INFLUENCE OF DIETARY FIBER AND COPPER ON GROWTH PERFORMANCE AND CARCASS CHARACTERISTICS OF FINISHING PIGS AND UTILIZING LINEAR PROGRAMMING TO DETERMINE PIG FLOW

by

KYLE FRANCIS COBLE

B.S., Oklahoma State University, 2010
M.S., Oklahoma State University, 2012

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Animal Science
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2015

Abstract

A total of 7,061 finishing pigs were used in 7 experiments. Experiment 1 investigated the effects of withdrawing high-fiber ingredients prior to marketing to optimize growth performance, carcass yield, and carcass fat quality. Switching pigs from a high-fiber to a low-fiber corn-soy diet approximately 15 to 19 d before slaughter restored carcass yield and partially decreased carcass fat IV compared to pigs fed the high-fiber diet until slaughter. Experiment 2 studied 30% distillers dried grains with solubles (DDGS) and 5% added fat prior to slaughter on growth performance and carcass characteristics. Adding 5% fat to finishing pig diets containing 30% DDGS approximately 20 d before slaughter improved ADG and G:F but did not overcome the reduction in carcass yield from feeding DDGS. Experiment 3 investigated the Cu source on growth performance and carcass characteristics. Increasing dietary Cu in high byproduct diets improved growth and feed intake, resulting in increased final BW and HCW for pigs fed both Cu sources. Experiment 4 examined added Cu and standardized ileal digestible (SID) lysine (Lys) level on growth performance, carcass characteristics, and carcass fat quality. Feeding 150 mg/kg Cu to pigs in the 100% SID Lys requirement diet had improved growth but in the 85 or 92.5% SID Lys requirement diet no response to added Cu was found. Furthermore, increasing SID Lys increased ADG and HCW, but added Cu did not influence growth when feeding low SID Lys. Experiment 5 investigated diet ingredient type and added Cu on growth performance, carcass characteristics, gross energy digestibility, and small intestine histology and gene expression. When comparing diet type and added Cu, pigs fed a byproduct diet with DDGS and bakery meal tended to have lower G:F and reduced HCW compared to pigs fed a corn-soy diet. Adding Cu did not influence growth or carcass characteristics. However, adding Cu to the byproduct diet improved gross energy digestibility and decreased the crypt depth in the distal small intestine.

Finally, a linear programming model was developed as a decision tool for commercial swine producers to help guide pig flow decisions to maximize the return to the operation.

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Dedication

I dedicate this to my late maternal grandparents, Dr. Glen "Remmy" and Mrs. Eloise "Bonny" Remsberg. I am proud to have finally joined your ranks as a K-Stater!

Preface

This dissertation is original work completed by the author, K. F. Coble. Chapters 1 through 5 were formatted for publication according to the required standards of the Journal of Animal Science. Chapter 6 was formatted for publication according to the required standards of the Journal of Swine Health and Production.

Chapter 1 - Effects of withdrawing high-fiber ingredients before marketing on finishing pig growth performance, carcass characteristics, intestinal weights, and carcass fat quality

Abstract

Two experiments were conducted to determine the duration of high-fiber ingredient removal from finishing pig diets before marketing to optimize growth performance, and restore carcass yield and carcass fat IV, similar to pigs fed a corn-soy diet. In Exp. 1, a total of 288 pigs (initially 38.4 ± 0.3 kg BW) were used in an 88-d study and fed either a low-fiber corn-soy diet from d 0 to 88, or high-fiber diet containing 30% distillers dried grains with solubles (DDGS) and 19% wheat middlings (midds) fed until 20, 15, 10, 5, or 0 d before slaughter and switched to the low-fiber corn-soy diet thereafter. Pigs continuously fed the high-fiber diet tended to have increased ADFI ($P = 0.066$) and decreased G:F and carcass yield ($P = 0.001$) compared to pigs fed the low-fiber corn-soy diet. As days of withdrawal increased, pigs fed the high-fiber diet had increased carcass yield (quadratic; $P = 0.039$). Jowl iodine value (IV) was greater ($P = 0.001$) in pigs fed the high-fiber diet compared with those fed the low-fiber corn-soy diet and decreased (linear; $P = 0.001$) as withdraw time increased. Pigs continuously fed the high-fiber diet had heavier full large intestines ($P = 0.003$) than pigs fed the corn-soy diet. Full large intestine weight decreased (linear; $P = 0.018$) as withdrawal time increased. In Exp. 2, a total of 1,089 pigs (initially 44.5 ± 0.1 kg BW) were used in a 96-d study with the same exact dietary treatments, except pigs were fed the high-fiber diet until 24, 19, 14, 9, or 0 d before slaughter and switched to the low-fiber corn-soy diet. Pigs fed the high-fiber diet through the entire study had decreased ADG and G:F ($P = 0.001$) compared with those fed the low-fiber corn-soy diet. For pigs initially fed the high-fiber diet and then switched to the low-fiber corn-soy diet, G:F tended to improve (linear; P = 0.070) as withdrawal period increased from 0 to 24 d. Pigs fed the high-fiber diet throughout had decreased HCW (P = 0.001) compared to those fed the low-fiber corn-soy diet. Percentage carcass yield using the farm live weight was not significantly influenced by high-fiber diet withdrawal period. However, HCW increased (linear; P = 0.052) as withdrawal period increased. In summary, switching pigs from a high-fiber to a low-fiber corn-soy diet approximately 15 to 19 d before slaughter restored carcass yield and partially decreased carcass fat IV compared to pigs fed the high-fiber diet until slaughter.

Key Words: energy, fat quality, fiber, intestinal weights, pigs, withdrawal

Introduction

Byproduct ingredients generally contain higher amounts of dietary fiber and are lower in energy than their originating grain sources (NRC, 2012). For both nutritionists and producers, there is a large amount of research that has investigated various byproduct ingredients showing both benefits and negative impacts in finishing pig diets. For instance, in a review researchers (Stein and Shurson, 2009) report that up to 30% distillers dried grains with solubles (DDGS) can be fed without detrimental effects on growth performance but decreases carcass fat saturation and carcass yield.

While there are certainly economic advantages to using byproduct ingredients when they are cost effective, it has been shown that the higher amounts of dietary fiber negatively impacts carcass yield by increasing the weight of intestinal contents (Turlington, 1984). Previous research has sought to better understand the effects of switching pigs from a high-fiber to low-fiber corn-soy diet before slaughter on growth, carcass yield, and carcass fat quality (Nemechek et al., 2013; Asmus et al., 2014; Graham et al., 2014). Research by Asmus et al. (2014) and Graham et al. (2014) reported that pigs switched from a high-fiber diet containing 30% DDGS and 19% midds approximately 3 wk before slaughter had similar carcass yield and decreased carcass IV compared to those fed a corn-soy diet throughout an entire finishing phase. However, researchers have yet to investigate the potential changes in ADG, carcass yield and IV within this critical window of time between slaughter and the 3 wk prior. Thus, using this dietary model (Asmus et al., 2014), the objective of our studies were to determine the optimal duration that finishing pigs should be switched from a high- to low-fiber corn-soy diet before slaughter to optimize growth performance, carcass yield, and IV.

Materials and Methods

All experimental procedures and animal care were approved by the Kansas State University Institutional Animal Care and Use Committee.

General

Experiment 1 was conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. Pigs were housed in an enclosed environmentally regulated, mechanically ventilated barn containing 36 pens (2.44 m × 3.05 m). The pens had adjustable gates facing the alleyway and allowed 0.93m^2/pig. Each pen was equipped with a cup waterer and a single-sided, dry self-feeder (Farmweld, Teutopolis, IL) with 2 eating spaces located in the fence line for ad libitum access to feed and water. Pens were located over a completely slatted concrete floor with a manure storage pit underneath (1.20-m deep).

Experiment 2 was conducted in a commercial research facility in southwestern Minnesota. The facility was double-curtain sided with completely slatted concrete flooring. The barn contained 48 pens (3.05 m × 5.49 m) equipped with a 5-hole conventional dry self-feeder (Thorp Equipment, Thorp, WI) and a cup waterer providing ad libitum access to feed and water. Facilities in both Exp. 1 and 2 were equipped with a computerized feeding system (FeedPro; Feedlogic Corp., Willmar, MN) that delivered and recorded daily feed additions of specific diets to each pen.

Animals and Diets

Pens of pigs were randomly allotted to 1 of 6 dietary feeding strategies consisting of a low-fiber corn-soybean meal-based diet containing no DDGS or midds (9% NDF) fed from d 0 to 88, or a high-fiber diet containing 30% DDGS and 19% midds (19% NDF) fed until 20, 15, 10, 5, or 0 d before slaughter after which they were switched to the low-fiber, corn-soybean meal-based diet for the remainder of the study. Dietary treatments were fed in 4 phases (Tables 1-1 and 1-2). All diets were fed in meal form and balanced to similar standardized ileal digestible (SID) Lys concentrations within each phase, but were not balanced for energy. Nutrient values used in diet formulation for corn, soybean meal, and midds were from the NRC (2012). For DDGS, AA concentration and SID AA values were from Stein (2007). The ME (3,395 kcal/kg) values for corn were used for the energy values of DDGS, in accordance to Pedersen et al. (2007). The NE (2,525 kcal/kg) values for DDGS were calculated based upon the oil content, as described by Graham et al. (2014).

Feed samples were collected for Exp. 1 at the time of feed delivery and Exp. 2 feed samples were collected from each feeder for each phase and treatment. The complete feed samples, as well as samples of DDGS and midds for each experiment collected at the time of feed manufacturing, were combined into a composite sample and analyzed for moisture (934.01; AOAC International, 2006), CP (990.03; AOAC International, 2006), ether extract (920.39 A;

AOAC International, 2006), crude fiber (978.10; AOAC International, 2006), ADF and NDF (Van Soest, 1963) at a commercial laboratory (Ward Laboratories, Inc. Kearney, NE; Tables 1-3 to 1-6). Bulk density (mass per unit volume, g/L) was also measured for the complete feed using a grain density cup (Seedburo Model 8800; Seedburo Equipment, Chicago, IL; Tables 1-7 and 1-8). Pens of pigs and feeders were weighed approximately every 3 wk to determine ADG, ADFI, and G:F. During the high-fiber withdrawal period, all pens of pigs and feeders were weighed each time a treatment group switched diets.

Experiment 1

A total of 288 pigs (PIC 327 × 1050; PIC, Hendersonville, TN; initially 38.4 ± 0.3 kg) were used in an 88-d experiment. Pens of pigs (4 barrows and 4 gilts per pen) were randomly allotted to 1 of the 6 dietary withdrawal strategies with average pig BW balanced across each treatment with 6 replications (pens) per treatment. On d 68, pigs fed the high-fiber diet were realloted to withdrawal strategy, balancing on both d 0 and d 68 BW. This was done to ensure that any response criteria were not influenced by prior performance when all pigs were fed the same diet.

Before harvest, pigs were individually tattooed for identification purposes at the packing plant. On the final day of the experiment, all pigs and feeders were weighed and each pig was weighed individually to allow carcass yield to be calculated on an individual basis. The second heaviest gilt was identified in each pen (1 pig per pen, 6 pigs per treatment) and transported 3.2 km to the Kansas State University Meat Laboratory while all other pigs were transported 256 km to a commercial packing plant (Triumph Food LLC, St. Joseph, MO). The gilts selected for harvest at the Kansas State University Meats Laboratory were blocked by treatment and randomly assigned to a slaughter order to equalize withdrawal time before slaughter. Feeders were removed from the pens at 1800 h the night before harvest and harvest began at approximately 0600 h the following morning.

Following evisceration, the entire pluck (heart, kidneys, spleen, stomach, cecum, large intestine, small intestine, and reproductive tract) was collected, separated, and weighed. After the full organs were weighed, the stomach, cecum, and large intestine were physically stripped of digestive contents and flushed with water and weighed. Carcass quality measurements were taken 24 h after slaughter on the right side of the carcass, which was ribbed at the 10th rib. Marbling and color scores were determined for the loin according to the American Meat Science Association (AMSA, 2001) and the National Pork Producers Council (NPPC), and ultimate pH was measured using a portable HACCP compliant pH meter designed for meat (model HI 99163; Hanna Instruments, Smithfield, RI).

Fat samples that included adipose from all 3 fat layers were collected from the jowl, belly, backfat, and ham collar. Jowl fat samples were collected from the dorsal end of the carcass. Belly samples were taken from behind the second teat on the teat line. Backfat samples were taken at the 10th rib on the outer edge of the loin. Ham collar samples were collected from the middle portion of the ham collar.

Fatty acid analysis was determined by gas chromatography (model 14 A, Shimadzu, Tokyo, Japan) as described by Cromwell et al. (2011) for the DDGS and midds, complete diets, and carcass fat samples at the University of Georgia Department of Animal and Dairy Sciences (Athens, GA). Iodine value was calculated for the fat samples using the following equation (AOCS, 1998): $IV = [C16:1] \times 0.950 + [C18:1] \times 0.860 + [C18:2] \times 1.732 + [C18:3] \times 2.616 + [C20:1] \times 0.785 + [C20:4] \times 3.201 + [C22:1] \times 0.723 + [C22:5] \times 3.697 + [C22:6] \times 4.463$, where brackets indicate concentration (%). Measurements of belly quality were also collected from the bellies cut from the left side of each carcass. Weight, length, width, and height were recorded for each belly. Also, a measure of belly flex, as described by Rentfrow et al. (2003), was used to determine the firmness of each belly. This was completed with both the skin-side up and skin-side down. The measurements were completed in a room that was maintained at 5°C.

Pigs harvested at the commercial packing plant were also slaughtered at approximately 0600 h, equalizing the 12 h feed withdrawal period across both groups. Hot carcass weights were measured immediately after evisceration and each carcass evaluated for carcass yield, backfat depth, loin depth, percentage lean, and jowl IV. Carcass yield was calculated by dividing the HCW at the plant by the live weight at the farm before transport to the plant. Fat depth and loin depth were measured with an optical probe inserted between the third and fourth last rib (counting from the ham end of the carcass) at a distance approximately 7 cm from the dorsal midline. Jowl fat samples were collected and analyzed by near infrared spectroscopy (Bruker MPA, Breman, Germany) for fat IV using the equation of Cocciardi et al. (2009).

Experiment 2

A total of 1,089 pigs (PIC 337 × 1050; PIC, Hendersonville, TN; initially 44.5 ± 0.1 kg) were used in this 96-d study, serving as a commercial field validation experiment for Exp. 1. Pens of pigs (similar number of barrows and gilts; 25 to 27 pigs per pen) were randomly allotted to 1 of 6 dietary withdrawal strategies with average pig BW balanced across each treatment with 7 replications per treatment. Pigs were intended to have the same exact withdrawal timeline as Exp. 1; however inclement weather shut down the packing plant and increased the original withdrawal schedule by 4 d; such that pigs were switched to the low-fiber corn-soy diet at d 24, 19, 14, 9, or 0 before slaughter. On d 64, the 3 heaviest pigs in each pen were weighed and sold according to standard farm procedures. After removing those pigs, pens of pigs on the high-fiber diets were realloted to withdrawal regimen, balancing on both d 0 and 64 BW. This was done to ensure that any response criteria were not influenced by prior performance when all pigs were fed the same diet. Before marketing, pigs were individually tattooed with a pen identification number to allow for carcass measurements to be collected on a pen basis.

On d 96, final pen weights were taken and pigs were transported 111 km to a commercial packing plant (JBS Swift and Company, Worthington, MN). Hot carcass weight was measured immediately after evisceration and each carcass evaluated for carcass yield, backfat depth, loin depth, and percentage lean. Carcass yield was calculated by dividing the HCW at the plant by the both the live weight at the farm before transport to the plant, or immediately after arrival at the plant. Fat depth and loin depth were measured with an optical probe inserted between the third and fourth last rib (counting from the ham end of the carcass) at a distance approximately 7 cm from the dorsal midline.

Statistical Analysis

Experimental data were analyzed using the PROC MIXED procedure in SAS (SAS Institute Inc., Cary, NC) with pen serving as the experimental unit. Experiment 1 was analyzed as a completely randomized design and Exp. 2 was analyzed as a randomized complete-block design with initial BW as a blocking factor. Residual assumptions were checked using standardized diagnostics on studentized residuals. The assumptions were reasonable met. Linear and quadratic contrast were completed to determine the effects of withdrawing the high-fiber diet before slaughter, as well as contrast between continuously feeding the low-fiber corn-soy or high-fiber diet. In both experiments, backfat depth, loin depth, and lean percentage were adjusted to a common hot carcass weight for analysis. Results from the experiment were considered significant at $P \leq 0.05$ and a tendency between $P > 0.05$ and $P \leq 0.10$.

Results

Diet and Ingredient Analysis

For Exp. 1 and 2, the DDGS and midds had analyzed nutrient values similar to those used in diet formulation (Tables 1-5 and 1-6). Proximate analysis of the diets also resulted in values similar to those intended in diet formulation. Bulk density of the high-fiber diets in Exp. 1 and 2 were reduced by 22% and 17%, respectively, compared to the low-fiber corn-soy diet (Tables 1-7 and 1-8). For Exp. 1, the fatty acid analysis of the high-fiber diet had increased amounts of palmitic acid (C16:0) and palmitoleic acid (C16:1), and decreased amounts of stearic acid (C18:0; Table 1-9) in each phase. The iodine value product (IVP) for the complete feed were similar across phases, with the high-fiber diet having analyzed IVP values greater than the low-fiber corn-soy diet.

Experiment 1

From d 0 to 63, pigs fed the high-fiber diet tended to have decreased ADG ($P = 0.066$) and G:F ($P = 0.001$) compared with pigs fed the low-fiber corn-soy diet (Table 1-10). From d 63 to 88, pigs fed the high-fiber diet throughout tended to have increased ADG ($P = 0.056$) and ADFI ($P = 0.001$) compared to pigs fed the low-fiber corn-soy diet, which resulted in no difference in G:F. For pigs switched from the high-fiber diet to the low-fiber corn-soy diet, there were no differences in ADG or G:F; however, ADFI increased then decreased (quadratic; $P = 0.049$) as days of fiber withdrawal before slaughter increased. Overall (d 0 to 88), pigs fed the high-fiber diet throughout tended to have increased ADG ($P = 0.072$) compared to pigs fed the low-fiber corn-soy diet. Length of withdrawal from the high-fiber diet before slaughter did not influence overall ADG or G:F. Caloric efficiency on an ME basis was worse ($P = 0.030$) for pigs fed the high-fiber diet compared with pigs fed the low-fiber diet, which suggest the energy content on an ME basis of either the DDGS or midds was over estimated. However, there was no difference between treatments for NE caloric efficiency, suggesting the NE values used for formulation were accurate.

Percentage carcass yield and backfat depth were decreased (*P* = 0.001), whereas jowl IV (*P* = 0.001) and percentage lean (*P* = 0.069) tended to increase, for pigs fed the high-fiber diet throughout compared to those fed the low-fiber corn-soy diet (Table 1-11). As high-fiber diet withdrawal for pigs increased, percentage carcass yield improved (quadratic *P* = 0.039), and jowl IV decreased (linear, *P* = 0.001). Pigs fed the high-fiber diet throughout tended (*P* = 0.059) to have increased belly width compared to those fed the low-fiber corn-soy diet. In addition, belly firmness decreased both when measured skin-side up (*P* = 0.013) and skin-side down (*P* = 0.002) for pigs fed the high-fiber diet throughout compared to pigs fed the low-fiber corn-soy diet continuously.

Intestinal mass was determined on both an absolute weight (Table 1-12) and percentage BW basis (Table 1-13). Pigs fed the high-fiber diet throughout had heavier whole intestine weights (*P* = 0.043) and full large intestines (*P* = 0.003) compared to pigs fed the low-fiber corn-soy diet. As withdrawal time increased for pigs fed the high-fiber diet then switch to the low-fiber corn-soy diet, whole intestine weight tended to decrease (*P* = 0.059) and full large intestine weight decreased (linear; *P* = 0.018). The rinsed weights of the organs did not differ among withdrawal strategies. The full weight of the small intestine tended to decrease and then increase (quadratic, *P* = 0.083) as high-fiber withdrawal before market increased. With the exception of the lungs which tended to increase (linear, *P* = 0.084) as withdrawal period increased, all other organs were not influenced by diet or withdrawal strategy.

When organ mass was expressed as a percentage of BW, the whole intestine tended to be a greater ($P = 0.055$) and full large intestine mass increased ($P = 0.002$) in pigs fed the high-fiber diet throughout compared with pigs fed the low-fiber corn-soy diet (Table 1-13). Unexpectedly, the percentage mass for the spleen was also decreased ($P = 0.040$) in pigs fed the high-fiber diet compared to the low-fiber diet. Furthermore, as withdrawal days increased, the percentage of whole intestinal and full large intestine mass decreased (linear, $P < 0.05$). Similar to the absolute weight, full large intestine weight tended to be reduced (quadratic; $P = 0.063$) as days of withdrawal increased, indicating that much of the change in full intestine weight occurred in the first 5 d of withdrawal. Again, the percentage mass of the lungs tended to increase (linear, $P = 0.090$), but spleen percentage mass also tended to increase ($P = 0.054$) as withdrawal days increased.

For pigs fed the high-fiber diet throughout, the concentration of polyunsaturated fatty acids (PUFA) was increased in jowl fat ($P = 0.010$), partially because of the increase ($P = 0.010$) in linoleic acid (C18:2n-6) and α-linoleic (C18:3n-3) acid compared to those fed the low-fiber corn-soy diet (Table 1-14). Total *trans* fatty acids increased ($P = 0.014$) in pigs fed the high-fiber diet throughout compared with pigs fed the low-fiber corn-soy diet. The PUFA:SFA (saturated fatty acid) ratio and IV also were greater ($P = 0.010$) in the jowl fat of pigs fed the high-fiber diet compared with the corn-soy diet. For pigs switched from the high-fiber diet to the low-fiber corn-soy diet, the concentration of palmitoleic acid (C16:1) increased (linear; $P = 0.030$) in jowl fat as the number of days withdrawn from the high-fiber diet increased. However, this was the only fat quality criteria affected by withdrawal period.

Belly fat of pigs fed the high-fiber diet had decreased concentrations of MUFA ($P = 0.007$; monounsaturated fatty acids) and greater concentrations of PUFA ($P = 0.010$) compared with those fed the low-fiber corn-soy diet (Table 1-15). This was mainly due to the shift from decreased amounts of oleic acid (C18:1 *cis*-9) and greater amounts of linoleic and α-linoleic acid ($P < 0.05$) in the belly fat of pigs fed the low-fiber corn-soy diet compared with those fed the high-fiber diet. The PUFA:SFA ratio and IV also were greater ($P < 0.05$) in the belly fat of pigs fed the high-fiber diet for the entire study compared with pigs fed the low-fiber corn-soy diet. The concentration of eicosatrienoic acid (C20:3n-6) decreased (linear; $P = 0.013$) and PUFA:SFA ratio and IV tended to decrease ($P < 0.10$) in belly fat with increasing withdrawal time.

The total concentration of PUFA, total *trans* fatty acids, PUFA:SFA ratio, and IV increased ($P = 0.010$) in backfat of pigs fed the high-fiber diet compared with the low-fiber corn-soy diet (Table 1-16). In addition, eicosatrienoic acid (C20:3n-3), dihomo-γ-linoleic acid (C20:3n-6), and arachidonic acid (C20:4n-6) concentrations were also greater ($P < 0.05$) in pigs fed the high-fiber diet throughout compared with the low-fiber corn-soy diet. However, palmitic acid and oleic acid (C18:1 *cis*-9) were lower ($P < 0.05$) in pigs fed the high-fiber diet throughout compared to the low-fiber corn-soy diet while linoleic and conjugated linoleic acid were increased ($P < 0.05$) in backfat. The concentration of total *trans* fatty acids were greater ($P = 0.010$) only in backfat of pigs fed the high-fiber diet compared with the low-fiber corn-soy diet. The total concentration of PUFA, PUFA:SFA ratio, and IV decreased (quadratic; $P < 0.05$) with the increase in withdrawal time. The difference in total concentration of PUFA was due in part to the change (quadratic; $P < 0.05$) in concentrations of α-linoleic, linoleic acid, and arachidonic acid as withdrawal time increased. Dihomo-γ-linoleic acid concentration decreased (quadratic; $P = 0.010$) as withdrawal time increased.

Similar differences were observed in the ham collar fat as was observed for the backfat (Table 1-17). However, in addition to those differences, total concentration of PUFA in ham collar fat increased (quadratic; $P = 0.001$) as withdrawal time increased, partially because of the increase in α-linoleic and arachidonic acid (quadratic; $P < 0.05$). Furthermore, the concentration of C16:0 and dihomo-γ-linoleic (C20:3n-6) also increased (quadratic; $P < 0.05$) in ham collar fat as withdrawal time increased from 0 to 20 d.

Experiment 2

From d 0 to 64, pigs fed the high-fiber diet had decreased ADG ($P = 0.001$), ADFI ($P = 0.016$), and G:F ($P = 0.023$) compared with pigs fed the low-fiber corn-soy diet. As a result, pigs fed the high-fiber diet weighed approximately 3.5 kg less ($P = 0.001$) than those fed the low-fiber corn-soy diet on d 64 (Table 1-18). From d 64 to 96, unlike Exp. 1, there was no difference in ADG or ADFI between pigs fed the high-fiber or low-fiber corn-soy diets throughout the study; however, G:F (P = 0.053), and final BW (P = 0.001) decreased for pigs fed the high-fiber diet throughout compared with the low-fiber corn-soy diet. There were no differences in ADG, ADFI, G:F, or final BW for pigs fed the high-fiber diet with different withdrawal regimens. Overall (d 0 to 96), pigs continuously fed the high-fiber diet had decreased ($P < 0.05$) ADG and G:F compared with the low-fiber corn-soy diet, decreasing final BW ($P = 0.001$) by 4.2 kg. For pigs initially fed the high-fiber diet and then switched to the low-fiber corn-soy diet, ADG and ADFI were not different between withdrawal days; however, G:F tended to improve (linear; $P = 0.070$) as withdrawal days increased from 0 to 24 d, with the pigs withdrawn 19 and 24 days before harvest being the most efficient.

Pigs fed the high-fiber diet throughout had a 4.3 kg lighter HCW ($P = 0.001$) compared with pigs fed the low-fiber corn-soy diet although percentage carcass yield was unaffected by dietary treatment (Table 1-19). Nevertheless, pigs switched from the high-fiber diet tended to have heavier HCW (linear; $P = 0.052$) as withdrawal days increased. Backfat and loin depth were both decreased ($P < 0.05$) in pigs continuously fed the high-fiber diet compared with pigs fed the low-fiber corn-soy diet. Loin depth increased (quadratic; $P = 0.042$) as withdrawal time increased.

Discussion

The objective of these studies were to use a proven dietary model to examine the effects of different durations of switching pigs from a high-fiber to low-fiber diet during the last 3 wk of growth before slaughter. Previous research (Asmus et al., 2014) has determined that 21-d of returning to a corn-soy diet was sufficient to restore carcass yield compared to longer feeding durations. However, durations under 21-d had not been evaluated.

The reduction in ADG and G:F shown in Exp. 1 (d 0 to 63) and Exp. 2 (d 0 to 96) for pigs fed the high-fiber diet compared to those fed the low-fiber corn-soy diet is consistent with others whom have fed similar diets with DDGS and midds (Nemechek et al., 2013; Asmus et al., 2014; Graham et al., 2014). This response was not unexpected as the diets were not isocaloric, as the high-fiber diet was lower in dietary energy. However, pigs fed the high-fiber diet in Exp. 1 tended to have an increase in ADFI whereas pigs in Exp. 2 did not. The reason for the difference in overall ADFI for Exp. 1 is increased feed intake that was observed from d 63 to 88. This is not consistent with others whom fed up to 20 or 30% DDGS and reported no change in feed intake (Whitney et al., 2006; Linneen et al., 2008); however, the DDGS used in those experiments were higher in fat than the sources used in the present study. The increase in feed intake is most likely explained by the need for pigs to consume feed amounts based on their energy requirement, and in order to meet this requirement, they ate more of the high-fiber, low energy diet.

Similar to other research, when pigs were switched from the high-fiber diet to the low-fiber corn-soy diet ADFI increased (Jacela et al., 2010; Asmus et al., 2014; Graham et al., 2014). Others speculated to the possibility that pigs continue to eat similar volumetric amounts of feed and, due to the increase in bulk density for the low-fiber corn-soy diet compared to the high-fiber diet, the result is an increase in ADFI. The reduction in bulk density when DDGS and midds were included in the high-fiber diet is similar to those reported by Asmus et al. (2014) whom reported a 31% reduction, and Graham et al. (2014) whom reported a 32% reduction in bulk density between a high-fiber diet containing 30% DDGS and 19% midds and a low-fiber corn-soy diet. This theory would be supported by Turlington (1984) whom reported that while the weight of feed intake per day did not change as NDF level in the diet increased, the volume of feed intake per day significantly increased.

Furthermore, the difference in the ADG response between Exp. 1 and Exp. 2 is related to the difference in ADFI. Pigs fed at the university in Exp. 1 had a higher ADFI compared to pigs fed at the commercial research facility in Exp. 2; therefore, consuming more total energy for growth. It can be speculated that because there was no difference in ADG between dietary treatments in Exp. 1, pigs withdrawn from the high-fiber diets were shifting more of the gain towards lean and fat deposition rather than gut content and viscera weight. This would explain the increase in HCW for pigs withdrawn from the high-fiber diet and switched to the corn-soy diet.

As expected, in both Exp. 1 and Exp. 2 there was a reduction in carcass yield because of the reduction in HCW when pigs were fed the high-fiber diet compared to the low-fiber corn-soy diet, which is consistent with published literature (Whitney et al., 2006; Salyer et al., 2012, Tsai et al., 2014). These results are similar to others who reported high-fiber ingredients reduce carcass yield (Turlington, 1984; Anugwa et al., 1989). Turlington (1984) reported that as the level of added NDF increased from 0 to 9.9%, similar to the added levels of the current study, carcass yield was decreased and the weight of gut fill and intestinal contents increased in the colon and cecum. More recently, Stewart et al. (2013) reported a decrease in carcass yield in pigs fed either 30% midds or 30% soybean hulls compared to pigs fed a low-fiber corn-soy diet. This could be explained as they reported an increase in full visceral weight but no increase in empty visceral weight.

The 30% heavier full large intestinal weights in Exp. 1 were the reason for the observed reduction in carcass yield in pigs fed the high-fiber diet compared with those fed the low-fiber corn-soy diet. In the present experiments pigs were withdrawn from feed for approximately 12 hr prior to harvesting, thus residual digestive contents in the lower digestive tract would still be present and influenced by diet type. This is consistent with both Asmus et al. (2014) and Graham et al. (2014) whom reported a 25% and 19% increase, respectively, in large intestine weights of pigs fed the high-fiber diet compared to those fed the low-fiber corn-soy diet throughout.

The increase in gut fill is mostly explained by the type of fiber in the byproduct ingredients. Insoluble fiber (lignin, resistant starch, cellulose, and hemicellulose) has been shown to cause the digestive contents to swell in the large intestine by absorbing water and increasing the rate of passage by decreasing the viscosity (Knudsen and Hansen, 1991; Takahashi et al., 2008). Distillers dried grains with solubles and midds contain high amounts of insoluble fiber, which translates to an elevated level of insoluble fiber in the high-fiber diet compared to the corn-soy diet.

In our study, the high-fiber diet had increased amounts of insoluble fiber and decreased diet bulk density, which resulted in an increase in total volume of feed intake for pigs fed that diet. These results allow us to determine that the increase in intestinal weights are not the result of reduced passage rate and increased viscosity, but the shear total increase in fecal volume combined with an increase amount of water content in the digestive contents. This is because the insoluble fiber in the high-fiber diet increases the water holding capacity and bulking potential. Kim et al. (2012) reported that when finishing pigs were fed 25% DDGS compared to a corn-soy diet, DM excretion was increased by 24%. We observed that it was only the residual digestive contents in the large intestine and cecum that accounted for increases in full intestinal weight because the weight of the rinsed weights were not different between pigs fed the high-fiber and corn-soy diets.

Asmus et al. (2014) and Graham et al. (2014) switched pigs from the high-fiber diet to the low-fiber corn-soy diet approximately 3 wk before slaughter and restored carcass yield to values similar to that of those fed the low-fiber corn-soy diet. Further, both of the previously mentioned studies reported reductions in full large intestinal weight of at least 18% for pigs switched to a low-fiber corn-soy diet approximately 3 wk before slaughter compared to those fed the high-fiber diet throughout. Our results demonstrate that full large intestinal weights can be decreased by almost 1 kg in as few as 5 d when pigs are switched to a low-fiber corn-soy diet. However, this study determined that the optimal time period to switch pigs from a high-fiber diet to a low-fiber corn-soy diet is 15 (Exp. 1) to 19 (Exp. 2) days before slaughter to increase HCW and restore carcass yield.

Although the reduction in carcass yield in the commercial validation study was not statistically significant, it was successful at reporting a reduction in HCW for pigs fed a high-fiber diet compared to those fed the low-fiber corn-soy diet. In contrast, Gaines et al. (2007) observed that a 6 wk withdrawal time was needed to restore carcass yield when pigs were fed 30% DDGS. Conversely, Xu et al. (2010) did not report a difference in carcass yield regardless of DDGS inclusion level and duration of withdraw.

The reduction in backfat depth in pigs fed the high-fiber diet compared to the low-fiber corn-soy diet is consistent between both of the current experiments and other research where low-energy diets were fed (Pond et al., 1988; Hinson et al., 2011). Although Graham et al. (2014) did not report statistical differences in backfat depth, there was a numerical reduction in pigs fed the high-fiber diet compared to the low-fiber corn-soy diet. Percentage lean tended to be increased in Exp. 1 for pigs fed the high-fiber diet compared to the low-fiber corn-soy diet. While not statistically significant in Exp. 2, a similar numerical difference was observed.

