 1997	J	1	2	Mixed	0.56-0.79	27.2	97-105	0.026-0.035
Edmonds et al., 1998	J	1	2	Mixed	0.50-0.74	18.0	107-126	0.022-0.029
Hyun et al., 1998a	J	1	2	Mixed	0.25-0.56	34.7	53-57	0.018-0.038
Hyun et al., 1998b	J	1	2	Mixed	0.25-0.57	35.8	54-57	0.017-0.037
Gonyou and Stricklin, 1998	J	1	3	Mixed	0.58-0.94	25.0	95-99	0.027-0.043
Dritz et al., 1999	M	2	Exp. 1: 2	Mixed	0.61-0.69	29.3	98-99	0.028-0.032
			Exp. 2: 2	Mixed	0.61-0.69	98-99	116-117	0.025-0.029
Matthews et al., 2001	J	1	2	Mixed	0.56-0.81	51.0	104-110	0.025-0.035
Brumm et al., 2001	J	2	Exp. 1: 2	Mixed	0.56-0.78	20.0	109-111	0.024-0.033
			Exp. 2: 2	Mixed	0.60-0.74	22.0	110	0.026-0.032
Hamilton et al., 2003	J	2	Exp. 1: 2	Mixed	0.37-0.93	40.0	80.0	0.020-0.050
			Exp. 2: 2	Mixed	0.56-0.93	80.0	120-121	0.023-0.038
Edmonds and Baker, 2003	J	1	2	Mixed	0.56-1.12	49.0	118-126	0.023-0.044
Brumm et al., 2004	J	1	2	Barrows	0.55-0.74	30.0	107-109	0.024-0.032
Brumm, 2004	J	2	Exp 1: 5	Barrows or gilts	0.58-0.74	22-23	114-116	0.024-0.027
			Exp 2: 2	Mixed	0.58-0.74	30-31	122-125	0.023-0.029
Peterson, 2004	T	1	3	Mixed	0.61-0.74	34.0	113-116	0.025-0.031
DeDecker at al., 2005[5]	J	1	4	Mixed	0.65-1.30	106-113	122-126	0.026-0.052
Gonyou and Street, 2007	J	1	2	Mixed	0.52-0.78	37.0	93-95	0.025-0.037

Anil et al., 2007	J	1	4	Barrows	0.64-0.88	31.0	115-121	0.027-0.035
White et al., 2008	J	1	2	Gilts	0.66-0.93	88.0	106-111	0.029-0.040
Young et al., 2008	J	1	2	Gilts	0.77-1.13	38.0	127-128	0.030-0.044
Jacela et al., 2009[5]	M	2	Exp. 1: 3	Mixed	0.67-0.80	107-109	125-126	0.026-0.032
			Exp. 2: 5	Mixed	0.62-0.88	114-118	124-126	0.024-0.035
Shull, 2010	T	2	Exp. 1:5	Mixed	0.21-0.44	24.0	45-50	0.016-0.032
			Exp. 2:5	Mixed	0.35-0.73	61.0	77-89	0.019-0.036
Potter et al., 2010	M	1	4	Mixed	0.59-0.76	28-29	120-126	0.024-0.030
Potter et al., 2011[5]	M	1	4	Gilts	0.84-2.09	117.0	139-144	0.031-0.075
Landero et al., 2014	M	1	6	Mixed	0.63-0.76	32.0	120-124	0.025-0.030

[1] Mixed refers to floor space treatments applied to pens containing both barrows and gilts.

[2] For papers that did not report final BW the study length, initial BW and ADG were used to calculate final BW. For papers that reported Final BW but not study length, then ADG, initial BW, and final BW were used to calculate study length.

[3] Coefficient *k* is the constant in the equation k = floor space (m^2)/$BW^{0.67}$. *K* was recalculated for each experimental unit based on final BW and floor space allowance.

[4] Two experiments were reported in the literature but only data from Exp. 2 was used in the analysis.

[5] Studies in which removing pigs to relieve stocking pressure and achieve floor space allowance treatments was conducted.

Table 4-2. Descriptive statistics for data included in prediction models

		BW, kg									
	Days	Initial[1]	Final[2]	Feeder space[3]	Water space[4]	Group size[5]	Floor space, m^2	*k*[6]	ADG, g	ADFI, g	G:F
Database without pig removal studies											
ADG[7]											
Mean	77.5	38.5	101.8	5.9	10.0	15.2	0.66	0.02959	815	---	---
SD	31.3	18.2	22.6	2.8	4.8	10.1	0.19	0.00670	111	---	---
Minimum	27.0	18.0	45.1	2.0	4.0	3.0	0.21	0.01640	600	---	---
Maximum	133.0	98.5	137.7	12.0	28.0	43.0	1.20	0.05000	1,077	---	---
ADFI and G:F[8]											
Mean	75.4	39.2	100.6	6.0	9.5	14.9	0.64	0.02916	---	2,440	0.339
SD	32.0	18.9	23.0	2.9	4.1	10.3	0.19	0.00681	---	365	0.066
Minimum	27.0	18.0	45.1	2.0	4.0	3.0	0.21	0.01640	---	1,450	0.240
Maximum	133.0	98.5	137.7	12.0	28.0	43.0	1.20	0.05000	---	3,227	0.537
Database with pig removal studies											
ADG[9]											
Mean	69.3	48.4	105.3	5.8	11.0	16.5	0.68	0.02998	832	---	---
SD	36.0	30.5	23.0	2.7	5.6	10.5	0.21	0.00700	126	---	---
Minimum	10	18.0	45.1	2.0	4.0	3.0	0.21	0.01640	600	---	---
Maximum	133.0	117.9	141.0	12.0	28.0	52.0	1.39	0.05200	1,170	---	---
ADFI and G:F[10]											
Mean	67.0	49.6	104.4	5.9	10.6	16.3	0.67	0.02963	---	2,516	0.336
SD	36.3	31.1	23.4	2.8	5.3	10.7	0.21	0.00713	---	397	0.064

Minimum	10.0	18.0	45.1	2.0	4.0	3.0	0.21	0.01640	---	1,450	0.240
Maximum	133.0	117.9	141.0	12.0	28.0	52.0	1.39	0.05200	---	3,370	0.537

[1] Refers to the BW of pigs at the beginning of the experiment.
[2] Refers to the BW of pigs at the end of the experiment.
[3] Number of pigs per feeder hole.
[4] Number of pigs per waterer.
[5] Number of pigs per pen.
[6] Coefficient *k* is the constant in the equation k = floor space (m^2)/$BW^{0.67}$.
[7] The final database represents 27 papers with 97 observations for the ADG database without pig removal studies.
[8] The final database represents 25 papers with 92 observations for the ADFI and G:F databases without pig removal studies.
[9] The final database represents 30 papers with 112 observations for the ADG database with pig removal studies.
[10] The final database represents 28 papers with 107 observations for the ADFI and G:F databases with pig removal studies.

Table 4-3. Single variable models used to predict ADG and ADFI for finishing pigs

Item	k[1]	Floor space, m^2	BW, kg		Days	Feeder space[2]	Water space[3]	Group size[4]	Gender[5]	Floortype[6]
			Initial	Final						
Database without pig removal studies										
ADG										
Probability, $P <$	0.001	0.001	0.824	0.013	0.425	0.692	0.002	0.057	0.436	0.854
BIC[7]	1,033	1,047	1,110	1,102	1,109	1,110	1,110	1,100	1,109	1,110
ADFI										
Probability, $P <$	0.001	0.001	0.005	0.001	0.437	0.001	0.001	0.001	0.044	0.408
BIC	1,175	1,179	1,234	1,184	1,240	1,228	1,227	1,219	1,236	1,240
Database with pig removal studies										
ADG										
Probability, $P <$	0.001	0.001	0.629	0.005	0.230	0.356	0.003	0.010	0.559	0.831
BIC	1,221	1,234	1,302	1,292	1,301	1,302	1,294	1,296	1,303	1,302
ADFI										
Probability, $P <$	0.001	0.001	0.001	0.001	0.316	0.001	0.001	0.001	0.033	0.890
BIC	1,391	1,395	1,442	1,733	1,456	1,439	1,439	1,444	1,451	1,457

[1] Coefficient k is the constant in the equation k = floor space (m^2)/$BW^{0.67}$.

[2] Represents the number of pigs per feeder hole.

[3] Represents the number of pigs per waterer.

[4] Group size represents the number of pigs per pen.

[5] Gender for each database consisted of barrow, gilt and mixed (barrow and gilt) information.

[6] Floor types observed for finishing databases were partially and fully slatted concrete flooring.

[7] Bayesian Information Criterion values were used to compare the precision of the model. Models that minimized Bayesian Information Criterion (BIC) within database were used to select variables for initial model building.

Table 4-4. Regression equations generated from existing data for ADG, ADFI, and G:F of finishing pigs

Dependent variable	Models	BIC
Database without pig removal studies		
ADG,g	=395.57+(15,727 × k)-(221,705 × k^2)-(3.6478 × Initial BW, kg)+(2.2090 × Final BW, kg)+(67.6294 × k × Initial BW, kg)	999
ADFI,g	=802.07+(20,121 × k^2)-(301,210 × k^2)-(1.5985 × Initial BW, kg)+(11.8907 × Final BW, kg)+(159.79 × k × Initial BW, kg)	1,118
G:F	=Predicted ADG/Predicted ADFI	636
Database with pig removal studies		
ADG,g	=337.57+(16,468 × k)-(237,350 × k^2)-(3.1209 × Initial BW, kg)+(2.5690 × Final BW, kg)+(71.6918 × k × Initial BW, kg)	1,183
ADFI,g	=833.41+(24,785 × k)-(388,998 × k^2)-(3.0027 × Initial BW, kg)+(11.2460 × Final BW, kg)+(187.61 * k × Initial BW, kg)	1,317
G:F	= Predicted ADG/Predicted ADFI	758

Table 4-5. Evaluation of model fit to databases

Model	$r^{2(1)}$	Mean Bias, g/d[2]	C_b[3]	CCC[4]	RMSEP, g/d[5]	MEF[6]	CD[7]
Database without pig removal studies							
ADG	0.968	-1.32	0.999	0.983	20.08	0.967	1.08
ADFI	0.981	-0.21	0.999	0.990	50.54	0.981	1.04
G:F	0.986	-0.0005	0.999	0.993	0.0080	0.986	1.02
Database with pig removal studies							
ADG	0.949	-1.63	0.999	0.989	28.68	0.948	1.13
ADFI	0.978	0.06	0.999	0.988	59.24	0.978	1.04
G:F	0.978	-0.0007	0.999	0.988	0.0099	0.977	1.04

[1] Coefficient of determination (Neter et al., 1996). Values measure the fit of the residual variance and do not infer information from random effects in the model; therefore, they are higher than a simple fixed effect model.

[2] Mean bias was computed by subtracting the mean of observed values minus the mean of the predicted values (Cochran and Cox, 1957). A negative value insinuates an over estimation.

[3] Bias correction factor (C_b) is a component of the CCC statistic that indicates how far the regression line deviates from the slope of unity (45°; Lin, 1989).

[4] Concordance Correlation Coefficient (CCC), also known as reproducibility index, assesses both the precision and accuracy of the model (Lin, 1989).

[5] Root mean square error of prediction (RMSEP) is used to measure the predictive accuracy of the model (Mitchell, 1997).

[6] Modeling efficiency statistic (MEF) is used as an indicator of goodness of fit (Mayer and Butler, 1993). A MEF value closer to 1 suggests better fit and a value less than zero indicates that the model predicted values are worse than the observed mean.