Belly firmness was reduced both when measured skin-up and skin-down when pigs were fed the high-fiber diet compared to the low-fiber corn-soy. This is consistent with others who have shown a decrease in belly firmness as the amount of DDGS in the diet increases, as a result of the increased levels of unsaturated fatty acids in those diets (Whitney et al., 2006; Cromwell et al., 2011). This is also consistent with a review by Stein and Shurson (2009) that encompassed literature before 2009 about the effects of DDGS in swine diets ($n = 3$), all reporting a significant reduction in belly firmness.

In both Exp. 1 and Exp. 2, pigs fed the corn-soy diet had decreased jowl IV compare to those fed the high-fiber diet throughout. The increase in jowl IV in pigs fed the high-fiber diet, due to the elevated level of unsaturated fatty acids in the DDGS and not dietary fiber, is consistent with previous research (Pompeau et al., 2013). Similar to others, this data demonstrates that the increase in IV is a result of the decrease in SFA and increase in PUFA. The results for jowl fatty acid analysis were similar to the changes between diet types for the other fat depots of backfat, belly fat, and ham collar fat.

Furthermore, a linear improvement in jowl IV as withdrawal days increased for those slaughtered at the commercial plant was observed, but not in the subsample slaughtered at KSU. The reason for this difference in response could be related to a smaller sample size among pigs slaughtered at KSU. The reduction in IV as the period of withdrawal from the high-fiber diet increases observed in this study is similar to Asmus et al. (2014) and Graham et al. (2014). The rate of change amongst the different depots is slightly different, with the jowl less responsive to withdrawal periods relative to the other depots (Wiegand et al., 2011). This study confirms that withdrawing diets that include DDGS at levels greater than 15% can reduce the carcass IV in all depots (Xu et al., 2010; Nemechek et al., 2013). However, unlike carcass yield, carcass fatty acid composition takes longer to be influenced by DDGS withdrawal strategies to return values similar to that of the low-fiber corn-soy diet.

In summary, reducing the dietary fiber level in finishing swine diets for approximately 15 to 19 days before slaughter is beneficial to increase gain, HCW, and restore carcass yield. Furthermore, reducing high-fiber diets that contain increased amounts of unsaturated fatty acids can improve carcass fat IV; however, none of the withdrawal strategies in this trial were successful at restoring carcass fat IV to levels similar to pigs fed the low-fiber corn-soy diet. This is an important finding which will allow producers and nutritionists to make more knowledgeable decisions when marketing pigs based on the diet type being utilized.

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Table 1-1. Composition of diets, Exp. 1 (as-fed basis)[1]

		Phase 1		Phase 2		Phase 3		Phase 4	
Item	Fiber level[2]:	Low	High	Low	High	Low	High	Low	High
Ingredient, %									
Corn		73.71	34.88	78.93	39.99	82.65	43.56	84.97	45.79
Soybean meal, 46.5% CP		23.80	13.74	18.84	8.71	15.32	5.20	13.15	3.04
Distillers dried grains with solubles		---	30.00	---	30.00	---	30.00	---	30.00
Wheat middlings		---	19.00	---	19.00	---	19.00	---	19.00
Monocalcium P, 21% P		0.45	---	0.35	---	0.25	---	0.20	---
Limestone		1.05	1.30	1.00	1.28	0.98	1.29	0.93	1.28
Salt		0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin premix[3]		0.15	0.15	0.13	0.13	0.10	0.10	0.08	0.08
Trace mineral premix[4]		0.15	0.15	0.13	0.13	0.10	0.10	0.08	0.08
L-Lys × HCl		0.170	0.310	0.150	0.293	0.135	0.278	0.128	0.270
DL-Met		0.020	---	---	---	---	---	---	---
L-Thr		0.025	---	0.010	---	---	---	---	---
Phytase[5]		0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Calculated analysis									
Standardized ileal digestible (SID) amino acids, %									
Lys		0.93	0.93	0.79	0.79	0.69	0.69	0.63	0.63
Ile:Lys		69	72	70	74	72	76	73	78
Met:Lys		30	34	30	37	32	40	33	43
Met + Cys:Lys		59	70	62	77	66	83	69	88
Thr:Lys		63	66	63	69	64	72	66	74
Trp:Lys		19	19	19	19	19	19	19	19
Val:Lys		78	88	81	94	85	99	87	103
Total Lys, %		1.04	1.09	0.89	0.94	0.78	0.83	0.72	0.77
SID Lys:ME, g/Mcal		2.82	2.88	2.39	2.44	2.08	2.13	1.90	1.94
ME, kcal/kg		3,296	3,232	3,307	3,240	3,316	3,245	3,324	3,249
NE, kcal/kg		2,474	2,388	2,507	2,419	2,533	2,441	2,549	2,455
CP, %		17.5	20.8	15.6	18.9	14.3	17.6	13.5	16.7
Ca, %		0.59	0.58	0.53	0.56	0.49	0.55	0.46	0.54
P, %		0.47	0.58	0.42	0.56	0.39	0.55	0.37	0.54
Available P, %		0.27	0.39	0.25	0.38	0.22	0.38	0.21	0.37
Crude fiber, %		2.5	4.9	2.5	4.9	2.4	4.8	2.4	4.8
NDF, %		9.2	18.9	9.3	19.0	9.3	19.0	9.3	19.0

[1] Phase 1 diets were fed from d 0 to 22, phase 2 from d 22 to 42, phase 3 from d 42 to 63, and phase 4 from d 63 to 88.

[2] Each diet was fed in meal form.

[3] Provided per kilogram of premix: 4,409,200 IU vitamin A; 551,150 IU vitamin D_3; 17,637 IU vitamin E; 1,764 mg vitamin K; 3,307 mg riboflavin; 11,023 mg pantothenic acid; 19,841 mg niacin; and 15.4 mg vitamin B_{12}.

[4] Provided per kilogram of premix: 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulphate, 11g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.

[5] Phyzyme 600 (Danisco Animal Nutrition, St. Louis, MO) provided 780 phytase units (FTU)/kg, with a release of 0.11% available P.

Table 1-2. Composition of diets, Exp. 2 (as-fed basis)[1]

	Phase 1		Phase 2		Phase 3		Phase 4	
Item Fiber level[2]:	Low	High	Low	High	Low	High	Low	High
Ingredient, %								
Corn	73.15	34.18	76.85	37.83	80.16	41.17	83.10	43.99
Soybean meal, 46.5% CP	24.55	14.68	20.97	11.10	17.78	7.82	14.90	5.04
Distillers dried grains with solubles	---	30.00	---	30.00	---	30.00	---	30.00
Wheat middlings	---	19.00	---	19.00	---	19.00	---	19.00
Monocalcium P, 21% P	0.60	---	0.55	---	0.45	---	0.40	---
Limestone	0.95	1.25	0.93	1.20	0.95	1.18	0.95	1.15
Salt	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin and trace mineral premix[3]	0.10	0.10	0.10	0.10	0.08	0.08	0.08	0.08
L-Lys·SO_4	0.265	0.435	0.245	0.415	0.225	0.400	0.210	0.380
Methionine hydroxy analogue[4]	0.010	---	---	---	---	---	---	---
L-Thr	0.015	---	0.005	---	---	---	0.005	---
Phytase[5]	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Calculated analysis								
Standardized ileal digestible (SID) amino acids, %								
Lys	0.95	0.95	0.85	0.85	0.76	0.76	0.68	0.68
Ile:Lys	69	74	70	75	71	77	72	79
Met:Lys	28	35	29	37	30	39	32	42
Met + Cys:Lys	58	66	60	70	63	75	66	80
Thr:Lys	62	65	62	67	63	69	65	71
Trp:Lys	19	19	19	19	19	19	19	19
Val:Lys	78	90	80	93	83	97	85	102
Total Lys, %	1.07	1.13	0.93	1.02	0.86	0.92	0.77	0.84
SID Lys:ME, g/Mcal	2.87	2.93	2.57	2.62	2.29	2.34	2.05	2.09
ME, kcal/kg	3,304	3,245	3,310	3,250	3,317	3,255	3,321	3,258
NE, kcal/kg	2,476	2,392	2,499	2,414	2,520	2,435	2,538	2,452
CP, %	17.8	21.3	16.5	19.9	15.3	18.7	14.2	17.6
Ca, %	0.58	0.58	0.55	0.55	0.53	0.53	0.51	0.51
P, %	0.50	0.55	0.48	0.54	0.44	0.53	0.42	0.52
Available P, %	0.26	0.31	0.25	0.31	0.22	0.31	0.21	0.30
Crude fiber, %	2.6	5.3	3.3	5.1	2.5	5.2	2.4	5.2
NDF, %	9.2	20.5	9.2	20.5	9.3	20.6	9.3	20.6

[1] Phase 1 diets were fed from d 0 to 14, phase 2 from d 14 to 37, phase 3 from d 37 to 64, and phase 4 from d 64 to 96.

[2] Each diet was fed in meal form.

[3] Provided per kilogram of premix: 4,509,410 IU vitamin A; 701,464 IU vitamin D_3; 24,050 IU vitamin E; 1,402 mg vitamin K; 3,006 mg riboflavin; 12,025 mg pantothenic acid; 18,038 mg niacin; and 15.0 mg vitamin B_{12}, 40 g Mn from manganese oxide, 90 g Fe from ferrous sulfate, 100 g Zn from zinc oxide, 10 g Cu from copper sulfate, 500 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[4] MHA (88% methionine; Novus International, St. Charles, MO)

[5] Optiphos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 phytase units (FTU)/kg, with a release of 0.07% available P.

Table 1-3. Chemical analysis of diets, Exp. 1 (as-fed basis)[1]

	Phase 1		Phase 2		Phase 3		Phase 4	
Item,% Fiber level[2]:	Low[3]	High[4]	Low	High	Low	High	Low	High
DM	89.92	90.76	89.53	90.52	89.70	90.51	89.95	91.01
CP	19.60	22.30	15.90	19.40	14.40	17.00	13.60	18.70
ADF	3.50	7.30	3.60	7.60	3.40	6.60	3.40	6.80
NDF	8.50	17.20	8.50	18.40	7.70	16.80	8.20	16.00
Ether extract	3.20	4.50	3.10	4.40	2.90	5.00	3.10	4.80
Ash	4.73	5.98	4.03	5.30	3.56	5.24	3.61	5.00

[1] Phase 1 diets were fed from d 0 to 22, phase 2 from d 22 to 42, phase 3 from d 42 to 63, and phase 4 from d 63 to 88.

[2] Each diet was fed in meal form.

[3] Refers to low-fiber diet without distillers dried grains with solubles (DDGS) or wheat middlings (midds).

[4] Refers to high-fiber diet with 30% DDGS and 19% midds.

Table 1-4. Chemical analysis of diets, Exp. 2 (as-fed basis)[1]

	Phase 1		Phase 2		Phase 3		Phase 4	
Item,% Fiber level[2]:	Low[3]	High[4]	Low	High	Low	High	Low	High
DM	90.01	91.15	90.00	90.82	89.98	90.93	89.94	90.92
CP	18.20	24.60	17.10	22.40	15.40	19.80	13.50	18.20
ADF	3.70	7.90	3.60	7.50	3.60	6.60	3.10	6.70
NDF	7.20	18.50	6.60	15.70	7.20	16.50	6.70	17.40
Ether extract	3.60	6.70	3.00	6.50	3.00	5.50	3.00	5.70
Ash	3.96	4.68	3.91	4.34	4.06	5.12	3.71	4.04

[1] Phase 1 diets were fed from d 0 to 14, phase 2 from d 14 to 37, phase 3 from d 37 to 64, and phase 4 from d 64 to 96.

[2] Each diet was fed in meal form.

[3] Refers to low-fiber diet without distillers dried grains with solubles (DDGS) or wheat middlings (midds).

[4] Refers to high-fiber diet with 30% DDGS and 19% midds.

Table 1-5. Chemical analysis of distillers dried grains with solubles (DDGS) and wheat middlings, Exp. 1(as-fed basis)

Item, %	DDGS	Wheat middlings
DM	91.45	90.22
CP	27.5 (27.2)[1]	15.0 (15.9)
Ether extract	8.0	3.7
Crude fiber	7.3 (7.7)	7.8 (7.0)
ADF	12.4 (9.9)	12.2 (10.7)
NDF	28.9 (25.3)	34 (35.6)
Ash	4.64	5.55

[1] Values in parenthesis indicate those used in diet formulation.

Table 1-6. Chemical analysis of distillers dried grains with solubles (DDGS) and wheat middlings, Exp. 2 (as-fed basis)

Item, %	DDGS	Wheat middlings
DM	90.35	90.72
CP	29.4 (27.3)[1]	15.5 (15.9)
Ether extract	11.2	4.4
Crude fiber	7.4 (8.9)	8.4 (7.0)
ADF	9.1 (12.0)	11.9 (10.7)
NDF	22.4 (30.4)	34.6 (35.6)
Ash	3.89	4.97

[1] Values in parenthesis indicate those used in diet formulation.

Table 1-7. Bulk density of diets, Exp. 1 (as-fed basis)[1,2]

Bulk density, g/L	Low-fiber[3]	High-fiber[4]
Phase 1	618	482
Phase 2	599	479
Phase 3	621	482
Phase 4	606	465

[1] Diet samples were collected from the feed delivery truck before unloading during each phase.

[2] Phase 1 was d 0 to 22; Phase 2 was d 22 to 42; Phase 3 was d 42 to 63; Phase 4 was d 63 to 88.

[3] Refers to low-fiber diet without distillers dried grains with solubles (DDGS) or wheat middlings (midds).

[4] Refers to high-fiber diet with 30% DDGS and 19% midds.

Table 1-8. Bulk density of diets, Exp. 2 (as-fed basis)[1,2]

Bulk density, g/L	Low-fiber[3]	High-fiber[4]
Phase 1	586	492
Phase 2	584	515
Phase 3	570	458
Phase 4	577	452

[1] Diet samples were collected from the tops of each feeder during each phase.

[2] Phase 1 was d 0 to 14; Phase 2 was d 14 to 37; Phase 3 was d 37 to 64; Phase 4 was d 64 to 96.

[3] Refers to low-fiber diet without distillers dried grains with solubles (DDGS) or wheat middlings (midds).

[4] Refers to high-fiber diet with 30% DDGS and 19% midds.

Table 1-9. Fatty acid analysis of ingredients and diets, Exp. 1 (DM basis)[1]

	Phase 1		Phase 2		Phase 3		Phase 4		Ingredients	
Item Fiber level:	Low[2]	High[3]	Low	High	Low	High	Low	High	DDGS[4]	Midds[5]
Myristic acid (C14:0), %	0.04	0.09	0.07	0.08	0.12	0.07	0.03	0.08	0.07	0.14
Palmitic acid (C16:0), %	14.93	16.03	15.22	15.29	14.47	14.80	15.14	15.49	15.80	16.17
Palmitoleic acid (C16:1), %	0.03	0.13	0.11	0.15	0.11	0.14	0.03	0.16	0.22	0.15
Stearic acid (C18:0), %	2.88	2.41	2.79	2.30	2.34	2.16	2.47	2.10	2.52	1.37
Oleic acid (C18:1 *cis*-9), %	23.03	24.14	25.53	25.21	26.33	25.94	25.08	24.31	26.02	19.21
Linoleic acid (C18:2n-6), %	55.09	53.96	52.45	53.28	53.44	53.88	53.77	54.58	52.25	57.11
α-linoleic acid (C18:3n-3), %	2.87	2.52	2.69	2.36	2.13	2.03	2.51	2.30	1.50	4.36
Arachidic acid (C20:0), %	0.39	0.36	0.27	0.39	0.42	0.40	0.14	0.35	0.40	0.24
Gadoleic acid (C20:1), %	0.10	0.26	0.12	0.37	0.28	0.35	0.06	0.29	0.27	0.73
Other fatty acids, %	0.63	0.10	0.72	0.56	0.38	0.23	0.77	0.34	0.94	0.52
Total SFA,[6] %	18.24	18.90	18.42	18.17	17.35	17.51	17.78	18.09	18.92	18.08
Total MUFA,[7] %	23.17	24.53	25.76	25.73	26.71	26.44	25.16	24.77	26.52	20.09
Total PUFA,[8] %	57.96	56.48	55.14	55.64	55.57	55.91	56.28	56.88	53.75	61.47
UFA:SFA ratio[9]	4.45	4.29	4.39	4.48	4.74	4.70	4.58	4.51	4.24	4.51
PUFA:SFA ratio[10]	3.18	2.99	2.99	3.06	3.20	3.19	3.17	3.14	2.84	3.40
Analyzed dietary lipids, %	1.73	2.59	1.47	3.37	1.79	3.62	1.29	1.69	4.43	2.72
Iodine value,[11] g/100g	122.8	121.1	120.0	120.6	121.1	121.4	121.4	121.8	117.2	127.6
Analyzed IVP[12]	21.2	31.4	17.5	40.6	21.7	43.9	15.7	20.6	51.9	34.7

[1] Values represent the mean of composite samples that were analyzed in duplicate.

[2] Refers to low-fiber diet without distillers dried grains with solubles (DDGS) or wheat middlings (midds).

[3] Refers to high-fiber diet with 30% DDGS and 19% midds.

[4] Distillers dried grains with solubles.

[5] Wheat middlings.

[6] Total SFA = ([C8:0] + [C10:0] + [C12:0] + [C14:0] + [C16:0] + [C18:0] + [C20:0] + [C22:0] + [C24:0]); brackets indicate concentration.

[7] Total MUFA = ([C14:1] + [C16:1] + [C18:1*cis*-9] + [C18:1n-7] + [C20:1] + [C24:1]); brackets indicate concentration.

[8] Total PUFA = ([C18:2n-6] + [C18:3n-3] + [C18:3n-6] + [C20:4n-6]); brackets indicate concentration.

[9] UFA:SFA = (total MUFA+PUFA)/ total SFA.

[10] PUFA:SFA = total PUFA/ total SFA.

[11] Calculated as IV = [C16:1] × 0.950 + [C18:1] × 0.860 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C20:4] × 3.201 + [C22:1] × 0.723 + [C22:5] × 3.697 + [C22:6] × 4.463; brackets indicate concentration.

[12] Iodine value product of dietary lipids calculated from the iodine value × % analyzed dietary lipids × 0.10.

Table 1-10. Effect of dietary fiber withdrawal before market on growth performance of finishing pigs, Exp. 1[1]

		High-fiber ingredient withdrawal before market,[2] d						Probability, $P <$		
								Low-fiber vs	Duration	
Item	Low-fiber[3]	20[4]	15	10	5	0	SEM	0-d withdrawal	Linear	Quadratic
BW, kg										
d 0	38.3	38.3	38.4	38.5	38.3	38.6	1.08	0.825	0.894	0.992
d 63	105.0	102.8	102.9	102.9	103.0	102.9	1.74	0.399	0.967	0.969
d 88	126.0	124.9	126.0	125.2	125.8	125.7	1.93	0.904	0.834	0.895
d 0 to 63										
ADG, kg	1.06	1.02	1.02	1.02	1.02	1.02	0.015	0.066	---	---
ADFI, kg	2.76	2.76	2.80	2.82	2.81	2.80	0.045	0.535	---	---
G:F	0.385	0.371	0.366	0.364	0.363	0.365	0.003	0.001	---	---
d 63 to 88										
ADG, kg	0.84	0.87	0.92	0.89	0.91	0.91	0.025	0.056	0.328	0.482
ADFI, kg	2.87	3.06	3.23	3.17	3.30	3.16	0.056	0.001	0.143	0.049
G:F	0.293	0.283	0.285	0.281	0.277	0.287	0.006	0.498	0.948	0.436
d 0 to 88										
ADG, kg	1.00	0.98	1.00	0.99	0.99	0.99	0.014	0.613	0.707	0.655
ADFI, kg	2.79	2.85	2.93	2.92	2.95	2.90	0.043	0.072	0.331	0.197
G:F	0.358	0.344	0.340	0.339	0.336	0.341	0.003	0.001	0.287	0.147
Caloric efficiency, Mcal/kg										
ME	9.24	9.47	9.58	9.61	9.68	9.51	0.084	0.030	0.512	0.124
NE	7.03	6.97	7.04	7.06	7.09	6.97	0.062	0.519	0.763	0.124

[1] A total of 280 pigs [PIC 327 × 1050, PIC (Hendersonville, TN); initial BW = 38.4 ± 0.3 kg] were used in this 88-d study; 6 pens per treatment and 8 pigs per pen.

[2] Refers to high-fiber diet with 30% distillers dried grains with solubles (DDGS) and 19% wheat middlings (midds).

[3] Refers to low-fiber diet without DDGS or midds.

[4] Refers to the number of days pigs were switched from the high-fiber diet to the low-fiber diet before market.

Table 1-11. Effect of dietary fiber withdrawal before market on carcass characteristics of finishing pigs, Exp. 1[1]

								Probability, $P <$		
		High-fiber ingredient withdrawal before market,[2] d						Low-fiber vs	Duration	
Item	Low-fiber[3]	20[4]	15	10	5	0	SEM	0-d withdrawal	Linear	Quadratic
Carcass characteristics										
HCW, kg	92.2	91.0	91.4	91.1	90.7	89.3	1.39	0.140	0.334	0.488
Carcass yield,[5] %	72.7	72.5	72.5	72.2	72.0	71.2	0.21	0.001	0.001	0.039
Backfat depth,[6] mm	19.8	17.2	17.6	17.9	17.5	16.4	0.65	0.001	0.421	0.129
Loin depth,[6] mm	59.2	59.8	59.9	57.8	60.2	58.0	0.91	0.349	0.248	0.987
Lean,[6] %	52.7	53.7	53.3	53.0	53.7	53.6	0.33	0.069	0.859	0.240
Jowl iodine value[7]	66.8	72.5	73.2	73.2	73.8	74.5	0.35	0.001	0.001	0.650
Loin characterisitics[8]										
Loin marbling	1.50	1.33	1.30	1.25	1.08	1.25	0.168	0.258	0.440	0.628
Loin color	2.25	2.17	2.00	2.42	1.67	2.17	0.221	0.772	0.609	0.828
Ultimate pH	5.49	5.51	5.52	5.48	5.48	5.50	0.033	0.670	0.595	0.591
Belly characteristics										
Weight, kg	4.94	5.05	5.19	4.95	5.19	5.30	0.235	0.257	0.480	0.618
Length, cm	59.8	58.6	59.9	57.0	59.4	60.4	0.92	0.618	0.241	0.142
Width, cm	22.7	23.6	23.4	23.5	23.3	24.3	0.65	0.059	0.483	0.318
Height, cm	3.85	3.84	3.88	3.77	3.88	3.66	0.167	0.402	0.486	0.594
Belly Firmness[9]										
Skin-up, cm	13.11	7.07	7.56	8.90	8.22	7.65	1.592	0.013	0.697	0.455
Skin-down, cm	19.33	11.12	10.44	12.30	10.55	10.48	1.960	0.002	0.841	0.726

[1] A total of 280 pigs (PIC 327 × 1050; PIC, Hendersonville, TN; initially 38.4 ± 0.3 kg) were used in this 88-d study; 6 pens per treatment and 8 pigs per pen.

[2] Refers to high-fiber diet with 30% distillers dried grains with solubles (DDGS) and 19% wheat middlings (midds).

[3] Refers to low-fiber diet without DDGS or midds.

[4] Refers to the number of days pigs were switched from the high-fiber diet to the low-fiber diet before market.

[5] Carcass yield calculated by dividing HCW by live weight obtained at the farm before transportation to the packing plant.

[6] Adjusted by using HCW as a covariate.

[7] Jowl iodine value (g/100g) was measured at the plant by near-infrared spectroscopy.

[8] Measurements taken on a subsample (1 pig/pen) at the Kansas State University Meats Laboratory.

[9] Values represent the distance from each end of the belly when centered upon a fulcrum point.

Table 1-12. Effect of dietary fiber withdrawal before market on organ weights of finishing pigs, kg, Exp. 1[1]

								Probability, $P <$		
		High-fiber ingredient withdrawal before market,[2] d						Low-fiber vs	Duration	
Item	Low-fiber[3]	20[4]	15	10	5	0	SEM	0-d withdrawal	Linear	Quadratic
Full pluck	13.42	13.38	14.44	14.10	14.04	14.76	0.611	0.101	0.195	0.847
Whole intestine	8.82	8.59	9.60	9.17	9.26	10.09	0.465	0.043	0.059	0.917
Stomach										
Full	1.22	1.13	1.11	1.33	1.19	1.30	0.118	0.624	0.229	0.782
Rinsed	0.90	0.91	0.93	0.93	0.96	0.98	0.054	0.266	0.323	0.904
Cecum										
Full	0.73	0.72	0.89	0.85	0.86	0.92	0.088	0.108	0.158	0.576
Rinsed	0.31	0.28	0.33	0.28	0.32	0.31	0.018	1.000	0.297	0.567
Large intestine										
Full	2.90	2.96	3.41	2.90	3.19	4.10	0.283	0.003	0.018	0.088
Rinsed	1.79	1.75	2.00	1.79	1.86	1.91	0.095	0.333	0.530	0.702
Small intestine										
Full	3.23	2.98	3.42	3.25	3.19	3.04	0.173	0.403	0.843	0.083
Heart	0.47	0.47	0.47	0.49	0.50	0.48	0.037	0.876	0.724	0.686
Lungs	1.08	1.17	1.12	1.18	0.99	1.07	0.064	0.892	0.084	0.924
Liver	1.86	1.98	2.03	2.05	2.01	1.91	0.099	0.725	0.564	0.274
Kidneys	0.38	0.43	0.45	0.45	0.40	0.44	0.030	0.156	0.772	0.862
Spleen	0.26	0.26	0.22	0.26	0.22	0.21	0.025	0.113	0.111	0.869
Reproductive tract	0.48	0.47	0.52	0.49	0.64	0.46	0.068	0.799	0.623	0.245

[1] A total of 36 pigs PIC 327 × 1050; PIC, Hendersonville, TN; initially 38.4 ± 0.3 kg) were used in this 88-d study; 6 pens per treatment and 1 pig per pen.

[2] Refers to high-fiber diet with 30% distillers dried grains with solubles (DDGS) and 19% wheat middlings (midds).

[3] Refers to low-fiber diet without DDGS or midds.

[4] Refers to the number of days pigs were switched from the high-fiber diet to the low-fiber diet before market.

Table 1-13. Effect of dietary fiber withdrawal before market on organ weights of finishing pigs, %, Exp. 1[1,2]

								Probability, $P <$		
		High-fiber ingredient withdrawal before market,[3] d						Low-fiber vs	Duration	
Item	Low-fiber[4]	20[5]	15	10	5	0	SEM	0-d withdrawal	Linear	Quadratic
Full pluck	10.95	10.76	11.44	11.46	11.14	11.75	0.378	0.146	0.176	0.740
Whole intestine	7.20	6.92	7.61	7.46	7.33	8.04	0.295	0.055	0.047	0.966
Stomach										
Full	0.99	0.90	0.89	1.09	0.94	1.03	0.086	0.740	0.250	0.683
Rinsed	0.73	0.73	0.74	0.76	0.76	0.78	0.035	0.382	0.313	0.938
Cecum										
Full	0.60	0.58	0.71	0.69	0.67	0.74	0.062	0.138	0.169	0.552
Rinsed	0.25	0.23	0.26	0.23	0.25	0.25	0.013	0.709	0.375	0.557
Large intestine										
Full	2.37	2.38	2.69	2.34	2.53	3.26	0.188	0.002	0.013	0.063
Rinsed	1.47	1.41	1.59	1.45	1.47	1.52	0.059	0.527	0.571	0.637
Small intestine										
Full	2.64	2.41	2.71	2.66	2.54	2.42	0.136	0.273	0.746	0.093
Heart	0.38	0.38	0.37	0.40	0.40	0.38	0.030	0.939	0.720	0.624
Lungs	0.88	0.95	0.89	0.96	0.79	0.85	0.051	0.688	0.090	0.984
Liver	1.52	1.59	1.61	1.67	1.60	1.52	0.059	0.984	0.422	0.144
Kidneys	0.31	0.34	0.35	0.36	0.32	0.35	0.018	0.153	0.660	0.838
Spleen	0.21	0.21	0.18	0.21	0.17	0.17	0.015	0.040	0.054	0.872
Reproductive tract	0.39	0.38	0.41	0.39	0.52	0.37	0.053	0.743	0.624	0.252

[1] A total of 36 pigs PIC 327 × 1050; PIC, Hendersonville, TN; initially 38.4 ± 0.3 kg) were used in this 88-d study; 6 pens per treatment and 1 pig per pen.

[2] All values are a percentage of live weight ((i.e., (reproductive tract/live weight) × 100)).

[3] Refers to high-fiber diet with 30% distillers dried grains with solubles (DDGS) and 19% wheat middlings (midds).

[4] Refers to low-fiber diet without DDGS or midds.

[5] Refers to the number of days pigs were switched from the high-fiber diet to the low-fiber diet before market.

Table 1-14. Effect of dietary fiber withdrawal before market on jowl fatty acid analysis, Exp. 1 (DM basis)[1]

								Probability, $P <$		
	Low-	High-fiber ingredient withdrawal before market,[3] d						Low-fiber vs.	Duration	
Item	fiber[2]	20[4]	15	10	5	0	SEM	0-d withdrawal	Linear	Quadratic
Myristic acid (C14:0). %	1.30	1.41	1.38	1.34	1.33	1.28	0.071	0.840	0.150	0.980
Myristoleic acid (C14:1), %	0.02	0.03	0.02	0.02	0.02	0.02	0.003	0.734	0.120	0.150
Palmitic acid (C16:0), %	23.30	22.23	24.99	22.25	22.33	21.98	1.203	0.401	0.375	0.417
Palmitoleic acid (C16:1), %	3.29	3.67	3.41	3.12	3.32	2.94	0.234	0.260	0.030	0.755
Stearic acid (C18:0), %	10.26	8.67	11.00	9.55	9.18	9.57	0.735	0.470	0.990	0.270
Oleic acid (C18:1 *cis*-9), %	48.56	44.95	37.91	44.55	44.58	43.72	2.979	0.218	0.631	0.579
Linoleic acid (C18:2n-6), %	9.95	15.33	16.91	15.25	15.50	16.45	0.998	0.010	0.780	0.850
α-linoleic acid (C18:3n-3), %	0.44	0.60	0.63	0.57	0.59	0.61	0.041	0.010	0.873	0.680
γ-linoleic acid (C18:3n-6), %	0.15	0.13	0.14	0.13	0.14	0.15	0.017	0.889	0.373	0.890
Conjugated Linoleic acid (*c*9, *t*11), %	0.09	0.11	0.12	0.11	0.12	0.11	0.011	0.195	0.984	0.944
Arachidic acid (C20:0), %	0.20	0.18	0.19	0.19	0.19	0.18	0.012	0.218	0.948	0.353
Gadoleic acid (C20:1), %	0.88	0.78	0.99	0.93	0.84	0.90	0.069	0.833	0.706	0.180
Eicosadienoic acid (C20:2), %	0.06	0.14	0.24	0.06	0.05	0.06	0.077	0.997	0.143	0.962
Eicosatrienoic acid (C20:3n-3), %	0.07	0.08	0.09	0.09	0.08	0.09	0.010	0.078	0.496	0.827
Dihomo-γ-linoleic acid (C20:3n-6), %	0.08	0.11	0.11	0.11	0.10	0.11	0.010	0.034	0.963	0.494
Arachidonic acid (C20:4n-6), %	0.21	0.27	0.31	0.25	0.25	0.27	0.022	0.060	0.370	0.810
Other fatty acids, %	0.69	0.68	0.82	0.72	0.69	0.79	0.063	0.222	0.632	0.985
Total SFA,[5] %	35.06	32.49	37.56	33.34	33.03	33.01	1.916	0.413	0.538	0.350
Total MUFA,[6] %	52.75	49.42	42.32	48.62	48.75	47.58	2.871	0.174	0.745	0.569
Total PUFA,[7] %	10.96	16.66	18.41	16.47	16.72	17.74	1.049	0.010	0.880	0.840
Total *trans* fatty acids,[8] %	0.59	0.73	0.76	0.70	0.73	0.76	0.049	0.014	0.865	0.703
UFA:SFA ratio[9]	1.82	2.04	1.74	1.96	1.98	1.97	0.117	0.306	0.756	0.345
PUFA:SFA ratio[10]	0.31	0.51	0.49	0.49	0.50	0.53	0.022	0.010	0.340	0.130
Iodine value,[11] g/100g	65.0	72.1	68.9	71.1	71.7	72.4	1.143	0.010	0.300	0.120

[1] A total of 36 pigs PIC 327 × 1050; PIC, Hendersonville, TN; initially 38.4 ± 0.3 kg) were used in this 88-d study; 6 pens per treatment and 1 pig per pen.

[2] Refers to low-fiber diet without DDGS or midds.

[3] Refers to high-fiber diet with 30% distillers dried grains with solubles (DDGS) and 19% wheat middlings (midds).

[4] Refers to the number of days pigs were switched from the high-fiber diet to the low-fiber diet before market.

[5] Total SFA = ([C8:0] + [C10:0] + [C12:0] + [C14:0] + [C16:0] + [C18:0] + [C20:0] + [C22:0] + [C24:0]); brackets indicate concentration.

[6] Total MUFA = ([C14:1] + [C16:1] + [C18:1*cis*-9] + [C18:1n-7] + [C20:1] + [C24:1]); brackets indicate concentration.

[7] Total PUFA = ([C18:2n-6] + [C18:3n-3] + [C18:3n-6] + [C20:2] + [C20:3n-3] + [C20:3n-6] + [C20:4n-6]); brackets indicate concentration.

[8] Total *trans* fatty acids = ([C18:1trans] + [C18:2trans] + [C18:3trans]); brackets indicate concentration.

[9] UFA:SFA = (total MUFA+PUFA)/ total SFA.

[10] PUFA:SFA = total PUFA/ total SFA.

[11] Calculated as IV = [C16:1] × 0.950 + [C18:1] × 0.860 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C20:4] × 3.201 + [C22:1] × 0.723 + [C22:5] × 3.697 + [C22:6] × 4.463; brackets indicate concentration.

Table 1-15. Effect of dietary fiber withdrawal before market on belly fatty acid analysis, Exp. 1 (DM basis)[1]

								Probability, $P <$		
	Low-	High-fiber ingredient withdrawal before market,[3] d						Low-fiber vs.	Duration	
Item	fiber[2]	20[4]	15	10	5	0	SEM	0-d withdrawal	Linear	Quadratic
Myristic acid (C14:0). %	1.30	1.41	1.23	1.39	1.38	1.33	0.043	0.649	0.828	0.528
Myristoleic acid (C14:1), %	0.02	0.02	0.02	0.02	0.03	0.02	0.004	0.664	0.413	0.528
Palmitic acid (C16:0), %	24.70	24.74	23.69	23.78	24.03	23.48	0.471	0.055	0.123	0.481
Palmitoleic acid (C16:1), %	3.41	3.33	3.07	2.95	3.28	3.10	0.164	0.151	0.596	0.292
Stearic acid (C18:0), %	11.46	11.14	11.06	11.01	10.56	10.33	0.544	0.120	0.194	0.712
Oleic acid (C18:1 *cis*-9), %	49.03	43.92	46.47	42.95	43.87	43.91	1.302	0.010	0.494	0.897
Linoleic acid (C18:2n-6), %	7.16	12.42	11.32	14.41	13.53	14.27	1.345	0.010	0.142	0.953
α-linoleic acid (C18:3n-3), %	0.31	0.47	0.42	0.54	0.51	0.53	0.058	0.006	0.218	0.970
γ-linoleic acid (C18:3n-6), %	0.11	0.04	0.06	0.08	0.09	0.08	0.027	0.443	0.167	0.439
Conjugated Linoleic acid (*c*9*, t*11), %	0.085	0.089	0.070	0.084	0.093	0.078	0.014	0.720	0.991	0.949
Arachidic acid (C20:0), %	0.21	0.19	0.16	0.19	0.16	0.18	0.012	0.072	0.530	0.464
Gadoleic acid (C20:1), %	0.84	0.69	0.82	0.79	0.76	0.83	0.066	0.897	0.262	0.652
Eicosadienoic acid (C20:2), %	0.28	0.21	0.24	0.20	0.23	0.22	0.075	0.521	0.987	0.956
Eicosatrienoic acid (C20:3n-3), %	0.03	0.02	0.03	0.06	0.05	0.06	0.012	0.057	0.013	0.379
Dihomo-γ-linoleic acid (C20:3n-6), %	0.05	0.09	0.06	0.09	0.08	0.09	0.014	0.026	0.470	0.518
Arachidonic acid (C20:4n-6), %	0.20	0.25	0.26	0.26	0.26	0.28	0.016	0.010	0.371	0.934
Other fatty acids, %	0.52	0.56	0.55	0.65	0.60	0.65	0.064	0.137	0.230	0.884
Total SFA,[5] %	37.66	37.48	36.14	36.37	36.12	35.31	0.927	0.060	0.119	0.856
Total MUFA,[6] %	53.30	47.96	50.39	46.71	47.94	47.86	1.447	0.007	0.534	0.985
Total PUFA,[7] %	8.14	13.50	12.40	15.65	14.75	15.53	1.386	0.010	0.131	0.940
Total *trans* fatty acids,[8] %	0.42	0.51	0.49	0.61	0.60	0.61	0.075	0.055	0.150	0.759
UFA:SFA ratio[9]	1.63	1.64	1.74	1.71	1.74	1.80	0.068	0.078	0.146	0.869
PUFA:SFA ratio[10]	0.22	0.36	0.34	0.43	0.41	0.44	0.042	0.010	0.092	0.946
Iodine value,[11] g/100g	60.2	65.1	65.2	67.8	67.3	68.6	1.682	0.010	0.080	0.907

[1] A total of 36 pigs PIC 327 × 1050; PIC, Hendersonville, TN; initially 38.4 ± 0.3 kg) were used in this 88-d study; 6 pens per treatment and 1 pig per pen.

[2] Refers to low-fiber diet without DDGS or midds.

[3] Refers to high-fiber diet with 30% distillers dried grains with solubles (DDGS) and 19% wheat middlings (midds).

[4] Refers to the number of days pigs were switched from the high-fiber diet to the low-fiber diet before market.

[5] Total SFA = ([C8:0] + [C10:0] + [C12:0] + [C14:0] + [C16:0] + [C18:0] + [C20:0] + [C22:0] + [C24:0]); brackets indicate concentration.

[6] Total MUFA = ([C14:1] + [C16:1] + [C18:1*cis*-9] + [C18:1n-7] + [C20:1] + [C24:1]); brackets indicate concentration.

[7] Total PUFA = ([C18:2n-6] + [C18:3n-3] + [C18:3n-6] + [C20:2] + [C20:3n-3] + [C20:3n-6] + [C20:4n-6]); brackets indicate concentration.

[8] Total *trans* fatty acids = ([C18:1trans] + [C18:2trans] + [C18:3trans]); brackets indicate concentration.

[9] UFA:SFA = (total MUFA+PUFA)/ total SFA.

[10] PUFA:SFA = total PUFA/ total SFA.

[11] Calculated as IV = [C16:1] × 0.950 + [C18:1] × 0.860 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C20:4] × 3.201 + [C22:1] × 0.723 + [C22:5] × 3.697 + [C22:6] × 4.463; brackets indicate concentration.

Table 1-16. Effect of dietary fiber withdrawal before market on backfat fatty acid analysis, Exp. 1 (DM basis)[1]

								Probability, $P <$		
	Low-	High-fiber ingredient withdrawal before market,[3] d						Low-fiber vs.	Duration	
Item	fiber[2]	20[4]	15	10	5	0	SEM	0-d withdrawal	Linear	Quadratic
Myristic acid (C14:0). %	1.23	1.40	1.18	1.30	1.27	1.23	0.061	0.992	0.218	0.339
Myristoleic acid (C14:1), %	0.01	0.02	0.01	0.01	0.01	0.01	0.002	0.514	0.542	0.844
Palmitic acid (C16:0), %	24.42	20.46	23.46	24.38	23.61	22.70	1.615	0.416	0.334	0.098
Palmitoleic acid (C16:1), %	2.75	2.66	2.30	2.36	2.50	2.35	0.139	0.036	0.311	0.298
Stearic acid (C18:0), %	13.64	13.40	13.44	10.81	12.27	11.88	0.998	0.183	0.158	0.357
Oleic acid (C18:1 *cis*-9), %	44.07	41.35	41.41	41.19	39.40	39.03	1.171	0.010	0.061	0.554
Linoleic acid (C18:2n-6), %	10.76	17.17	14.75	16.26	17.36	18.95	0.796	0.010	0.010	0.010
α-linoleic acid (C18:3n-3), %	0.43	0.64	0.53	0.57	0.63	0.66	0.035	0.010	0.160	0.020
γ-linoleic acid (C18:3n-6), %	0.13	0.12	0.13	0.13	0.12	0.11	0.013	0.411	0.483	0.446
Conjugated Linoleic acid (*c*9*, t*11), %	0.07	0.08	0.09	0.09	0.09	0.10	0.007	0.018	0.111	0.823
Arachidic acid (C20:0), %	0.25	0.25	0.24	0.24	0.24	0.22	0.019	0.163	0.282	0.835
Gadoleic acid (C20:1), %	0.77	0.72	0.81	0.87	0.75	0.78	0.054	0.860	0.635	0.115
Eicosadienoic acid (C20:2), %	0.05	0.04	0.04	0.04	0.04	0.04	0.008	0.498	0.981	0.722
Eicosatrienoic acid (C20:3n-3), %	0.05	0.07	0.06	0.08	0.08	0.08	0.006	0.010	0.030	0.440
Dihomo-γ-linoleic acid (C20:3n-6), %	0.08	0.10	0.08	0.10	0.10	0.11	0.004	0.010	0.080	0.010
Arachidonic acid (C20:4n-6), %	0.19	0.25	0.22	0.22	0.21	0.26	0.018	0.011	0.931	0.026
Other fatty acids, %	0.65	0.67	0.64	0.65	0.67	0.73	0.060	0.340	0.432	0.396
Total SFA,[5] %	39.55	35.51	38.32	36.74	37.39	36.03	1.447	0.070	0.976	0.230
Total MUFA,[6] %	47.60	44.75	44.53	44.43	42.67	42.18	1.290	0.010	0.073	0.623
Total PUFA,[7]%	11.69	18.39	15.81	17.40	18.53	20.21	0.843	0.010	0.020	0.010
Total *trans* fatty acids,[8] %	0.56	0.76	0.65	0.70	0.75	0.78	0.040	0.010	0.306	0.057
UFA:SFA ratio[9]	1.50	1.79	1.57	1.68	1.64	1.73	0.145	0.232	0.586	0.235
PUFA:SFA ratio[10]	0.30	0.52	0.41	0.47	0.50	0.56	0.045	0.010	0.400	0.030
Iodine value,[11] g/100g	61.8	71.2	66.4	69.0	69.5	72.1	1.716	0.010	0.330	0.040

[1] A total of 36 pigs PIC 327 × 1050; PIC, Hendersonville, TN; initially 38.4 ± 0.3 kg) were used in this 88-d study; 6 pens per treatment and 1 pig per pen.

[2] Refers to low-fiber diet without DDGS or midds.

[3] Refers to high-fiber diet with 30% distillers dried grains with solubles (DDGS) and 19% wheat middlings (midds).

[4] Refers to the number of days pigs were switched from the high-fiber diet to the low-fiber diet before market.

[5] Total SFA = ([C8:0] + [C10:0] + [C12:0] + [C14:0] + [C16:0] + [C18:0] + [C20:0] + [C22:0] + [C24:0]); brackets indicate concentration.

[6] Total MUFA = ([C14:1] + [C16:1] + [C18:1*cis*-9] + [C18:1n-7] + [C20:1] + [C24:1]); brackets indicate concentration.

[7] Total PUFA = ([C18:2n-6] + [C18:3n-3] + [C18:3n-6] + [C20:2] + [C20:3n-3] + [C20:3n-6] + [C20:4n-6]); brackets indicate concentration.

[8] Total *trans* fatty acids = ([C18:1trans] + [C18:2trans] + [C18:3trans]); brackets indicate concentration.

[9] UFA:SFA = (total MUFA+PUFA)/ total SFA.

[10] PUFA:SFA = total PUFA/ total SFA.

[11] Calculated as IV = [C16:1] × 0.950 + [C18:1] × 0.860 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C20:4] × 3.201 + [C22:1] × 0.723 + [C22:5] × 3.697 + [C22:6] × 4.463; brackets indicate concentration.

Table 1-17. Effect of dietary fiber withdrawal before market on ham collar acid analysis, Exp. 1 (DM basis)[1]

								Probability, *P* <		
	Low-	High-fiber ingredient withdrawal before market,[3] d						Low-fiber vs.	Duration	
Item	Fiber[2]	20[4]	15	10	5	0	SEM	0-d withdrawal	Linear	Quadratic
Myristic acid (C14:0). %	1.36	1.44	1.26	1.38	1.39	1.35	0.096	0.937	0.856	0.630
Myristoleic acid (C14:1), %	0.01	0.01	0.01	0.02	0.01	0.01	0.003	0.961	0.477	0.358
Palmitic acid (C16:0), %	23.87	25.56	22.19	22.99	22.80	22.69	1.173	0.442	0.144	0.181
Palmitoleic acid (C16:1), %	3.41	3.47	2.95	3.05	3.28	2.79	0.191	0.017	0.073	0.788
Stearic acid (C18:0), %	11.13	11.57	10.31	10.30	9.81	10.60	0.767	0.593	0.283	0.181
Oleic acid (C18:1 *cis*-9), %	46.38	35.89	43.22	42.69	42.25	40.50	2.882	0.125	0.334	0.079
Linoleic acid (C18:2n-6), %	10.45	18.12	16.26	15.69	16.61	17.71	1.081	0.001	0.887	0.056
α-linoleic acid (C18:3n-3), %	0.48	0.73	0.64	0.60	0.67	0.69	0.047	0.002	0.730	0.038
γ-linoleic acid (C18:3n-6), %	0.15	0.11	0.13	0.13	0.13	0.13	0.016	0.289	0.457	0.523
Conjugated Linoleic acid (*c*9*, t*11), %	0.09	0.10	0.11	0.09	0.11	0.09	0.012	0.914	0.455	0.805
Arachidic acid (C20:0), %	0.22	0.21	0.18	0.19	0.20	0.19	0.013	0.097	0.513	0.591
Gadoleic acid (C20:1), %	0.81	0.76	0.79	0.89	0.81	1.03	0.110	0.126	0.091	0.570
Eicosadienoic acid (C20:2), %	0.10	0.08	0.06	0.14	0.06	0.17	0.045	0.291	0.171	0.567
Eicosatrienoic acid (C20:3n-3), %	0.07	0.10	0.08	0.09	0.08	0.09	0.008	0.035	0.784	0.130
Dihomo-γ-linoleic acid (C20:3n-6), %	0.09	0.12	0.11	0.10	0.11	0.12	0.007	0.001	0.903	0.017
Arachidonic acid (C20:4n-6), %	0.24	0.33	0.30	0.26	0.28	0.31	0.020	0.010	0.326	0.017
Other fatty acids, %	0.71	0.76	0.75	0.71	0.72	0.81	0.074	0.324	0.773	0.355
Total SFA,[5] %	36.58	38.78	33.95	34.87	34.20	34.83	1.939	0.489	0.186	0.173
Total MUFA,[6] %	50.61	40.13	46.97	46.64	46.35	44.34	2.816	0.095	0.351	0.079
Total PUFA,[7] %	11.58	19.59	17.57	17.01	17.94	19.22	1.138	0.001	0.920	0.050
Total *trans* fatty acids,[8] %	0.63	0.84	0.76	0.73	0.79	0.82	0.052	0.009	0.937	0.089
UFA:SFA ratio[9]	1.70	1.54	1.90	1.83	1.88	1.82	0.105	0.360	0.284	0.185
PUFA:SFA ratio[10]	0.32	0.51	0.52	0.49	0.52	0.55	0.028	0.001	0.304	0.235
Iodine value,[11] g/100g	64.3	69.4	71.7	70.2	71.8	72.1	1.349	0.001	0.169	0.837

[1] A total of 36 pigs PIC 327 × 1050; PIC, Hendersonville, TN; initially 38.4 ± 0.3 kg) were used in this 88-d study; 6 pens per treatment and 1 pig per pen.

[2] Refers to low-fiber diet without DDGS or midds.

[3] Refers to high-fiber diet with 30% distillers dried grains with solubles (DDGS) and 19% wheat middlings (midds).

[4] Refers to the number of days pigs were switched from the high-fiber diet to the low-fiber diet before market.

[5] Total SFA = ([C8:0] + [C10:0] + [C12:0] + [C14:0] + [C16:0] + [C18:0] + [C20:0] + [C22:0] + [C24:0]); brackets indicate concentration.

[6] Total MUFA = ([C14:1] + [C16:1] + [C18:1*cis*-9] + [C18:1n-7] + [C20:1] + [C24:1]); brackets indicate concentration.

[7] Total PUFA = ([C18:2n-6] + [C18:3n-3] + [C18:3n-6] + [C20:2] + [C20:3n-3] + [C20:3n-6] + [C20:4n-6]); brackets indicate concentration.

[8] Total *trans* fatty acids = ([C18:1trans] + [C18:2trans] + [C18:3trans]); brackets indicate concentration.

[9] UFA:SFA = (total MUFA+PUFA)/ total SFA.

[10] PUFA:SFA = total PUFA/ total SFA.

[11] Calculated as IV = [C16:1] × 0.950 + [C18:1] × 0.860 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C20:4] × 3.201 + [C22:1] × 0.723 + [C22:5] × 3.697 + [C22:6] × 4.463; brackets indicate concentration.

Table 1-18. Effect of dietary fiber withdrawal before market on growth performance of finishing pigs, Exp. 2[1]

								Probability, $P <$		
		High-fiber ingredient withdrawal before market,[2] d						Low-fiber vs	Duration	
Item	Low-fiber[3]	24[4]	19	14	9	0	SEM	0-d withdrawal	Linear	Quadratic
BW, kg										
d 0	44.5	44.5	44.5	44.6	44.6	44.5	0.94	1.000	0.885	0.921
d 64	105.3	101.7	101.5	101.7	101.6	101.8	1.47	0.001	0.850	0.734
d 96	132.5	129.3	129.5	129.1	128.3	128.3	1.58	0.001	0.233	0.797
d 0 to 64										
ADG, kg	0.95	0.90	0.89	0.89	0.89	0.89	0.013	0.001	---	---
ADFI, kg	2.55	2.44	2.44	2.45	2.45	2.49	0.031	0.016	---	---
G:F	0.372	0.367	0.365	0.364	0.364	0.359	0.004	0.023	---	---
d 64 to 96										
ADG, kg	0.85	0.87	0.86	0.87	0.83	0.84	0.019	0.720	0.199	0.982
ADFI, kg	2.83	2.97	2.92	2.97	2.92	2.93	0.055	0.185	0.611	0.954
G:F	0.302	0.292	0.295	0.292	0.284	0.289	0.005	0.053	0.262	0.981
d 0 to 96										
ADG, kg	0.92	0.89	0.88	0.88	0.87	0.88	0.010	0.001	0.285	0.786
ADFI, kg	2.64	2.60	2.59	2.61	2.60	2.62	0.035	0.683	0.526	0.656
G:F	0.348	0.340	0.340	0.339	0.336	0.335	0.003	0.001	0.070	0.791
Caloric efficiency, Mcal/kg										
ME	9.54	9.61	9.61	9.64	9.72	9.71	0.091	0.180	0.205	0.909
NE	7.24	7.21	7.21	7.22	7.28	7.25	0.068	0.854	0.396	0.971

[1] A total of 1,089 pigs (PIC 337 × 1050, PIC, Hendersonville, TN; initially 44.5 ± 0.1 kg) were used in this 96-d study; 7 pens per treatment and 25 to 27 pigs per pen.

[2] Refers to high-fiber diet with 30% distillers dried grains with solubles (DDGS) and 19% wheat middlings (midds).

[3] Refers to low-fiber diet without DDGS or midds.

[4] Refers to the number of days pigs were switched from the high-fiber diet to the low-fiber diet before market.

Table 1-19. Effect of dietary fiber withdrawal before market on carcass characteristics of finishing pigs, Exp. 2[1]

		High-fiber ingredient withdrawal before market,[2] d						Probability, $P <$		
								Low-fiber vs	Duration	
Item	Low-fiber[3]	24[4]	19	14	9	0	SEM	0-d withdrawal	Linear	Quadratic
Carcass characteristics										
HCW, kg	99.1	95.8	96.6	96.2	95.5	94.8	0.91	0.001	0.052	0.077
Carcass yield,[5] %										
Farm	74.9	74.1	74.6	74.5	74.4	73.9	0.50	0.194	0.723	0.275
Plant	75.4	74.3	74.6	75.1	74.9	74.5	0.71	0.392	0.688	0.371
Backfat depth,[6] mm	17.9	16.7	17.1	16.6	16.3	16.4	0.42	0.018	0.206	0.790
Loin depth,[6] mm	66.5	64.9	65.6	65.5	65.9	63.9	0.77	0.019	0.388	0.042
Lean,[6] %	55.9	56.5	56.3	56.6	56.9	56.5	0.30	0.141	0.390	0.752

[1] A total of 1,089 pigs (PIC 337 × 1050, PIC, Hendersonville, TN; initially 44.5 ± 0.1 kg) were used in this 96-d study; 7 pens per treatment and 25 to 27 pigs per pen.

[2] Refers to high-fiber diet with 30% distillers dried grains with solubles (DDGS) and 19% wheat middlings (midds).

[3] Refers to low-fiber diet without DDGS or midds.

[4] Refers to the number of days pigs were switched from the high-fiber diet to the low-fiber diet before market.

[5] Carcass yield calculated by dividing HCW by live weight obtained at the farm and plant before transportation to the packing plant.

[6] Adjusted by using HCW as a covariate.

Chapter 2 - Effects of distillers dried grains with solubles and added fat fed immediately before slaughter on growth performance and carcass characteristics of finishing pigs

Abstract

The addition of dietary fat has been shown to increase HCW and carcass yield in pigs fed low-fiber corn-soy diets; however, the impact of added fat in high-fiber, low-energy diets is less known. Therefore, the potential for fat to ameliorate the negative effect high-fiber diets have on carcass yield during the last 3 wk before slaughter is of high importance. This experiment was conducted to determine the interactive effects of 30% distillers dried grains with solubles (DDGS) and 5% added fat fed before slaughter on growth performance and carcass characteristics. A total of 1,258 pigs in two groups (initially 105.8 ± 0.1 kg BW; group 1 PIC 337 × 1050; group 2 PIC 327 × 1050) were used in a 20-d experiment. All pigs were fed a common diet with 30% DDGS until 20 d before slaughter. Then, all pens were weighed and allotted to treatments with 20 replicate pens per treatment. Dietary treatments were arranged in a 2 × 2 factorial with 2 diet types (corn-soybean meal–based with or without 30% DDGS) and added fat (0 or 5%; group 1 = tallow; group 2 = choice white grease). Diets were formulated to a constant standardized ileal digestible Lys:NE ratio. There were no treatment × group interactions for any response criteria. Thus, data for the two groups were combined for analysis. Overall, there was a tendency for a diet type × added fat interaction for ADG ($P = 0.054$), whereas this was significant for G:F ($P = 0.008$). This was a result of 5% added fat increasing ADG and G:F to a greater magnitude for pigs fed the diet containing 30% DDGS than for pigs fed the corn-soy diet. Although diet type did not affect final live BW, pigs fed the diet containing DDGS had decreased HCW and carcass yield ($P < 0.05$). Adding 5% fat did not affect carcass yield. Jowl fat iodine value was increased by added fat (*P* = 0.006) and feeding DDGS (*P* = 0.001). In conclusion, adding 5% fat to finishing pig diets containing 30% DDGS approximately 20 d before slaughter improved ADG and G:F but did not overcome the reduction in carcass yield from feeding DDGS.

Key Words: fat, fiber, finishing pigs, withdrawal, yield

Introduction

Feeding pigs high-fiber containing ingredients, such as distillers dried grains with solubles (DDGS) and wheat middlings (midds), throughout the finishing period negatively affects HCW and carcass yield (Whitney et al., 2006; Salyer et al., 2012). Turlington (1984) determined that the reduction in carcass yield from feeding high-fiber ingredients resulted from an increase in gut fill; specifically, an increase in the weight of residual digestive contents in the colon and cecum. Feeding high levels of byproducts throughout the finishing period can potentially reduce feed cost; however, this benefit could be offset if revenue is lost due to lower HCW. Thus, development of mitigation strategies to overcome the reduction in carcass yield when feeding high-fiber ingredients could prove beneficial for swine producers.

One strategy to overcome the carcass yield reduction is the removal of high-fiber diets approximately 3 wk before slaughter by reducing gut fill (Asmus et al. 2014; Graham et al., 2014). Coble (2015) determined that removal of high-fiber ingredients in finishing pigs 15 to 19 d before slaughter was sufficient to restore carcass yield. Still, there is interest in determining if other dietary manipulations during late finishing can improve carcass yield when high-fiber ingredients are fed. Adding fat has consistently been shown to improve ADG and G:F in finishing pigs, and in some experiments increase HCW and carcass yield (Smith et al., 1999; Engel et al., 2001). Recently, Davis et al. (2015) reported that adding beef tallow to a corn-soy diet or one that contained 30% DDGS improved carcass yield when fed for the entire finishing period. However, research has yet to consider if adding fat during a withdrawal period, the most important period of finishing when there are concerns of reduced carcass yield, can overcome fiber's negative effect on carcass yield. Thus, the objective of this study was to determine if adding 5% fat for 20 d before slaughter to a high-fiber diet containing 30% DDGS would ameliorate the negative effect of on carcass yield.

Materials and Methods

All experimental procedures and animal care were approved by the Kansas State University Institutional Animal Care and Use Committee.

General

The experiment was conducted with two groups of pigs utilizing a total of 1,258 pigs (initially 105.7 kg ± 0.1 kg BW) in a 20-d study. Group 1 (972 pigs, PIC 337 × 1050; PIC, Hendersonville, TN) was housed in a commercial research facility in southwestern Minnesota. The facility was double-curtain sided with completely slatted concrete flooring. The barn contained 48 pens (3.05 × 5.49 m), with 20 to 23 pigs per pen, equipped with a 5-hole conventional dry self-feeder (Thorp Equipment, Thorp, WI) and a cup waterer providing ad libitum access to feed and water. Group 2 (286 pigs, PIC 327 × 1050; PIC, Hendersonville, TN) was housed at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. Pigs were housed in an enclosed environmentally regulated, mechanically ventilated barn containing 36 pens (2.44m × 3.05 m). Pens contained 7 to 8 pigs and had adjustable gates facing the alleyway which allowed $0.93m^2$/pig. Each pen was equipped with a cup waterer and a single-sided, dry self-feeder (Farmweld, Teutopolis, IL) with 2 eating spaces located in the fence line for ad libitum access to feed and water. Pens were located over a completely slatted concrete floor with a manure storage pit underneath (1.20-m deep). Facilities for both Group 1 and 2 were equipped with a computerized feeding system (FeedPro; Feedlogic Corp., Willmar, MN) that delivered and recorded daily feed additions of specific diets to each pen.

Before the start of the experiment, pigs were fed a common diet containing 30% DDGS (group 1 for 21 d and group 2 for 53 d). On d 0 (20 d before slaughter), pens of pigs were weighed, ranked by BW, and randomly allotted to 1 of 4 dietary treatments within BW block. Group 1 consisted of 11 pens per treatment and group 2 consisted of 9 pens per treatment for a total of 20 replications per treatment. Dietary treatments were arranged in a 2 × 2 factorial with 2 diet types; a low-fiber corn-soybean meal-based diet or a high fiber corn-soybean meal-based diet with 30% DDGS, and 2 levels of added fat (0 or 5%; Tables 2-1 and 2-2). Beef tallow served as the fat source for group 1 and choice white grease served as the added fat source for group 2. All diets were fed in meal form and balanced on a standardized ileal digestible (SID) Lys:NE ratio to be above the estimated requirements (NRC, 2012), but not balanced for energy. Diets were also formulated to be above requirements for AA based on previous research in these facilities.

Samples of the DDGS were obtained at the time of diet manufacturing. Samples of each treatment diet were obtained by collecting samples 2 d after initiating and 2 d before completing the experiment. Samples were combined for a composite sample of each treatment diet, and DDGS, and analyzed for moisture (934.01; AOAC International, 2006), CP (990.03; AOAC International, 2006), ADF and NDF (Van Soest, 1963), crude fiber (978.10; AOAC International, 2006), Ca and P (Campbell and Plank, 1991), ether extract (920.39 A; AOAC International, 2006), and ash (942.05; AOAC International, 2006) at a commercial laboratory (Ward Laboratories, Inc. Kearney, NE; Tables 2-3 to 2-4). Bulk density (mass per unit volume, g/L) was also measured for the complete feed with a grain density cup (Seedburo Model 8800; Seedburo Equipment, Chicago, IL).

Pens of pigs were weighed and feed disappearance determined on d 0 and 20 to calculate ADG, ADFI, G:F, and ME and NE caloric efficiency. After final weights were taken on d 20, pigs were transported (group 1 – 111 km; group 2 – 256 km) to a commercial packing plant (group 1 – JBS Swift and Company, Worthington, MN; group 2 – Triumph Foods, LLC, St. Joseph, MO) for processing and data collection. Pigs in both groups were not allowed access to feed for 12 h before slaughter. Hot carcass weights at both plants were measured immediately after evisceration and each carcass evaluated for carcass yield, backfat depth, loin depth, and percentage lean. Carcass yield was calculated by dividing the HCW at the plant by the live weight at the farm before transport to the plant. Fat depth and loin depth were measured with an optical probe inserted between the third and fourth last rib (counting from the ham end of the carcass) at a distance approximately 7 cm from the dorsal midline. Jowl fat samples were also collected from pigs in group 2 and analyzed by near infrared spectroscopy (Bruker MPA, Breman, Germany) for fat IV using the equation of Cocciardi et al. (2009). Hot carcass weight ADG was calculated by subtracting the assumed initial HCW, determined by multiplying d 0 BW by an assumed yield of 75%, from the final HCW, then divided by 20 d for the period of the experiment. Hot carcass weight G:F was calculated by dividing HCW gain by feed intake over the 20 d experiment.

Statistical Analysis

Experimental data were analyzed in a randomized complete-block design using the PROC MIXED procedure in SAS (SAS Institute Inc., Cary, NC) with pen serving as the experimental unit and initial BW serving as the blocking factor. Data from groups 1 and 2 were analyzed as a combined dataset with the random effect of block within group and the fixed effects of treatment, group, and treatment × group. Residual assumptions were checked using standardized diagnostics on studentized residuals. The assumptions were reasonable met. No treatment × group interactions were observed for any of the response criteria measured and was subsequently removed from the model. Contrasts were tested between pigs fed the corn-soy and 30% DDGS diet, with or without added fat, and the interaction between diet type and added fat was. Backfat depth, loin depth, and lean percentage were adjusted to a common hot carcass weight for analysis. Results from the experiment were considered significant at $P \leq 0.05$ and a tendency between $P > 0.05$ and $P \leq 0.10$.

Results and Discussion

Diet and Ingredient Analysis

The diets used in the experiment were formulated to a constant SID Lys:NE ratio to insure that dietary SID Lys concentration did not influence growth (Tables 2-1 and 2-2). The same source of DDGS was used throughout the experiment within each group of pigs. Chemical analysis of the diets confirmed the expected increases in fiber fraction and ether extract level when DDGS and added fat were added to the diets (Tables 2-3 and 2-4). When 30% DDGS were added, NDF increased by 4.4 and 3.8 percentage units in group 1 and 2, respectively; similar to others whom fed a high-fiber diet with 30% DDGS (Urriola and Stein, 2010). Furthermore, the analyzed values for ether extract were 4 to 5 percentage units greater in diets containing 5% added fat than diets without added fat, verifying the correct added fat concentrations were achieved. Bulk density was decreased in diets containing DDGS compared to the low-fiber corn-soy diet, as expected (Wang et al., 2007). Similar to Asmus (2012) and Salyer et al. (2012), when fat was added to the diet, bulk density was further reduced.

Growth Performance and Carcass Characteristics

Overall, there was a tendency ($P = 0.054$) for a DDGS × added fat interaction for ADG, whereas this interaction was significant ($P < 0.05$) for G:F and caloric efficiency on an ME and NE basis (Table 2-5). Interestingly, these interactions were the result of pigs fed the diet containing 30% DDGS having a greater improvement in ADG and G:F to added fat compared to when fat was added to the diet for pigs fed the corn-soy diet. Before d 0, when pigs were fed the common diet, ADG was 0.95 kg per d, thus part of this interaction is due to the increase in ADG for pigs switched from the DDGS diet to the corn-soy diet without added fat compared with those that continued to eat the

DDGS diet (0.99 vs. 0.93 kg per d). These results are not consistent with those reported by Davis et al. (2015) whom fed a diet with and without 30% DDGS and 5% beef tallow for an entire finishing period and observed no interaction between diet type and added fat for ADG or G:F. The difference between Davis et al. (2015) and our study may partly be explained by the fact that dietary treatments were applied for only the last 20 d before slaughter in our study whereas Davis et al. (2015) fed dietary treatments for an entire finishing period.

A possible explanation for the increase in ADG for pigs fed the corn-soy diet compared to those fed the 30% DDGS diet when fat was not added, is that when pigs are switched from a high-fiber diet to a corn-soy diet, feed intake has been shown to increase (Jacela et al., 2009; Asmus et al., 2014). Turlington (1984) reported that while the weight of feed intake per day did not change, the volume of feed consumed increased when pigs are fed increasing levels of fiber. Pigs generally consume amounts of feed based on their energy requirement, but because of the increase in bulk density and increase in gut fill with fiber, pigs may not have been able to consume enough feed to meet their energy requirement (Whittemore et al., 2001). Ellis and Augspurger (2001) suggest that pigs eat to their current or past energy requirement, which supports both the increase in feed intake for pigs switched to the corn-soy diet and that pigs may not have been consuming their required amounts of energy. Therefore, after the change in diets, pigs most likely continued to eat similar volumetric amounts of feed, but because of the increased bulk density and energy concentration of the corn-soy diet compared to a diet with 30% DDGS, the pig consumes more total kg of feed and energy. This theory is supported by the feed intake data as pigs fed the corn-soy diet had greater (P = 0.001) ADFI compared with pigs that continued to eat the diet with 30% DDGS.

As for the interaction in G:F and caloric efficiency, it’s important to understand that because of the elevated dietary fiber level in the diets with 30% DDGS, the protein and energy in those diets are less digestible (Degen et al., 2009; Urriola and Stein, 2010). However, potentially adding 5% added fat, which is highly digestible, to the DDGS diet met the pig's energy requirement (Kim et al., 2013). This may explain why added fat caused more of a response in growth in the high-fiber diet compared to the low-fiber corn-soy diet, as the energy in the corn-soy diet is more digestible and therefore pigs consuming it were closer to their energy requirement, even without added fat.

The interaction for caloric efficiency could further be explained by evaluating the total caloric intake where there was not an interaction, and gives a possible value to suggest what the energy requirement for the pigs may have been. Pigs fed the DDGS diet consumed fewer calories ($P < 0.05$) per d on an ME and NE basis, but consumed more calories ($P < 0.05$) when fat was added to the diet. When adding fat to the DDGS diet, pigs consumed 8.40 Mcal per d on an NE basis. Pigs consuming the corn-soy diet without added fat consumed 8.17 Mcal per d and 8.76 Mcal per d with added fat. The ADG was similar between both diet types when adding fat, suggesting that the energy requirement is most likely between 8.17 and 8.40 Mcal per d. Adding DDGS to the diet also decreased bulk density and increased gut fill which limited energy intake, thus pigs were likely in an energy dependent state (Campbell and Taverner, 1988).