[7] The coefficient of model determination (CD) explains the proportion of the total variance of the observed values explained by the predicted data. The closer the CD value to 1 the better, with ratios over 1 insinuating model under prediction of total variance, and a ratio less than 1 suggesting an over estimation of the total variance by the model.

Table 4-6. Validation of available equations to predict floor space allowance effects on growth[1]

	Flohr et al.				
	Without pig removals	With pig removals	Gonyou et al.	Powell et al.	Harper and Kornegay
ADG					
$r^{2(2)}$	0.99	0.99	0.98	0.96	0.95
Mean bias, g[3]	-1.50	-0.63	-2.13	-8.50	-11.38
C_b[4]	0.99	0.99	0.99	0.98	0.96
CCC[5]	0.99	0.99	0.99	0.96	0.94
RMSEP[6]	4.03	3.86	6.15	11.81	14.86
MEF[7]	0.99	0.99	0.98	0.92	0.87
CD[8]	1.01	1.00	0.91	0.99	1.05
ADFI					
r^2	0.98	0.98	0.97	0.95	0.97
Mean bias, g	-15.50	-13.38	-2.88	-35.13	-46.25
C_b	0.99	0.99	0.99	0.98	0.97
CCC	0.99	0.99	0.98	0.96	0.96
RMSEP	31.32	29.71	43.52	53.81	58.02
MEF	0.97	0.97	0.94	0.92	0.90
CD	1.04	1.04	0.78	0.97	0.84
G:F[9]					
r^2	0.86	0.87	---	0.87	---
Mean bias, g	0.003	0.003	---	0.003	---
C_b	0.97	0.97	---	0.97	---
CCC	0.90	0.90	---	0.90	---
RMSEP	0.005	0.005	---	0.005	---
MEF	0.76	0.77	---	0.77	---
CD	0.79	0.81	---	0.81	---

[1] All predicted values were adjusted for each of the three experiment data sets by subtracting the predicted value from the observed value for the high floor space allowance treatment. That difference was added to all predicted values within the experiment. Validation inputs for floor space treatments without pig removals were used for these validation calculations.

[2] Coefficient of determination (Neter et al., 1996).

[3] Mean bias was computed by subtracting the mean of observed values minus the mean of the predicted values (Cochran and Cox, 1957). A negative value indicates an over estimation.

[4] Bias correction factor (C_b) is a component of the CCC statistic that indicates how far the regression line deviates from the slope of unity (45°; Lin, 1989).

[5] Concordance correlation coefficient (CCC), also known as the reproducibility index, assesses both the precision and accuracy of the model (Lin, 1989).

[6] Root mean square error of prediction (RMSEP) is used to measure the predictive accuracy of the model (Mitchell, 1997).

[7] Modeling efficiency statistic (MEF) is used as an indicator of goodness of fit (Mayer and Butler, 1993). A MEF value closer to 1 suggests better fit and a value less than zero indicates that the model predicted values are worse than the observed mean.

[8] The coefficient of model determination (CD) explains the proportion of the total variance of the observed values explained by the predicted data. The closer the CD value to 1 the better, with ratios over 1 insinuating model under prediction of total variance, and a ratio less than 1 suggesting an over estimation of the total variance by the model.

[9] Gonyou et al. (2006) did not report an equation to predict G:F differences associated with floor space allowances, and Harper and Kornegay provided a prediction equation for F:G rather than G:F; therefore, both papers were not included in feed efficiency equation validation calculations.

Table 4-7. Validation of available prediction equations and those developed herein, from the database with pig removal studies, to predict floor space effects on growth[1]

	Flohr et al.[2]	Gonyou et al.	Powell et al.	Harper and Kornegay
ADG				
$r^{2(3)}$	0.81	0.77	0.74	0.72
Mean bias, g[4]	10.00	-6.00	-6.12	-11.18
C_b[5]	0.98	0.99	0.99	0.99
CCC[6]	0.89	0.87	0.86	0.84
RMSEP[7]	35.64	35.64	37.42	39.81
MEF[8]	0.74	0.74	0.71	0.67
CD[9]	0.76	0.92	0.99	0.99
ADFI				
r^2	0.82	0.85	0.68	0.70
Mean bias, g	-5.18	-7.88	-63.00	-58.94
C_b	0.99	0.99	0.86	0.88
CCC	0.90	0.92	0.71	0.73
RMSEP	51.12	47.92	91.87	87.73
MEF	0.81	0.83	0.39	0.44
CD	1.06	0.99	0.97	0.94
G:F[10]				
r^2	0.89	---	0.86	---
Mean bias, g	0.005	---	0.005	---
C_b	0.98	---	0.97	---
CCC	0.93	---	0.90	---
RMSEP	0.009	---	0.01	---
MEF	0.84	---	0.79	---
CD	0.92	---	0.88	---

[1] All predicted values were adjusted for each of the three experiment data sets by subtracting the predicted value from the observed value for the high floor space allowance treatment. That difference was added to all predicted values within the experiment. For Exp. 3 each period within the Exp. required an intercept adjustment.
[2] Equations developed from the database not containing pig removals were used.
[3] Coefficient of determination (Neter et al., 1996).
[4] Mean bias was computed by subtracting the mean of observed values minus the mean of the predicted values (Cochran and Cox, 1957). A negative value indicates an over estimation.
[5] Bias correction factor (Cb) is a component of the CCC statistic that indicates how far the regression line deviates from the slope of unity (45°; Lin, 1989).
[6] Concordance correlation coefficient (CCC), also known as reproducibility index, assesses both the precision and accuracy of the model (Lin, 1989).
[7] Root mean square error of prediction (RMSEP) is used to measure the predictive accuracy of the model (Mitchell, 1997).
[8] Modeling efficiency statistic (MEF) is used as an indicator of goodness of fit (Mayer and Butler, 1993). A MEF value closer to 1 suggests better fit and a value less than zero indicates that the model predicted values are worse than the observed mean.
[9] The coefficient of model determination (CD) explains the proportion of the total variance of the observed values explained by the predicted data. The closer the CD value to 1 the better, with ratios over 1 insinuating model under prediction of total variance, and a ratio less than 1 suggesting an over estimation of the total variance by the model.
[10] Gonyou et al. (2006) did not report an equation to predict G:F differences associated with floor space allowances, and Harper and Kornegay provided a prediction equation for F:G rather than G:F; therefore, both papers were not included in feed efficiency equation validation calculations.

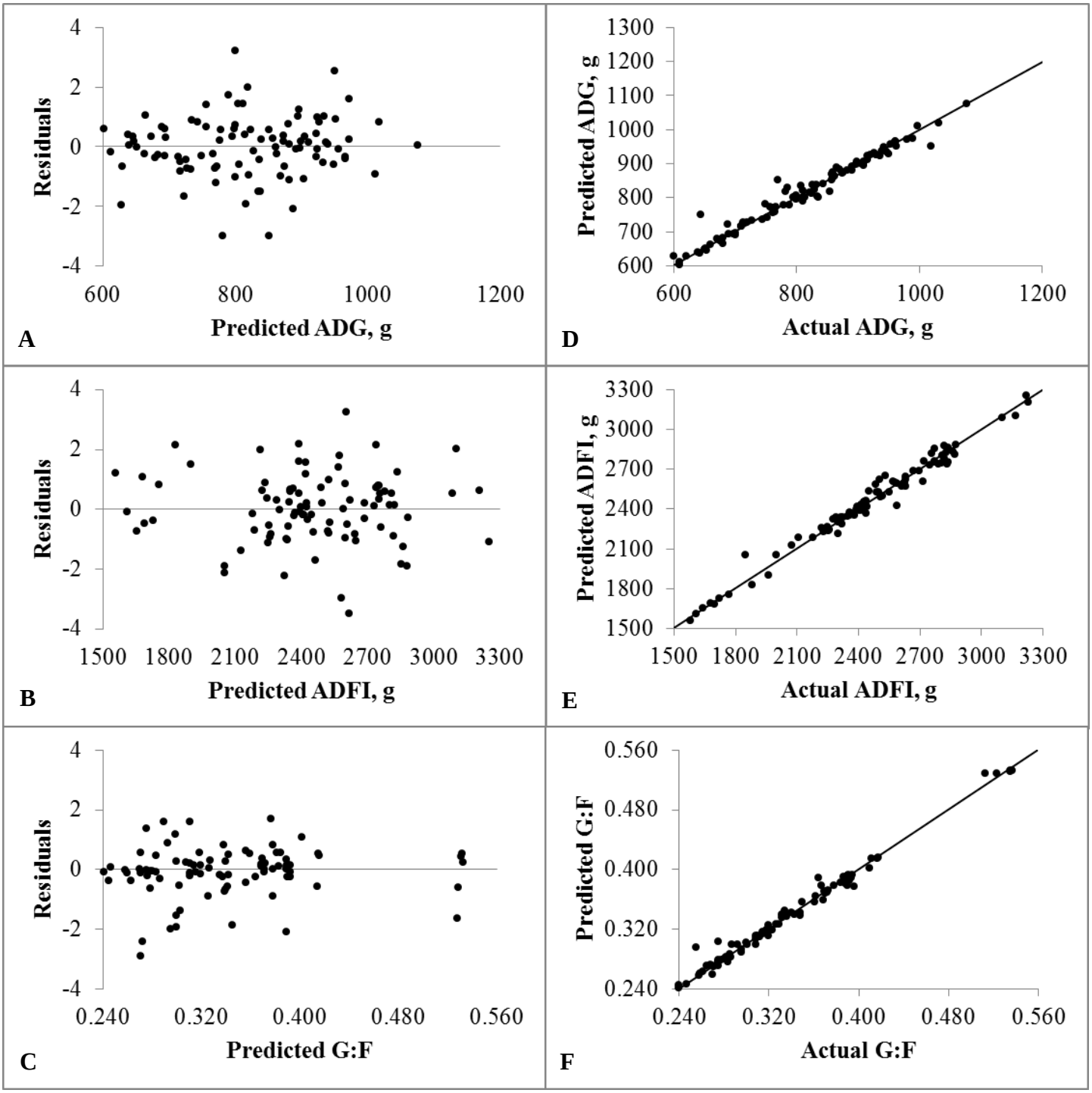

Figure 4-1. Plots of studentized residuals against predicted values for A) ADG, B) ADFI, and C) G:F, and plots of actual values vs. predicted values relative to the line of equality for D) ADG, E) ADFI, and F) G:F from the mixed model analysis for the first database without pig removal studies. The following equations were used A) ADG, g = 395.57+(15,727*k)-(221,705*k^2)-(3.6478*Initial BW, kg)+(2.209*Final BW, kg)+(67.6294*k*Initial BW, kg); B) ADFI, g = 802.07+(20,121*k)-(301,210*k^2)-(1.5985*Initial BW, kg)+(11.8907*Final BW, kg)+(159.79*k*Initial BW, kg); C) G:F =Predicted ADG/Predicted ADFI.

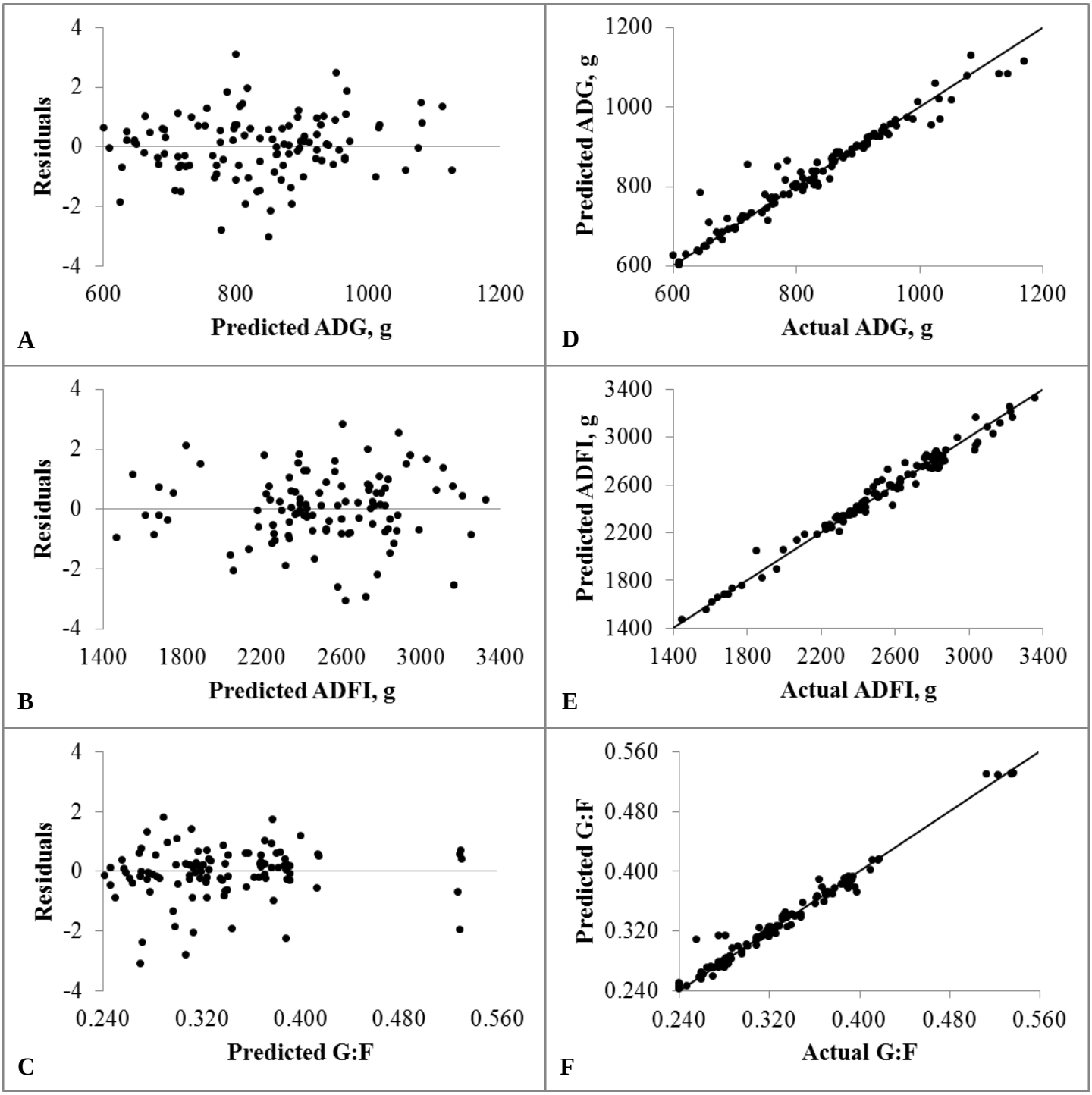

Figure 4-2. Plots of studentized residuals against predicted values for A) ADG, B) ADFI, and C) G:F, and plots of actual values vs. predicted values relative to the line of equality for D) ADG, E) ADFI, and F) G:F from the second database with pig removal studies. The following equations were used D) ADG, g =337.57+(16,468*k)-(237,350*k^2)-(3.1209*Initial BW, kg)+(2.569*Final BW, kg)+(71.6918*k*Initial BW, kg); E) ADFI, g = 833.41+(24,785*k)-(388,998*k^2)-(3.0027*Initial BW, kg)+(11.246*Final BW, kg)+(187.61*k*Initial BW, kg); F) G:F =Predicted ADG/Predicted ADFI.

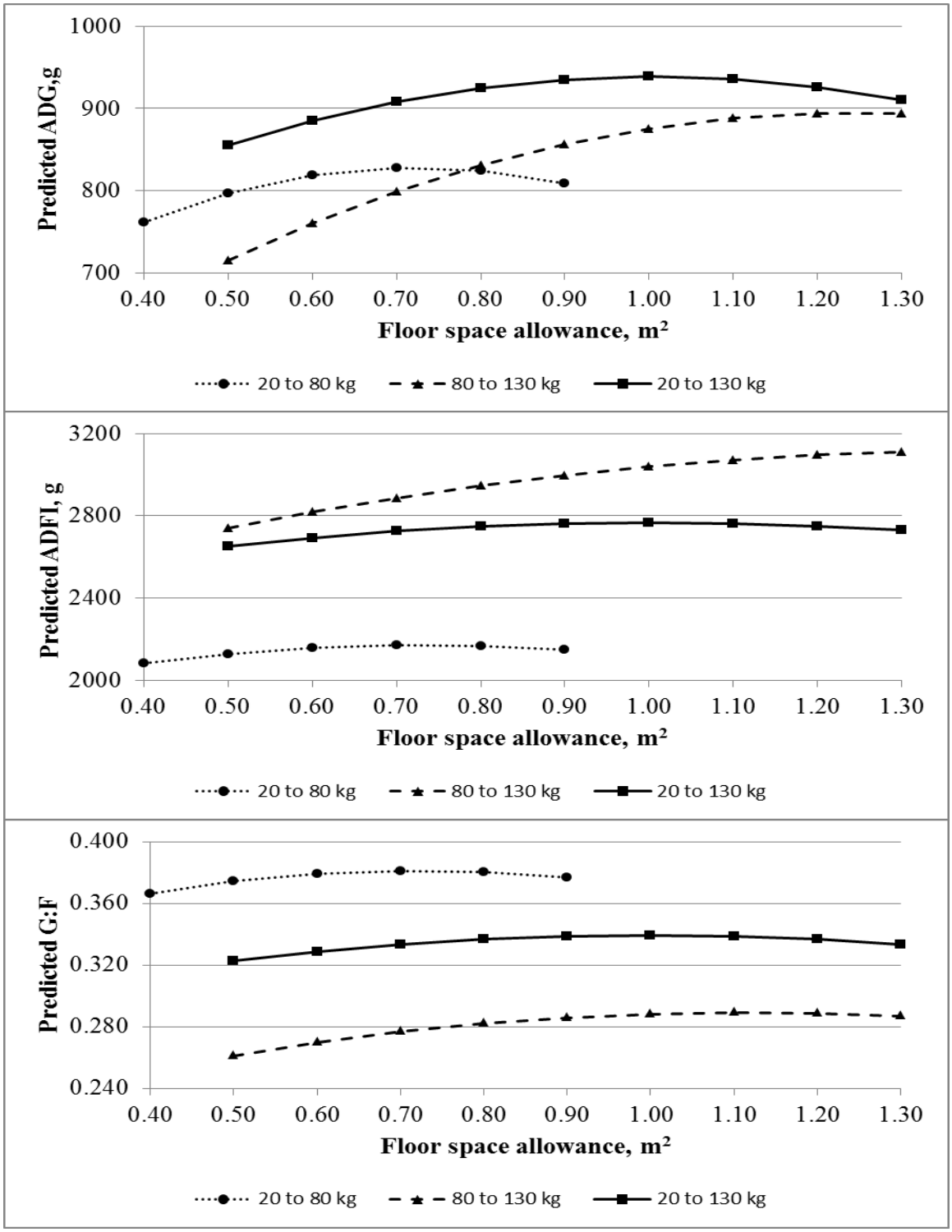

Figure 4-3. Predicted ADG, ADFI, and G:F of pigs from 20 to 80 kg, 80 to 130 kg, and from 20 to 130 kg as floor space allowance changes. Equations were developed from the first database without pig removal studies The predicted ADG, ADFI, and G:F values derived from the first database were calculated using the models with the following coefficients (± SE): ADG (g/d) = 15,727 ± 2,182.10 × *k* – 221,705 ± 38,599 × k^2 -3.6478 ± 1.0032 × Initial BW (kg) + 2.209 ± 0.7195 × Final BW (kg) + 67.6294 ± 24.3627 × *k* × Initial BW (kg) + 398.57 ± 70.5615; ADFI (g/d) = 20,121 ± 4,032.43 × *k* – 301,210 ± 70,095 × k^2 -1.5985 ± 3.4158× Initial BW (kg) + 11.8907 ± 2.1603 × Final BW (kg) + 159.79 ± 50.3081 × *k* × Initial BW (kg) + 802.07 ± 234.18; G:F = Predicted ADG/Predicted ADFI.