These results are not consistent with Asmus (2012) whom did not observe greater increases in ADG or improvements in G:F when pigs were fed 3% choice white grease in a high-fiber diet compared to those fed a low-fiber, corn-soy diet for 19 d before slaughter. However, their diets contained 9.5 or 19% wheat middlings in addition to a high level of DDGS. The lower addition of fat, 3% versus the current 5% also may be responsible for the lack of an interaction in Asmus (2012) compared to the current experiment because the lower level of added fat may have not sufficed to meet the pig's energy requirement; therefore, the pig is still in an energy dependent state of growth. Also, Asmus (2012) did not balance diets on an SID Lys:NE ratio. Salyer et al. (2012) fed 20%

wheat middlings in diets containing 2.5 or 5% added choice white grease and also did not report an interaction between diet type and fat for pig performance. However, similar to Davis et al. (2015), their diets were fed for the entire finishing period; not for the last 20 d before slaughter. In terms of the main effect of added fat, regardless of diet type, our research is similar to others whom have reported that added fat increases ADG and improves G:F (Pettigrew and Moser, 1991; De la Llata et al., 2001; Jackson et al., 2009)

For carcass data, there were no DDGS × added fat interactions observed (Table 2-6). Pigs fed the DDGS diet had deceased HCW ($P = 0.026$) and lower carcass yield ($P = 0.001$) compared to pigs fed the corn-soy diet. The reduction in carcass yield is consistent with most published literature where high-fiber diets are fed until marketing (Turlington, 1984; Whitney et al., 2006; Stewart et al., 2013). Presently, the only successful means to mitigate the reduction in carcass yield and HCW is to change the pigs from the high-fiber diet to a low-fiber corn-soy diet 15 to 20 d before slaughter (Asmus et al., 2014; Graham et al., 2014; Coble et al., 2015). This time period is sufficient to reduce large intestine fill associated with residual undigested fiber fractions remaining in the large intestine. Because of these results, determining the potential interaction between diet type and added fat during the last 20 d before slaughter was of high importance. However, added fat did not influence carcass yield.

Added fat has been shown in some cases to improve HCW and carcass yield (Smith et al., 1999; Jackson et al., 2009) while others have reported no improvements in carcass yield (Engel et al., 2001; Benz et al., 2011). Beaulieu et al. (2009) reported that for every 0.10 increase in Mcal/kg of DE, carcass yield improved by 0.20%. However, the previous work was completed in low-fiber diets containing mainly corn- or sorghum-based diets; not with high-fiber ingredients such as DDGS.

The lack on an interaction further suggests that adding fat to the DDGS diet does not negate the negative effect of high-fiber diets on carcass yield. Similarly, Davis et al. (2015) did not find a diet type by added fat interaction for yield when adding fat to diets containing none or 30% DDGS throughout the finishing period. Adding 3% choice white grease to diets containing DDGS and wheat middlings (Asmus, 2012) or adding 2.5 or 5% choice white grease to diets containing 20% wheat middlings (Salyer et al., 2012) also did not improve HCW or carcass yield, even though the type and amount of fiber is different in each experiment. One explanation for added fat not being able to overcome a reduction in carcass yield in higher fiber diets, could be that added fat slows down that rate of passage and higher amounts of insoluble fiber decreases the bulk density; increasing the total volume, weight, and water holding capacity of excreta (Mateos et al., 1982; Knudsen and Hansen, 1991; Takahashi et al., 2008). The current results demonstrating the lack of benefit to fat during the withdrawal period, coupled with the earlier data, suggest that adding fat in short or long term periods before slaughter does not overcome the negative effect of dietary fiber on carcass yield.

Pigs fed 5% added fat tended to have greater backfat depth ($P = 0.061$) compared to pigs not fed added fat, which led to a slight reduction in carcass lean. Increased carcass backfat depth is the one carcass trait most consistently increased with added dietary fat, due to a higher energy intake (Beaulieu et al., 2009; Benz et al., 2011; Salyer et al., 2012). Jowl IV was increased ($P < 0.05$) by both diet type and added fat. It is important to note, that only pigs from group 2 were able to be sampled for jowl IV and choice white grease was the fat source fed to this group. Adding fat increased jowl IV by 0.79 and 0.46 g/100g for pigs fed the corn-soy diet and diet with 30% DDGS, respectively. Adding choice white grease increased the amount of dietary unsaturated fatty acids, thus increasing jowl IV, similar to data of Benz et al. (2011). Pigs fed the DDGS diet had 1.36

higher jowl IV compared to pigs switched to the corn-soy diet at 20 d before slaughter. Iodine value has been shown to increase by more than 10 g/100g when feeding 30% DDGS throughout (Cromwell et al., 2011). Coble (2015) found that jowl IV was increased by 8 g/100g for pigs fed a high fiber diet with 30% DDGS and 19% midds compared to those fed a corn-diet for 88 d. They reported a reduction of 2 g/100g when pigs were switched to the corn-soy diet from the high-fiber diet 20 d before market. The current study agrees with this research, suggesting that although IV can be reduced when pigs are switched to a corn-soy diet 20 d before slaughter, longer amounts of time are needed to further reduce jowl IV.

Because most pork producers are paid on a carcass basis, another measurement of response to observe is carcass performance. Pigs fed the high-fiber diet with DDGS had decreased HCW ADG ($P = 0.001$) and worse HCW G:F ($P = 0.014$) compared to those fed the low-fiber corn-soy diet. Because the DDGS diet reduced yield, the amount of time required to raise a pig to a desired HCW is increased and the efficiency of the growth is reduced. Pigs fed added fat had increased ($P < 0.05$) HCW ADG and G:F compared to those not fed added fat.

In summary, adding 5% added fat to either the diet containing 30% DDGS or low-fiber corn-soy diet for 20 d before slaughter improved ADG and G:F; however, greater improvements in growth performance were observed in the high-fiber diet containing 30% DDGS. Hot carcass weight and yield were reduced for pigs fed the diet with 30% DDGS compared to those switched to the corn-soy diet, but adding 5% fat did not influence carcass yield. Although the improvements in live and carcass performance with added fat were consistent with previous research, added dietary fat did not overcome the decreased carcass yield and HCW associated with dietary fiber.

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Table 2-1.Composition of diets, Group 1 (as-fed basis)[1]

Distillers dried grains with solubles, %:	0		30	
Item And added fat, %	0	5	0	5
Ingredient, %				
Corn	84.76	76.88	66.41	58.87
Soybean meal, 46.5% CP	13.20	16.06	1.41	3.94
Distillers dried grains with solubles	---	---	30.00	30.00
Beef tallow	---	5.00	---	5.00
Dicalcium P, 18.5% P	0.35	0.35	---	---
Limestone	0.92	0.92	1.18	1.18
Salt	0.35	0.35	0.35	0.35
Vitamin premix[2]	0.05	0.05	0.05	0.05
Trace mineral premix[3]	0.05	0.05	0.05	0.05
L-Lys HCl	0.23	0.22	0.45	0.45
DL-Met	0.02	0.04	---	---
L-Thr	0.06	0.06	0.06	0.07
L-Trp	---	---	0.03	0.03
Phytase[4]	0.03	0.03	0.03	0.03
Total	100.00	100.00	100.00	100.00
Calculated analysis				
Standardized ileal digestible (SID) Lys:NE, g/Mcal	2.57	2.57	2.57	2.57
SID AA, %				
Lys	0.66	0.71	0.65	0.70
Ile:Lys	62	62	58	58
Met:Lys	31	33	36	34
Met + Cys:Lys	60	60	66	63
Thr:Lys	65	65	65	65
Trp:Lys	18	19	18	18
Val:Lys	70	70	73	72
Total Lys, %	0.75	0.80	0.79	0.84
ME, kcal/kg	3,325	3,545	3,342	3,563
NE, kcal/kg	2,551	2,745	2,524	2,720
CP, %	12.7	13.4	14.4	15.0
Ca, %	0.47	0.47	0.46	0.47
P, %	0.38	0.38	0.36	0.36
Available P, %	0.25	0.25	0.30	0.30

[1] Each diet was fed in meal form.

[2] Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D_3; 35,273 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 24 mg vitamin B_{12}.

[3] Provided per kilogram of premix: 33.1 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc oxide, 16.5 g Cu from copper sulfate, 331 mg I from calcium iodate, and 300 mg Se from sodium selenite.

[4] Optiphos 2000 (Huvepharma, Sofia, Bulgaria) provided 1,251 phytase units (FTU)/kg, with a release of 0.13% available P.

Table 2-2. Composition of diets, Group 2 (as-fed basis)[1]

Distillers dried grains with solubles, %:	0		30	
Item — And added fat, %:	0	5	0	5
Ingredient, %				
Corn	84.63	76.41	66.26	58.60
Soybean meal, 46.5% CP	13.05	16.30	1.32	4.00
Distillers dried grains with solubles	---	---	30.00	30.00
Choice white grease	---	5.00	---	5.00
Monocalcium P, 21% P	0.33	0.33	---	---
Limestone	1.07	1.05	1.28	1.25
Salt	0.35	0.35	0.35	0.35
Vitamin premix[2]	0.08	0.08	0.08	0.08
Trace mineral premix[3]	0.08	0.08	0.08	0.08
L-Lys HCl	0.23	0.21	0.45	0.45
DL-Met	0.03	0.05	---	---
L-Thr	0.06	0.07	0.07	0.07
L-Trp	0.01	---	0.03	0.03
Phytase[4]	0.10	0.10	0.10	0.10
Total	100.00	100.00	100.00	100.00
Calculated analysis				
Standardized ileal digestible (SID) Lys:NE, g/Mcal	2.57	2.57	2.57	2.57
SID AA, %				
Lys	0.66	0.71	0.65	0.70
Ile:Lys	61	62	58	58
Met:Lys	33	34	36	34
Met + Cys:Lys	61	61	67	63
Thr:Lys	66	66	66	66
Trp:Lys	19	19	19	19
Val:Lys	70	70	73	73
Total Lys, %	0.75	0.81	0.79	0.81
ME, kcal/kg	3,317	3,551	3,336	3,570
NE, kcal/kg	2,545	2,750	2,519	2,728
CP, %	12.6	13.5	14.3	15.0
Ca, %	0.50	0.50	0.50	0.50
P, %	0.38	0.38	0.36	0.36
Available P, %	0.23	0.24	0.28	0.28

[1] Each diet was fed in meal form.

[2] Provided per kilogram of premix: 4,409,200 IU vitamin A; 551,150 IU vitamin D3; 17,637 IU vitamin E; 1,764 mg vitamin K; 3,307 mg riboflavin; 11,023 mg pantothenic acid; 19,841 mg niacin; and 15.4 mg vitamin B12.

[3] Provided per kilogram of premix: 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulphate, 11g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.

[4] Natuphos 600 (BASF Corporation, Florham Park, NJ) provided 1,324 phytase units (FTU)/kg, with a release of 0.11% available P.

Table 2-3. Chemical analysis and bulk density of diets and distillers dried grains with solubles (DDGS), Group 1 (as-fed basis)[1]

Distillers dried grains with solubles, %:	0		30		
And added fat,[2] %:	0	5	0	5	DDGS
Item					
DM, %	87.76	88.28	88.23	88.79	92.10
CP, %	12.9	12.4	15.7	15.2	30.6
ADF, %	3.1	3.0	4.4	5.3	10.1
NDF, %	7.6	7.2	12.2	11.3	25.5
Crude fiber, %	1.8	1.8	2.9	2.9	8.0
Ca, %	0.51	0.56	0.64	0.71	0.07
P, %	0.31	0.35	0.36	0.39	0.74
Ether extract, %	2.8	7.5	4.4	8.5	9.2
Ash, %	3.19	3.17	3.69	3.90	4.08
Bulk density, g/L	644	631	611	600	---

[1] Diet samples were collected from the tops of each feeder at the beginning and ending of the experiment.

[2] Beef tallow served as the added fat source in diets for group 1 and choice white grease for group 2.

Table 2-4. Chemical analysis and bulk density of diets and distillers dried grains with solubles (DDGS), Group 2 (as-fed basis)[1]

Distillers dried grains with solubles, %:	0		30		
And added fat,[2] %:	0	5	0	5	DDGS
Item					
DM, %	88.91	89.51	89.70	90.03	89.95
CP, %	14.5	15.7	16.6	17.1	29.7
ADF, %	2.5	4.2	4.4	5.7	11.8
NDF, %	5.5	8.1	10.2	10.9	24.1
Crude fiber, %	1.3	2.1	2.1	3.0	7.1
Ca, %	0.62	0.63	0.68	0.63	0.08
P, %	0.35	0.47	0.46	0.47	0.87
Ether extract, %	2.4	6.9	3.7	8.7	6.9
Ash, %	3.64	3.69	3.96	3.92	4.17
Bulk density, g/L	743	670	691	657	578

[1] Diet samples were collected from the tops of each feeder at the beginning and ending of the experiment.

[2] Beef tallow served as the added fat source in diets for group 1 and choice white grease for group 2.

Table 2-5. Effect of 30% DDGS and 5% added fat fed 20 d before slaughter on growth performance of finishing pigs[1]

Distillers dried grains with solubles, %:	0		30			Probability, *P* <		
And added fat,[2] %:	0	5	0	5	SEM	DDGS × Added fat	DDGS	Added fat
BW, kg								
d 0	105.7	105.6	105.7	105.6	0.75	0.982	0.989	0.880
d 20	125.4	125.8	124.4	125.8	0.75	0.338	0.400	0.135
d 0 to 20								
ADG, kg	0.99	1.01	0.93	1.01	0.014	0.054	0.056	0.001
ADFI, kg	3.21	3.19	3.14	3.08	0.029	0.472	0.001	0.182
G:F	0.308	0.317	0.297	0.328	0.004	0.008	0.902	0.001
Caloric intake,[4] Mcal/d								
ME	10.65	11.32	10.49	11.00	0.010	0.407	0.011	0.001
NE	8.17	8.76	7.92	8.40	0.076	0.443	0.001	0.01
Caloric efficiency,[5] Mcal/kg								
ME	10.83	11.28	11.27	10.91	0.141	0.006	0.809	0.709
NE	8.31	8.74	8.51	8.34	0.108	0.007	0.376	0.232

[1] 1,258 pigs (initial 105.7 ± 0.1 kg; Group 1 PIC 337 × 1050; Group 2 PIC 327 × 1050) were used in a 20-d experiment with 20 pens per treatment; Group 1 (11 pens per treatment and 20 to 23 pigs per pen) and Group 2 (9 pens per treatment and 7 to 8 pigs per pen).

[2] Beef tallow served as the added fat source in diets for group 1 and choice white grease for group 2.

[4] Caloric intakes were calculated by the following equation (ADFI × Mcal).

[5] Caloric efficiencies were calculated by the following equation (ADFI × Mcal) ÷ (ADG).

Table 2-6. Effect of 30% DDGS and 5% added fat fed 20 d before slaughter on carcass characteristics and performance of finishing pigs[1]

Distillers dried grains with solubles, %:	0		30			Probability, $P <$		
And added fat,[2] %:	0	5	0	5	SEM	DDGS × Added fat	DDGS	Added fat
Carcass characteristics								
HCW, kg	91.9	92.3	90.7	91.6	0.55	0.556	0.026	0.122
Carcass yield, %	73.0	73.2	72.7	72.7	0.13	0.294	0.001	0.633
Loin depth,[3] mm	59.7	59.4	59.9	60.5	0.48	0.342	0.168	0.738
Backfat depth,[3] mm	19.9	20.2	19.3	19.9	0.28	0.522	0.190	0.061
Lean,[3] %	53.26	53.03	53.58	53.22	0.182	0.735	0.165	0.101
Jowl iodine value[4]	71.49	72.28	73.02	73.48	0.210	0.423	0.001	0.006
Carcass performance								
HCW ADG,[5] kg	0.632	0.656	0.572	0.621	0.013	0.354	0.001	0.006
HCW G:F[6]	0.197	0.206	0.182	0.201	0.004	0.198	0.014	0.001

[1] 1,258 pigs (initial 105.7 ± 0.1 kg; Group 1 PIC 337 × 1050; Group 2 PIC 327 × 1050) were used in a 20-d experiment with 20 pens per treatment; Group 1 (11 pens per treatment and 20 to 23 pigs per pen) and Group 2 (9 pens per treatment and 7 to 8 pigs per pen).

[2] Beef tallow served as the added fat source in diets for group 1 and choice white grease for group 2.

[3] Adjusted by using HCW as a covariate.

[4] Jowl iodine value (g/100g) was measured at the plant by near-infrared spectroscopy in pigs from group 2.

[5] HCW ADG = (HCW – (d 0 wt. ×75% yield)) ÷ 20 d.

[6] HCW F/G = (HCW- (d 0 wt. × 75% yield)) ÷ (ADFI × 20).

Chapter 3 - The effects of copper source on growth performance and carcass characteristics of finishing pigs

Abstract

A total of 1,143 pigs (PIC 337 × 1050, initially 25.1 ± 0.03 kg BW) were used in a 111-d study to determine the effects of copper sulfate (CuSO4) or tribasic copper chloride (TBCC, IntelliBond C; Micronutrients, Indianapolis, IN) on growth performance, carcass characteristics and pen cleanliness. Pens of pigs were allotted to 1 of 6 dietary treatments, balanced on average pen weight in a randomized-complete block design with 25 to 28 pigs per pen and 7 replications per treatment. Treatments included a corn-soybean meal-based diet (corn-soy), a high byproduct diet with 30% distillers dried grain with solubles (DDGS) and 15% bakery meal (byproduct diet), or the byproduct diet with 75 or 150 mg/kg added Cu from $CuSO_4$ or TBCC. At the conclusion of the trial, a digital photo of each pen was taken to allow 3 independent observers to score manure texture and buildup and to assess pen cleanliness prior to power washing. Furthermore, the time required to power wash each pen was also measured. Overall, pigs fed the byproduct diet tended to have increased ADFI ($P = 0.083$) and had decreased G:F ($P = 0.005$) compared to those fed the corn-soy diet. No Cu source × level interactions or Cu source differences were observed ($P > 0.05$). From d 0 to 71, pigs fed increasing Cu had increased (quadratic, $P < 0.05$) ADG, d 71 BW, and ADFI. From d 71 to 111, pigs fed increasing Cu tended to have increased ADFI (linear, $P = 0.068$) and decreased G:F (quadratic, $P = 0.056$). Overall (d 0 to 111), pigs fed diets containing increasing Cu had increased ($P < 0.05$) ADG, final BW, and ADFI (quadratic, $P = 0.026$). Hot carcass weight increased (linear, $P = 0.023$) by 2.4 kg with increasing Cu. Increasing Cu also increased loin depth (linear, $P = 0.019$) and percentage lean (quadratic, *P* = 0.024). Manure buildup and wash time (s/pen) increased (*P* < 0.05) for byproduct diet pens compared to corn-soy pens; however, neither wash time nor pen cleanliness was influenced by added Cu. In summary, increasing dietary Cu in high byproduct diets improved growth and feed intake, resulting in increased final BW and HCW for pigs fed both Cu sources, without influencing pen wash time.

Key Words: copper sulfate, finishing pig, tribasic copper chloride, wash time

Introduction

In the nursery phase, typical improvements in ADG of 12% and ADFI of 8.4% can be observed when adding pharmalogical levels (≤ 250 mg/kg) of Cu (Cromwell, 1997). The reason for improvements in growth is believed to be an antimicrobial-like response (Miller et al., 1969; Cromwell, 2001); however, uncertainty still remains as to the exact mode-of-action (Zhou et al., 1994a). Various inorganic and organic forms of Cu can be used in swine diets, with some forms having greater bioavailability in the pig than others (Cromwell et al., 1978; Cromwell et al., 1989). While $CuSO_4$ has historically been the most commonly utilized inorganic source in swine diets, tribasic copper chloride (TBCC; Intellibond C, Micronutrients, Inc., Indianapolis) is another alternative.

Cromwell et al. (1998) and Hastad (2002) demonstrated that feeding 200 mg/kg Cu from TBCC provided similar improvements in growth performance as those fed $CuSO_4$ for nursery pigs and finishing pigs, respectively. However, Kampf and Paboeuf (2014) recently reported that Cu added in the form of TBCC increased ADG and ADFI more than $CuSO_4$ in nursery pigs. One consistent response when feeding pharmalogical levels of Cu is an increase in ADFI and ADG;

typically only observed during the early finishing period (NCR-42, 1974; Hastad, 2002). The specific reasons for the differing responses over different BW ranges are not fully understood.

Research involving Cu supplementation has historically been based on corn-soybean meal-based diets. However, most pig diets in the United States currently contain byproduct ingredients. Furthermore, an observational consequence of feeding diets high in byproduct ingredients, as well as supplemental Cu, is an increase in manure buildup and pen wash time; however, no published data is available to support these claims. Therefore, the objective of this experiment was to evaluate the effects of $CuSO_4$ and TBCC on growth performance, carcass characteristics, and pen cleanliness of finishing pigs fed diets containing byproduct ingredients.

Materials and Methods

All experimental procedures and animal care were approved by the Kansas State University Institutional Animal Care and Use Committee.

General

The experiment was conducted in a commercial research facility in southwestern Minnesota. Pigs were housed in a facility that was double-curtain sided with completely slatted concrete flooring. The barn contained 48 pens (3.05 m × 5.49 m) equipped with a 5-hole conventional dry self-feeder (Thorp Equipment, Thorp, WI) and a cup waterer providing ad libitum access to feed and water. The facility was equipped with a computerized feeding system (FeedPro; Feedlogic Corp., Willmar, MN) that delivered and recorded daily feed additions of specific diets to each pen.

Animals and Diets

A total of 1,143 pigs (PIC 337 × 1050; PIC, Hendersonville, TN; initially 25.1 ± 0.03 kg) were used in a 111-d experiment. Before the start of the experiment, all pigs were fed a common diet containing 186 mg/kg Cu from tribasic copper chloride (TBCC, Intellibond C; Micronutrients, Inc., Indianapolis, IN). On d 0, pens of pigs (25 to 28 pigs per pen; similar numbers of barrows and gilts) were weighed, ranked by average pen BW, and randomly allotted to 1 of the 6 dietary treatments in a 2 × 2 plus 2 factorial arrangement with average pig BW balanced across each treatment. There were 7 replications per treatment. Treatments included a corn-soybean meal-based diet (corn-soy), a diet containing 30% distillers dried grains with solubles (DDGS) and 15% bakery meal (byproduct), or the byproduct diet with either 75 or 150 mg/kg added Cu from either copper sulfate ($CuSO_4$) or TBCC (Tables 3-1 and 3-2).

All diets contained a basal level of 20 mg/kg added Cu from $CuSO_4$ provided by the trace mineral premix. Treatment diets were fed in 5 dietary phases in meal form, and in the last phase contained 5 mg/kg ractopamine HCl (Paylean; Elanco Animal Health, Greenfield, IN). All diets were formulated on a standardized ileal digestible (SID) Lys basis 0.05% below the estimated requirement for pigs raised in this facility during each phase, determined by previous research (Main et al., 2008). However, the SID Lys and all other nutrient requirements, met the NRC (2012) requirements. Nutrient values for ingredients used in formulation were from the NRC (2012). Treatment diet samples were collected for each treatment during each phase from multiple feeders 2 d after the beginning of a phase and 2 d before ending a phase. The 2 samples were combined to form a composite sample for each treatment within each phase and analyzed, in duplicate, for total Cu (985.01, AOAC International, 2000).

Pens of pigs were weighed and feed disappearance was recorded approximately every 3 wk to determine ADG, ADFI, G:F, and caloric efficiency on and ME and NE basis. Caloric efficiencies were calculated by dividing the sum of total feed intake and diet calorie content, by total gain. On d 92, the 3 heaviest pigs in each pen were weighed and sold according to standard farm procedures. These pigs were used in calculation of pen growth performance, but not carcass characteristics. Prior to marketing the remaining pigs in the barn, all pigs were individually tattooed with a pen identification number to allow for carcass measurements to be recorded on an individual basis. On d 111, final pen weights were taken and pigs were transported to a commercial packing plant (JBS Swift and Company, Worthington, MN) for processing and carcass data collection. Hot carcass weights were measured immediately after evisceration and each carcass evaluated for carcass yield, backfat depth, loin depth, and percentage lean. Carcass yield was calculated by dividing the HCW at the plant by the live weight at the farm before transport to the plant. Fat depth and loin depth were measured with an optical probe inserted between the third and fourth last rib (counting from the ham end of the carcass) at a distance approximately 7 cm from the dorsal midline.

At the conclusion of the experiment, a digital photo of each pen was taken to allow 3 independent observes to score manure texture and buildup to asses pen cleanliness before power washing. The scores were averaged to determine a mean score for each pen, which was used for analysis. Manure textures were categorized as firm, medium, or loose with scores of 1, 2, and 3, respectively. Manure buildup was categorized as 1 for visual buildup and (-1) for no visual buildup. Afterward, a professional power-washing crew, blinded to treatments, recorded the wash time for each pen with a stop watch to determine the difference in wash time between treatments.

Statistical Analysis

Experimental data were analyzed using the PROC MIXED procedure in SAS (SAS Institute Inc., Cary, NC) as a randomized complete-block design with pen serving as the experimental unit and initial BW as a blocking factor. Residual assumptions were checked using standard diagnostics on studentized residuals. The assumptions were reasonable met. The main effect of Cu source, linear and quadratic effects of added Cu level, and their interactions were tested. Additionally, the contrast between the corn-soybean meal-based diet and byproduct diet was also evaluated. Backfat depth, loin depth, and lean percentage were adjusted to a common hot carcass weight for analysis. Results from the experiment were considered significant at $P \leq 0.05$ and a tendency between $P > 0.05$ and $P \leq 0.10$.

Results

Diets had analyzed Cu concentrations generally similar to calculated values, and within an acceptable range based on analytical variation (Table 3-3; AFFCO, 2014). The analyzed values for the corn-soy diet and byproduct diet that only had Cu added to the diet via the trace mineral premix were from 21 to 42 mg/kg. For treatment diets with 75 mg/kg added Cu, analyzed Cu concentrations ranged from 116 to 137 mg/kg when in the form of $CuSO_4$, and 83 to 134 mg/kg when in the form of TBCC. For treatment diets with 150 mg/kg added Cu, analyzed Cu concentrations ranged from 192 to 267 mg/kg when in the form of $CuSO_4$, and 157 to 189 mg/kg when in the form of TBCC.

Pigs fed the corn-soybean meal based diet or the high byproduct diet, had similar ADG from d 0 to 71, 71 to 111, and overall (d 0 to 111; Table 3-4). Pigs fed the byproduct diet tended to have increased ADFI ($P < 0.083$) from d 0 to 71 and d 0 to 111 compared to those fed the corn-soy diet. As a result, G:F decreased ($P = 0.031$) for pigs fed the byproduct compared to the corn-soy diet from d 71 to 111 and overall. Caloric efficiency on both an ME and NE basis was reduced ($P < 0.05$) in pigs fed the byproduct diet compared to the corn-soy diet.

No significant Cu level × source interactions, or differences between Cu sources ($P > 0.05$) were observed for any of the response criteria. From d 0 to 71, pigs fed increasing Cu had increased ADG (quadratic, $P = 0.002$) and ADFI (linear, $P = 0.007$), while G:F tended to decrease ($P = 0.052$). As a result, BW on d 71 increased (quadratic, $P = 0.004$) with increasing added Cu. From d 71 to 111, ADFI tended to increase (linear, $P = 0.068$) while G:F tended (quadratic, $P = 0.056$) to decrease for pigs fed 75 mg/kg added Cu but increased for those fed 150 mg/kg added Cu. Overall, from d 0 to 111, increasing Cu increased (linear, $P < 0.05$) ADG and ADFI, which led to an increase in final BW (linear, $P = 0.003$).

For carcass characteristics, pigs fed the corn-soy diet tended to have increased loin depth ($P = 0.079$) compared to those fed the byproduct diet (Table 3-5). Pigs fed increasing Cu had increased HCW (linear, $P = 0.023$), loin depth (linear, $P = 0.019$) and percentage lean (quadratic, $P = 0.024$). For pen cleanliness, pigs fed the byproduct diet with DDGS and bakery meal had increased ($P < 0.05$) manure buildup and pen wash time compared to the pigs fed the corn-soy diet. No differences in pen cleanliness characteristics were observed between Cu sources or level.

Discussion

Due to the evolving ingredient composition of finishing pig diets, it is important to re-evaluate Cu supplementation in diets that contain byproduct ingredients to determine if this response has changed. Copper sulfate, the most commonly used source of added Cu, has been the predominant source of Cu studied in published literature. This is partly because inorganic sources of Cu are typically more cost effective than organic sources and past research has suggested the two sources are equally efficacious (Cromwell et al., 1998; Miles et al., 1998). However, there is less published literature comparing inorganic sources of $CuSO_4$ and TBCC, especially in diets containing byproduct ingredients.

Copper sulfate is manufactured from Cu metal and sulfuric acid whereas TBCC is a byproduct of the circuit board manufacturing process where acidic cupric chloride and alkaline cuprammine chloride solution are neutralized to form a green purified source of Cu. Copper sulfate has been shown to be highly soluble whereas TBCC is less than 1% soluble in water (Miles et al., 1998). The particle size of TBCC is less than 150 um compared to $CuSO_4$ at 150 to 850 um in size. Because of the small particle size and uniformity, mixer efficiency has been shown to be improved with TBCC compared to $CuSO_4$ (Lou et al., 2005). The concentration of Cu is also twice as high (55.6%) in TBCC compared to $CuSO_4$ (25.4%). Furthermore, less oxidative instability during storage has been shown with TBCC compared to $CuSO_4$, which may offer benefits when including in a vitamin trace mineral premix (Lou et al., 2005).

The diets used in formulation were formulated 0.05% below the estimated SID Lys requirement, based on the procedures of Rochell et al. (2015). Rochell et al. (2015) fed broilers two levels of digestible Lys (1.00 or 1.20%) and two levels of added Cu (0 or 200 mg/kg) from TBCC. They reported that broilers fed low amounts of digestible Lys and 200 mg/kg of added Cu from TBCC had greater improvements in ADFI compared with broilers fed the high level of digestible Lys. This however, has yet to be investigated in finishing pigs. Although we did not compare SID Lys level, results from Rochell et al. (2015) suggested the potential for a more definitive response if SID Lys was reduced. The estimated SID Lys requirements for each phase were determined by previous research conducted in this facility with the same sire line (Main et al., 2008).

The NRC (2012) suggests that the dietary requirement for Cu is 3 to 6 mg/kg for pigs from 5 to 135 kg of BW, respectively. The corn-soy diet and byproduct diet that contained no added Cu had analyzed values that ranged from 21 to 42 mg/kg, exceeding the pig's nutrient requirement estimated for Cu. These analyzed values are similar to what would be expected due to the 20 mg/kg of Cu provided to the diet in the trace mineral premix and Cu originating from the ingredients used in formulation. Similar, the analyzed total Cu had analyzed values across phases within treatments similar to expected, given the control diet levels and the analytical variation that can be observed in lab analysis of complete feeds (NCR-42, 2003; AFFCO, 2014).

Much of published literature investigating added Cu suggests that Cu improves growth performance during the early finishing period, with little to no response during the late finishing period. The NCR-42 Committee for swine nutrition concluded that Cu improved growth performance during the first 8 wk from 22 to 61 kg BW, but not the last 8 wk of the finishing period from 61 to 91 kg (NCR-42, 1974). Hastad (2002) also suggested that Cu, in the form of either $CuSO_4$ or TBCC, provided growth benefits only until approximately 61 kg. In contrast, Davis et al. (2002) reported that pigs fed 125 mg/kg from $CuSO_4$ had increase in ADG and G:F in both the early grower periods, 32 kg to 68 kg, and in the finishing period from 68 kg to 106 kg.

For the current experiment, pigs fed either source of added Cu had increased ADFI and ADG during the early finishing period, similar to Hastad (2002). However, ADFI and G:F also tended to improve during the late finishing period with added Cu, although the response was not as large as the response observed by Davis et al. (2002). The lack of consistency for a Cu response during the late finishing period is poorly understood. One potential reason for the improvements in ADG and G:F observed by Davis et al. (2002) could be that their diets contained 5% added fat as Lou and Dove (1996) suggested that added Cu improves fat digestibility in weanling pigs. However, more research is needed to determine if this effect is present in finishing pigs, and if differences in fat digestibility in the response of high Cu is found between added dietary fat and in endogenous fat within feed ingredients.

The 3% increase in overall ADG with added Cu is similar to other responses in corn-soybean meal based diets (NCR-42, 1974; Hastad, 2002; Davis et al., 2002). However the 4% increase in ADFI in the current experiment is 2 percentage units higher than previously reported. While diet type could have possibly influenced this, exact reasons are unknown. However, pigs in the current experiment were fed to a heavier final weight than in most previous experiments.

The increased feed intake of pigs fed increasing Cu during the finishing period is also not completely understood. For much of the past few decades, researchers have believed the mode of action for Cu to improve growth was antimicrobial-like because the performance was similar to pigs whom were fed antibiotics (Barber et al., 1956; Wallace et al., 1960). This theory was further demonstrated when Miller et al. (1969) reported that fecal bacterial counts were reduced in pigs fed Cu from CuSO4, with the reduction being greater than even that observed from the antibiotics. A reduction in bacterial counts in the GI could result in less competition for nutrients to be absorbed thus improving growth with added Cu. Interestingly, recent research has even suggested that genes associated with antimicrobial resistance are reduced in fecal contents of pigs fed added Cu (Agga et al., 2015). However, more current research suggest that antimicrobial properties of Cu may not be responsible for the all of the responses observed with feeding addition Cu (Zhou et al., 1994a; Li et al., 2008).

Previous research has ruled out the possibility for Cu to increase ADFI though improvements in palatability. Coble et al. (2014) determined that when pigs are given a choice, pigs prefer diets without added Cu, regardless if the Cu is in the form of $CuSO_4$ or TBCC. However, they also reported that when pigs were given a choice between $CuSO_4$ or TBCC, pigs preferred TBCC. It is unclear, if the results of a preference study where pigs are given a choice between two or more feeds, will correlate to what is observed when pigs only have access to one feed at a time.

While no statistical differences were observed between Cu source for growth, Klasing and Naziripour (2010) reported that the amount of Cu along the GI tract available for absorption was much greater along the entire length of the ileum in broilers fed TBCC compared to $CuSO_4$. Miles et al. (1998) reported that TBCC was 6% more bioavailable than $CuSO_4$ in broilers. These studies would potentially suggest that more Cu could be transported into the portal blood for utilization by the animal when in the form of TBCC.

An increase in the amount of available Cu offers a possible explanation for the increase in feed intake. Yang et al. (2011) reported an increase in mRNA expression levels for growth hormone-releasing hormone (GhRH), which provides positive feedback to the hypothalamus to increased appetite. This increase in appetite comes as a result of increasing neuropeptide Y (NPY) concentration, a neurotransmitter in the brain that signals increased feed intake and has also been demonstrated to be increased as a result of feed Cu additions to diets fed to swine (Li et al., 2008). Also, Zhou et al. (1994b) reported that mRNA concentrations for growth hormone (GH) in the pituitary gland was numerically higher in pigs fed 215 mg/kg added Cu.

Furthermore, Zhou et al. (1994a) also reported that pigs whom were injected with a Cu solution to achieve circulating blood levels of those consuming 250 mg/kg of Cu via feed, also had improvements in ADG and G:F, suggesting that Cu impacts growth and metabolism in additional ways, other than its antimicrobial like properties.

The last focus of this experiment was to determine if diet type and supplemental Cu negatively impacted manure buildup and wash time in a commercial finishing barn. Reports from producers suggest that when byproducts or when pharmalogical levels of Cu are added to the diet, barn wash time increases. In this experiment, manure buildup and pen wash time was increased in pens where pigs were fed diet containing byproduct ingredients compared to the corn-soybean meal-based diet. However, this experiment showed that adding pharmalogical Cu has little influence on manure buildup but no impact on pen wash time. The change in fecal color associated with feeding Cu (Hill et al., 2000) may simply be creating the illusion of more fecal content in the pen and increased wash time

In conclusion, adding supplemental Cu in the form of either $CuSO_4$ or TBCC improved growth performance, leading to an increase in HCW. The magnitude of response to added Cu may have been higher than previous research because we fed diets that were formulated to be slightly below the SID Lys requirement, however further research is needed to determine if the response to feeding Cu is SID Lys dependent. Diets high in byproduct ingredients did increase manure buildup in the pen and increased pen wash time; however, added Cu did not negatively impact wash time.

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Table 3-1. Composition of diets for phases 1, 2, and 3 (as-fed basis)[1]

	Phase 1[2]		Phase 2		Phase 3	
Item	Corn-soy	Byproduct	Corn-soy	Byproduct	Corn-soy	Byproduct
Ingredient, %						
Corn	73.07	36.05	77.96	41.07	81.76	44.69
Soybean meal, 46.5% CP	23.98	16.51	19.47	11.80	15.80	8.24
Distillers dried grains with solubles	---	30.00	---	30.00	---	30.00
Bakery meal	---	15.00	---	15.00	---	15.00
Monocalcium P, 21 %	0.75	0.18	0.55	---	0.52	---
Limestone	1.18	1.25	1.11	1.17	1.08	1.15
Salt	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin and trace mineral premix[3]	0.10	0.10	0.10	0.10	0.10	0.10
Lysine sulfate[4]	0.460	0.565	0.400	0.515	0.360	0.470
L-Thr	0.060	---	0.040	---	0.030	---
Methionine hydroxyl analogue[5]	0.055	---	0.015	---	---	---
Phytase[6]	0.005	0.005	0.005	0.005	0.005	0.005
Copper source[7]	±	±	±	±	±	±
Total	100.0	100.0	100.0	100.0	100.0	100.0
Calculated analysis						
Standard ileal digestible (SID) amino acids, %						
Lys	1.00	1.00	0.86	0.86	0.75	0.75
Ile:Lys	63	71	64	74	65	77
Meth:Lys	30	32	29	35	29	38
Met + Cys:Lys	55	59	56	64	58	69
Thr:Lys	60	60	60	62	61	64
Trp:Lys	18	18	18	18	18	18
Val:Lys	70	82	72	87	75	92
Total lysine, %	1.13	1.20	0.97	1.04	0.85	0.93
SID lysine:ME, g/Mcal	3.04	2.95	2.60	2.53	2.26	2.20
ME, kcal/kg	3,294	3,388	3,307	3,402	3,311	3,406
NE, kcal/kg	2,471	2,476	2,504	2,508	2,526	2,531
CP, %	17.9	21.3	16.1	19.5	14.6	18.0
Ca, %	0.65	0.58	0.57	0.51	0.54	0.49
P, %	0.52	0.47	0.46	0.41	0.44	0.39
Available P, %	0.28	0.28	0.24	0.24	0.22	0.23
Crude fiber, %	2.4	4.0	2.3	3.9	2.2	3.9
NDF, %	8.6	14.1	8.7	14.1	8.7	14.2

[1] Phase 1 diets were fed from d 0 to 27, phase 2 diets fed from d 27 to 49, and phase 3 diets fed from d 49 to 71.

[2] Each diet was fed in meal form.

[3] Provided per kilogram of premix: 4,509,410 IU vitamin A; 701,464 IU vitamin D_3; 24,050 IU vitamin E; 1,402 mg vitamin K; 3,006 mg riboflavin; 12,025 mg pantothenic acid; 18,038 mg niacin; and 15.0 mg vitamin B_{12}, 40 g Mn from manganese oxide, 90 g Fe from ferrous sulfate, 100 g Zn from zinc oxide, 10 g Cu from copper sulfate, 500 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[4] Lysine source (Evonik, Inc., Kennesaw, GA).

[5] MHA (88% methionine; Novus International, St. Charles, MO)

[6] Optiphos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 phytase units (FTU)/kg, with a release of 0.07% available P.

[7] Supplemental copper provided in the form of $CuSO_4$ or TBCC (Intellibond C; Micronutrients, Inc., Indianapolis, IN) at either 75 or 150 mg/kg at the expense of corn in the byproduct diet.

Table 3-2. Composition of diets for phases 4 and 5 (as-fed basis)[1]

Item	Phase 4[2]		Phase 5	
	Corn-soy	Byproduct	Corn-soy	Byproduct
Ingredient, %				
Corn	84.42	47.29	76.66	39.65
Soybean meal, 46.5% CP	13.25	5.69	20.79	13.13
Distillers dried grains with solubles	---	30.00	---	30.00
Bakery meal	---	15.00	---	15.00
Monocalcium P, 21 %	0.48	---	0.44	---
Limestone	1.05	1.13	1.08	1.18
Salt	0.35	0.35	0.35	0.35
Vitamin and trace mineral premix[3]	0.10	0.10	0.10	0.10
Lysine sulfate[4]	0.325	0.435	0.415	0.530
L-Thr	0.025	---	0.090	0.035
Methionine hydroxyl analogue[5]	---	---	0.050	---
Phytase[6]	0.005	0.005	0.005	0.005
Ractopamine HCL[7]	---	---	0.025	0.025
Copper source[8]	±	±	±	±
Total	100.0	100.0	100.0	100.0
Calculated analysis				
Standard ileal digestible (SID) amino acids, %				
Lys	0.67	0.67	0.90	0.90
Ile:Lys	67	79	64	73
Meth:Lys	31	40	31	34
Met + Cys:Lys	61	74	58	63
Thr:Lys	62	67	65	65
Trp:Lys	18	18	18	18
Val:Lys	78	97	72	85
Total lysine, %	0.77	0.84	1.02	1.09
SID lysine:ME, g/Mcal	2.02	1.97	2.72	2.65
ME, kcal/kg	3,318	3,408	3,311	3,399
NE, kcal/kg	2,544	2,546	2,500	2,500
CP, %	13.5	17.0	16.6	20.0
Ca, %	0.52	0.48	0.55	0.52
P, %	0.42	0.38	0.44	0.41
Available P, %	0.21	0.23	0.21	0.24
Crude fiber, %	2.2	3.8	2.3	4.0
NDF, %	8.8	14.2	8.7	14.1

[1] Phase 4 diets were fed from d 71 to 92, and phase 5 diets fed from d 92 to 111.

[2] Each diet was fed in meal form.

[3] Provided per kilogram of premix: 4,509,410 IU vitamin A; 701,464 IU vitamin D_3; 24,050 IU vitamin E; 1,402 mg vitamin K; 3,006 mg riboflavin; 12,025 mg pantothenic acid; 18,038 mg niacin; and 15.0 mg vitamin B_{12}, 40 g Mn from manganese oxide, 90 g Fe from ferrous sulfate, 100 g Zn from zinc oxide, 10 g Cu from copper sulfate, 500 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[4] Lysine source (Evonik, Inc., Kennesaw, GA).

[5] MHA (88% methionine; Novus International, St. Charles, MO)

[6] Optiphos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 phytase units (FTU)/kg, with a release of 0.07% available P. [7] Paylean (Elanco Animal Health, Greenfield, IN)

[8] Supplemental copper provided in the form of $CuSO_4$ or TBCC (Intellibond C; Micronutrients, Inc., Indianapolis, IN) at either 75 or 150 mg/kg at the expense of corn in the byproduct diet.

Table 3-3. Total copper analysis of complete diets[1]

			$CuSO_4$, mg/kg		TBCC,[2] mg/kg	
Phase	Corn-soy	Byproduct	75	150	75	150
1	27	21	137	208	83	180
2	24	38	129	192	77	157
3	28	38	116	200	134	172
4	27	37	136	267	104	187
5	42	32	135	257	129	189

[1] Values represent means from one composite sample, analyzed in duplicate.

[2] Tribasic copper chloride (Intellibond C; Micronutrients, Inc., Indianapolis, IN).

Table 3-4. Effects of copper sulfate ($CuSO_4$) or tribasic copper chloride (TBCC) on growth performance of finishing pigs[1]

								Probability,[5] $P <$			
			$CuSO_4$, mg/kg		TBCC,[4] mg/kg			Corn-soy vs.	Cu	Cu level	
Item	Corn-soy[2]	Byproduct[3]	75	150	75	150	SEM	Byproduct	source	Linear	Quadratic
BW, kg											
d 0	25.1	25.1	25.1	25.1	25.1	25.1	0.93	0.971	0.990	0.991	0.972
d 71	84.6	86.3	89.3	88.3	90.6	89.0	1.77	0.187	0.248	0.034	0.004
d 111	124.5	124.2	127.6	127.5	128.4	130.0	2.04	0.875	0.145	0.003	0.157
d 0 to 71											
ADG, kg	0.84	0.86	0.90	0.89	0.92	0.89	0.015	0.162	0.332	0.035	0.002
ADFI, kg	1.95	2.03	2.14	2.15	2.18	2.13	0.046	0.056	0.643	0.007	0.012
G:F	0.429	0.424	0.424	0.413	0.421	0.420	0.004	0.175	0.425	0.052	0.464
d 71 to 111											
ADG, kg	1.03	1.00	1.00	1.02	0.99	1.06	0.020	0.286	0.533	0.142	0.248
ADFI, kg	2.90	2.95	3.02	3.00	2.99	3.07	0.051	0.453	0.561	0.068	0.658
G:F	0.356	0.340	0.333	0.341	0.331	0.344	0.006	0.031	0.817	0.742	0.056
d 0 to 111											
ADG, kg	0.90	0.91	0.94	0.93	0.94	0.95	0.011	0.757	0.231	0.007	0.064
ADFI, kg	2.27	2.34	2.44	2.44	2.46	2.45	0.043	0.083	0.565	0.004	0.026
G:F	0.397	0.388	0.385	0.383	0.383	0.388	0.004	0.005	0.369	0.335	0.244
Caloric efficiency, Mcal/kg											
ME	8.33	8.78	8.84	8.89	8.88	8.77	0.080	0.001	0.404	0.369	0.249
NE	6.33	6.49	6.54	6.58	6.56	6.49	0.060	0.005	0.400	0.372	0.247

[1] A total of 1,143 pigs (PIC 337 × 1050 PIC, Hendersonville, TN; initial BW = 25.1 ± 0.03 kg) were used in this 111-d study; 8 pens per treatment and 25 to 28 pigs per pen.

[2] Refers to a corn-soybean meal-based diet without byproducts.

[3] Refers to a corn-soybean meal-based diet with 30% distillers dried grains with solubles (DDGS) and 15% bakery meal. Added Cu, regardless of source or level, was added to the byproduct diet.

[4] Tribasic copper chloride (Intellibond C, Micronutrients, Inc., Indianapolis, IN).

[5] No copper level × source interactions ($P > 0.05$).

Table 3-5. Effects of copper sulfate ($CuSO_4$) or tribasic copper chloride (TBCC) on carcass characteristics and pen cleanliness of finishing pigs[1]

								Probability,[5] $P <$			
			$CuSO_4$, mg/kg		TBCC,[4] mg/kg			Corn-soy vs.	Cu	Cu level	
Item	Corn-soy[2]	Byproduct[3]	75	150	75	150	SEM	Byproduct	source	Linear	Quadratic
Carcass characteristics											
HCW, kg	92.5	91.8	93.3	93.1	93.6	95.3	1.19	0.589	0.111	0.023	0.587
Yield, %	73.3	72.8	72.4	72.5	72.5	72.9	0.40	0.350	0.555	0.857	0.467
Backfat depth,[6] mm	17.4	17.0	15.8	16.7	16.6	16.8	0.44	0.464	0.306	0.635	0.702
Loin depth,[6] mm	64.2	62.4	63.4	65.1	66.0	64.2	0.72	0.079	0.225	0.019	0.055
Lean,[6] %	55.9	56.0	56.8	56.5	56.7	56.3	2.90	0.777	0.443	0.172	0.024
Pen cleanliness											
Texture[7]	2.00	2.09	1.86	1.81	1.80	2.19	0.214	0.767	0.445	0.733	0.268
Buildup[8]	-1.00	0.62	0.90	0.62	-0.05	1.00	0.206	0.001	0.141	0.416	0.116
Wash time, sec	268	417	413	383	373	389	21.5	0.001	0.432	0.242	0.673

[1] A total of 1,143 pigs (PIC 337 × 1050 PIC, Hendersonville, TN; initial BW = 25.1 ± 0.03 kg) were used in this 111-d study; 8 pens per treatment and 25 to 28 pigs per pen.

[2] Refers to a corn-soybean meal-based diet without byproducts.

[3] Refers to a corn-soybean meal-based diet with 30% distillers dried grains with solubles (DDGS) and 15% bakery meal. Added Cu, regardless of source or level, was added to the byproduct diet.

[4] Tribasic copper chloride (Intellibond C, Micronutrients, Inc., Indianapolis, IN).

[5] No copper level × source interactions ($P > 0.05$).

[6] Adjusted by using HCW as a covariate.

[7] Residual manure texture in the pen after pigs were marketed was categorized as firm, medium, or loose with scores of 1, 2, and 3, respectively.

[8] Residual manure buildup in the pen after pigs were marketed was based on a value of 1 for visual buildup and -1 for no visual manure buildup.

Chapter 4 - Effect of standardized ileal digestible lysine level and added copper on growth performance, carcass characteristics, and fat quality

Abstract

Two, 120-d, experiments were completed to determine the effects of standardized ileal digestible (SID) Lys and added Cu (TBCC, Intellibond C; Micronutrients, Inc., Indianapolis, IN), and duration of Cu supplementation on growth performance, carcass characteristics, and fat quality in finishing pigs. For Exp. 1, 1,248 pigs (initially 29.0 ± 0.1 kg BW) were allotted to 1 of 6 dietary treatments, balanced on average pen weight in a randomized complete-block design with 26 pigs per pen and 8 replications per treatment. Treatments were arranged in a 3 × 2 factorial with main effects of SID Lys (85, 92.5, and 100% of the estimated requirement) and added Cu (0 or 150 mg/kg). There were no Cu × SID Lys interactions observed for growth performance or liver Cu concentrations. Increasing SID Lys increased (linear, $P < 0.05$) ADG, G:F, final BW, HCW, HCW ADG, and HCW G:F. Pigs fed 150 mg/kg added Cu tended ($P < 0.10$) to have increased ADG, G:F and final BW. Liver Cu concentrations were greater ($P = 0.001$) in pigs fed added Cu and tended to decrease (quadratic; $P = 0.092$) as SID Lys increased. A tendency for an interaction for jowl fat iodine value (IV; Cu × Lys interaction, $P = 0.052$) was observed as increasing SID Lys in pigs fed added Cu increased IV, but decreased IV in pigs not fed added Cu. For Exp. 2, 1,267 pigs (PIC 337×1050; initially 26.4 ± 0.1 kg BW) were allotted to 1 of 8 dietary treatments arranged in a split-plot design. Whole-plot treatments included 2 SID Lys levels (92.5 or 100% of the estimated requirement). Within each Lys level, there was a 2 × 2 factorial arrangement of treatments with either 0 or 150 mg/kg added Cu with 2 feeding durations (60 or 120 d). Added Cu did not affect growth performance. Pigs fed 100% of the SID Lys requirement had increased (*P* < 0.05) ADG, G:F, and final BW compared with those fed 92.5%. A significant Cu × SID Lys interaction (*P* < 0.05) was observed for carcass yield and backfat depth. Pigs fed 92.5% SID Lys had increased carcass yield and decreased backfat depth with added Cu; however, pigs fed 100% SID Lys had decreased carcass yield and increased backfat depth with added Cu. When pigs were fed 100% SID Lys compared with those fed 92.5%, HCW and HCW ADG increased (*P* < 0.05), and tended (*P* < 0.10) to increase in pigs fed added Cu compared with those not. In summary, the growth response to added Cu was inconsistent between experiments; however, increasing SID Lys improved growth performance and carcass characteristics.

Key Words: copper chloride, fat quality, growth, lysine, pigs

Introduction

Adding pharmalogical levels of Cu in the finishing period has consistently shown increased ADG and ADFI during the early finishing periods, but inconsistently demonstrated growth benefits when fed during late finishing (Hastad, 2002; Davis et al., 2002). Hastad (2002) reported that adding 200 mg/kg Cu did not provide growth benefits past 61 kg. However, Davis et al. (2002) observed improvements in ADG and G:F beyond 68 kg of BW.

Coble (2015) also demonstrated that Cu fed in the form of copper sulfate ($CuSO_4$) or tribasic copper chloride (TBCC; Intellibond C; Micronutrients, Inc., Indianapolis, IN) potentially offered growth benefits longer into the finishing period, increasing ADFI and G:F in pigs heavier than 88 kg BW. The response reported was found in diets formulated 0.05% below the estimated standardized ileal digestible (SID) Lys requirement. Previous research evaluating the effect of SID Lys level on the response to added Cu in finishing pigs is not available. Rochell et al. (2015) demonstrated that broilers fed a low digestible Lys diet (1.00%) had greater improvements in ADFI and ADG with 200 mg/kg of added Cu from TBCC compared with broilers fed a high digestible Lys diet (1.20%). They also reported that N digestibility was increased in chicks fed the low Lys diet with TBCC, but not in the high Lys diet. Other research has shown improvements in fat and energy digestibility with added Cu in nursery pigs (Lou and Dove, 1996; Gonzales-Eguia et al., 2009), as well increased N digestibility in finishing pigs (Kim et al., 2006).

Thus, it is important to understand if adding Cu to diets limiting in SID Lys could improve growth performance in finishing pig diets and how feed duration may affect the growth response. Therefore, 2 experiments were designed to investigate the effects of dietary SID Lys with or without 150 mg/kg added Cu from TBCC, and the duration of feeding 150 mg/kg added Cu, on finishing pig growth performance, carcass characteristics, and fat quality.

Materials and Methods

All experimental procedures and animal care were approved by the Kansas State University Institutional Animal Care and Use Committee.

General

Two, separate, 120 d experiments were conducted in a commercial research facility in southwestern Minnesota. The facility was double-curtain sided with completely slatted concrete flooring. The barn contained 48 pens (3.05 × 5.49 m) equipped with a 5-hole conventional dry self-feeder (Thorp Equipment, Thorp, WI) and a cup waterer providing ad libitum access to feed and water. The facility was equipped with a computerized feeding system (FeedPro; Feedlogic Corp., Willmar, MN) that delivered and recorded daily feed additions of the diets to each pen.

Before d 0, pigs were fed a common diet for 7 d containing 205 and 188 mg/kg Cu from tribasic copper chloride (TBCC; Intellibond C; Micronutrients Inc., Indianapolis, IN) in Exp. 1 and Exp. 2, respectively. Samples of experimental diets were obtained by collecting samples at the feeder 2 d after initiating and 2 d prior to completing each dietary phase. Samples were combined for a composite sample of each treatment diet during each phase. Samples were analyzed in duplicate for total Cu (985.01, AOAC International, 2000) at Cumberland Valley Analytical Services (Hagerstown, MD), and total AA (method 994.12; AOAC Int., 2012), and CP (method 990.03; AOAC Int., 2012) at Ajinomoto Heartland, Inc. (Eddyville, IA). On d 0, pens of pigs were weighed and allotted to dietary treatments in a randomized complete-block design, with initial average BW serving as the blocking factor.

Pens of pigs were weighed and feed disappearance was recorded approximately every 3 wk to determine ADG, ADFI, G:F, and ME and NE caloric efficiency. In Exp. 1, the heaviest 3 pigs in each pen were weighed and marketed on d 97 according to standard farm protocol. Similarly in Exp. 2, the heaviest 5 pigs were weighed and marketed on d 101. These pigs were used in calculation of pen growth performance, but not carcass characteristics. The remaining pigs were marketed on d 120 in each experiment. Before marketing, final pen weights were taken and pigs were individually tattooed with a pen ID number to allow for carcass measurements to be recorded on a pen basis. Pigs were then transported to a commercial processing packing plant in southwestern Minnesota (JBS Swift and Company, Worthington, MN) for processing and carcass data collection. Twelve h after final pen weights were taken, HCW was measured immediately after evisceration and each carcass evaluated for carcass yield, backfat depth, loin depth, and percentage lean. Carcass yield was calculated by dividing the HCW at the plant by the live weight at the farm prior to transport to the plant. Fat depth and loin depth were measured with an optical probe inserted between the third and fourth last rib (counting from the ham end of the carcass) at a distance approximately 7 cm from the dorsal midline. An assumed yield of 75% was used to calculate initial HCW at the beginning of the experiments. Hot carcass weight ADG was calculated by subtracting initial HCW from the final HCW obtained at the plant, then divided by the 120 d on test. Hot carcass weight G:F was calculated by dividing HCW gain by feed intake over the 120 d experiments.

Experiment 1

A total of 1,248 pigs (PIC 337 × 1050 PIC, Hendersonville, TN; initial BW = 29.0 ± 0.1 kg) were allotted to 1 of 6 dietary treatments with 26 pigs (similar numbers of barrows and gilts) per pen and 8 replications per treatment. Treatments were arranged in a 2 × 3 factorial with main effects of added Cu from TBCC (0 or 150 mg/kg) and SID Lys (85, 92.5 or 100% of the estimated requirement based on previous experiments in this facility; Main et al., 2008). All diets were corn-soybean meal-based with 30% distillers dried grains with solubles (DDGS) and 15% bakery meal and contained 17 mg/kg of Cu from copper sulfate ($CuSO_4$) provided by the trace mineral premix. Treatment diets were fed in 5 phases (Tables 4-1 to 4-3). During the last phase, all diets contained 10 mg/kg ractopamine HCl (Paylean; Elanco Animal Health, Greenfield, IN).

On d 120 when pigs were marketed, 3 individual pigs per pen were identified to represent the mean individual pig weight of the pen and transported to a small commercial packing plant in northwestern Iowa (Natural Foods Holdings, Inc., Sioux City, IA) for measuring liver mineral concentrations and color, and collection of backfat and jowl fat samples. Pigs were slaughtered 12 h after final pen weights were taken at the farm. The entire liver was obtained from the pluck for sampling and objective color scoring. Prior to sampling, a MiniScan EZ (Model 4500L;

Hunter Associates Laboratory, Reston, VA) was used to determine L*, a*, and b* color values to indicate lightness, redness, and yellowness, respectively, by taking three scans of each liver and obtaining and average for each color value. From these values, hue angle and chroma were calculated to describe the blemish or taint of color and saturation of color, respectively. Samples of the liver were then collected from the top left lobe immediately after pigs were eviscerated, placed on dry ice, and shipped to Michigan State University for analysis. At Michigan State University, liver samples were microwave digested (MARS 5; CEM Corp., Matthews, NC) in 10 mL of HNO_3 and then in an addition 2 mL of H_2O_2. Samples were then brought to the desired volume for analysis by flame atomic absorption spectrophotometry according (Shaw et al., 2002; UNICAM 989 Solar AA Spectrometer, Thermo Elemental Corp., Franklin, MA). Fat samples were taken from pigs 1 h after slaughter from the jowl and 10th rib backfat (all 3 layers), placed on dry ice, and shipped to the University of Georgia for complete fatty acid analysis. Fatty acid analysis was determined by gas chromatography (model 14 A, Shimadzu, Tokyo, Japan) described by Cromwell et al. (2011). Iodine value was calculated for the fat samples using the following equation (AOCS, 1998): $IV = [C16:1] \times 0.950 + [C18:1] \times 0.860 + [C18:2] \times 1.732 + [C18:3] \times 2.616 + [C20:1] \times 0.785 + [C20:4] \times 3.201 + [C22:1] \times 0.723 + [C22:5] \times 3.697 + [C22:6] \times 4.463$, where brackets indicate concentration (%).

Experiment 2

A total of 1,267 pigs (PIC 337 × 1050 PIC, Hendersonville, TN; initial BW = 26.4 ± 0.1 kg) were allotted to 1 of 8 dietary treatments with 26 to 27 pigs (similar numbers of barrows and gilts) per pen with 6 replications per treatment. Treatments were arranged in a split-plot design. Whole-plot treatments were 2 levels of estimated SID Lys requirement (92.5 or 100%). Within each level of Lys, there was a 2 × 2 factorial arrangement with main effects of Cu level (0 or 150 mg/kg from TBCC) and duration (60 or 120 d). All diets were corn-soybean meal-based with 30% DDGS and contained 17 mg/kg Cu from $CuSO_4$ provided by the trace mineral premix. Treatment diets were fed in 5 phases (Tables 4-4 to 4-6). During the last phase, all diets contained 5 mg/kg ractopamine HCl (Paylean; Elanco Animal Health, Greenfield, IN).

Statistical Analysis

Data for both Exp. 1 and Exp. 2 were analyzed separately using the MIXED procedure of SAS (SAS Institute, Inc., Cary, NC) as a randomized complete-block design with pen serving as the experimental unit and initial BW as the blocking factor. Block was included in both models as a random effect. Residual assumptions were checked using standard diagnostics on studentized residuals. The assumptions were reasonable met in both experiments. For Exp. 1, linear and quadratic contrasts were tested to determine if SID Lys affected the response to added Cu. If the interaction was significant, pairwise comparisons for added Cu within SID Lys were determined to describe the interaction. The main effect of Cu and linear and quadratic effects of SID Lys were also tested.

For Exp. 2, the 3-way interaction of Early Cu × Late Cu × SID Lys and 2-way interactions of Early Cu × SID Lys, Late Cu × SID Lys, and Early Cu × Late Cu were tested, and no interactions were observed. Furthermore, the interaction of Cu × SID Lys, main effect of Cu, and main effect of SID Lys for the overall period were tested and reported.

For Exp. 1 and 2, backfat depth, loin depth, and lean percentage were adjusted to a common hot carcass weight for analysis. Results from the experiments were considered significant at $P \leq 0.050$ and a tendency between $P > 0.050$ and $P \leq 0.100$.

Results

Diet and Ingredient Analysis

In both Exp. 1 and 2, the analyzed total Cu concentrations were similar to expected values and within acceptable limits, given the Cu level provided by the trace mineral premix and the exogenous copper from the ingredients (AAFCO, 2014; Tables 4-7 and 4-8). For Exp. 1, diets with no additional Cu, ranged from 25 to 56 mg/kg total Cu. Diets with 150 mg/kg added Cu ranged from 178 to 246 mg/kg total Cu. For Exp. 2, diets with no additional Cu, ranged from 28 to 42 mg/kg total Cu and 201 to 272 mg/kg total Cu when 150 mg/kg Cu was included. Phase 5 diets for Exp. 2 were not available for analysis. For AA analysis, diets had analyzed AA values similar to expected when observed across all phases within treatment for both Exp. 1 and Exp. 2. As SID Lys increased, total Lys concentrations increased, as well as the other AA as expected; suggesting that the diet formulation successfully created the Lys gradient intended by the design of the experiment.

Experiment 1

From d 0 to 70, SID Lys affected the response to Cu for ADG (Cu × Lys interaction, linear, $P = 0.034$; Table 4-9). This was due to the significant increase ($P = 0.003$) in ADG with added Cu when pigs were fed 100% of the estimated SID Lys requirement, while there was no observed benefit within the 85 or 92.5% SID Lys treatments. As a result, pigs fed added Cu and 100% SID Lys tended to have increased BW by d 70 (Cu × Lys interaction, linear, $P = 0.089$). Similarly, SID Lys tended to affect the ADFI response to Cu (Cu × Lys interaction, quadratic, $P = 0.095$) as pigs fed added Cu and 100% SID Lys had increased ADFI ($P = 0.019$) compared to those not fed added Cu. As expected, ADG and G:F improved as SID Lys increased (linear, $P = 0.001$). From d 70 to 120, neither Cu or SID Lys level affected ADG, ADFI, or G:F.

Overall (d 0 to 120), adding Cu to the diet tended ($P < 0.10$) to increase ADG and G:F. Average daily gain and G:F increased as SID Lys increased (linear, $P = 0.001$). These differences led to an increase in final BW with added Cu ($P = 0.006$) and increasing SID Lys (linear, $P = 0.001$). Caloric efficiency on both an ME and NE basis tended to improve ($P < 0.05$) when Cu was added to the diet and improved ($P < 0.05$) as SID Lys increased.

For carcass characteristics, increasing SID Lys increased (linear, $P = 0.007$) HCW by over 2 kg, or almost 3%, in pigs fed 100% of their estimated SID Lys requirement compared with those fed only 85% (Table 4-10). The Cu response for increasing loin depth tended to be influenced by SID Lys (Cu × Lys linear; $P = 0.068$) as pigs fed increasing SID Lys with added Cu had an increase in loin depth, whereas pigs not fed supplemental Cu did not. Standardized ileal digestible Lys also tended to affect percentage lean only when Cu was included in the diet (Cu × Lys quadratic, $P < 0.057$), specifically within the 92.5% SID Lys treatment. Evaluating performance on a HCW basis showed that HCW ADG increased and HCW G:F improved (linear, $P < 0.012$) as the SID Lys level increased.

For liver color, added Cu led to a decrease ($P = 0.027$) in a*, suggesting that Cu decreased the redness of the liver (Table 4-11). The a* value also tended to decrease as SID Lys increased (linear, $P = 0.097$). Furthermore, Cu tended to decrease ($P = 0.071$) chroma, or the intensity of the liver color. Adding 150 mg/kg Cu increased liver Cu concentrations ($P = 0.001$) by 19 mg/kg, and tended to decrease liver Zn concentrations ($P = 0.095$; Table 4-12). As SID Lys increased, liver concentrations of Cu (quadratic, P = 0.092) and Zn (linear, $P = 0.099$) tended to decrease.

For backfat fatty acid profile, an SID Lys × Cu interaction was observed for gadoleic (C20:1; quadratic, $P = 0.028$) and eicosatrienoic (C20:3n-3; linear, $P = 0.054$) acid; however, both of these fatty acids represent less than 1% of the fatty acid composition (Table 4-13).

Increasing SID Lys increased (linear, $P < 0.05$) the concentrations of heptadecanoic (C17:0) and eicosadienoic (C20:2) fatty acid concentrations, and tended (linear, $P < 0.10$) to increase α-linoleic (C18:3n-3) and other fatty acid concentrations. Although the increases in these particular fatty acid concentrations are important, they equate to less than 3% of the total fatty acid composition. To this, these small changes in fatty acid composition did not influence the backfat IV.

For jowl fatty acid concentrations, total SFA decreased in pigs fed added Cu as SID Lys increased; however, were relatively unchanged in pigs no fed added Cu (Cu × Lys linear, $P = 0.019$). This is the results of increasing palmitoleic acid (C16:1) concentration and decreasing stearic acid (C18:0) concentration as SID Lys increased with added Cu compared to no added Cu. Increasing SID Lys with added Cu also increased the UFA:SFA; however, this was not observed when increasing SID Lys in diets without added Cu (Cu × Lys linear, $P = 0.032$). This is due to the fact that within pigs fed 85% of the SID Lys requirement, the UFA:SFA ratio tended to be lower with added Cu than without ($P = 0.089$). These differences are also partly responsible for the tendency for jowl IV to increase in pigs fed added Cu and increasing SID Lys (Cu × Lys linear, $P = 0.052$) compared to the reduction in jowl IV with increasing SID Lys in pigs fed no added Cu.

Experiment 2

For any of the measured responses, no 3-way interactions for early Cu × late Cu × SID Lys, or 2-way interactions for early Cu × SID Lys, late Cu × SID Lys, or early Cu × late Cu were observed ($P > 0.10$).

For growth performance during the early finishing period (d 0 to 60), there was a Cu × SID Lys interaction for ADFI ($P = 0.023$; Table 4-15). This is the result of pigs fed 100% of the estimated SID Lys requirement having increased ADFI with added Cu, whereas pigs fed 92.5% of the estimated SID Lys requirement had decreased ADFI with added Cu. Furthermore, pigs fed 100% of the estimated SID Lys requirement had decreased G:F with added Cu compared to pigs fed 92.5% of the estimated SID Lys requirement whom had increased G:F with added Cu (Cu × SID Lys interaction, $P = 0.098$). For the main effect of SID Lys from d 0 to 60, pigs fed 100% of the estimated SID Lys requirement had increased ADG and BW on d 60 ($P < 0.05$) compared to pigs only fed 92.5% of the estimated SID Lys requirement. During the late finishing period (d 60 to 120), pigs fed 100% of the estimated SID Lys requirement had increased ($P < 0.05$) ADG, BW on d 120, and G:F compared to pigs fed 92.5% of the estimated SID Lys requirement.