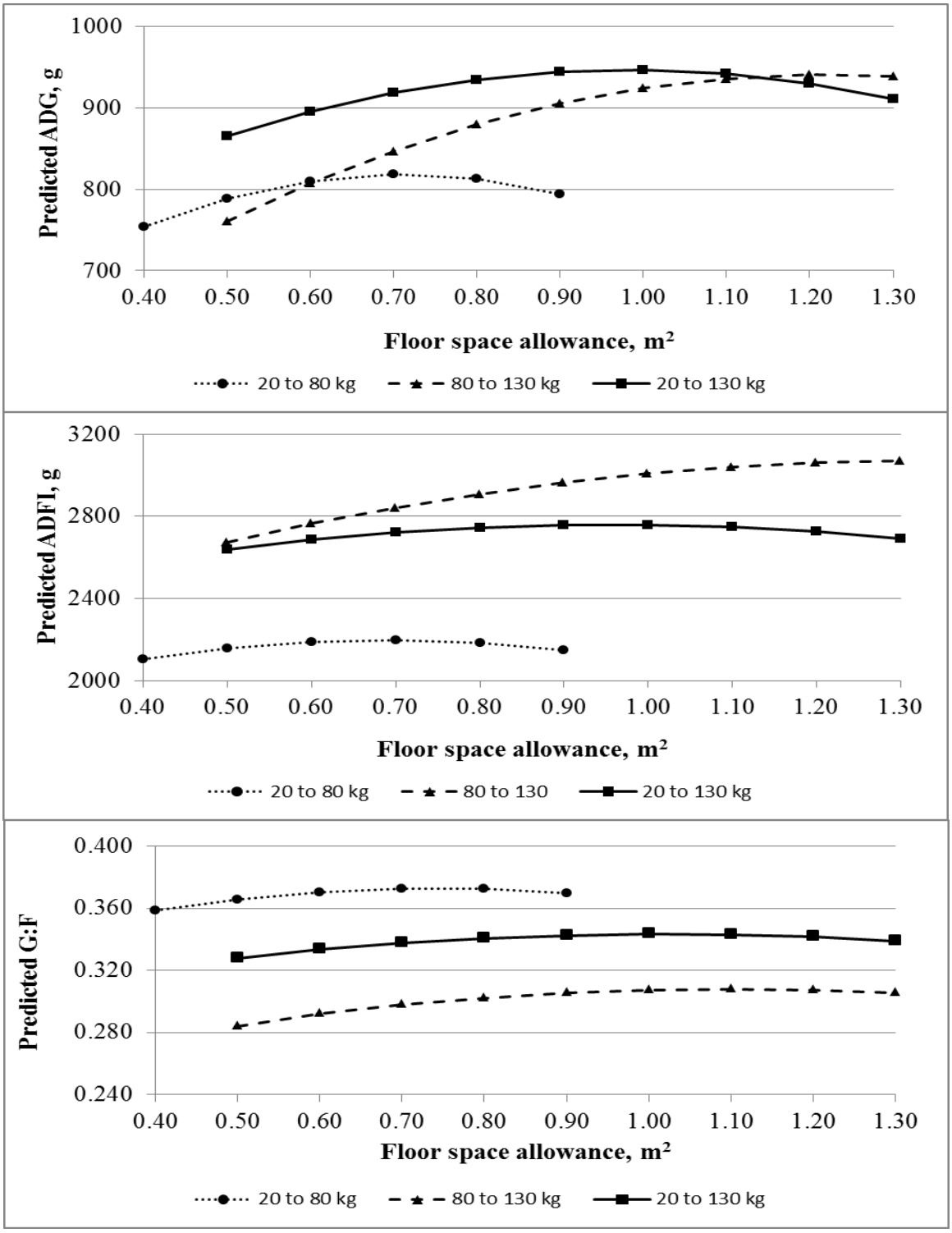

Figure 4-4. Predicted ADG, ADFI, and G:F of pigs from 20 to 80 kg, 80 to 130 kg, and from 20 to 130 kg as floor space allowance changes. Equations were developed from the second database with pig removal studies The predicted ADG, ADFI, and G:F values derived from the second database were calculated using the models with the following coefficients (± SE): ADG (g/d) = 16,468 ± 2,129.36 × *k* – 237,350 ± 37,353 × k^2 -3.1209 ± 0.9016 × Initial BW (kg) + 2.5690 ± 0.7902 × Final BW (kg) + 71.6918 ± 18.8745 × *k* × Initial BW (kg) + 337.57 ± 81.5622; ADFI (g/d) = 24,785 ± 4,468.30 × *k* – 388,998 ± 75,164 × k^2 -3.0027 ± 1.9869× Initial BW (kg) + 11.2460 ± 1.9570 × Final BW (kg) + 187.61 ± 37.2306 × *k* × Initial BW (kg) + 833.41 ± 188.05; G:F = Predicted ADG/Predicted ADFI.

Chapter 5 - A survey of current feeding regimens for vitamins and trace minerals in the U.S. swine industry

SUMMARY

Nutritionists representing production systems across the United States were surveyed about added vitamin and trace mineral concentrations in swine diets used from March to August of 2014. In total, 18 production systems representing approximately 2.3 million sows (~40% of the U.S. sow herd) participated in the survey. Data were compiled into relatively consistent weight ranges and dietary phases across all participating producers. Results were pooled to determine descriptive statistics (average, weighted average, standard deviation, median, minimum, maximum, 25^{th} percentile, and 75^{th} percentile). Within each dietary phase, the nutrients of interest were: vitamins A, D, E, and K; thiamin; riboflavin; niacin; pantothenic acid; pyridoxine; biotin; folic acid; vitamin B_{12}; choline; betaine; vitamin C; carnitine; Cu; I; Fe; Mn; Se; Zn; Co; and Cr. Average supplementation rates for vitamins and trace minerals within each phase of production were compared to the requirement estimates reported in the NRC (2012). Results indicated tremendous variation in supplementation rates, but most vitamins and trace minerals were included at levels above the requirement estimates reported in the NRC (2012). Ultimately, evaluating current supplementation practices can be used to develop future experimental designs to test vitamin and trace mineral supplementation practices.

Keywords: swine, trace minerals, vitamins, swine industry, survey

INTRODUCTION

The proper vitamin and trace mineral supplementation required to optimize performance, but also minimize unnecessary cost, is an area of limited knowledge for production nutritionists. Most commercial diets are formulated well above NRC (2012) requirement estimates a margin of safety needed to account for potential ingredient concentration variation and bioavailability, fluctuations in daily feed intake, or degradation of vitamins resulting from unfavorable storage conditions. A notable survey conducted by Coelho and Cousins (1997[1]) examined vitamin supplementation rates from 23 swine entities. From the survey, researchers found that all entities supplied vitamins at levels higher than NRC (1988[2]) recommendations. Also, entities in the highest quartile supplied vitamins at rates of 2 to 10 times that of the lowest quartile. This survey showed that a wide range of supplementation rates were used across commercial systems. Ultimately, since publication of this survey, two NRC publications have illustrated the long lapse in time since a survey was conducted to examine industry vitamin supplementation rates. To our knowledge, there has never been a survey of the supplementation rates of trace minerals used in commercial diet formulation. Mahan et al. (2013[3]) discussed the potential need to express trace mineral pig requirements on a digestible basis which would help account for the impact that exogenous enzymes and mineral sources may have on the requirement of the nutrient. Because of the increased usage of phytase and other enzymes, along with the increased availability of organic trace mineral sources there is interest in characterizing trace mineral usage in the swine industry. With this information, future research examining various vitamin and trace mineral concentrations of commercially raised pigs could be conducted. Potential for future research,

based on findings of the survey, will better help determine vitamin and trace mineral requirements needed to optimize performance and maximize economic return.

MATERIALS AND METHODS

The procedures for this survey were approved by the Kansas State University Committee for Research Involving Human Subjects. The survey information was gathered in an electronically based spreadsheet in Excel® (Microsoft, Redmond, Washington).

The subjects of the survey were swine producers within the United States. Nutritionists for the swine producers were contacted via email or phone from March to August of 2014 and were asked if they were willing to participate. Those willing to participate were provided the survey spreadsheet, or a phone interview was conducted to collect their information.

The goal of the survey was to determine and identify industry levels of added vitamins and trace minerals in complete diets for different phases of production. The phases of production were: nursery (weaning to 23 kg), finishing (23 kg to market), gilt development (pre-breeding), and breeding herd diet formulations. Producers provided approximate weight breaks for feeding phases within each stage of production along with the premix specifications, inclusion rates, and inclusion rates of any other added vitamin, vitamin-like nutrients and trace minerals.

Results were compiled and pooled to determine descriptive statistics for the supplementation rates. The descriptive statistics used included: average, weighted average (determined by the total number of sows), median, minimum, maximum, 25^{th} percentile (lowest quartile), and 75^{th} percentile (highest quartile). Sow inventories were obtained from the successful farmer 2013 Pork Powerhouse list[4], and producers who were not on the top 25

producers list were asked to provide a current sow inventory. All values were determined using Excel formula functions including average, standard deviation (STDEV.S), median, minimum(MIN), maximum (MAX), 25th and 75th percentiles (QUARTILE.EXC). Weighted averages were calculated using the sumproduct function of Excel in which producer supplementation rate was multiplied by the size of the producer (sow herd size) then divided by the total number of sows for all participating producers.

Feeding phases and approximate dietary weight breaks varied from producer to producer; however; results are reported in broad weight ranges that were relatively consistent across all participating producers. Feeding phases for this summary were divided into the following: nursery diets— phase 1 (weaning to 7 kg), phase 2 (7 to 11 kg), and phase 3 (11 to 23 kg); finishing diets — early finishing (23 to 55 kg), mid-finishing (55 to 100 kg), late finishing (100 kg to market), and late finishing with ractopamine HCl (100 kg to market); and breeding herd diets — gilt development (20 kg to breeding), gestation, lactation, and boar.

Within each dietary phase, the vitamins, vitamin-like substances, and trace minerals of interest were: vitamins A, D, E, and K (menadione); thiamin; riboflavin; niacin; pantothenic acid; pyridoxine; biotin; folic acid; vitamin B_{12}; choline; betaine; vitamin C (ascorbic acid); carnitine; copper (Cu); iodine (I); iron (Fe); manganese (Mn); selenium (Se); zinc (Zn); cobalt (Co); and chromium (Cr). Participants were also asked to provide the specified source of the nutrient used within each dietary phase in order to distinguish potential differences in the use of vitamin/trace mineral sources.

RESULTS AND DISCUSSION

Average supplementation rates for vitamins and trace minerals within each phase of production were compared to NRC (2012[5]) total dietary requirements to quantify supplementation rates of the industry compared to published requirement estimates (Table 5-1).

In total, 18 U.S. swine production systems participated in the survey, totaling approximately 2,268,900 sows. Using the December 2013 U. S. Department of Agriculture sow inventory estimate of 5,760,000 (USDA, 2013[6]), this survey sampled information from approximately 40% of the U.S. sow herd.

Nursery

Phase 1 (weaning to 7 kg) nursery diet supplementation rates (Table 5-2) were provided by 13 producers, which represented approximately 19.4% of the U.S. sow inventory. Fat-soluble vitamins were supplemented (average nutrient) at a rate of 4.6 to 11.6 times that of their NRC (2012) requirement estimates. Vitamin D was supplemented at 11.6 times that of the NRC requirement estimate, and a high amount of variation (SD; 2,303 IU/kg) occurred in vitamin D supplementation across producers. Water-soluble vitamins were supplemented from 0.4 to 5.5 times their NRC requirement estimates. Both pyridoxine and choline were supplemented below their requirement estimate, presumably because other ingredients in the diet provide adequate concentrations of the nutrients. One producer supplied betaine as a methyl donor rather than choline, and one producer added vitamin C to the weaning-to-7-kg diet. Trace minerals were supplemented from 1.0 to 30.3 times their requirement estimate. Iron and Se were those supplemented at their requirement estimate, and Cu and Zn were supplemented well above their requirement estimate, at 18.6 and 30.3 times, respectively. Presumably, the high inclusion rate is used for growth promotion discussed previously by Reese and Hill (2010[7]). Carnitine was

supplemented by one producer, and 5 producers supplemented Cr to the weaned pigs during this phase.

Phase 2 (7 to 11 kg) nursery diet supplementation rates (Table 5-3) were provided from 17 participants, representing 39.0% of the U.S. sow herd. Fat-soluble vitamins were supplemented at rates ranging from 4.0 to 8.1 times their NRC requirement estimates. Water-soluble vitamins were supplemented at rates from 0.4 to 7.1 times their respective NRC requirement estimates. Similar to phase 1 diets, added choline and pyridoxine were supplemented below NRC requirement estimate, presumably because other ingredients provide these nutrients. Trace minerals were supplemented at rates of 1.0 (Se) to 9.1 times their NRC requirement estimates, except for Zn (20.8) and Cu (19.7), which are likely supplemented at high concentrations for growth promotion purposes. One producer supplemented betaine rather than choline as a methyl donor, and 5 producers supplemented Cr in phase 2 nursery diets.

Phase 3 (11 to 23 kg) nursery diet supplementation rates (Table 5-4) were provided by all 18 producers who participated in the survey. Fat-soluble vitamins were supplemented at 4.3 to 7.7 times their respective NRC requirement estimates. Water-soluble vitamins were supplemented at 1.2 to 6.3 times their respective NRC requirement estimates. No producers who participated in the survey supplemented choline in phase 3 nursery diets. Trace minerals were supplemented at rates of 1.0 to 9.8 times their NRC requirement estimates, except for Cu, which was supplemented at a rate of 31.6 times the pig's requirement estimate — probably due to its growth-promotion influences. One producer supplemented Co in phase 3 nursery diets.

Finishing

Early finishing diet (23 to 55 kg) supplementation rates (Table 5-5) were provided by all 18 producers who participated in the survey. Fat-soluble vitamins were supplemented at 2.5 to

6.7 times their respective NRC requirement estimates. Water-soluble vitamins were supplemented from 0.9 to 2.2 times their respective NRC requirement estimates. On average, niacin was supplemented below the estimated requirement. It is speculated this may be due to the increase (10 to 30 mg/kg) in niacin requirement from the 1998[8] to the 2012 NRC publication. Biotin was supplemented in early finishing diets by two producers. Trace minerals were supplemented at rates of 28.1 times Cu, 3.0 times Fe, 1.4 times I, 12.6 times Mn, 1.4 times Se, and 1.6 times Zn requirement estimates. Again, presumably, the high inclusion of added copper is used for growth promotion. One producer supplemented Co at 0.39 mg/kg.