Overall (d 0 to 120), there were no Cu × SID Lys interactions for growth performance, final BW, or caloric efficiency. Pigs fed 100% of the estimated SID Lys requirement had increased ($P < 0.05$) ADG, final BW, and G:F compared to pigs fed 92.5% of the estimated SID Lys requirement. Furthermore, pigs fed 100% of the estimated SID Lys requirement had improved ($P < 0.05$) caloric efficiency on both an ME and NE basis.

For carcass characteristics, there was a Cu × SID Lys interaction ($P < 0.022$) for carcass yield and backfat (Table 4-16). This was the result of pigs fed 100% of the estimated SID Lys requirement having increased backfat and a moderate reduction in carcass yield with added Cu, whereas pigs fed 92.5% of the estimated SID Lys requirement had an increase in carcass yield and reduction in backfat with added Cu. Furthermore, Cu tended to influence the response to SID Lys for HCW G:F ($P = 0.071$) as pigs fed 100% of the estimated SID Lys requirement had no change in HCW G:F with added Cu; however, pigs fed 92.5% of the estimate SID Lys requirement had a 3.5% increase in HCW G:F with added Cu.

For the main effect of SID Lys, pigs fed 100% of the estimated SID Lys requirement had increased ($P < 0.05$) HCW and HCW ADG compared to pigs fed 92.5% of the estimated SID

Lys requirement. Pigs fed added Cu had reduced carcass yield (*P* = 0.048) but tended to have increased (*P* < 0.10) HCW, HCW ADG, and HCW G:F compared to pigs fed no added Cu.

Discussion

The purpose of these two experiments were to first, determine if SID Lys could be limited in diets containing added Cu without negatively impacting growth performance, and second, determine the duration of added Cu supplementation that results in the maximum response. The estimated SID Lys requirements used in the study were based on the results of Main et al. (2008) which included a series of seven experiments that were conducted to determine the optimal Lys:calorie ratio in both barrows and gilts. The present study was completed in the same facility with pigs of a similar a similar genotype. Consequently, our estimates for SID Lys requirement of the pigs used in our study are well supported. While the current study was successful at reporting improvements in growth performance with increasing SID Lys, added Cu did not provide a response when SID Lys was limiting. Furthermore, added Cu did not influence growth in Exp. 2 when efforts were focused on determining the optimal duration of added Cu supplementation.

To our knowledge, the first research to evaluate dietary AA by TBCC interactions was completed by Rochell et al. (2015) in broilers. They fed broilers 2 levels of digestible Lys (1.00 or 1.20%) and 2 levels of added Cu (0 or 200 mg/kg) from TBCC. They reported that broilers fed the low digestible Lys and 200 mg/kg of added Cu from TBCC had greater improvements in ADG and ADFI compared with broilers fed high digestible Lys. In addition to the improvements in growth, they also reported that N and OM digestibility were each increased by nearly 4%, in broilers fed 200 mg/kg of added Cu in the low Lys diet. Furthermore, they reported the AA digestibility for various essential AA was improved in the low Lys diet with added Cu from

TBCC, but not in high Lys diet. Specifically, AID of most of the indispensable AA was increased by at least 1.5%.

While Rochell et al. (2015) is currently the only published data to investigate the interaction between Cu and Lys, others have investigated the effects of Cu on digestibly in diets formulated to the pigs Lys requirement. Gonzales-Eguia et al. (2009) investigated the effects of 50 mg/kg of Cu from nanoCu ($CuSO_4$ and SiO_2 processed and ground to particle size < 200µ; 37.38% Cu) and $CuSO_4$ (400 to 1000µ; 25.4% Cu) on nutrient digestibility in growing pigs (30 to 65 kg). They reported that DM, CP, and ash digestibility were not affected by added Cu or Cu source. However, crude fat and GE digestibility was increased by at least 3.5% for either copper source. They further reported that nanoCu increased crude fat digestibility more than $CuSO_4$, but suggested this was due to particle size. In contrast, Kim et al. (2006) reported that 60 mg/kg added Cu from $CuSO_4$ decreased DM digestibility by 3% and increased N digestibility by at least 2.5%. One difference between these studies is Kim et al. (2006) observed their responses in pigs greater than 65 kg BW whereas Gonzales-Eguia et al. (2009) utilized pigs between 30 and 65 kg BW.

Based on the results of Rochell et al. (2015), Coble (2015) investigated the effects $CuSO_4$ and TBCC in high byproduct diets formulated to 0.05% below the estimated SID Lys requirement in growing and finishing swine. They determined that adding supplemental Cu in the form of TBCC or $CuSO_4$ potentially improved growth for longer durations during the finishing period than previously reported, where the SID Lys of diets was at or above the requirement (Hastad, 2002). Thus, it was important to determine if there was an interaction between SID Lys and added Cu, and the duration of feeding. This was of scientific importance and economic importance, as the potential to decrease AA of diets without negatively impacting performance has benefits for swine producers.

Although we did not measure the digestibility of nutrients in the current study, the growth data suggest that digestibility of neither N nor energy was likely improved with added Cu as Rochell et al. (2015) and Gonzales-Eguia et al. (2009) suggested. Differences between the current study and those previously mentioned do exist which could explain why the results are not similar. The current study was completed in older, heavier pigs, and utilized a diet with high amounts of byproduct ingredients. Rochell et al. (2015) utilized diets with low amounts of DDGS, included 2.6 to 3.8% soybean oil, and was completed it broilers. Gonzales-Eguia et al. (2009) fed diets containing 2.4% soybean oil, did not include byproduct ingredients, and utilized younger pigs. However, our results suggest that SID Lys should not be limited to achieve the maximum growth response to Cu.

The lack of an overall growth response to added Cu in Exp. 2 suggests that growth improvements are not always seen in during the finishing period when feeding additional Cu (Davis et al., 2002; Hastad, 2002); further challenging the ability to determine an optimal duration of supplementation. Consequently, additional research should be conducted to better define the most optimum timing and duration of Cu supplementation to maximize growth performance and carcass characteristics. Hastad (2002) reported that 200 mg/kg added Cu only improved growth performance until pigs were only 61 kg. Davis et al. (2002) observed improvements in ADG and G:F beyond 69 kg. The elongated response reported by Davis et al. (2002) could potentially be related to fat digestibility. They utilized diets that contained 5% added fat, in addition to the 175 mg/kg of added Cu included in the diet. Lou and Dove (1996) reported that adding 250 mg/kg of Cu increased fat digestibility in nursery pigs when 5% added fat was included in the diet. However, more research is needed to understand how diet ingredient and nutrient composition may affect the response to added Cu throughout the finishing. Although the growth performance in Exp. 2 did not provide the intended answers for determining the optimal duration of feeding, the observed improvement in carcass performance with 150 mg/kg added Cu is consistent with the other research that demonstrated improvements with added Cu (Coble, 2015).

As expected, increasing SID Lys improved ADG, G:F, and HCW in both experiments. Overall across experiments, ADG and G:F were increased by 3.3 and 2.5%, respectively. During the early finish period from 26 to 78 kg, the relative change between the low and high SID Lys treatments were similar to Main et al. (2008). However, during the late finishing period, Main et al. (2008) reported more significant changes in ADG and G:F (over 6% reduction). One possible reason for this difference is, unlike Main et al. (2008), pigs were fed ractopamine in the last phase of production and diets were formulated 0.3% above the late finishing requirement for diets not containing ractopamine. Even though the percentage of difference between each SID Lys level was exactly the same as in the previous phases, collectively each diet was well above the SID Lys requirement for pigs fed diets without ractopamine.

As TBCC is green in color, determining the potential for TBCC to affect internal body tissue color, such as the liver where Cu is stored, and negatively impact offal value is important. While adding Cu in the form of TBCC did decrease the redness and color saturation of the livers, the current study suggests that liver color is only minimally impacted and should not decrease the potential value. In our study, increasing SID Lys reduced liver redness which would be similar to the response Apple et al. (2004) observed in other tissues. Ultimately, the small changes in liver color that we observed would not be detectable by the human eye, even though instrumentally they are difference (T. Houser, Kansas State University, Manhattan, personal communication).

The liver stores about 8 to 10% of the total Cu in tissue, and the liver serves as a sink for Cu (Luza and Speisky, 1996; Hill and Spears, 2001). Feeding high levels of Cu can increase liver

Cu concentrations. The slight increase in liver Cu concentrations (approximately 20 mg/kg) for pigs fed 150 mg/kg added Cu from TBCC is consistent with others whom fed higher levels of TBCC, suggesting that more significant increases in liver Cu concentrations are not observed until pigs are fed levels greater than 150 mg/kg (Cromwell et al., 1998, Miles et al., 1998).

Lastly, the current experiment also measured the differences in carcass fatty acid composition in both jowl and backfat. Earlier published research suggested that increasing dietary Cu increased the amount of unsaturated fatty acids (primarily C16:1 and C18:1) while decreasing the amount of saturated fatty acids (C16:0 and C18:0; Elliot and Bowland, 1968). Although recently published literature is scarce, determining if carcass fat quality is influenced by dietary Cu is important as many packers have quality requirements related to IV. Surprisingly, backfat IV increased with increasing levels of SID Lys and added Cu, but that response was not observed when no additional Cu was added to the diet. This was the result of a reduction in C18:0 with added Cu, decreasing the concentration of saturated fatty acids, which is consistent with Elliot and Bowland (1968). Increasing the amount of SID Lys increased the CP of the diet, which has also been shown to decrease the amount of SFA and increase PUFA, consistent with the current research (Tous et al., 2014). While these changes are important, the carcass IV for both depots measured were relatively high, likely related to the high level of byproduct ingredients used in formulation that contain higher amounts of UFA (Salyer et al., 2012; Asmus et al., 2014).

In conclusion, feeding an additional 150 mg/kg Cu from TBCC did not result in improved performance when fed in deficient SID Lys diets. However, when additional Cu was fed in diets at the estimated SID Lys requirement, improved growth performance in Exp. 1, and increased carcass performance in Exp. 2 were observed. Furthermore, this data showed inconsistencies in the response to added dietary Cu, similar to other published research.

Additionally, more data is needed to understand the impacts of Cu role in nutrient digestibility in growing-finishing pigs, and if the response is potentially impacted by diet type. More data is need to fully understand the effects of adding high levels of Cu in finishing pig diets, including studies that allow for better understanding of the mode of action of high levels of added Cu.

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Table 4-1. Composition of diets for phases 1 and 2, Exp. 1 (as-fed basis)[1,2]

	Phase 1 SID Lys,[3] %			Phase 2 SID Lys, %		
Item	85.0	92.5	100.0	85.0	92.5	100.0
Ingredient, %						
Corn	39.42	36.82	34.23	43.31	41.07	38.82
Soybean meal, 46.5% CP	13.02	15.59	18.15	9.42	11.64	13.86
Distillers dried grains with solubles	30.00	30.00	30.00	30.00	30.00	30.00
Bakery meal	15.00	15.00	15.00	15.00	15.00	15.00
Monocalcium P, 21 %	0.25	0.25	0.25	---	---	---
Dicalcium P, 18.5%	---	---	---	0.13	0.13	0.13
Limestone	1.25	1.25	1.25	1.15	1.15	1.15
Salt	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin premix[4]	0.08	0.08	0.08	0.08	0.08	0.08
Trace mineral premix[5]	0.10	0.10	0.10	0.10	0.10	0.10
Lysine sulfate[6]	0.505	0.535	0.565	0.460	0.488	0.515
L-Thr	0.025	0.025	0.025	---	---	---
Phytase[7]	0.005	0.005	0.005	0.005	0.005	0.005
TBCC[8]	±	±	±	±	±	±
Total	100.0	100.0	100.0	100.0	100.0	100.0
Calculated analysis						
Standard ileal digestible (SID) amino acids, %						
Lys	0.88	0.96	1.04	0.77	0.84	0.91
Ile:Lys	74	72	71	77	75	73
Meth:Lys	34	33	31	37	35	34
Met + Cys:Lys	63	61	58	69	65	63
Thr:Lys	65	63	62	64	63	61
Trp:Lys	18.2	18.2	18.2	18.2	18.2	18.2
Val:Lys	87	84	82	91	88	86
Total lysine, %	1.07	1.16	1.24	0.95	1.03	1.10
SID lysine:ME, g/Mcal	2.61	2.84	3.08	2.28	2.48	2.68
ME, kcal/kg	3,387	3,384	3,382	3,397	3,395	3,393
NE, kcal/kg	2,492	2,477	2,462	2,518	2,506	2,493
CP, %	19.9	20.9	22.0	18.5	19.4	20.3
Ca, %	0.59	0.59	0.60	0.53	0.53	0.54
P, %	0.47	0.48	0.49	0.42	0.43	0.44
Available P, %	0.32	0.32	0.33	0.28	0.28	0.29

[1] Phase 1 diets fed from d 0 to 23 and phase 2 diets fed from d 23 to 38.

[2] Each diet was fed in meal form.

[3] Standardized ileal digestible; SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production phase.

[4] Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D_3; 35,274 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 26 mg vitamin B_{12}.

[5] Provided per kilogram of premix: 17 g Mn from manganese oxide, 110 g Fe from ferrous sulfate, 110 g Zn from zinc oxide, 17 g Cu from copper sulfate, 331 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[6] Biolys (Evonik, Inc., Kennesaw, GA).

[7] Optiphos 2000 (Huvepharma, Inc., Peachtree City, GA) provided 200 phytase units (FTU)/kg, with a release of 0.05% available P.

[8] Tribasic copper chloride (Intellibond C; Micronutrients, Inc., Indianapolis, IN) provided 150 mg/kg Cu and was added at the expense of corn.

Table 4-2. Composition of diets for phases 3 and 4, Exp. 1 (as-fed basis)[1,2]

	Phase 3 SID Lys,[3] %			Phase 4 SID Lys, %		
Item	85.0	92.5	100.0	85.0	92.5	100.0
Ingredient, %						
Corn	46.59	44.58	42.57	48.80	46.98	45.17
Soybean meal, 46.5% CP	6.31	8.30	10.28	4.15	5.95	7.74
Distillers dried grains with solubles	30.00	30.00	30.00	30.00	30.00	30.00
Bakery meal	15.00	15.00	15.00	15.00	15.00	15.00
Limestone	1.15	1.15	1.15	1.13	1.13	1.13
Salt	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin premix[4]	0.08	0.08	0.08	0.08	0.08	0.08
Trace mineral premix[5]	0.10	0.10	0.10	0.10	0.10	0.10
Lysine sulfate[6]	0.425	0.448	0.470	0.395	0.415	0.435
Phytase[7]	0.005	0.005	0.005	0.005	0.005	0.005
TBCC[8]	±	±	±	±	±	±
Total	100.0	100.0	100.0	100.0	100.0	100.0
Calculated analysis						
Standard ileal digestible (SID) amino acids, %						
Lys	0.68	0.74	0.80	0.61	0.67	0.72
Ile:Lys	80	78	76	83	81	79
Meth:Lys	74	70	67	79	75	72
Met + Cys:Lys	74	70	67	79	75	72
Thr:Lys	67	65	64	70	68	66
Trp:Lys	18.2	18.2	18.2	18.3	18.3	18.3
Val:Lys	97	93	90	102	98	95
Total lysine, %	0.85	0.92	0.98	0.85	0.92	0.98
SID lysine:ME, g/Mcal	2.00	2.17	2.35	1.80	1.96	2.12
ME, kcal/kg	3,401	3,403	3,405	3,407	3,406	3,404
NE, kcal/kg	2,517	2,528	2,540	2,553	2,543	2,532
CP, %	17.2	18.0	18.8	16.4	17.1	17.8
Ca, %	0.49	0.49	0.50	0.47	0.48	0.48
P, %	0.38	0.39	0.40	0.37	0.38	0.39
Available P, %	0.25	0.26	0.26	0.25	0.25	0.26

[1] Phase 3 diets fed from d 38 to 70 and phase 4 diets fed from d 70 to 97.

[2] Each diet was fed in meal form.

[3] Standardized ileal digestible; SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production phase.

[4] Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D_3; 35,274 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 26 mg vitamin B_{12}.

[5] Provided per kilogram of premix: 17 g Mn from manganese oxide, 110 g Fe from ferrous sulfate, 110 g Zn from zinc oxide, 17 g Cu from copper sulfate, 331 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[6] Biolys (Evonik, Inc., Kennesaw, GA).

[7] Optiphos 2000 (Huvepharma, Inc., Peachtree City, GA) provided 200 phytase units (FTU)/kg, with a release of 0.05% available P.

[8] Tribasic copper chloride (Intellibond C; Micronutrients, Inc., Indianapolis, IN) provided 150 mg/kg Cu and was added at the expense of corn.

Table 4-3. Composition of diets for phase 5, Exp. 1 (as-fed basis)[1,2]

	Phase 5 SID Lys,[3] %		
Item	85.0	92.5	100.0
Ingredient, %			
Corn	41.81	39.39	36.97
Soybean meal, 46.5% CP	11.04	13.40	15.79
Distillers dried grains with solubles	30.00	30.00	30.00
Bakery meal	15.00	15.00	15.00
Limestone	1.15	1.15	1.15
Salt	0.35	0.35	0.35
Vitamin premix[4]	0.08	0.08	0.08
Trace mineral premix[5]	0.10	0.10	0.10
Lysine sulfate[6]	0.450	0.475	0.500
L-Thr	0.030	0.030	0.030
Phytase[7]	0.005	0.005	0.005
Ractopamine HCl[8]	0.025	0.025	0.025
TBCC[9]	±	±	±
Total	100.0	100.0	100.0
Calculated analysis			
Standard ileal digestible (SID) amino acids, %			
Lys	0.81	0.88	0.95
Ile:Lys	77	75	74
Meth:Lys	36	35	33
Met + Cys:Lys	67	64	62
Thr:Lys	68	66	65
Trp:Lys	18.6	18.6	18.6
Val:Lys	91	88	85
Total lysine, %	0.99	1.07	1.14
SID lysine:ME, g/Mcal	2.38	2.59	2.80
ME, kcal/kg	3,399	3,397	3,395
NE, kcal/kg	2,511	2,498	2,485
CP, %	19.1	20.1	21.0
Ca, %	0.50	0.51	0.52
P, %	0.41	0.42	0.43
Available P, %	0.26	0.27	0.28

[1] Phase 5 diets fed from d 97 to 120.

[2] Each diet was fed in meal form.

[3] Standardized ileal digestible; SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production phase.

[4] Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D_3; 35,274 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 26 mg vitamin B_{12}.

[5] Provided per kilogram of premix: 17 g Mn from manganese oxide, 110 g Fe from ferrous sulfate, 110 g Zn from zinc oxide, 17 g Cu from copper sulfate, 331 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[6] Biolys (Evonik, Inc., Kennesaw, GA).

[7] Optiphos 2000 (Huvepharma, Inc., Peachtree City, GA) provided 200 phytase units (FTU)/kg, with a release of 0.05% available P.

[8] Paylean 9 (Elanco Animal Health, Inc., Greenfield, IN) provided 5 mg/kg ractopamine HCl.

[9] Tribasic copper chloride (Intellibond C; Micronutrients, Inc., Indianapolis, IN) provided 150 mg/kg Cu and was added at the expense of corn.

Table 4-4. Composition of diets for phase 1 and 2, Exp. 2 (as-fed basis)[1,2]

	Phase 1 SID Lys,[3] %		Phase 2 SID Lys, %	
Item	92.5	100.0	92.5	100.0
Ingredient, %				
Corn	56.06	52.94	59.94	57.20
Soybean meal, 46.5% CP	11.23	14.33	7.56	10.29
Distillers dried grains with solubles	30.00	30.00	30.00	30.00
Limestone	1.60	1.60	1.45	1.45
Salt	0.35	0.35	0.35	0.35
Vitamin premix[4]	0.08	0.08	0.08	0.08
Trace mineral premix[5]	0.10	0.10	0.10	0.10
L-Lys HCl	0.475	0.475	0.450	0.450
DL-Meth	0.005	0.025	---	---
L-Thr	0.050	0.050	0.030	0.035
L-Trp	0.043	0.040	0.041	0.039
Phytase[6]	0.005	0.005	0.005	0.005
TBCC[7]	±	±	±	±
Total	100.0	100.0	100.0	100.0
Calculated analysis				
Standard ileal digestible (SID) amino acids, %				
Lys	0.95	1.03	0.84	0.91
Ile:Lys	62	62	63	63
Meth:Lys	31	32	32	31
Met + Cys:Lys	58	58	61	59
Thr:Lys	62	62	62	62
Trp:Lys	19	19	19	19
Val:Lys	71	70	73	73
Total lysine, %	1.14	1.22	1.02	1.09
SID lysine:ME, g/Mcal	2.87	3.11	2.53	2.74
ME, kcal/kg	3,318	3,314	3,327	3,322
NE, kcal/kg	2,456	2,436	2,480	2,465
CP, %	19.3	20.5	17.7	18.8
Ca, %	0.65	0.66	0.58	0.59
P, %	0.42	0.42	0.39	0.40
Available P, %	0.28	0.28	0.26	0.27

[1] Phase 1 diets fed from d 0 to 21 and phase 2 diets fed from d 21 to 38.

[2] Each diet was fed in meal form.

[3] Standardized ileal digestible; SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production phase.

[4] Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D_3; 35,274 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 26 mg vitamin B_{12}.

[5] Provided per kilogram of premix: 17 g Mn from manganese oxide, 110 g Fe from ferrous sulfate, 110 g Zn from zinc oxide, 17 g Cu from copper sulfate, 331 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[6] Optiphos 2000 (Huvepharma, Inc., Peachtree City, GA) provided 200 phytase units (FTU)/kg, with a release of 0.05% available P.

[7] Tribasic copper chloride (Intellibond C; Micronutrients, Inc., Indianapolis, IN) provided 150 mg/kg Cu and was added at the expense of corn.

Table 4-5. Composition of diets for phase 3 and 4, Exp. 2 (as-fed basis)[1,2]

	Phase 3 SID Lys,[3] %		Phase 4 SID Lys, %	
Item	92.5	100.0	92.5	100.0
Ingredient, %				
Corn	62.61	60.20	64.14	61.98
Soybean meal, 46.5% CP	5.04	7.45	3.65	5.81
Distillers dried grains with solubles	30.00	30.00	30.00	30.00
Limestone	1.38	1.38	1.30	1.30
Salt	0.35	0.35	0.35	0.35
Vitamin premix[4]	0.08	0.08	0.08	0.08
Trace mineral premix[5]	0.10	0.10	0.10	0.10
L-Lys HCl	0.400	0.400	0.350	0.350
L-Thr	---	0.005	---	---
L-Trp	0.039	0.038	0.031	0.030
Phytase[6]	0.005	0.005	0.005	0.005
TBCC[7]	±	±	±	±
Total	100.0	100.0	100.0	100.0
Calculated analysis				
Standard ileal digestible (SID) amino acids, %				
Lys	0.74	0.80	0.67	0.72
Ile:Lys	65	66	69	69
Meth:Lys	35	34	38	36
Met + Cys:Lys	66	64	71	69
Thr:Lys	62	62	66	65
Trp:Lys	19.5	19.5	19.5	19.5
Val:Lys	78	77	83	82
Total lysine, %	0.91	0.97	0.83	0.89
SID lysine:ME, g/Mcal	2.22	2.40	2.00	2.16
ME, kcal/kg	3,311	3,329	3,333	3,331
NE, kcal/kg	2,496	2,482	2,507	2,493
CP, %	16.7	17.6	16.0	16.9
Ca, %	0.55	0.55	0.52	0.52
P, %	0.38	0.39	0.37	0.38
Available P, %	0.25	0.25	0.23	0.24

[1] Phase 3 diets fed from d 38 to 60 and phase 4 diets from d 60 to 95.

[2] Each diet was fed in meal form.

[3] Standardized ileal digestible; SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production phase.

[4] Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D_3; 35,274 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 26 mg vitamin B_{12}.

[5] Provided per kilogram of premix: 17 g Mn from manganese oxide, 110 g Fe from ferrous sulfate, 110 g Zn from zinc oxide, 17 g Cu from copper sulfate, 331 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[6] Optiphos 2000 (Huvepharma, Inc., Peachtree City, GA) provided 200 phytase units (FTU)/kg, with a release of 0.05% available P.

[7] Tribasic copper chloride (Intellibond C; Micronutrients, Inc., Indianapolis, IN) provided 150 mg/kg Cu and was added at the expense of corn.

Table 4-6. Composition of diets for phase 5, Exp. 2 (as-fed basis)[1,2]

	Phase 4 SID Lys,[3] %	
Item	92.5	100.0
Ingredient, %		
Corn	60.63	57.92
Soybean meal, 46.5% CP	7.16	9.87
Distillers dried grains with solubles	30.00	30.00
Limestone	1.10	1.10
Salt	0.35	0.35
Vitamin premix[4]	0.08	0.08
Trace mineral premix[5]	0.10	0.10
L-Lys HCl	0.450	0.450
L-Thr	0.055	0.060
L-Trp	0.045	0.044
Ractopamine HCl[6]	0.025	0.025
Phytase[7]	0.005	0.005
TBCC[8]	±	±
Total	100.0	100.0
Calculated analysis		
Standard ileal digestible (SID) amino acids, %		
Lys	0.83	0.90
Ile:Lys	63	63
Meth:Lys	32	31
Met + Cys:Lys	61	59
Thr:Lys	65	65
Trp:Lys	19.5	19.5
Val:Lys	73	73
Total lysine, %	1.01	1.08
SID lysine:ME, g/Mcal	2.49	2.70
ME, kcal/kg	3,338	3,336
NE, kcal/kg	2,491	2,476
CP, %	17.6	18.7
Ca, %	0.46	0.46
P, %	0.39	0.40
Available P, %	0.23	0.24

[1] Phase 5 diets fed from d 95 to 120.

[2] Each diet was fed in meal form.

[3] Standardized ileal digestible; SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production phase.

[4] Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D_3; 35,274 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 26 mg vitamin B_{12}.

[5] Provided per kilogram of premix: 17 g Mn from manganese oxide, 110 g Fe from ferrous sulfate, 110 g Zn from zinc oxide, 17 g Cu from copper sulfate, 331 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[6] Paylean 9 (Elanco Animal Health, Inc., Greenfield, IN) provided 5 mg/kg ractopamine HCl.

[7] Optiphos 2000 (Huvepharma, Inc., Peachtree City, GA) provided 200 phytase units (FTU)/kg, with a release of 0.05% available P.

[8] Tribasic copper chloride (Intellibond C; Micronutrients, Inc., Indianapolis, IN) provided 150 mg/kg Cu and was added at the expense of corn.

Table 4-7. Chemical analysis of complete diets, Exp. 1 (as-fed basis)[1]

Added Cu,[2] mg/kg:	0			150		
SID lysine,[3] %:	85.0	92.5	100.0	85.0	92.5	100.0
Total Cu, mg/kg						
Phase 1	45	38	28	217	218	218
Phase 2	34	25	29	188	178	215
Phase 3	30	29	41	182	219	196
Phase 4	42	39	56	222	246	232
Phase 5	34	39	33	187	225	221
Amino acids, %						
Phase 1						
CP	20.06	20.65	21.42	19.72	20.62	21.22
Lys	1.03	1.13	1.23	1.10	1.11	1.15
Met + Cys	0.72	0.71	0.75	0.73	0.73	0.74
Thr	0.78	0.79	0.81	0.78	0.79	0.81
Trp	0.20	0.21	0.22	0.19	0.21	0.22
Val	0.95	0.97	1.00	0.93	0.97	0.99
Phase 2						
CP	19.06	19.05	20.58	19.72	20.38	21.72
Lys	0.93	1.02	1.17	1.05	1.02	1.20
Met + Cys	0.70	0.71	0.73	0.72	0.72	0.75
Thr	0.71	0.73	0.76	0.76	0.74	0.82
Trp	0.18	0.19	0.21	0.20	0.20	0.22
Val	0.89	0.92	0.96	0.93	0.83	1.01
Phase 3						
CP	17.88	20.40	22.27	17.50	19.12	18.67
Lys	0.88	1.23	1.26	0.75	0.90	0.81
Met + Cys	0.68	0.71	0.78	0.65	0.66	0.66
Thr	0.68	0.79	0.86	0.65	0.69	0.67
Trp	0.17	0.21	0.23	0.16	0.18	0.17
Val	0.86	0.95	1.03	0.80	0.85	0.83
Phase 4						
CP	17.20	16.69	17.58	16.78	17.23	20.92
Lys	0.79	0.82	0.83	0.81	0.74	1.10
Met + Cys	0.63	0.62	0.64	0.61	0.64	0.72
Thr	0.63	0.62	0.65	0.60	0.62	0.78
Trp	0.15	0.15	0.16	0.14	0.15	0.21
Val	0.77	0.75	0.79	0.75	0.77	0.93
Phase 5						
CP	18.65	20.87	20.73	20.08	20.36	20.87
Lys	1.04	1.12	1.11	1.05	1.05	1.15
Met + Cys	0.67	0.73	0.72	0.69	0.70	0.73
Thr	0.73	0.79	0.78	0.75	0.78	0.81
Trp	0.19	0.20	0.21	0.19	0.20	0.21
Val	0.88	0.95	0.93	0.90	0.91	0.96

[1] Values represent means from one composite sample, analyzed in duplicate.

[2] Tribasic copper chloride (Intellibond C; Micronutrients, Indianapolis, IN).

[3] Standardized ileal digestible; SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production stage.

Table 4-8. Chemical analysis of complete diets, Exp. 2 (as-fed basis)[1]

Added Cu,[2] mg/kg:	0		150	
SID lysine,[3] %:	92.5	100.0	92.5	100.0
Total Cu, mg/kg				
Phase 1	37	31	249	201
Phase 2	31	28	272	214
Phase 3	38	42	246	210
Phase 4	34	32	246	219
Phase 5[4]	---	---	---	---
Amino acids, %				
Phase 1				
CP	19.70	20.96	19.82	20.49
Lys	1.10	1.20	1.12	1.21
Met + Cys	0.69	0.74	0.70	0.73
Thr	0.74	0.77	0.75	0.79
Trp	0.22	0.23	0.22	0.23
Val	0.91	0.96	0.91	0.93
Phase 2				
CP	18.30	19.38	17.34	19.34
Lys	1.07	1.03	0.94	1.02
Met + Cys	0.68	0.70	0.64	0.68
Thr	0.70	0.77	0.65	0.69
Trp	0.19	0.19	0.18	0.20
Val	0.86	0.90	0.81	0.85
Phase 3				
CP	16.41	17.46	16.07	16.20
Lys	0.83	0.97	0.85	0.87
Met + Cys	0.59	0.60	0.59	0.61
Thr	0.58	0.62	0.57	0.60
Trp	0.17	0.18	0.16	0.17
Val	0.74	0.79	0.75	0.77
Phase 4				
CP	15.50	15.64	15.65	15.73
Lys	0.72	0.82	0.81	0.83
Met + Cys	0.60	0.60	0.61	0.62
Thr	0.57	0.57	0.59	0.59
Trp	0.34	0.34	0.34	0.37
Val	0.16	0.16	0.16	0.16
Phase 5[4]	---	---	---	---

[1] Values represent means from one composite sample, analyzed in duplicate.

[2] Tribasic copper chloride (Intellibond C; Micronutrients, Indianapolis, IN).

[3] Standardized ileal digestible (SID) lysine values were based on 100% of the estimated SID Lys requirement finishing pigs within this production system.

[4] Phase 5 diets were not available for analysis.

Table 4-9. Effect of standardized ileal digestible (SID) lysine (Lys) and added Cu on growth performance of finishing pigs, Exp. 1[1]

								Probability, *P* <				
Added Cu,[2] mg/kg:	0			150				Cu × Lys			SID Lys	
SID Lys,[3] %:	85.0	92.5	100.0	85.0	92.5	100.0	SEM	Linear	Quadratic	Cu	Linear	Quadratic
BW, kg												
d 0	29.0	29.0	29.0	29.0	28.9	29.0	0.93	0.896	0.940	0.915	0.930	0.840
d 70	84.2	86.6	86.6	84.5	86.3	88.7	1.50	0.089[5]	0.124	0.089	0.001	0.325
d 120	122.8	125.4	126.1	123.7	125.8	130.0	1.38	0.110	0.169	0.006	0.001	0.636
d 0 to 70												
ADG, kg	0.79	0.82	0.82	0.79	0.82	0.85	0.010	0.034[6]	0.222	0.057	0.001	0.236
ADFI, kg	1.96	2.00	1.97	1.97	1.98	2.04	0.039	0.172	0.095[7]	0.184	0.053	0.765
G:F	0.402	0.410	0.415	0.400	0.414	0.418	0.005	0.392	0.470	0.494	0.001	0.299
d 70 to 120												
ADG, kg	0.81	0.81	0.82	0.82	0.82	0.83	0.012	0.772	0.956	0.514	0.339	0.519
ADFI, kg	2.52	2.51	2.52	2.51	2.50	2.51	0.031	0.897	0.997	0.599	0.979	0.752
G:F	0.322	0.322	0.325	0.325	0.326	0.331	0.004	0.532	0.925	0.110	0.168	0.597
d 0 to 120												
ADG, kg	0.80	0.82	0.82	0.80	0.82	0.84	0.007	0.109	0.414	0.095	0.001	0.740
ADFI, kg	2.19	2.20	2.19	2.19	2.19	2.23	0.032	0.414	0.333	0.654	0.227	0.949
G:F	0.365	0.370	0.373	0.366	0.374	0.379	0.004	0.276	0.786	0.090	0.001	0.582
Caloric efficiency, Mcal/kg[4]												
ME	9.32	9.19	9.11	9.31	9.10	8.97	42.9	0.278	0.837	0.087	0.001	0.541
NE	6.93	6.81	6.71	6.92	6.74	6.61	31.7	0.276	0.831	0.085	0.001	0.535

[1] A total of 1,248 pigs (PIC 337 × 1050 PIC, Hendersonville, TN; initial BW = 29.0 ± 0.1 kg) were used in a 120 d study; 8 pens per treatment and 26 pigs per pen.

[2] Tribasic copper chloride (Intellibond C; Micronutrients, Indianapolis, IN).

[3] SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production stage.

[4] Caloric efficiencies were calculated by the following equation: sum of (ADFI × Mcal) ÷ (ADG) for each period.

[5] Effect of Cu within 100 % SID Lys: $P = 0.007$.

[6] Effect of Cu within 100% SID Lys: $P = 0.003$.

[7] Effect of Cu within 100% SID Lys: $P = 0.019$.

Table 4-10. Effect of standardized ileal digestible (SID) lysine (Lys) and added Cu on carcass characteristics of finishing pigs, Exp. 1[1]

								Probability, $P <$				
Added Cu,[2] mg/kg:	0			150				Cu × Lys			SID Lys	
SID Lys,[3] %:	85.0	92.5	100.0	85.0	92.5	100.0	SEM	Linear	Quadratic	Cu	Linear	Quadratic
Carcass characteristics[4]												
HCW, kg	92.6	94.7	94.3	93.3	94.6	96.7	1.15	0.346	0.290	0.170	0.007	0.619
Carcass yield,[5] %	75.45	75.51	74.76	75.47	75.16	74.97	0.464	0.838	0.557	0.921	0.203	0.666
Backfat, [6]mm.	16.3	16.8	15.7	16.0	16.3	16.0	0.43	0.745	0.509	0.765	0.553	0.215
Loin depth, [6]mm.	69.6	68.8	68.8	68.8	69.6	70.6	0.66	0.068[9]	0.930	0.260	0.340	0.601
Lean,[6] %	57.42	57.31	58.12	57.59	58.04	57.87	0.222	0.342	0.057[10]	0.249	0.040	0.696
Carcass performance												
HCW ADG,[7] kg	0.591	0.608	0.605	0.597	0.607	0.625	0.007	0.321	0.276	0.151	0.006	0.591
HCW G:F[8]	0.271	0.276	0.276	0.273	0.278	0.281	0.004	0.581	0.642	0.137	0.012	0.412

[1] A total of 1,248 pigs [PIC 337 × 1050, PIC (Hendersonville, TN); initial BW = 29.0 ± 0.1 kg] were used in a 120 d study; 8 pens per treatment and 26 pigs per pen.

[2] Tribasic copper chloride (Intellibond C; Micronutrients, Indianapolis, IN).

[3] SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production stage.

[4] 1,069 pigs (19 to 23 pigs/pen) were transported to a commercial packing plant for processing and data collection (Swift and Company, Worthington, MN) and 144 pigs (3 pigs/pen) visually assumed to represent the mean live weight of the pen were subsampled and shipped to a separate processing facility for further carcass measurements (Natural Foods Holdings, Inc., Sioux Center, IA). The weighted average of the two plants were used for HCW, farm yield, and backfat.

[5] Carcass yield determined by dividing HCW at the plant by live BW at the farm prior to transport.

[6] HCW was used as a covariate.

[7] HCW ADG = (HCW – (d 0 wt. × 75% yield)) ÷ 120 d.

[8] HCW G:F = (HCW – (d 0 wt. × 75% yield)) ÷ (ADFI × 120)

[9] Effect of Cu within 100% SID Lys: $P = 0.063$.

[10] Effect of Cu within 92.5% SID Lys: $P = 0.062$.

Table 4-11. Effect of standardized ileal digestible (SID) lysine (Lys) and added Cu on liver color of finishing pigs, Exp. 1[1]

								Probability, $P <$				
Added Cu,[2] mg/kg:	0			150				Cu × Lys			SID Lys	
SID Lys,[3] %:	85.0	92.5	100.0	85.0	92.5	100.0	SEM	Linear	Quadratic	Cu	Linear	Quadratic
Liver color												
Lightness, L*[4]	32.55	31.18	32.24	31.48	31.05	32.08	0.594	0.431	0.888	0.160	0.800	0.191
Redness, a*[5]	14.86	15.01	14.71	14.77	14.09	13.71	0.359	0.206	0.537	0.027	0.097	0.912
Yellowness, b*[6]	6.42	5.59	6.19	6.75	5.61	5.68	0.461	0.357	0.271	0.303	0.163	0.695
Hue Angle,[7] °	0.399	0.409	0.389	0.424	0.370	0.379	0.199	0.376	0.186	0.647	0.170	0.639
Chroma[8]	16.24	16.43	16.02	16.28	15.23	14.98	0.488	0.266	0.404	0.071	0.125	0.908

[1] A total of 144 pigs (PIC 337 × 1050 PIC, Hendersonville, TN; initial BW = 29.0 ± 0.1 kg) were used (3 pigs/pen) in a 120 d study; 8 replications per treatment.

[2] Tribasic copper chloride (Intellibond C; Micronutrients, Indianapolis, IN).

[3] SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production stage.

[4] L*, 0 = black, 100 = white.

[5] a* – values = green; + values = red.

[6] b* – values = blue; + values = yellow.

[7] Hue angle = $\tan^{-1}(b^*/a^*)$.

[8] Chroma = $(\sqrt{}a^* + b^*) / L^*$.

Table 4-12. Effect of standardized ileal digestible (SID) lysine (Lys) and added Cu on liver mineral concentrations (DM basis) of finishing pigs, Exp. 1[1]

								Probability, $P <$				
Added Cu,[2] mg/kg:	0			150				Cu × Lys			SID Lys	
SID Lys,[3] %:	85.0	92.5	100.0	85.0	92.5	100.0	SEM	Linear	Quadratic	Cu	Linear	Quadratic
Concentration, mg/kg												
Cu	13	13	12	33	39	26	3.27	0.393	0.105	0.001	0.182	0.092
Fe	196	221	211	200	203	205	11.43	0.654	0.368	0.437	0.344	0.322
Zn	62	59	59	59	57	55	2.29	0.566	0.806	0.095	0.099	0.841

[1] A total of 144 pigs (PIC 337 × 1050 PIC, Hendersonville, TN; initial BW = 29.0 ± 0.1 kg) were used (3 pigs/pen) in a 120 d study; 8 replications per treatment.

[2] Tribasic copper chloride (Intellibond C; Micronutrients, Indianapolis, IN).

[3] SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production stage.

Table 4-13. Effect of standardized ileal digestible (SID) lysine and added Cu on backfat fatty acid analysis (DM Basis) of finishing pigs, Exp. 1[1]

								Probability, $P <$				
Added Cu,[2] mg/kg:	0			150				Cu × Lys			SID Lys	
SID Lys, [3]%:	85.0	92.5	100.0	85.0	92.5	100.0	SEM	Linear	Quadratic	Cu	Linear	Quadratic
Myristic acid (C14:0). %	1.11	1.14	1.13	1.12	1.14	1.09	0.027	0.419	0.664	0.597	0.909	0.277
Palmitic acid (C16:0), %	19.82	20.22	20.07	19.75	19.80	19.63	0.262	0.469	0.725	0.145	0.797	0.382
Palmitoleic acid (C16:1), %	1.88	1.91	1.87	1.83	1.95	1.87	0.071	0.731	0.597	0.880	0.842	0.280
Heptadecanoic acid (C17:0), %	0.41	0.41	0.47	0.40	0.40	0.47	0.021	0.786	0.953	0.486	0.004	0.089
Stearic acid (C18:0), %	9.97	10.37	10.17	10.38	10.05	10.17	0.266	0.455	0.272	0.896	0.975	0.859
Oleic acid (C18:1 *cis*-9), %	37.25	36.57	36.46	36.82	37.20	36.19	0.420	0.851	0.190	0.946	0.101	0.574
Linoleic acid (C18:2n-6), %	25.70	25.54	25.87	25.99	25.56	26.58	0.618	0.738	0.658	0.508	0.545	0.374
α-linoleic acid (C18:3n-3), %	0.92	0.93	0.94	0.93	0.95	0.98	0.021	0.402	0.688	0.235	0.098	0.945
γ-linoleic acid (C18:3n-6), %	0.10	0.10	0.10	0.10	0.11	0.10	0.007	0.630	0.593	0.617	0.448	0.822
Conjugated linoleic acid (*c*9, *t*11), %	0.14	0.14	0.12	0.15	0.16	0.14	0.009	0.539	0.870	0.064	0.224	0.113
Arachidic acid (C20:0), %	0.17	0.18	0.17	0.16	0.17	0.18	0.007	0.163	0.726	0.642	0.141	0.544
Gadoleic acid (C20:1), %	0.72	0.71	0.79	0.67	0.72	0.74	0.016	0.887	0.028[10]	0.018	0.001	0.302
Eicosadienoic acid (C20:2), %	0.94	0.95	1.01	0.93	0.96	1.01	0.026	0.803	0.647	0.845	0.005	0.487
Eicosatrienoic acid (C20:3n-3), %	0.12	0.12	0.11	0.11	0.12	0.12	0.005	0.054[9]	0.589	0.683	0.213	0.681
Dihomo-γ-linoleic acid (C20:3n-6), %	0.12	0.13	0.12	0.11	0.12	0.13	0.005	0.255	0.749	0.589	0.143	0.358
Arachidonic acid (C20:4n-6), %	0.34	0.31	0.30	0.33	0.32	0.33	0.015	0.100	0.837	0.510	0.100	0.711
Other fatty acids, %	0.28	0.27	0.29	0.26	0.27	0.29	0.010	0.303	0.224	0.309	0.081	0.309
Total SFA,[4] %	31.49	32.31	32.01	31.79	31.57	31.53	0.474	0.405	0.422	0.427	0.786	0.566
Total MUFA,[5] %	39.85	39.20	39.13	39.32	39.87	38.80	0.472	0.823	0.187	0.869	0.198	0.531
Total PUFA,[6] %	28.37	28.22	28.57	28.63	28.29	29.38	0.671	0.684	0.691	0.494	0.484	0.410
UFA:SFA ratio[7]	2.18	2.09	2.14	2.15	2.18	2.17	0.047	0.461	0.323	0.465	0.810	0.561
PUFA:SFA ratio	0.91	0.88	0.91	0.91	0.90	0.94	0.032	0.592	0.829	0.494	0.651	0.394
Iodine value,[8] g/100g	82.63	81.75	82.21	82.64	82.44	83.36	0.901	0.530	0.942	0.406	0.869	0.433

[1] A total of 144 pigs (PIC 337 × 1050 PIC, Hendersonville, TN; initial BW = 29.0 ± 0.1 kg) were used (3 pigs/pen) in a 120 d study; 8 replications per treatment.

[2] Tribasic copper chloride (Intellibond C; Micronutrients, Indianapolis, IN).

[3] SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production stage.

[4] Total SFA = ([C14:0] + [C16:0] + [C17:0] + [C18:0] + [C20:0]); brackets indicate concentration.

[5] Total MUFA = ([C16:1] + [C18:1*cis*-9] + [C20:1]); brackets indicate concentration.

[6] Total PUFA = ([C18:2n-6] + [C18:3n-3] + [C18:3n-6] + [*c*9,*t*11] + [C20:2] + [C20:3n-3] + [C20:3n-6] + [C20:4n-6]); brackets indicate concentration.

[7] UFA:SFA = (total MUFA+PUFA)/ total SFA.

[8] Calculated as IV = [C16:1] × 0.950 + [C18:1] × 0.860 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C20:4] × 3.201 + [C22:1] × 0.723 + [C22:5] × 3.697 + [C22:6] × 4.463; brackets indicate concentration.

[9] Effect of Cu within 100% SID Lys: $P = 0.030$ and within 85% SID Lys: $P = 0.012$.

[10] Effect of Cu within 100% SID Lys: $P < 0.070$.

Table 4-14. Effect of standardized ileal digestible (SID) lysine and added Cu on jowl fatty acid analysis (DM Basis) of finishing pigs, Exp. 1[1]

								Probability, $P <$				
Added Cu,[2] mg/kg:	0			150				Cu × Lys			SID Lys	
SID Lys, [3]%:	85.0	92.5	100.0	85.0	92.5	100.0	SEM	Linear	Quadratic	Cu	Linear	Quadratic
Myristic acid (C14:0). %	1.10	1.16	1.19	1.12	1.16	1.14	0.032	0.305	0.803	0.687	0.092	0.446
Palmitic acid (C16:0), %	18.63	18.22	19.00	19.00	18.80	18.51	0.377	0.218	0.282	0.573	0.858	0.358
Palmitoleic acid (C16:1), %	2.52	2.35	2.64	2.39	2.66	2.59	0.116	0.678	0.032[9]	0.628	0.129	0.744
Heptadecanoic acid (C17:0), %	0.41	0.44	0.43	0.40	0.41	0.42	0.026	0.924	0.760	0.446	0.496	0.733
Stearic acid (C18:0), %	8.07	8.55	8.10	8.91	7.95	7.67	0.289	0.024[10]	0.092	0.781	0.030	0.795
Oleic acid (C18:1 *cis*-9), %	40.70	40.07	40.23	40.19	40.98	39.98	0.568	0.811	0.174	0.911	0.537	0.605
Linoleic acid (C18:2n-6), %	24.52	25.12	24.34	24.08	24.01	25.45	0.630	0.211	0.176	0.776	0.332	0.950
α-linoleic acid (C18:3n-3), %	0.89	0.94	0.90	0.87	0.89	0.96	0.025	0.123	0.086[11]	0.946	0.044	0.771
γ-linoleic acid (C18:3n-6), %	0.10	0.10	0.10	0.09	0.09	0.10	0.005	0.660	0.774	0.100	0.515	0.907
Conjugated linoleic acid (*c*9, *t*11), %	0.16	0.15	0.14	0.16	0.17	0.18	0.008	0.047[12]	0.701	0.013	0.952	0.580
Arachidic acid (C20:0), %	0.13	0.14	0.13	0.13	0.14	0.14	0.006	0.878	0.266	0.882	0.746	0.156
Gadoleic acid (C20:1), %	0.80	0.78	0.80	0.76	0.80	0.80	0.019	0.245	0.281	0.692	0.261	0.974
Eicosadienoic acid (C20:2), %	1.02	1.04	1.03	1.00	1.02	1.08	0.026	0.178	0.463	0.891	0.109	0.798
Eicosatrienoic acid (C20:3n-3), %	0.13	0.13	0.13	0.12	0.13	0.14	0.005	0.154	0.450	0.443	0.152	0.704
Dihomo-γ-linoleic acid (C20:3n-6), %	0.13	0.15	0.14	0.12	0.14	0.14	0.005	0.492	0.637	0.090	0.017	0.259
Arachidonic acid (C20:4n-6), %	0.36	0.35	0.35	0.34	0.34	0.37	0.012	0.196	0.505	0.492	0.409	0.247
Other fatty acids, %	0.34	0.34	0.36	0.30	0.32	0.34	0.014	0.451	0.789	0.043	0.049	0.846
Total SFA,[4] %	28.35	28.49	28.85	29.56	28.45	27.87	0.501	0.019[13]	0.837	0.854	0.191	0.635
Total MUFA,[5] %	44.02	43.20	43.67	43.34	44.44	43.38	0.644	0.752	0.109	0.864	0.803	0.687
Total PUFA,[6] %	27.30	27.97	27.13	26.79	26.78	28.41	0.687	0.188	0.175	0.800	0.285	0.951
UFA:SFA ratio[7]	2.54	2.54	2.47	2.40	2.52	2.59	0.066	0.032[13]	0.941	0.756	0.294	0.562
PUFA:SFA ratio	0.97	1.00	0.95	0.91	0.95	1.03	0.037	0.073	0.339	0.672	0.233	0.835
Iodine value,[8] g/100g	84.20	84.62	83.61	82.73	83.61	85.48	0.861	0.052	0.402	0.769	0.202	0.882

[1] A total of 144 pigs (PIC 337 × 1050; PIC, Hendersonville, TN; initially 29.0 ± 0.1 kg) were used (3 pigs/pen) in a 120 d study; 8 replications per treatment.

[2] Tribasic copper chloride (Intellibond C; Micronutrients, Indianapolis, IN).

[3] SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production stage.

[4] Total SFA = ([C14:0] + [C16:0] + [C17:0] + [C18:0] + [C20:0]); brackets indicate concentration.

[5] Total MUFA = ([C16:1] + [C18:1*cis*-9] + [C20:1]); brackets indicate concentration.

[6] Total PUFA = ([C18:2n-6] + [C18:3n-3] + [C18:3n-6] + [*c*9,*t*11] + [C20:2] + [C20:3n-3] + [C20:3n-6] + [C20:4n-6]); brackets indicate concentration.

[7] UFA:SFA = (total MUFA+PUFA)/total SFA.

[8] Calculated as IV = [C16:1] × 0.950 + [C18:1] × 0.860 + [C18:2] × 1.732 + [C18:3] × 2.616 + [C20:1] × 0.785 + [C20:4] × 3.201 + [C22:1] × 0.723 + [C22:5] × 3.697 + [C22:6] × 4.463; brackets indicate concentration.

[9] Effect of Cu within 92.5% SID Lys: $P = 0.042$.

[10] Effect of Cu within 85% SID Lys: $P = 0.031$.

[11] Effect of Cu within 100% SID Lys: $P = 0.070$.

[12] Effect of Cu within 100% SID Lys: $P = 0.004$.

[13] Effect of Cu within 85% SID Lys: $P < 0.089$.

Table 4-15. Effects of standardized ileal digestible (SID) lysine (Lys) and duration of feeding Cu on growth performance of finishing pigs, Exp.2[1]

SID Lys,[2] %	92.5				100.0							
Early added Cu[3]:	-	+	-	+	-	+	-	+				
Late added Cu[4]:	-	-	+	+	-	-	+	+		Probability, [5]$P <$		
Treatment:	A	B	C	D	E	F	G	H	SEM	Cu x SID Lys[6]	Cu[7]	SID Lys[8]
Weight, kg												
d 0	26.4	26.4	26.4	26.4	26.4	26.4	26.4	26.4	0.662	0.913	0.998	0.987
d 60	78.1	78.5	78.2	78.3	79.1	79.7	79.1	79.5	1.002	0.833	0.567	0.031
d 120	129.4	129.8	130.8	129.2	132.3	132.4	132.1	133.4	1.202	0.428	0.527	0.001
d 0 to 60												
ADG, kg	0.86	0.86	0.86	0.86	0.88	0.88	0.87	0.88	0.009	0.463	0.681	0.018
ADFI, kg	2.08	2.12	2.06	2.05	2.05	2.06	2.08	2.12	0.031	0.023	0.391	0.461
G:F	0.413	0.408	0.416	0.418	0.427	0.429	0.418	0.418	0.005	0.098	0.592	0.109
d 60 to 120												
ADG, kg	0.90	0.92	0.92	0.90	0.93	0.93	0.94	0.93	0.010	0.951	0.931	0.007
ADFI, kg	2.77	2.78	2.77	2.79	2.82	2.75	2.83	2.78	0.025	0.283	0.576	0.326
G:F	0.326	0.329	0.332	0.325	0.331	0.337	0.333	0.336	0.004	0.338	0.591	0.032
d 0 to 120												
ADG, kg	0.88	0.89	0.89	0.88	0.90	0.91	0.90	0.91	0.007	0.566	0.732	0.001
ADFI, kg	2.42	2.43	2.40	2.40	2.42	2.39	2.44	2.44	0.022	0.365	0.900	0.235
G:F	0.365	0.365	0.369	0.366	0.373	0.378	0.371	0.373	0.003	0.735	0.870	0.009
Caloric efficiency[9]												
ME	9.13	9.13	9.02	9.10	8.93	8.81	8.98	8.93	0.067	0.754	0.832	0.007
NE	6.83	6.83	6.74	6.80	6.64	6.55	6.68	6.65	0.050	0.740	0.829	0.001

[1] A total of 1,267 pigs (PIC 337 × 1050 PIC, Hendersonville, TN; initial BW = 26.4 ± 0.1 kg) were used in a 120 d study; 6 pens per treatment and 26 to 27 pigs per pen.

[2] SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production stage.

[3] 150 mg/kg copper from tribasic copper chloride (TBCC; Intellibond C; Micronutrients, Indianapolis, IN) fed from d 0 to 60.

[4] 150 mg/kg copper from TBCC fed from d 60 to 120.

[5] No Early Cu × Late Cu × SID Lys, Early Cu × SID Ly, Late Cu × SID Lys, or Early Cu × Late Cu interactions, or early Cu vs. late Cu main effects, were observed.

[6] Contrast between Treatments A and H vs. D and E.

[7] Contrast between Treatments A and E vs. D and H.

[8] Contrast between Treatments A and D vs. E and H.

[9] Caloric efficiencies were calculated by the following equation: sum of (ADFI × Mcal) ÷ (ADG) for each period.

Table 4-16. Effect of standardized ileal digestible (SID) lysine (Lys) and duration of feeding Cu on carcass characteristics of finishing pigs, Exp. 2[1]

SID Lys,[2] %	92.5				100.0							
Early added Cu[3]:	-	+	-	+	-	+	-	+				
Late added Cu[4]:	-	-	+	+	-	-	+	+		Probability,[5] $P <$		
Treatment:	A	B	C	D	E	F	G	H	SEM	Cu × SID Lys[6]	Cu[7]	SID Lys[8]
Carcass characteristics												
HCW, kg	97.8	99.1	99.9	100.3	100.5	100.8	100.2	101.1	0.99	0.244	0.076	0.043
Carcass yield,[9] %	75.06	76.11	75.74	76.74	75.89	75.35	75.60	75.76	0.383	0.022	0.048	0.847
Backfat,[10] mm.	18.4	18.0	17.2	17.3	16.9	17.1	18.2	18.1	0.48	0.011	0.780	0.279
Loin depth,[10] mm.	56.0	55.7	56.5	56.5	56.9	56.2	55.4	56.2	0.45	0.117	0.953	0.289
Lean,[10] %	55.78	55.56	56.53	56.51	56.97	56.26	55.42	56.29	0.450	0.115	0.953	0.286
Carcass performance												
HCW ADG,[11] kg	0.649	0.661	0.667	0.671	0.672	0.675	0.670	0.677	0.007	0.232	0.064	0.035
HCW G:F[12]	0.269	0.272	0.278	0.279	0.278	0.282	0.275	0.278	0.003	0.071	0.086	0.198

[1] A total of 1,267 pigs (PIC 337 × 1050 PIC, Hendersonville, TN; initial BW = 26.4 ± 0.1 kg) were used in a 120 d study; 6 pens per treatment and 26 to 27 pigs per pen.

[2] SID Lys values were based on 100% of the estimated SID Lys requirement for these pigs in this environment and production stage.

[3] 150 mg/kg copper from tribasic copper chloride (TBCC; Intellibond C; Micronutrients, Indianapolis, IN) fed from d 0 to 60.

[4] 150 mg/kg copper from TBCC fed from d 60 to 120.

[5] No Early Cu × Late Cu × SID Lys, Early Cu × SID Ly, Late Cu × SID Lys, or Early Cu × Late Cu interactions, or early Cu vs. late Cu main effects, were observed.

[6] Contrast between Treatments A and H vs. D and E.

[7] Contrast between Treatments A and E vs. D and H.

[8] Contrast between Treatments A and D vs. E and H.

[9] Carcass yield determined by dividing HCW at the plant by live BW at the farm prior to transport.

[10] HCW was used as a covariate.

[11] HCW ADG = (HCW – (d 0 wt. × 75% yield)) ÷ 120 d.

[12] HCW G:F = (HCW – (d 0 wt. × 75% yield)) ÷ (ADFI × 120 d).

Chapter 5 - Effect of diet type and added copper on growth performance, carcass characteristics, energy digestibility, gut morphology, and mucosal mRNA expression of finishing pigs

Abstract

A total of 757 pigs (PIC 337 × 1050; initially 27.6 ± 0.05 kg BW) were used in a 117-d experiment to determine the effects of added Cu (TBCC; tribasic copper chloride, IntelliBond C; Micronutrients, Inc., Indianapolis, IN) and diet type on growth performance, carcass characteristics, energy digestibility, gut morphology, and mucosal mRNA expression of finishing pigs. Pens of pigs were allotted to 1 of 4 dietary treatments, balanced on average pen weight in a randomized-complete block design with 26 to 28 pigs per pen and 7 replications per treatment. Treatments were arranged in a 2 × 2 factorial arrangement with main effects of diet type, a corn-soybean meal-based diet (corn-soy) or a high byproduct diet (byproduct) with 30% distillers dried grains with solubles (DDGS) and 15% bakery meal, and added Cu (0 or 150 mg/kg added Cu). There were no Cu × diet type interactions for growth performance. Overall, neither added Cu nor diet type influenced growth performance. However, caloric efficiency was decreased (P = 0.001) for pigs fed the byproduct diet compared to the corn-soy diet. Pigs fed the byproduct diet had decreased carcass yield (P = 0.007) and HCW G:F (P = 0.011), and tended to have decreased HCW (P = 0.067) and HCW ADG (P = 0.056) compared to pigs fed the corn-soy diet. A Cu × diet type interaction ($P < 0.05$) existed for DM and GE digestibility during the early finishing period as added Cu improved digestibility of DM and GE in the corn-soy diet, but not in the byproduct diet. During the late finishing period, added Cu increased DM and GE digestibility (P = 0.060) while pigs fed the byproduct diet had decreased DM and GE digestibility (P = 0.001) compared to those fed the corn-soy diet. For gut morphology, pigs fed added Cu had decreased crypt depth ($P = 0.017$) in the distal small intestine compared to those fed no added Cu. Furthermore, relative mRNA expression of intestinal fatty acid binding protein (*iFABP*) was decreased ($P = 0.032$) in pigs fed added Cu compared to those fed no added Cu. In summary, adding 150 mg/kg added Cu or including 30% DDGS and 15% bakery meal into a corn-soy diet did not influence growth performance. However, HCW ADG and HCW G:F was reduced in pigs fed the byproduct diet compared to the corn-soy diet. Only minor differences in gut morphology or mRNA expression were observed from feed diets with high levels of Cu or byproducts compared to a corn-soybean meal-based diet.

Key Words: byproducts, copper, finishing pigs, gene expression, glucagon-like peptide 1

Introduction

For many years, copper (Cu) has been supplemented in nursery and early finishing diets to improve growth performance. While feeding high levels of Cu has been shown to improve growth, the duration and degree of response has not always been consistent. Research has typically shown that added Cu impacts growth the most during the early finishing period but not late finishing period, but the response is variable (Davis et al., 2002; Hastad, 2002). Recently, Coble et al. (2014) reported that adding 150 mg/kg Cu in finishing diets tended to increase ADFI and G:F during the late finishing period.

It has been postulated that the growth-promoting effects of Cu are partly due to its impact on tissue repair in the small intestine and its ability to stimulate the synthesis of digestive enzymes, resulting in a better digestion and absorption of nutrients (Hedemann et al., 2006). Lou and Dove (1996) report that nursery pigs fed 250 mg/kg Cu had improved fat digestibility. Rochell et al. (2015) reported an improvement in AA digestibility in low Lys diets with added

Cu in chicks, and Gonzales-Eguia et al. (2009) reported an improvement in OM and fat digestibility with added Cu in 30 to 60 kg growing pigs. Although the strategies for using Cu have not changed much over the years, the types of diets that are used in commercial production are different in ingredient composition from diets utilized in the original research with Cu. It has yet to be investigated if ingredient usage and diet formulation are an important factor to consider when adding Cu to improve growth performance. As a result, this study sought to investigate possible response criteria to potentially explain addition ways copper can improve growth. Therefore, the objective of this study was to determine the effects of added Cu and diet type on growth performance, carcass characteristics, energy digestibility, gut morphology, and mucosal gene expression of finishing pigs.

Material and Methods

All experimental procedures and animal care were approved by the Kansas State University Institutional Animal Care and Use Committee.

General

The experiment was conducted in a commercial research facility in southwestern Minnesota. The facility was double-curtain sided with completely slatted concrete flooring. The barn contained 48 pens (3.05 m × 5.49 m), with 26 to 28 pigs (similar number of barrows and gilts) in each, equipped with a 4-hole conventional dry self-feeder (Thorp Equipment, Thorp, WI) and a cup waterer providing ad libitum access to feed and water. A computerized feeding system (FeedPro; Feedlogic Corp., Willmar, MN) delivered and recorded daily feed additions of specific diets to each pen.

Animals and Diets

A total of 757 pigs (PIC 337 × 1050; PIC, Hendersonville, TN; initially 27.6 ± 0.1 kg BW) were used in a 117-d experiment. Before d 0, all pigs were fed a common diet with 205 mg/kg Cu from tribasic copper chloride (TBCC, Intellibond C; Micronutrients, Inc., Indianapolis, IN). On d 0, pens of pigs were weighed, ranked by average pen BW, and allotted to 1 of 4 dietary treatments in a 2 × 2 factorial arrangement with average pig BW balanced across each treatment. There were 7 replications per treatment. Treatments included 2 diet types, a corn-soybean meal-based diet (corn-soy) or a high byproduct diet with 30% distillers grain with solubles (DDGS) and 15% bakery meal (byproduct), and 2 levels of added Cu (0 or 150 mg/kg; Tables 5-1 to 5-3).

All diets contained a basal level of 17 mg/kg added Cu from $CuSO_4$ provided by the trace mineral premix. Treatment diets were fed in 5 dietary phases in meal form and formulated on a standardized ileal digestible (SID) Lys basis to meet or exceed requirements (NRC, 2012). Diets were balanced on a SID Lys:NE ratio across all treatments within phase to insure Lys was not a limiting factor for growth. Nutrient values for the ingredients were based on the NRC (2012), with the exception of the DDGS. The NE value (2,634 kcal/kg) for DDGS were calculated based upon the oil content, as described by Graham et al. (2014a). Treatment diets were collected from each treatment during each phase from multiple feeders 2 d after the beginning of a phase and 2 d before ending a phase. The 2 samples were combined to form a composite sample for each treatment within each phase and analyzed, in duplicate, for DM (930.15, AOAC International, 2000), CP (990.03, AOAC International, 2000), NDF (Van Soest et al., 1991), crude fiber (978.10, AOAC International, 2000), crude fat (2003.05, AOAC International, 2000), Ash (942.05, AOAC International, 2000), Ca, P, and Cu (985.01, AOAC International, 2000) at a commercial laboratory (Cumberland Valley Analytical Services, Hagerstown, MD; Table 5-4).

Bulk density (mass per unit volume, g/L) was also measured for the complete feed with a grain density cup (Seedburo Model 8800; Seedburo Equipment, Chicago, IL).

Pens of pigs were weighed and feed disappearance was recorded approximately every 3 wk to determine ADG, ADFI, G:F, and caloric efficiency on and ME and NE basis. Caloric efficiency was calculated by dividing the sum of total feed intake and diet calorie content, by total gain. On d 94, the 3 heaviest pigs in each pen were weighed and sold according to standard farm procedures. These pigs were used in calculation of pen growth performance, but not carcass characteristics. Prior to marketing, the remaining pigs in the barn were individually tattooed with a pen identification number to allow for carcass measurements to be recorded on an individual basis. On d 117, final pen weights were taken and feed disappearance was recorded. A subsample of two gilts per pen, representing the mean individual weight of the pen, were transported 108 km to a commercial packing plant for processing, intestinal sampling, and data collection (Packing Plant #1; Natural Foods Holdings, Sioux Center, IA). All remaining pigs were transported 95 km on d 118 to a commercial packing plant (Packing Plant #2; JBS Swift and Company, Worthington, MN) for processing and carcass data collection. Hot carcass weight was measured immediately after evisceration and each carcass evaluated for carcass yield, backfat depth, loin depth, and percentage lean.

Carcass yield was calculated by dividing the HCW at the plant, by the live weight at the farm before transport. Fat depth and loin depth were measured with an optical probe inserted between the third and fourth last rib (counting from the ham end of the carcass) at a distance approximately 7 cm from the dorsal midline. An assumed yield of 75% was used to calculate initial HCW at the beginning of the experiment. Hot carcass weight ADG was calculated by subtracting initial HCW from the final HCW obtained at the plant, then divided by 117 d on test.

Hot carcass weight G:F was calculated by dividing HCW gain by feed intake over the 117 d experiment.

Gross Energy Digestibility

Feed and fecal grab samples were collected from each pen over a 2 d period during phases 2 (d 25 to 26) and 4 (d 74 and 75) to determine DE content of the experimental diets (Beaulieu et al., 2009). Acid insoluble ash (Celite 545, Univar Inc., Redmond, WA) was included in the diet at 1.0% for 9 d at the beginning of the phase 2 and 4 to allow for a 7 d adaptation period and 2 d collection period. Feed and fecal samples from each pen and day were dried at both 50°C and 100°C, using a two-step drying process. Samples across days within pen were then pooled together for a composite sample for analysis (Jang et al., 2014). To determine the acid insoluble ash content of the feed and feces, samples were heated to 600°C for 18 h, digested in 2 N HCL for 5 min, filtered, and heated again to 600°C for 18 h, as explained by Atkinson et al. (1984). Gross energy values for the feed and feces were determined by oxygen bomb calorimetry (Model 1341EB, Parr Instrument Company, Moline, IL), according to Galyean (2010). Dry matter and GE digestibilites were calculated using the index method, according to Adeola (2001), using the following equation where AIA is acid insoluble ash:

$$Digestibility, \% = 100 - \left[100 \times \left(\frac{\%\ AIA\ in\ feed\ \times \%\ component\ in\ feces}{\%\ AIA\ in\ feces\ \times \%\ component\ in\ feed}\right)\right]$$

Serum Collection and Protein Analysis

Prior to transportation to the packing plant #1, blood was collected from the 2 gilts identified to be subsampled for intestinal collection that represented the mean weight of the pen. Samples were collected via jugular venipuncture into sterile vacutainer tubes (Tyco Health Care Group LP, Mansfield, MA) and immediately placed on ice until processed. Whole blood was centrifuged (2,000 × *g* for 15 min at 4°C) and the serum removed and frozen at -80°C until analyzed. Mammalian specific ELISA kits (EMD Millipore Corp., Billerica, MA) were used to determine serum concentrations of glucagon-like peptide 1 (GLP-1; Cat. # EZGLP1T-36K) and glucagon-like peptide 2 (GLP-2;Cat. # EZGLP2-37-K). Prior to completing the assay, kits were validated for parallelism and recovery of added mass. Fluorescence was measured at 450 nm with a 96-well microplate spectrophotometer (Eon, BioTek, Winooski, VT). The limit of detection for GLP-1 and GLP-2 was 1.4 pM, and 0.562 ng/mL, respectively. For samples with values below the detectable limit, the lowest detectable limit was used for analysis.