Mid-finishing (55 to 100 kg) supplementation rates (Table 5-6) were reported by all 18 producers participating in the survey. Fat-soluble vitamins were supplemented at rates of 2.1 to 5.7 times their respective NRC requirement estimates. Water-soluble vitamins were supplemented from 0.8 to 3.8 times their respective NRC requirement estimates. Similar to the previous phase, average niacin supplementation was below the current NRC suggested requirement. Two producers provided added biotin in their mid-finishing diets. Trace minerals were supplemented at rates of 1.6 to 2.7 times the requirement estimate for I, Fe, Se, and Zn. Average supplementation rates of Cu and Mn were 27.4 and 10.7 times their requirement estimates, respectively.

Late finishing (100 kg to market) vitamin and trace mineral supplementation rates (Table 5-7) were provided by all 18 producers who participated in the survey. Fat-soluble vitamins were supplemented at rates of 3.2 times vitamin A, 5.0 times vitamin D, 1.8 times vitamin E, and 3.6 times vitamin K requirement estimates. Water-soluble vitamins were supplemented at rates from 0.7 to 3.3 times their NRC requirement estimates. Niacin, on average, was supplemented at rates below the current NRC requirement. Two producers supplemented biotin in late finishing diets.

Trace minerals were supplemented at rates of 1.5 to 2.4 times the requirement estimate for I, Fe, Se, and Zn. Average supplementation rates of Cu and Mn were 22.0 and 9.3 times their requirement estimates, respectively. One producer did not supply added trace minerals in late finishing diets except for added Zn.

Supplementation rates of vitamins and trace minerals in late finishing diets with ractopamine HCl (Table 5-8) were reported by 7 of the 18 producers. Fat-soluble vitamin supplementation rates were 3.4 times vitamin A, 5.2 times vitamin D, 1.9 times vitamin E, and 3.9 times vitamin K requirement estimates. Water-soluble vitamins were supplemented at rates from 0.7 to 3.4 times their NRC requirement estimates. Niacin, on average, was supplemented at rates below the current NRC requirement estimate. Trace minerals were supplemented at rates of 1.4 to 2.3 times the requirement estimate for I, Fe, Se, and Zn. Average supplementation rates of Cu and Mn were 17.1 and 9.0 times their requirement estimates, respectively. Overall, producers who responded with information on both late finishing and late finishing diets with ractopamine HCl, supplemented 10% more vitamins, 8.5% more trace minerals (Cu, I, Fe, Mn, Se), and 33% more Zn in those diets that also contained ractopamine HCl.

Breeding herd diets

Large differences in weight categories were associated with gilt development diets (Table 5-9) across the participating production systems. To collate the information, the last diet fed before gilts entered the breeding herd was used (20 kg to breeding). Seventeen producers participated. Gilt development diets were compared to NRC growing pig (25-50 kg) and gestation requirements because most strategies were associated with feeding growing pigs of similar size or to gestation diet supplementation rates. When evaluating the gilt developer diets compared to the suggested growing pig requirements, average supplementation rates of fat-

soluble vitamins were 3.3 times the vitamin A, 4.9 times vitamin D, 2.6 times vitamin E, and 3.0 times vitamin K requirement estimates. Compared to gestation requirement estimates, average supplementation rates were 1.1 times vitamin A, 0.9 times vitamin D, 0.6 times vitamin E, and 3.0 times vitamin K requirements. Water-soluble vitamins were supplemented at average rates of 1.0 times thiamin, 1.3 times riboflavin, 0.6 times niacin, 1.4 times pantothenic acid, 1.5 times pyridoxine, 1.5 times vitamin B_{12}, 2.5 times biotin, 2.5 times folic acid, and 0.8 times choline requirement estimates for growing pigs. When evaluating the gilt developer diets compared to the suggested gestation requirement estimates, water-soluble vitamins were supplemented at an average of 1.0 times thiamin, 0.9 times riboflavin, 1.8 times niacin, 0.9 times pantothenic acid, 1.5 times pyridoxine, 1.0 times vitamin B_{12}, 0.6 times biotin, 0.6 times folic acid, and 0.2 times choline requirements. One producer supplemented vitamin C at 250 mg/kg. Trace minerals were supplemented at average rates of 5.7 times Cu, 3.7 times I, 1.6 times Fe, 18.6 times Mn, 1.4 times Se, and 2.0 times Zn growing pig requirement estimates. Compared to gestation requirement estimates, developing gilts were supplemented 2.3 times Cu, 3.7 times I, 1.2 times Fe, 1.5 times Mn, 1.9 times Se, and 1.2 times Zn requirements. Five producers supplemented Cr at 0.20 mg/kg, and one producer supplemented Co at 0.39 mg/kg. Two producers supplemented carnitine at a rate of 50 mg/kg of diet.

Gestation diet information (Table 5-10) was provided by 17 of the producers. Fat-soluble vitamins were supplemented at rates of 2.6 times vitamin A, 2.2 times vitamin D, 1.6 times vitamin E, and 7.3 times vitamin K requirement estimates. Water-soluble vitamins were supplemented at rates of 2.2 times thiamin, 2.2 times riboflavin, 4.6 times niacin, 2.3 times pantothenic acid, 3.4 times pyridoxine, 2.4 times vitamin B_{12}, 1.4 times biotin, and 1.3 times folic acid the requirement estimates. Choline was supplemented at 0.5 times its requirement

estimate due to partial reliance of choline from other ingredients to meet the animal's requirement. One producer supplemented vitamin C in gestation diets at a rate of 250 mg/kg. Trace mineral supplementation rates were 1.6 times Cu, 3.8 times I, 1.3 times Fe, 1.5 times Mn, 1.9 times Se, and 1.2 times Zn requirement estimates. Nine producers supplemented Cr, and 1 producer supplemented Co at 0.39 mg/kg. Two producers supplemented carnitine at a rate of 50 mg/kg.

Lactation diet information (Table 5-11) was provided by 17 of the producers. Fat-soluble vitamins were supplemented at rates of 5.2 times vitamin A, 2.2 times vitamin D, 1.6 times vitamin E, and 7.3 times vitamin K requirement estimates. Water-soluble vitamins were supplemented at rates of 2.2 times thiamin, 2.2 times riboflavin, 4.6 times niacin, 2.3 times pantothenic acid, 3.4 times pyridoxine, 2.4 times vitamin B_{12}, 1.4 times biotin, 1.3 times folic acid, and 0.5 times choline requirement estimates. One producer supplemented vitamin C in lactation diets at a rate of 250 mg/kg of diet. Trace mineral supplementation rates were 0.8 times Cu, 3.8 times I, 1.3 times Fe, 1.5 times Mn, 1.9 times Se, and 1.2 times Zn requirement estimates. Nine producers supplemented Cr at a rate of 0.20 mg/kg, and 1 producer supplemented Co at a rate of 0.39 mg/kg. Two producers supplemented carnitine at a rate of 50 mg/kg of diet.

Boar diet information (Table 5-12) was provided by 13 of the producers. Fat-soluble vitamins were supplemented at rates of 2.8 times vitamin A, 9.3 times vitamin D, 1.8 times vitamin E, and 7.0 times vitamin K requirement estimates. Water-soluble vitamins were supplemented at rates of 2.0 times thiamin, 2.2 times riboflavin, 4.5 times niacin, 2.3 times pantothenic acid, 3.2 times pyridoxine, 3.1 times vitamin B_{12}, 1.6 times biotin, 1.4 times folic acid, and 0.6 times choline requirement estimates. One producer supplemented vitamin C in boar

diets at a rate of 250 mg/kg of diet. Trace mineral supplementation rates were 4.0 times Cu, 4.4 times I, 1.4 times Fe, 2.3 times Mn, 1.0 times Se, and 2.8 times Zn requirement estimates. One producer supplemented added Se at levels (0.42 mg/kg) above the maximum concentration of 0.30 mg/kg, which was due to an increased inclusion rate of a premix that was also used in other diets. Seven producers supplemented Cr at a rate of 0.21 mg/kg and 1 producer supplemented Co at a rate of 0.39 mg/kg. One producer supplemented carnitine at a rate of 60 mg/kg of diet.

Nutrient Sources

Along with understanding supplementation rates of vitamins and trace minerals, participants were also asked about the sources of specific nutrients (Table 5-13) used within the diets. The most distinguishable differences among sources within this survey were associated with the supplementation of vitamin D from a cross-linked vitamin A/D_3 beadlet, potential use of natural (d-alpha-tocopherol) vitamin E as a source of vitamin E, and the use of organic trace minerals (Cu, Mn, Se, and Zn). For vitamin D_3, more than 50% of participants supplemented at least 25% of vitamin D from a vitamin A/D_3 cross-linked beadlet across all surveyed diet types. The use of natural (d-alpha-tocopherol) vitamin E as a potential source of vitamin E ranged from 29% to 62% across all surveyed diet types. It is important to note that this question only addresses producers that specifically note natural vitamin E as a possible source when ordering premix from premix blenders. It does not distinguish whether natural vitamin E was used within their premixes or complete diets. Use of organic sources for partial or complete supplementation of Cu, Mn, or Zn ranged from 0 to 46% across surveyed diet types. Organic Se for partial or total Se supplementation ranged from 0 to 77% of respondents across the different diets. Most organic trace mineral supplementation occurred in breeding herd and early nursery diets.

Conclusion

Overall, the collected information covered approximately 40% of the U.S. swine sow herd. Clearly, there is variation in vitamin and trace mineral supplementation rates across the population of respondents within this survey. A wide range of trace mineral supplementation practices was used in early nursery and breeding herd diets, along with wide variations in fat-soluble vitamin supplementation rates. Different sources of some vitamins and trace minerals are also used, which may explain some of the variation in supplementation rates of these nutrients. Most notably, organic trace minerals were supplemented more as a partial or complete sources of the trace mineral (Cu, Mn, Se, Zn) frequently in nursery and breeding herd diets. Also, a large percentage (50%) of producers supplemented at least 25% of vitamin D from an A/D_3 beadlet. In the future, this survey will be useful in developing experimental designs testing vitamin or trace mineral supplementation rates in various phases of production.

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TABLES AND FIGURES

Table 5-1. Comparing average industry supplementation rates to NRC requirements[1]

	Nursery phase			Finishing				Breeding herd				
	1	2	3	Early	Mid	Late	Ractopamine	Gilt development[2]		Gestation	Lactation	Boar
								Grower	Gestation			
Vitamins												
A	4.8	4.7	5.1	4.3	3.7	3.2	3.4	3.3	1.1	2.6	5.2	2.8
D	11.6	8.1	7.7	6.7	5.7	5.0	5.2	4.9	0.9	2.2	2.2	9.3
E	4.6	4.0	4.3	2.5	2.1	1.8	1.9	2.6	0.6	1.6	1.6	1.8
K	7.7	7.8	7.1	4.7	4.0	3.6	3.9	3.0	3.0	7.3	7.3	7.0
Thiamin	1.9	2.9	3.2	0.0	0.0	0.0	0.0	1.0	1.0	2.2	2.2	2.0
Riboflavin	2.3	2.5	2.5	2.0	2.1	1.8	1.9	1.3	0.9	2.2	2.2	2.2
Niacin	1.6	1.6	1.4	0.9	0.8	0.7	0.7	0.6	1.8	4.6	4.6	4.5
Pantothenic acid	2.5	3.0	2.9	2.1	2.1	1.8	1.9	1.4	0.9	2.3	2.3	2.3
Pyridoxine	0.5	0.6	1.2	0.0	0.0	0.0	0.0	1.5	1.5	3.4	3.4	3.2
Vitamin B_{12}	2.0	2.2	2.2	2.2	3.8	3.3	3.4	1.5	1.0	2.4	2.4	3.1
Biotin	4.2	7.1	5.2	1.2	1.1	1.0	0.0	2.5	0.6	1.4	1.4	1.6
Folic acid	5.5	5.9	6.3	0.0	0.0	0.0	0.0	2.5	0.6	1.3	1.3	1.4
Choline	0.4	0.4	0.0	0.0	0.0	0.0	0.0	0.8	0.2	0.5	0.5	0.6
Trace minerals												
Cu	18.6	19.7	31.6	28.1	27.4	22.0	17.1	5.7	2.3	1.6	0.8	4.0
I	3.7	3.9	3.5	3.0	2.7	2.4	2.1	3.7	3.7	3.8	3.8	4.4
Fe	1.0	1.1	1.0	1.4	1.9	1.7	1.8	1.6	1.2	1.3	1.3	1.4
Mn	9.1	8.8	9.8	12.6	10.7	9.3	9.0	18.6	1.5	1.5	1.5	2.3
Se	1.0	1.0	1.1	1.4	1.6	1.5	1.4	1.4	1.9	1.9	1.9	1.0
Zn	30.3	20.8	5.0	1.6	1.7	1.5	2.3	2.0	1.2	1.2	1.2	2.8

[1] Table values represent average supplementation rates as a proportion to total dietary vitamin and trace mineral requirements from the NRC 2012.

[2] Gilt development supplementation rates were compared to the NRC requirements of growing pigs from 25 to 50 kg and also to gestation requirements since most strategies for feeding the developing gilt were related to those two diet types.

Table 5-2. Added vitamin and trace mineral concentrations in phase 1 nursery diets (weaning to 7 kg)[1]

	Count[2]	Weighted average[3]	Average	Standard deviation	Low	25%	Median	75%	High
Vitamins									
A, IU/kg	13	11,033	10,600	832.0	8,800	9,900	9,900	11,002	14,630
D, IU/kg	13	2,222	2,554	2,303	1,542	1,705	1,995	2,200	10,175
E, IU/kg	13	86.0	73.9	27.7	44.0	59.6	66.0	77.0	150.0
K, mg/kg	13	3.7	4.0	0.53	3.1	3.5	4.0	4.4	4.4
Thiamin, mg/kg	5	2.9	2.9	0.42	2.2	2.4	3.1	3.3	3.3
Riboflavin, mg/kg	13	9.5	9.0	1.0	7.7	8.1	8.8	9.9	11.0
Niacin, mg/kg	13	45.8	49.1	11.4	36.1	43.6	45.3	52.4	82.5
Pantothenic acid, mg/kg	13	32.1	30.1	3.6	25.3	27.5	29.7	33.0	37.6
Pyridoxine, mg/kg	11	4.0	3.7	0.97	2.2	3.1	4.0	4.4	5.5
Vitamin B_{12}, µg/kg	13	41.1	38.9	0.24	33.0	33.4	38.5	44.0	45.1
Biotin, mg/kg	11	0.44	0.33	0.90	0.15	0.22	0.26	0.33	1.06
Folic acid, mg/kg	11	1.6	1.6	4.8	0.77	0.99	1.5	1.7	3.6
Choline, mg/kg	6	202.4	245.5	167.0	129.8	129.8	166.8	385.0	550.0
Vitamin C, mg/kg	1	250.0	250.0	---	250.0	---	250.0	---	250.0
Trace minerals									
Copper, mg/kg	13	157.3	111.4	96.9	11.2	15.8	157.7	194.0	248.5
Iodine, mg/kg	13	0.62	0.52	0.21	0.30	0.34	0.50	0.68	1.0
Iron, mg/kg	13	104.6	103.5	15.9	89.8	91.3	99.8	109.9	150
Manganese, mg/kg	13	38.2	36.6	7.7	26.5	30.0	34.9	39.8	55.0
Selenium, mg/kg	13	0.30	0.30	0.004	0.29	0.30	0.30	0.30	0.30
Zinc, mg/kg	13	3,173	3,032	599.5	1,906	2,804	2,931	3,475	4,002
Chromium, mg/kg	5	0.20	0.20	---	0.20	0.20	0.20	0.20	0.20
Conditionally essential nutrients									
Carnitine, mg/kg	1	50.0	50.0	---	50.0	---	50.0	---	50.0
Betaine, mg/kg	1	960.0	960.0	---	960.0	---	960.0	---	960.0

[1] Thirteen producers provided information for phase 1 nursery diets, totaling approximately 1,115,400 sows (19.4% of the U.S. sow herd). All reported values are on a complete feed basis.

[2] Count shows the number of producers who added levels of a nutrient.

[3] Weighted averages were calculated using the sumproduct function of Excel in which the producer supplementation rate was multiplied by the size of the producer (sow herd size), and after summing those products they were divided by the total number of sows for all participating producers.

Table 5-3. Added vitamin and trace mineral concentrations in phase 2 nursery diets (7 to 11 kg)[1]

	Count[2]	Weighted average[3]	Average	Standard deviation	Low	25%	Median	75%	High
Vitamins									
A, IU/kg	17	12,129	10,274	3,373	2,996	9,900	9,900	11,002	19,415
D, IU/kg	17	1,912	1,773	527.8	706.2	1,487	1,760	2,160	2,849
E, IU/kg	17	71.3	63.4	25.1	26.4	44.0	60.1	77.0	125.0
K, mg/kg	17	4.8	4.0	1.5	1.2	3.1	4.0	4.4	8.4
Thiamin, mg/kg	5	2.9	2.9	0.42	2.2	2.4	3.1	3.3	3.3
Riboflavin, mg/kg	17	9.7	8.6	2	3.3	7.7	8.4	9.9	13.6
Niacin, mg/kg	17	51.3	47.7	15.2	25.1	41.1	45.1	50.8	82.5
Pantothenic acid, mg/kg	17	35.6	29.7	8.6	10.6	26.4	29.3	33.0	54.8
Pyridoxine, mg/kg	9	4.0	4.0	0.81	3.1	3.3	4.0	4.6	5.5
Vitamin B_{12}, µg/kg	17	46.0	38.5	11.9	16.5	33.0	38.5	44.0	73.7
Biotin, mg/kg	11	0.37	0.35	0.22	0.15	0.22	0.29	0.33	0.99
Folic acid, mg/kg	11	1.8	1.8	0.90	0.88	1.1	1.5	2.2	3.5
Choline, mg/kg	4	224.4	209.0	97.0	129.8	129.8	187.0	308.0	330.0
Trace minerals									
Copper, mg/kg	17	169.1	118.2	96.0	11.2	15.0	156.5	195.1	248.5
Iodine, mg/kg	17	0.62	0.54	0.21	0.30	0.34	0.55	0.70	1.0
Iron, mg/kg	17	118.0	106.4	29.0	61.1	89.8	99.8	110.1	166.7
Manganese, mg/kg	17	33.5	35.0	7.8	24.2	29.1	33.1	39.5	55.0
Selenium, mg/kg	17	0.29	0.29	0.02	0.22	0.30	0.30	0.30	0.30
Zinc, mg/kg	17	2,340	2,081	751.4	75.0	1,908	2,050	2,527	3,294
Chromium, mg/kg	5	0.23	0.21	0.03	0.20	0.20	0.20	0.24	0.27
Conditionally essential nutrients									
Betaine, mg/kg	1	960.0	960.0	---	960.0	---	960.0	---	960.0

[1] Seventeen producers provided information for phase 2 nursery diets, totaling approximately 2,243,900 sows (39.0% of the U.S. sow herd). All reported values are on a complete feed basis.

[2] Count shows the number of producers who added levels of a nutrient.

[3] Weighted averages were calculated using the sumproduct function of Excel in which the producer supplementation rate was multiplied by the size of the producer (sow herd size), and after summing those products they were divided by the total number of sows for all participating producers.

Table 5-4. Added vitamin and trace mineral concentrations in phase 3 nursery diets (11 to 23 kg)[1]

	Count[2]	Weighted average[3]	Average	Standard deviation	Low	25%	Median	75%	High
Vitamins									
A, IU/kg	18	10,954	8,868	3,676	3,630	5,940	9,434	11,000	18,698
D, IU/kg	18	1,760	1,537	552.2	825.0	979.0	1,478	1,984	2,748
E, IU/kg	18	51.5	46.9	20.5	16.5	36.3	43.8	50.2	100.1
K, mg/kg	18	4.4	3.5	1.6	1.3	2.4	4.0	4.4	8.1
Thiamin, mg/kg	2	3.1	3.1	0.16	3.1	---	3.1	---	3.3
Riboflavin, mg/kg	18	8.6	7.5	2.4	3.3	5.5	8.1	9.0	13.2
Niacin, mg/kg	18	46.2	41.6	17.6	16.5	26.4	39.2	50.4	82.5
Pantothenic acid, mg/kg	18	32.1	25.7	9.7	10.8	19.4	25.1	30.6	52.8
Pyridoxine, mg/kg	5	4.2	3.5	1.9	0.88	1.8	4.0	5.3	5.5
Vitamin B_{12}, µg/kg	18	42.2	33.2	13.6	16.5	22.9	30.8	39.8	71.3
Biotin, mg/kg	7	0.26	0.26	0.07	0.13	0.22	0.26	0.33	0.33
Folic acid, mg/kg	6	1.9	1.9	1.1	0.99	0.99	1.4	3.1	3.5
Trace minerals									
Copper, mg/kg	18	159.5	158.0	81.3	11.2	99.5	158.4	200.6	326.5
Iodine, mg/kg	18	0.55	0.49	0.25	0.22	0.30	0.36	0.67	1.0
Iron, mg/kg	18	111.9	104.0	31.3	60.9	76.7	102.5	122.9	166.7
Manganese, mg/kg	18	28.0	29.3	10.9	9.0	24.7	29.8	33.2	55.0
Selenium, mg/kg	16	0.28	0.29	0.08	0.14	0.30	0.30	0.30	0.30
Zinc, mg/kg	18	672.6	401	959.4	65.8	104.4	120.3	145.8	3,030
Chromium, mg/kg	2	0.26	0.20	0.09	0.13	---	0.20	---	0.27
Cobalt, mg/kg	1	0.39	0.39	---	0.39	---	0.39	---	0.39

[1] Eighteen producers provided information for phase 3 nursery diets, totaling approximately 2,268,900 sows (39.4% of the U.S. sow herd). All reported values are on a complete feed basis.

[2] Count shows the number of producers who added levels of a nutrient.

[3] Weighted averages were calculated using the sumproduct function of Excel in which the producer supplementation rate was multiplied by the size of the producer (sow herd size), and after summing those products they were divided by the total number of sows for all participating producers.

Table 5-5. Added vitamin and trace mineral concentrations in early finishing diets (23 to 55 kg)[1]

	Count[2]	Weighted average[3]	Average	Standard deviation	Low	25%	Median	75%	High
Vitamins									
A, IU/kg	18	5,859	5,643	1,057	3,630	5,104	5,533	6,600	7,480
D, IU/kg	18	984.9	998.8	166.5	800.8	825.0	990.0	1,102	1,320
E, IU/kg	18	25.1	27.1	7.7	16.1	20.5	26.4	33.2	39.8
K, mg/kg	18	2.4	2.4	0.57	1.3	2.0	2.4	2.9	3.3
Riboflavin, mg/kg	18	4.8	4.8	1.3	3.3	4.0	4.8	5.7	8.8
Niacin, mg/kg	18	24.9	27.5	6.9	16.5	24.0	26.4	29.7	49.5
Pantothenic acid, mg/kg	18	17.4	16.9	2.9	10.8	14.7	16.5	18.9	22.4
Vitamin B_{12}, µg/kg	18	22.9	22.0	3.1	15.8	19.8	22.4	23.8	26.4
Biotin, mg/kg	2	0.07	0.07	---	0.07	---	0.07	---	0.07
Trace minerals									
Copper, mg/kg	18	80.8	112.3	81.3	4.6	66.9	135.7	156.7	242.1
Iodine, mg/kg	18	0.42	0.42	0.25	0.22	0.30	0.30	0.45	1.0
Iron, mg/kg	18	79.8	86.9	31.3	39.5	70.9	86.0	109.9	123.8
Manganese, mg/kg	18	21.5	25.2	10.9	6.6	15.0	29.3	33.0	40.0
Selenium, mg/kg	18	0.27	0.28	0.08	0.14	0.27	0.30	0.30	0.30
Zinc, mg/kg	18	86.0	98.8	959.4	30.4	78.7	110.0	120.7	150.0
Cobalt, mg/kg	1	0.39	0.39	---	0.39	---	0.39	---	0.39

[1] Eighteen producers provided information for early finishing diets, totaling approximately 2,268,900 sows (39.4% of the U.S. sow herd). All reported values are on a complete feed basis.

[2] Count shows the number of producers who added levels of a nutrient.

[3] Weighted averages were calculated using the sumproduct function of Excel in which the producer supplementation rate was multiplied by the size of the producer (sow herd size), and after summing those products they were divided by the total number of sows for all participating producers.

Table 5-6. Added vitamin and trace mineral concentrations in mid-finishing diets (55 to 100 kg)[1]

	Count[2]	Weighted average[3]	Average	Standard deviation	Low	25%	Median	75%	High
Vitamins									
A, IU/kg	18	5,192	4,842	955.2	3,520	3,852	5,280	5,603	6,162
D, IU/kg	18	874.9	859.1	150.7	550.0	790.7	880.0	990.0	1,057
E, IU/kg	18	22.2	23.3	7.9	16.1	17.4	19.8	27.7	39.8
K, mg/kg	18	2.2	2.0	0.46	1.3	1.7	2.2	2.2	2.9
Riboflavin, mg/kg	18	4.2	4.2	1.4	2.6	3.3	4.2	4.8	8.8
Niacin, mg/kg	18	22.0	23.5	5.1	16.5	20.7	22.0	26.4	34.5
Pantothenic acid, mg/kg	18	15.4	14.5	2.4	10.8	12.1	14.5	16.9	17.8
Vitamin B_{12}, µg/kg	18	20.2	18.9	3.1	13.2	15.8	19.6	22.0	24.2
Biotin, mg/kg	2	0.07	0.07	---	0.07	---	0.07	---	0.07
Trace minerals									
Copper, mg/kg	18	66.6	82.3	65.0	3.9	10.1	109.1	146.5	161.7
Iodine, mg/kg	18	0.39	0.37	0.25	0.16	0.20	0.30	0.39	1.0
Iron, mg/kg	18	73.7	75.0	22.5	32.9	61.5	73.3	88.5	123.8
Manganese, mg/kg	18	19.4	21.4	10.5	6.4	15.0	22.0	24.5	40.0
Selenium, mg/kg	18	0.26	0.24	0.04	0.11	0.20	0.24	0.30	0.30
Zinc, mg/kg	18	77.8	84.8	32.3	30.4	61.5	89.1	100.0	131.2
Cobalt, mg/kg	1	0.31	0.31	---	0.31	---	---	---	0.31

[1] Eighteen producers provided information for mid-finishing diets, approximately 2,268,900 sows (39.4% of the U.S. sow herd). All reported values are on a complete feed basis.

[2] Count shows the number of producers who added levels of a nutrient.

[3] Weighted averages were calculated using the sumproduct function of Excel in which the producer supplementation rate was multiplied by the size of the producer (sow herd size), and after summing those products they were divided by the total number of sows for all participating producers.

Table 5-7. Added vitamin and trace mineral concentrations in late finishing diets (100 kg to market)[1]

	Count[2]	Weighted average[3]	Average	Standard deviation	Low	25%	Median	75%	High
Vitamins									
A, IU/kg	18	4,616	4,187	999.2	2,904	3,520	3,942	4,840	6,160
D, IU/kg	18	781.7	745.8	209.0	412.5	550.0	756.4	897.6	1,078
E, IU/kg	18	19.6	20.0	6.6	8.1	16.5	17.6	24.0	33.4
K, mg/kg	18	1.9	1.8	0.53	1.0	1.3	1.8	2.2	2.9
Riboflavin, mg/kg	18	3.7	3.5	0.95	2.0	3.1	3.3	4.2	5.5
Niacin, mg/kg	18	19.4	20.2	4.8	15.0	16.7	18.3	22.4	33.0
Pantothenic acid, mg/kg	18	13.6	12.5	3.1	6.8	11.0	12.3	14.5	18.5
Vitamin B_{12}, µg/kg	18	18.0	16.5	3.5	7.9	15.2	16.5	18.5	22.2
Biotin, mg/kg	2	0.04	0.04	0.01	0.04	---	0.04	---	0.07
Trace minerals[4]									
Copper, mg/kg	17	56.3	65.9	71.0	3.1	8.1	10.0	147.2	160.8
Iodine, mg/kg	17	0.37	0.34	0.24	0.15	0.18	0.24	0.42	1.0
Iron, mg/kg	17	69.3	66.5	25.2	30.9	54.1	62.9	80.3	103.1
Manganese, mg/kg	17	17.7	18.6	9.8	3.3	14.7	19.4	23.0	40.0
Selenium, mg/kg	17	0.24	0.22	0.08	0.12	0.17	0.20	0.30	0.30
Zinc, mg/kg	18	71.7	73.8	26.8	30.4	55.0	74.9	90.1	131.2
Cobalt, mg/kg	1	0.31	0.31	---	0.31	---	0.31	---	0.31

[1] Eighteen producers provided information for late finishing, totaling approximately 2,268,900 sows (39.4% of the U.S. sow herd). All reported values are on a complete feed basis.

[2] Count shows the number of producers who added levels of a nutrient.

[3] Weighted averages were calculated using the sumproduct function of Excel in which the producer supplementation rate was multiplied by the size of the producer (sow herd size), and after summing those products they were divided by the total number of sows for all participating producers.

[4] One producer did not supplement trace minerals in the late finishing diets except for added zinc.

Table 5-8. Added vitamin and trace mineral concentrations in late finishing diets with ractopamine (100 kg to market)[1]

	Count[2]	Weighted average[3]	Average	Standard deviation	Low	25%	Median	75%	High
Vitamins									
A, IU/kg	7	5,247	4,473	1,099	3,520	3,630	3,960	5,500	6,160
D, IU/kg	7	911.0	774.0	284.9	440.0	550.0	770.0	1,008.3	1,078.0
E, IU/kg	7	25.5	21.1	7.5	10.1	17.6	20.9	27.5	30.8
K, mg/kg	7	2.2	2.0	0.48	1.3	1.7	2.0	2.4	2.9
Riboflavin, mg/kg	7	4.4	3.7	1.2	2.4	3.1	4.0	4.8	5.5
Niacin, mg/kg	7	20.2	20.5	2.9	16.5	18.7	20.7	22.0	24.6
Pantothenic acid, mg/kg	7	15.6	13.6	3.7	8.6	11.0	13.0	16.5	18.5
Vitamin B_{12}, µg/kg	7	18.5	16.9	4.4	9.9	13.2	17.6	19.8	22.0
Trace minerals									
Copper, mg/kg	7	66.2	51.4	76.6	3.9	8.9	11.5	154.7	159.7
Iodine, mg/kg	7	0.37	0.29	0.13	0.20	0.20	0.20	0.37	0.50
Iron, mg/kg	7	67.1	71.6	19.6	38.6	64.9	66.5	88.7	99.1
Manganese, mg/kg	7	19.8	18.0	10.2	4.1	4.5	20.9	24.9	27.4
Selenium, mg/kg	7	0.18	0.21	0.06	0.12	0.15	0.19	0.27	0.28
Zinc, mg/kg	7	113.9	112.5	29.6	74.8	99.1	105.2	131.2	160.2
Cobalt, mg/kg	1	0.35	0.35	---	0.35	---	0.35	---	0.35

[1] Seven producers provided information for late finishing diets with ractopamine, totaling approximately 556,000 sows (9.7% of the U.S. sow herd). All reported values are on a complete feed basis.

[2] Count shows the number of producers who added levels of a nutrient.

[3] Weighted averages were calculated using the sumproduct function of Excel in which the producer supplementation rate was multiplied by the size of the producer (sow herd size), and after summing those products they were divided by the total number of sows for all participating producers.

Table 5-9. Added vitamin and trace mineral concentrations in gilt development diet (20 kg to breeding)[1]

	Count[2]	Weighted average[3]	Average	Standard deviation	Low	25%	Median	75%	High
Vitamins									
A, IU/kg	17	8,452	9,405	2,444	4,400	9,900	9,979	11,000	11,986
D, IU/kg	17	1,339	1,621	497.2	687.5	1,320	1,760	1,996	2,218
E, IU/kg	17	52.1	62.5	29.7	16.5	48.4	60.1	66.0	150.0
K, mg/kg	17	3.1	3.3	1.1	1.3	2.4	3.1	4.4	4.8
Thiamin, mg/kg	5	2.0	2.2	0.77	1.1	1.7	2.2	2.8	3.3
Riboflavin, mg/kg	17	6.6	7.5	2.0	4.0	5.5	7.7	8.8	9.9
Niacin, mg/kg	17	34.3	40.3	10.8	20.9	38.5	44.0	45.3	55.0
Pantothenic acid, mg/kg	17	23.5	25.1	5.9	15.4	22.0	25.3	28.6	35.0
Pyridoxine, mg/kg	12	3.5	3.3	1.1	0.88	2.8	3.3	4.0	5.1
Vitamin B_{12}, µg/kg	17	30.1	32.1	7.7	19.4	27.5	33.0	37.2	44.0
Biotin, mg/kg	16	0.24	0.29	0.09	0.07	0.22	0.26	0.33	0.44
Folic acid, mg/kg	15	1.7	1.7	0.73	1.1	1.3	1.5	1.8	3.5
Choline, mg/kg	13	572.0	541.2	132.0	259.6	519.2	519.2	611.6	818.4
Vitamin C, mg/kg	1	250.0	250.0	---	250.0	---	250.0	---	250.0
Trace minerals									
Copper, mg/kg	17	25.1	22.9	30.0	8.8	12.2	15.0	16.5	136.8
Iodine, mg/kg	17	0.50	0.51	0.30	0.22	0.33	0.38	0.66	1.3
Iron, mg/kg	17	88.7	97.8	23.1	61.1	89.8	99.8	110.0	149.5
Manganese, mg/kg	17	30.7	37.2	14.4	14.2	26.5	33.1	50.0	70.0
Selenium, mg/kg	17	0.29	0.29	0.03	0.20	0.30	0.30	0.30	0.30
Zinc, mg/kg	17	105.3	121.5	26.8	60.8	110.1	123.8	130.0	173.6
Chromium, mg/kg	5	0.20	0.20	---	0.20	---	0.20	---	0.20
Cobalt, mg/kg	1	0.39	0.39	---	0.39	---	0.39	---	0.39
Conditionally essential nutrients									
Carnitine, mg/kg	2	50.0	50.0	---	50.0	---	50.0	---	50.0

[1] Seventeen producers provided information for gilt development diets, totaling approximately 2,223,600 sows (38.6% of the U.S. sow herd). All reported values are on a complete feed basis.

[2] Count shows the number of producers who added levels of a nutrient.

[3] Weighted averages were calculated using the sumproduct function of Excel in which the producer supplementation rate was multiplied by the size of the producer (sow herd size), and after summing those products they were divided by the total number of sows for all participating producers.

Table 5-10. Added vitamin and trace mineral concentrations in gestation diets[1]

	Count[2]	Weighted average[3]	Average	Standard deviation	Low	25%	Median	75%	High
Vitamins									
A, IU/kg	17	9,819	10,362	1,026	7,698	9,900	11,000	11,002	11,986
D, IU/kg	17	1,531	1,783	360.4	1,097	1,562	1,762	2,141	2,218
E, IU/kg	17	66.0	70.0	25.1	44.0	59.0	66.0	73.9	150.0
K, mg/kg	17	3.5	3.7	0.99	1.7	2.8	4.0	4.4	4.8
Thiamin, mg/kg	5	2.1	2.2	0.77	1.1	1.7	2.2	2.8	3.3
Riboflavin, mg/kg	17	7.5	8.1	1.4	5.5	7.3	8.4	9.5	9.9
Niacin, mg/kg	17	40.5	45.5	11.7	24.2	41.1	44.0	49.1	82.5
Pantothenic acid, mg/kg	17	26.8	27.3	4.0	22.0	24.4	27.5	29.5	35.0
Pyridoxine, mg/kg	13	4.0	3.5	1.1	0.88	3.0	3.3	4.4	5.1
Vitamin B_{12}, µg/kg	17	34.1	35.2	4.8	27.3	33.0	33.9	38.5	44.0
Biotin, mg/kg	17	0.26	0.29	0.07	0.22	0.22	0.24	0.33	0.44
Folic acid, mg/kg	17	1.7	1.7	0.59	1.1	1.3	1.7	1.7	3.5
Choline, mg/kg	17	645.3	610.7	114.4	389.8	519.6	571.8	713.0	788.7
Vitamin C, mg/kg	1	250.0	250.0	---	250.0	---	250.0	---	250.0
Trace minerals									
Copper, mg/kg	17	15.0	16.1	6.0	6.8	13.2	15.0	16.5	35.0
Iodine, mg/kg	17	0.56	0.53	0.30	0.16	0.31	0.50	0.68	1.3
Iron, mg/kg	17	101.8	102.2	28.8	45.4	89.9	100.0	115.1	165.0
Manganese, mg/kg	17	32.5	37.6	13.2	21.2	25.7	38.5	50.0	70.0
Selenium, mg/kg	17	0.29	0.29	0.04	0.14	0.30	0.30	0.30	0.30
Zinc, mg/kg	17	112.9	123.0	28.3	56.7	108.0	125.0	147.2	165.0
Chromium, mg/kg	9	0.20	0.20	---	0.20	0.20	0.20	0.20	0.20
Cobalt, mg/kg	1	0.39	0.39	---	0.39	---	0.39	---	0.39
Conditionally essential nutrients									
Carnitine, mg/kg	2	50.0	50.0	---	50.0	---	50.0	---	50.0

[1] Seventeen producers provided information for gestation diets, totaling approximately 2,223,600 sows (38.6% of the U.S. sow herd). All reported values are on a complete feed basis.

[2] Count shows the number of producers who added levels of a nutrient.

[3] Weighted averages were calculated using the sumproduct function of Excel in which the producer supplementation rate was multiplied by the size of the producer (sow herd size), and after summing those products they were divided by the total number of sows for all participating producers.

Table 5-11. Added vitamin and trace mineral concentrations in lactation diets[1]

	Count[2]	Weighted average[3]	Average	Standard deviation	Low	25%	Median	75%	High
Vitamins									
A, IU/kg	17	9,997	10,404	918.5	8,415	9,900	11,000	11,002	11,986
D, IU/kg	17	1,557	1,789	348.7	1,100	1,562	1,762	2,141	2,218
E, IU/kg	17	67.1	70.2	24.9	44.0	59.0	66.0	73.9	150.0
K, mg/kg	17	3.5	3.7	0.99	1.7	2.8	4.0	4.4	4.8
Thiamin, mg/kg	5	2.1	2.2	0.77	1.1	1.7	2.2	2.8	3.3
Riboflavin, mg/kg	17	7.7	8.1	1.4	5.5	7.3	8.4	9.5	9.9
Niacin, mg/kg	17	41.4	45.8	11.7	24.2	41.1	44.0	49.1	82.5
Pantothenic acid, mg/kg	17	27.3	27.5	3.7	22.0	24.6	27.5	29.5	35.0
Pyridoxine, mg/kg	13	4.0	3.5	1.1	0.88	3.0	3.3	4.4	5.1
Vitamin B_{12}, µg/kg	17	34.8	35.4	4.6	27.5	33.0	33.9	38.5	44.0
Biotin, mg/kg	17	0.29	0.29	0.07	0.22	0.22	0.24	0.33	0.44
Folic acid, mg/kg	17	1.7	1.7	0.59	1.1	1.3	1.7	1.8	3.5
Choline, mg/kg	17	478.5	533.9	108.5	259.8	519.6	519.6	609.6	675.6
Vitamin C, mg/kg	1	250.0	250.0	---	250.0	---	250.0	---	250.0
Trace minerals									
Copper, mg/kg	17	15.0	16.1	6.0	6.8	13.2	15.0	16.5	35.0
Iodine, mg/kg	17	0.56	0.53	0.30	0.16	0.31	0.50	0.68	1.3
Iron, mg/kg	17	101.8	102.2	28.8	45.4	89.9	100.0	115.1	165.0
Manganese, mg/kg	17	32.5	37.6	13.2	21.2	25.7	38.5	50.0	70.0
Selenium, mg/kg	17	0.29	0.29	0.04	0.14	0.30	0.30	0.30	0.30
Zinc, mg/kg	17	112.9	123.0	28.3	56.7	108.0	125.0	147.2	165.0
Chromium, mg/kg	9	0.21	0.20	0.01	0.20	0.20	0.20	0.20	0.22
Cobalt, mg/kg	1	0.39	0.39	---	0.39	---	0.39	---	0.39
Conditionally essential nutrients									
Carnitine, mg/kg	2	50.0	50.0	---	50.0	---	50.0	---	50.0

[1] Seventeen producers provided information for lactation diets, totaling approximately 2,223,600 sows (38.6% of the U.S. sow herd). All reported values are on a complete feed basis.

[2] Count shows the number of producers who added levels of a nutrient.

[3] Weighted averages were calculated using the sumproduct function of Excel in which the producer supplementation rate was multiplied by the size of the producer (sow herd size), and after summing those products they were divided by the total number of sows for all participating producers.

Table 5-12. Added vitamin and trace mineral concentrations in boar diets[1]

	Count[2]	Weighted average[3]	Average	Standard deviation	Low	25%	Median	75%	High
Vitamins									
A, IU/kg	13	10,549	11,249	1,898	7,698	9,957	11,000	12,558	15,400
D, IU/kg	13	1,608	1,847	442.9	1,097	1,541	1,760	2,141	2,614
E, IU/kg	13	72.2	77.4	31.0	44.0	59.0	66.0	99.0	150.0
K, mg/kg	13	3.5	3.5	1.0	1.8	2.6	3.7	4.4	4.8
Thiamin, mg/kg	5	2.1	2.0	1.2	0.09	1.1	2.2	2.8	3.3
Riboflavin, mg/kg	13	7.7	8.1	1.5	5.5	7.5	8.4	9.5	9.9
Niacin, mg/kg	13	41.4	44.9	6.6	33.0	41.4	45.1	49.5	55.0
Pantothenic acid, mg/kg	13	27.7	27.7	4.2	22.0	25.3	27.5	28.8	37.0
Pyridoxine, mg/kg	10	3.7	3.3	1.6	0.13	2.2	3.3	4.6	5.1
Vitamin B_{12}, µg/kg	13	39.2	46.4	34.8	27.3	33.0	37.2	44.0	160.8
Biotin, mg/kg	13	0.31	0.33	0.15	0.22	0.22	0.29	0.40	0.64
Folic acid, mg/kg	13	1.8	1.8	0.70	1.1	1.3	1.7	2.3	3.5
Choline, mg/kg	10	637.6	715.7	507.8	259.8	480.7	584.1	786.1	2,079
Vitamin C, mg/kg	1	250.0	250.0	---	250.0	---	250.0	---	250.0
Trace minerals									
Copper, mg/kg	13	16.6	19.8	10.6	11.2	13.7	15.1	23.9	46.5
Iodine, mg/kg	13	0.62	0.61	0.31	0.22	0.36	0.52	0.71	1.3
Iron, mg/kg	13	109.6	109.0	26.9	61.1	90.1	105.8	122.5	165.0
Manganese, mg/kg	13	35.3	45.1	22.9	21.2	28.1	38.5	64.9	96.8
Selenium, mg/kg	13	0.31	0.31	0.03	0.30	0.30	0.30	0.30	0.42
Zinc, mg/kg	13	122.3	142.5	50.5	83.8	112.8	129.8	170.0	279.3
Chromium, mg/kg	7	0.21	0.21	0.08	0.20	0.20	0.20	0.20	0.24
Cobalt, mg/kg	1	0.39	0.39	---	0.39	---	0.39	---	0.39
Conditionally essential nutrients									
Carnitine, mg/kg	1	60.0	60.0	---	60.0	---	60.0	---	60.0

[1] Thirteen producers provided information for boar diets, totaling approximately 1,921,100 sows (33.4% of the U.S. sow herd). All reported values are on a complete feed basis.

[2] Count shows the number of producers who added levels of a nutrient.

[3] Weighted averages were calculated using the sumproduct function of Excel in which the producer supplementation rate was multiplied by the size of the producer (sow herd size), and after summing those products they were divided by the total number of sows for all participating producers.

Table 5-13. Percentage of participating producers using alternative vitamin and trace mineral sources

	Nursery			Finishing				Breeding herd			
	Phase 1	Phase 2	Phase 3	Early	Mid	Late	Ractopamine	Gilt development	Gestation	Lactation	Boar
Participating producers	13	17	18	18	18	18	7	17	17	17	13
Vitamins											
A/D[1]	92%	76%	67%	67%	67%	67%	86%	65%	65%	65%	54%
E[2]	38%	62%	56%	56%	33%	33%	29%	41%	41%	41%	38%
Trace minerals[3]											
Cu	15%	18%	6%	0%	0%	0%	0%	29%	29%	29%	46%
Mn	15%	18%	6%	0%	0%	0%	0%	29%	29%	29%	46%
Se	69%	47%	33%	6%	6%	6%	0%	76%	76%	76%	77%
Zn	15%	18%	6%	0%	0%	0%	0%	29%	29%	29%	46%

[1] Values represent the percentage of participating producers that provide at least 25% of vitamin D_3 from a vitamin A/D_3 cross-linked beadlet.
[2] Values represent the percentage of participating producers that specify natural (d-alpha-tocopherol) vitamin E as a potential source of vitamin E.
[3] Values represent the percentage of participating producers that supplement partial or complete trace mineral concentrations from organic sources.