Intestinal Collection

On d 117, tissue samples and mucosal scrapings were collected from the two, pre-identified gilts per pen that were identified for small intestinal (SI) mucosal gene expression and gut morphology at packing plant #1. Approximately 15 min after the pigs were slaughtered, the entire viscera was collected and segregated. The small intestine was dissected from the stomach 2 cm distal from the pyloric sphincter of the stomach and 2 cm proximal the ileocaecal junction. From each intestine, two, 5 cm samples were collected from the proximal (2 m from the proximal end of the SI-duodenum) and distal (2 m from the distal end of the SI-ileum) sections of the SI. A mucosal scrape was collected from one of the samples by using a sterile plastic slide to scrape the intestinal cells off the lining of the lumen. Scrapings were placed in a sterile Whirl-Pak bag (Fisher Scientific), and snap chilled and stored in liquid N until all samples were collected. These samples were utilized for mRNA analysis and were maintained at -80°C until analysis. To preserve samples for histological analysis, samples were placed in 4% formaldehyde solution in a 50 mL conical tube for transport back to Kansas State University.

Small Intestine Histology

Approximately 48 h after samples were placed in the formaldehyde solution, samples were embedded in paraffin and 4 µm cross sections were cut and stained with hematoxalin and eosin (H & E) for histological examination of gut morphology, as described by Hedemann et al. (2006). Measurements included villus height, crypt depth, and villus height to crypt depth ratio. Slides were viewed using a Nikon Eclipse TI-U inverted microscope with 4× working distance magnification (Nikon Instruments Inc., Melville, NY). Villus height and crypt depth were measured using NIS Elements Imaging Software (Basic Research, 3.3; Nikon Instruments Inc.) and calibrated to the 4× objective. Measurements were recorded in µm and determined in real-time.

Ileal Mucosal Gene Expression

Ileal mucosal RNA was isolated and transcribed to cDNA as described by Gonzalez et al. (2014) and Paulk et al. (2015). Five nanogram equivalents of total RNA were amplified with gene-specific primers (Table 5-5), DNA polymerase, and SYBR green chemistry (Perfecta Sybr fast mix; Quanta Biosciences, Gaithersburg, MD) in a Realplex^2 S PCR System (Eppendorf North America, Hauppauge, NY). Thermal cycling parameters included an initial heating step of 50°C for 2 min and an initial denaturing step of 95°C for 10 min, followed by 50 cycles of 15 s at 95°C, an annealing step for 30 s at the appropriate temperature for each primer, and an extension step of 20 s at 68°C. A final dissociation step was included at 95°C for 15 s followed by annealing at 60°C for 15 s. Melting temperature analysis was then conducted between 60 and 95°C using a 20 min ramp time and continuous fluorescence detection to determine primer specificity for each reaction. Normalized expression (ΔCt) for each sample was determined using the *Ribosomal protein L4 (**RPL4**)* as an endogenous gene. Relative gene expression levels were calculated as $2^{-\Delta\Delta Ct}$, where ΔΔCt represents ΔCt sample – ΔCt calibrator, where a pooled sample representing all treatment groups served as the calibrator sample (Livak and Schmittgen, 2001).

Statistical Analysis

Experimental data were analyzed in a randomized complete-block design using the PROC MIXED procedure in SAS (SAS Institute Inc., Cary, NC) with pen serving as the experimental unit and initial BW serving as the blocking factor. The random effect of pen within treatment was included in the model when multiple observations were collected within an experimental unit (pen). Contrasts were used to evaluate the interaction between added Cu and diet type and main effects of added Cu or diet type. Residual assumptions were checked using standard diagnostics on studentized residuals. The assumptions were reasonable met with the exception of gene expression data. For the gene expression criteria, the values were ranked using the PROC RANK procedure prior to analysis. Degrees of freedom were estimated using the Kenward-Roger's approach. Backfat depth, loin depth, and lean percentage were adjusted to a common hot carcass weight. Results from the experiment were considered significant and $P \leq 0.05$ and a tendency between $P > 0.05$ and $P \leq 0.10$.

Results and Discussion

Chemical Analysis

The chemical analyses of the complete diets were similar to the intended formulation (Table 5-4). The addition of 30% DDGS and 15% bakery meal increased the CP, NDF, crude fiber, ether extract, and ash concentrations in the byproduct diet compared to the corn-soybean meal-based diet as anticipated. Total Ca and P levels were similar between diet types across each dietary phase. The total analyzed Cu levels ranged from 30 to 58 mg/kg in the diets without added Cu, and ranged from 159 to 211 mg/kg for the diets with 150 mg/kg added Cu. These values are within the acceptable analytical limits according to the Association of American Feed Control Officials (AFFCO, 2014), given 17 mg/kg of Cu was provided by the trace mineral premix and the Cu provided by that of the ingredients used in formulation. For diet characteristics, the byproduct diet decreased bulk density of the diet by an average of 7.4% compared to the corn-soy diet, which is similar to others whom fed diets containing 30% or more of byproduct ingredients (Wang et al., 2007, Asmus et al., 2014).

Growth Performance

Added Cu effects. During the early finishing period (d 0 to 45), there were no Cu × diet type interactions. Feeding pigs 150 mg/kg added Cu tended to increase ADG ($P = 0.076$) by 2.4% compared to pigs fed no added Cu (Table 5-6). During the late finishing period (d 45 to 117), diet type tended to influence the response to Cu for G:F (Cu × diet type interaction, $P = 0.060$). This was the result of a decrease in G:F for pigs fed the byproduct diet compared to the corn-soy diet when added Cu was fed, while pigs fed no added Cu had a slight increase in G:F when fed the byproduct diet compared to the corn-soy diet. Overall (d 0 to 117) added Cu did not influence growth performance.

The magnitude of increase for ADG during the early finishing period in the current study has been consistently observed in other experiments with similar levels of added Cu. Furthermore, Davis et al. (2002) and Coble et al. (2015) observed that feeding 175 mg/kg or 150 mg/kg added Cu increased overall ADG by 3 to 6%. However, the current study was unable to demonstrate an overall growth response to added Cu. Even with the numerous studies that have shown positive responses with added Cu during the finishing stage; other work has shown no evidence of an effect (Lauridsen et al., 1999). The lack of replication, small sample size of pigs, and individual housing could have been contributing factors for not observing a response to Cu. Furthermore, the G:F interaction during the late finishing period is partly due to the numerical increase in ADFI with added Cu in the byproduct diet without an increase in ADG.

Diet Type effects. From d 0 to 45, pigs fed the byproduct diet had decreased BW on d 45 (P = 0.004) in response to a 3.5% decrease in ADG (P = 0.001) and 7.5% decrease in ADFI (P = 0.009) compared to the corn-soy diet. However, from d 45 to 117 and overall, growth performance and final BW were not influenced by diet type. The reduction in growth performance during the early finishing period was not surprising and is consistent with others whom have fed high-fiber, byproduct diets not equalized for dietary energy. Coble et al. (2015) reported that G:F was reduced by 2.3% over the entire finishing period for pigs fed a byproduct diet, containing the same amounts of bakery meal and DDGS as the current study, compared to a corn-soy diet as a result of the lower amount of NE in the byproduct diet. Salyer et al. (2012) reported that increasing the amount of wheat middlings from 0 to 20%, in diets containing 30% DDGS decreased ADG by 4%. Furthermore, Paulk et al. (2012) reported that ADG decreased as bakery meal increased from 0 to 15% in diets containing 15 to 50% DDGS.

Although in our study, overall growth performance was not affected by diet type, caloric efficiency was worse ($P < 0.05$) for pigs fed the byproduct diet compared to the corn-soy diet as they required more Mcal of energy per kg of gain on both an ME and NE basis. This is partly due to both the numerical reduction in G:F for pigs fed the byproduct diet compared to the corn-soy diet, as well as the potential overvaluing of the energy content of either the DDGS, bakery meal, or both, during formulation. To predict the energy content of the DDGS, an equation from Graham et al. (2014a) was used to determine the NE based on oil content. However, the ME and NE values for bakery meal are variable, as reflected by the NRC (2012) which reported nutrient values for bakery meal that were determined from 1 observation. This is further supported by the fact that research published after the NRC (2012), reported the ME value for bakery meal was 600 kcal/kg less than the NRC (2012) value (Rojas et al., 2013). Therefore, these data highlight the need for more research to determine the energy value for bakery meal.

Diet Digestibility

Diet type influenced the response to Cu (Cu × diet type interaction, $P < 0.05$) for both DM and GE digestibility during early finishing (Table 5-7). Pigs fed the byproduct diet had a greater decrease in DM and GE digestibility compared to the corn-soy diet when Cu was added in the diet, compared to when Cu was not added to the diet. Despite the interaction, pigs fed the byproduct diet had decreased ($P < 0.05$) DM and GE digestibility compared to pigs fed the corn-soy diet during the early and late finishing periods. However, adding Cu tended to increase the digestibility of DM ($P = 0.060$) and GE ($P = 0.003$) whereas adding Cu improved GE digestibility in pigs by 2.3% compared to pigs not fed added Cu.

Due to the differences in growth response previously seen from added Cu in early and late finishing, the two different time points for GE and DM digestibility were measured in this study. In understanding how Cu can affect diet digestibility, research has suggested that Cu potentially improves fat digestibility (Dove and Haydon, 1992). Dove (1995) reported that weanling pigs fed 5% added fat had greater improvements in ADG when 250 mg/kg added Cu from CuSO4 was included in the diet compared to diets without added Cu. The improvement was possibly the result of increased intestinal lipase and phospholipase activity (Lou and Dove, 1996).

Although added Cu influenced the response for DM and GE digestibility and G:F between the two diet types, no biological explanation exists to describe the response. Importantly though, the current experiment was successful at demonstrating the potential for Cu to improve

GE digestibility in a higher total dietary fat diet containing byproducts. This could possibly explain the improvement Davis et al. (2002) observed for G:F in both the early and late finishing periods with added Cu, as their diets contained 4% added fat. While our diets did not contain added fat, the high byproduct diet had approximately 2.5% higher crude fat compared to the corn-soybean meal diet. However, because of the inconsistency in response between phases, more research is needed to clarify how Cu may impact fat digestibility in finishing swine and whether the response is different for fat contributed from within the basal ingredients as compared to fat contributed from added oils or fat.

Although the potential for Cu to improve GE digestibility in finishing pigs is less known, the reduction in DM and GE digestibility for pigs fed a byproduct diet containing DDGS compared to those fed a corn-soy diet is more understood. Dietary fiber has been shown to decrease the digestibility of nutrients and energy (Degen et al., 2009; Urriola and Stein, 2010). Even though the byproduct diet contained more total energy and analyzed crude fat, the apparent digestibility of that energy is lower than that from a supplemental oil source (Kil et al., 2010; Kim et al., 2013). The ATTD of DM and GE for diets containing 30% DDGS has been reported to be decreased by at least 6% compared to diets without DDGS (Liu et al., 2012). The GE digestibility has also been shown to vary for DDGS based on oil content (Graham et al., 2014a). This is mainly due to the reduction in ATTD of the insoluble fiber in DDGS (Stein and Shurson, 2009). The impact of bakery meal in this diet and its contribution to the GE digestibility is less known, as previously stated, and more research is need to verify these results.

Carcass Characteristics

For carcass characteristics, pigs fed the byproduct diet compared to the corn-soy diet tended to have decreased HCW (*P* = 0.067), and a significant reduction in carcass yield (*P* = 0.007; Table 5-8). As a result of the decrease in HCW, HCW ADG also tended to decreased (*P* = 0.056) for pigs fed the byproduct diet compared to the corn-soy. The numerical reduction in G:F and significant reduction in carcass yield for pigs fed the byproduct diet compared to the corn-soy diet also led to a decrease in HCW G:F (*P* = 0.011) for pigs fed the byproduct diet compared to the corn-soy diet. Added Cu did not increase HCW or HCW ADG, which is not consistent with previous research completed by Coble et al. (2014). However, the reduction in HCW and carcass yield for pigs fed the byproduct diet compared to those fed the corn-soy diet is consistent with most published literature (Turlington, 1984; Asmus et al., 2014; Graham et al., 2014b). Byproduct ingredients generally contain high amounts of dietary fiber and have a low bulk density, which increases gut fill and weight in the large intestine (Turlington, 1984; Asmus et al., 2014; Coble, 2015).

Serum Concentrations of Metabolites

As a result of the variability in proposed modes of action for Cu, other areas of research have evolved to suggest that Cu may potentially be improving growth performance by acting on specific neurological pathways shown to be associated with feed intake. Yang et al. (2011) reported an increase in relative mRNA expression for growth hormone-releasing hormone (GhRH), which provides positive feedback to the hypothalamus to increase appetite. This increase in appetite comes as a result of increasing neuropeptide Y (NPY) concentration, a neurotransmitter in the brain that signals increased feed intake and also has been demonstrated to be increased as a result of feeding 250 mg/kg added Cu from $CuSO_4$ in swine (Li et al., 2008). In efforts to continue to expand our knowledge, we sought to investigate other areas of possible modes of action for Cu to increase feed intake that have been of high importance in human medicine.

Glucagon-like peptide 1 (GLP-1) is an incretin hormone that is released by the L-cells in the intestine in the response to food ingestion, stimulating insulin secretion (Keiffer and Habener, 1999) and as a result, therapeutic administration of GLP-1 has been an important therapy for type-2 diabetic patients. However, in addition to GLP-1 mediating glucose levels it also signals the brain to the slow the rate of digestion, and has been shown to directly influence feed intake (Tang-Christensen et al., 1996; Daily and Moran, 2013). In addition, GLP-2 is a hormone that is secreted in a 1 to 1 ratio with GLP-1, also from the L-cells in the intestine (Janssen et al., 2013). Glucagon-like peptide 2 has been shown to improve intestinal health through increasing the growth and functionality of mucosa in the small intestine (Janssen et al., 2013). Thymann et al. (2014) reported that pigs under low sanitary conditions had an increase in small intestine weight, villus height, and crypt depth when GLP-2 was administered.

In the current experiment, there was no evidence for a difference in serum concentrations of glucagon-like peptide-1 (GLP-1) or glucagon like peptide-2 (GLP-2; Table 5-9) between diet types or with added Cu. The concentration level of GLP-1 was greater than other reported values for pigs (Nagell et al., 2006); however, the circulating levels of GLP-2 were only slightly higher than those reported by Thymann et al. (2014; 1.54 ng/mL versus current experiment levels of 1.76 ng/mL). Factors that could have affected this could be that the current experiment measured the concentrations in serum versus plasma, the age of the pig, and time of collection. Both GLP-1 and GLP-2 have a relatively short half-life (7-17 min) after being released into the blood stream, and feed intake was not controlled across each animal since all pigs were allowed ab libitum intake.

Digestive Tract Morphology

Research has demonstrated that added Cu and diet type potentially impact gut morphology. Fry et al. (2012) reported that nursery pigs fed 225 mg/kg of added Cu in the form of $CuSO_4$ had reduced villus height in the duodenum and proximal jejunum compared to those fed no added Cu. However, they further reported that pigs fed 225 mg/kg of added Cu from TBCC did not have a difference in villus height when compared to pigs fed no added Cu. In our study, in the proximal section of the small intestine, neither villus height, crypt depth, nor villus height to crypt depth ratio were not influenced by added Cu or diet type (Table 5-10). In contrast, in the distal section of the small intestine, crypt depth was decreased in pigs fed added Cu compared to those not fed added Cu ($P = 0.017$). Hedemann et al. (2006) observed that 175 mg/kg added Cu from $CuSO_4$ also decreased crypt depth in both the proximal and distal small intestine, but no differences was observed from Radecki et al. (1992) who fed 250 mg/kg added Cu from $CuSO_4$. For diet type, Agyekum et al. (2012) reported that nursery pigs fed a diet containing 30% DDGS tended to have a decrease in villus height and villus height to crypt depth ratio.

Relative mRNA Gene Expression

In order to further investigate the different modes of action for Cu, the relative ileal mucosal mRNA expression of proteins involved with digestion were measured. In combination with the GE digestibility measurements and the results of Lou and Dove (1996), intestinal fatty acid binding protein (*iFABP*) mRNA expression was measured because of the importance it has on fatty acid transport across cell membranes. In addition to the serum concentration, *GLP-1R* mRNA expression was measured for the reasons mentioned previously. Furthermore, mRNA expression of an important protein involved in Cu transport across the cell wall, copper transporter protein-1 (*CTR1*) was also measured (Hill and Link, 2008).

For relative mucosal mRNA expression, there was no evidence for any diet type × Cu interactions for the measured genes in the proximal or distal small intestine (Table 5-11). Furthermore, there was no evidence of a difference for the relative mRNA expression of *iFABP, CTR1, or GLP-1R* in the mucosal layer of the proximal small intestine. However, relative mRNA expression of *iFABP* in the mucosal layer of the distal small intestine was decreased ($P = 0.032$) in pigs fed added Cu compared to those not fed added Cu. A decrease in *iFABP* of the distal small intestine mucosa of pigs fed added Cu would suggest that the gene responsible for *iFABP* transcription is possibly down regulated with added Cu. If fat digestibility is truly increased, we would expect this to be upregulated. No data is available to compare the results of the relative mRNA expression of *GLP-1* or *iFABP* in response to diet composition type or added Cu in finishing pigs; however, Fry et al. (2012) reported that 225 mg/kg added Cu in the form of either $CuSO_4$ or TBCC did not affect *CTR-1* mRNA expression in the liver of weanling pigs, similar to the current experiment.

In conclusion, adding 150 mg/kg Cu to the diet during the early finishing period tended to increase in ADG, but growth performance for the overall growth study was not influenced by added Cu. Pigs fed the byproduct diet compared to the corn-soy diet had decreased ADG and ADFI during the early finishing period, but diet type did not affect overall growth performance even though pigs fed the byproduct diet had a reduction in carcass yield and HCW. The changes in growth performance typically observed in finishing pigs fed added Cu does not appear to be related to the changes in serum metabolite profile for GLP-1 and GLP-2 concentrations or relative mRNA expression of *GLP-1R*, or *CTR1*. However, more research is need to clarify the impacts that added Cu has on DM and GE digestibility, especially since we observed that Cu influenced energy digestibility during the late finishing period.

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Table 5-1. Composition of diets for phases 1 and 2 (as-fed basis)[1]

	Phase 1		Phase 2	
Item Diet type:	Corn-soy	Byproduct	Corn-soy	Byproduct
Ingredient, %				
Corn	69.43	37.91	75.51	44.30
Soybean meal, 46.5% CP	27.83	14.19	21.88	7.92
Distillers dried grains with solubles	---	30.00	---	30.00
Bakery meal	---	15.00	---	15.00
Monocalcium P, 21% P	0.60	0.10	0.60	0.13
Limestone	1.25	1.55	1.13	1.40
Salt	0.35	0.35	0.35	0.35
Vitamin premix[2]	0.08	0.08	0.08	0.08
Trace mineral premix[3]	0.10	0.10	0.10	0.10
L-Lys HCl	0.225	0.560	0.238	0.575
DL-Met	0.075	0.020	0.055	---
L-Thr	0.055	0.100	0.050	0.095
L-Trp	---	0.032	0.001	0.041
Phytase[4]	0.013	0.013	0.013	0.013
TBCC[5]	±	±	±	±
Total	100.0	100.0	100.0	100.0
Calculated analysis				
Standardized ileal digestible (SID) Lys:NE, g/Mcal	4.29	4.29	3.67	3.67
SID AA, %				
Lys	1.050	1.105	0.912	0.958
Ile:Lys	65	59	63	56
Met:Lys	31	29	31	28
Met + Cys:Lys	56	56	56	56
Thr:Lys	62	62	62	62
Trp:Lys	19.7	19	19.0	19.0
Val:Lys	69	69	69	69
Total Lys, %	1.19	1.29	1.03	1.13
ME, kcal/kg	3,289	3,351	3,300	3,362
NE, kcal/kg	2,449	2,571	2,487	2,610
CP, %	19.0	21.1	16.6	18.6
Ca, %	0.66	0.66	0.59	0.59
P, %	0.51	0.49	0.48	0.46
Available P, %	0.36	0.36	0.35	0.35

[1] Phase 1 diet fed from d 0 to 21 and phase 2 fed from d 21 to 45; provided in meal form.

[2] Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D_3; 35,274 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 26 mg vitamin B_{12}.

[3] Provided per kilogram of premix: 17 g Mn from manganese oxide, 110 g Fe from ferrous sulfate, 110 g Zn from zinc oxide, 17 g Cu from copper sulfate, 331 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[4] Optiphos 2000 (Huvepharma, Sofia, Bulgaria) provided 1,102 phytase units (FTU)/kg, with a release of 0.10% available P.

[5] Tribasic copper chloride (Intellibond C, Micronutrients, Inc., Indianapolis, IN) provided 150 mg/kg Cu at the expense of corn.

Table 5-2. Composition of diets for phases 3 and 4 (as-fed basis)[1]

	Phase 3		Phase 4	
Item Diet type:	Corn-soy	Byproduct	Corn-soy	Byproduct
Ingredient, %				
Corn	79.76	47.27	83.32	47.36
Soybean meal, 46.5% CP	17.70	5.15	14.17	5.32
Distillers dried grains with solubles	---	30.00	---	30.00
Bakery meal	---	15.00	---	15.00
Monocalcium P, 21% P	0.65	0.13	0.60	0.08
Limestone	1.03	1.30	1.03	1.28
Salt	0.35	0.35	0.35	0.35
Vitamin premix[2]	0.08	0.08	0.08	0.08
Trace mineral premix[3]	0.10	0.10	0.10	0.10
L-Lys HCl	0.240	0.520	0.250	0.400
DL-Met	0.040	---	0.035	---
L-Thr	0.045	0.065	0.055	0.015
L-Trp	0.005	0.035	0.011	0.017
Phytase[4]	0.013	0.013	0.013	0.013
TBCC[5]	±	±	±	±
Total	100.0	100.0	100.0	100.0
Calculated analysis				
Standardized ileal digestible (SID) Lys:NE, g/Mcal	3.22	3.22	2.88	2.88
SID AA, %				
Lys	0.810	0.846	0.730	0.756
Ile:Lys	63	58	61	66
Met:Lys	30	31	31	34
Met + Cys:Lys	56	61	57	68
Thr:Lys	62	62	63	63
Trp:Lys	19.0	19.0	19.0	19.0
Val:Lys	69	73	69	82
Total Lys, %	0.92	1.01	0.83	0.93
ME, kcal/kg	3,305	3,366	3,311	3,369
NE, kcal/kg	2,511	2,627	2,533	2,628
CP, %	14.9	17.4	13.5	17.3
Ca, %	0.55	0.55	0.53	0.53
P, %	0.47	0.45	0.45	0.44
Available P, %	0.34	0.34	0.33	0.33

[1] Phase 3 diets fed from d 45 to 68 and phase 4 diets fed from d 68 to 94; provided in meal form.

[2] Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D_3; 35,274 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 26 mg vitamin B_{12}.

[3] Provided per kilogram of premix: 17 g Mn from manganese oxide, 110 g Fe from ferrous sulfate, 110 g Zn from zinc oxide, 17 g Cu from copper sulfate, 331 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[4] Optiphos 2000 (Huvepharma, Sofia, Bulgaria) provided 1,102 phytase units (FTU)/kg, with a release of 0.10% available P.

[5] Tribasic copper chloride (Intellibond C, Micronutrients, Inc., Indianapolis, IN) provided 150 mg/kg Cu and was added at the expense of corn.

Table 5-3. Composition of diets for phase 5 (as-fed basis)[1]

		Phase 5	
Item	Diet type:	Corn-soy	Byproduct
Ingredient, %			
Corn		86.10	47.45
Soybean meal, 46.5% CP		11.36	5.41
Distillers dried grains with solubles		---	30.00
Bakery meal		---	15.00
Monocalcium P, 21% P		0.65	0.05
Limestone		1.00	1.25
Salt		0.35	0.35
Vitamin premix[2]		0.08	0.08
Trace mineral premix[3]		0.10	0.10
L-Lys HCl		0.250	0.300
DL-Met		0.030	---
L-Thr		0.065	---
L-Trp		0.014	0.002
Phytase[4]		0.013	0.013
TBCC[5]		±	±
Total		100.0	100.0
Calculated analysis			
Standardized ileal digestible (SID) Lys:NE, g/Mcal		2.59	2.59
SID AA, %			
Lys		0.66	0.68
Ile:Lys		61	74
Met:Lys		31	38
Met + Cys:Lys		58	76
Thr:Lys		65	68
Trp:Lys		19.0	19.0
Val:Lys		69	91
Total Lys, %		0.75	0.85
ME, kcal/kg		3,314	3,369
NE, kcal/kg		2,551	2,628
CP, %		12.3	17.2
Ca, %		0.52	0.52
P, %		0.44	0.44
Available P, %		0.33	0.33

[1] Phase 5 diets fed from d 94 to 117, provided in meal form.

[2] Provided per kilogram of premix: 7,054,720 IU vitamin A; 1,102,300 IU vitamin D_3; 35,274 IU vitamin E; 3,527 mg vitamin K; 6,173 mg riboflavin; 22,046 mg pantothenic acid; 39,683 mg niacin; and 26 mg vitamin B_{12}.

[3] Provided per kilogram of premix: 17 g Mn from manganese oxide, 110 g Fe from ferrous sulfate, 110 g Zn from zinc oxide, 17 g Cu from copper sulfate, 331 mg I from ethylenediamine dihydroiodide, and 300 mg Se from sodium selenite.

[4] Optiphos 2000 (Huvepharma, Sofia, Bulgaria) provided 1,102 phytase units (FTU)/kg, with a release of 0.10% available P.

[5] Tribasic copper chloride (Intellibond C, Micronutrients, Inc., Indianapolis, IN) provided 150 mg/kg Cu and was added at the expense of corn.

Table 5-4. Chemical analysis of diets (as-fed)[1]

Added Cu,[2] mg/kg:	0		150	
Item Diet type:	Corn-soy	Byproduct	Corn-soy	Byproduct
Phase 2[3]				
DM, %	85.90	88.00	86.00	88.00
CP, %	15.98	18.30	15.74	18.48
NDF, %	6.61	14.87	8.00	15.05
Crude fiber, %	2.06	4.05	2.32	4.22
Ether extract, %	2.14	4.63	1.94	4.76
Ash, %	4.70	5.10	4.21	4.73
Ca, %	0.74	0.74	0.73	0.69
P, %	0.46	0.51	0.47	0.49
Cu, mg/kg	54	44	211	190
Bulk density, g/L	665	614	644	606
Phase 3				
DM, %	86.30	88.40	86.30	88.20
CP, %	13.81	16.53	13.72	15.88
NDF, %	6.82	15.20	7.25	14.02
Crude fiber, %	1.98	3.98	2.16	3.79
Ether extract, %	1.96	4.95	2.07	4.64
Ash, %	3.71	4.66	4.03	5.01
Ca, %	0.72	0.72	0.81	0.78
P, %	0.43	0.50	0.47	0.49
Cu, mg/kg	41	33	209	204
Bulk density, g/L	662	596	651	597
Phase 4				
DM, %	85.80	87.50	85.80	87.60
CP, %	11.50	15.93	12.70	15.94
NDF, %	8.24	14.70	9.87	14.37
Crude fiber, %	2.40	4.03	2.83	3.94
Ether extract, %	2.36	4.38	1.99	4.55
Ash, %	3.35	4.20	3.53	4.70
Ca, %	0.67	0.57	0.63	0.68
P, %	0.42	0.51	0.46	0.48
Cu, mg/kg	58	30	159	187
Bulk density, g/L	624	596	610	590
Phase 5				
DM, %	85.80	87.20	85.50	87.40
CP, %	11.93	15.52	11.54	15.47
NDF, %	7.89	14.04	7.35	14.95
Crude fiber, %	2.23	4.01	2.05	3.67
Ether extract, %	1.68	4.59	1.98	4.71
Ash, %	3.73	4.68	3.62	5.26
Ca, %	0.72	0.72	0.71	0.75
P, %	0.49	0.54	0.47	0.54
Cu, mg/kg	48	39	209	203
Bulk density, g/L	632	604	630	603

[1] Values represent means from one composite sample, analyzed in duplicate.

[2] Tribasic copper chloride (Intellibond C; Micronutrients, Inc., Indianapolis, IN).

[3] Phase 1 diets were not available for analysis.

Table 5-5. Sequences, annealing temperatures, amplicon length, and efficiency of primers used for real-time PCR quantification of gene expression

Item	Forward primer (5′ to 3′)	Reverse primer (5′ to 3′)	T_m,[1] °C	Amplicon length	Efficiency
Small intestine genes					
Copper transport protein -1	CCATGATGATGCCTATGACCTT	ATAGAACATGGCTAGTAAAAACACC	60.5	131	1.12
Glucan-like peptide-1	TACTTCTGGCTGCTGGTGGAG	ACCCCAGCCTATGCTCAGGTA	62.4	104	1.11
Intestinal fatty acid binding protein	CCTCGCAGACGGAACTGAAC	GTCTGGACCATTTCATCCCCG	64.5	135	1.03
Normalizing gene					
Ribosomal protein L4	AGGAGGCTGTTCTGCTTCTG	TCCAGGGATGTTTCTGAAGG	60.5	184	1.06

[1] T_m = melting temperature

Table 5-6. Effect of added Cu and diet type on growth performance of finishing pigs[1]

Added Cu,[2] mg/kg:	0		150			Probability, $P <$		
Diet type:	Corn-soy	Byproduct[3]	Corn-soy	Byproduct[3]	SEM	Cu × Diet type	Cu	Diet type
BW, kg								
d 0	27.6	27.6	27.6	27.6	0.63	1.000	0.954	0.988
d 45	65.6	64.0	66.3	64.9	1.02	0.776	0.082	0.004
d 117	125.4	125.6	127.7	126.1	1.42	0.419	0.237	0.567
d 0 to 45								
ADG, kg	0.84	0.81	0.86	0.83	0.012	0.874	0.076	0.001
ADFI, kg	1.70	1.67	1.76	1.68	0.029	0.221	0.114	0.009
G:F	0.497	0.483	0.490	0.493	0.006	0.147	0.771	0.303
d 45 to 117								
ADG, kg	0.85	0.87	0.88	0.87	0.015	0.207	0.504	0.551
ADFI, kg	2.68	2.72	2.70	2.75	0.039	0.881	0.519	0.224
G:F	0.318	0.321	0.324	0.315	0.004	0.060	0.946	0.414
d 0 to 117								
ADG, kg	0.85	0.85	0.87	0.85	0.010	0.311	0.191	0.269
ADFI, kg	2.29	2.31	2.32	2.32	0.029	0.814	0.376	0.824
G:F	0.370	0.368	0.374	0.366	0.003	0.356	0.705	0.114
Caloric efficiency[4]								
ME	8.94	9.16	8.84	9.20	0.084	0.345	0.720	0.001
NE	6.80	7.13	6.72	7.16	0.064	0.346	0.723	0.001

[1] A total of 757 pigs (PIC 337 × 1050; initially 27.6 ± 0.05 kg BW) were used in a 117-d experiment with 26 to 28 pigs per pen and 7 replications per treatment.

[2] Tri-basic copper chloride (TBCC; Intellibond C; Micronutrients, Indianapolis, IN).

[3] Refers to a diet containing 30% distillers dried grains with solubles (DDGS) and 15% bakery meal.

[4] Caloric efficiency is expressed as kcal of intake per kg of live weight gain.

Table 5-7. Effect of added Cu and diet type on DM and GE digestibility of finishing pigs, %[1]

Added Cu,[2] mg/kg:	0		150			Probability, $P <$		
Diet type:	Corn-soy	Byproduct[3]	Corn-soy	Byproduct[3]	SEM	Cu × Diet type	Cu	Diet type
Phase 2 digestibility[4]								
DM	94.31	92.09	95.02	91.45	0.306	0.029	0.906	0.001
GE	81.67	75.96	83.57	71.16	1.110	0.005	0.187	0.001
Phase 4 digestibility[5]								
DM	95.72	93.14	96.47	93.46	0.280	0.435	0.060	0.001
GE	85.97	77.88	88.11	80.32	0.676	0.832	0.003	0.001

[1] A total of 757 pigs (PIC 337 × 1050; initially 27.6 ± 0.05 kg BW) were used in a 117-d experiment with 26 to 28 pigs per pen and 7 replications per treatment.

[2] Tri-basic copper chloride (TBCC; Intellibond C; Micronutrients, Indianapolis, IN).

[3] Refers to a diet containing 30% DDGS and 15% bakery meal.

[4] Phase 2 fecal samples collected over a 2 d period from d 25 to 26.

[5] Phase 4 fecal samples collected over a 2 d period from d 74 to 75.

Table 5-8. Effect of added Cu and diet type on carcass characteristics of finishing pigs[1]

Added Cu,[2] mg/kg:	0		150			Probability, $P <$		
Diet type:	Corn-soy	Byproduct[3]	Corn-soy	Byproduct[3]	SEM	Cu × Diet type	Cu	Diet type
Carcass characteristics								
HCW, kg	93.8	92.1	95.4	93.2	1.21	0.776	0.195	0.067
Carcass yield, %	74.28	73.12	74.37	73.26	0.370	0.953	0.752	0.007
Backfat depth,[4] mm	18.7	18.1	18.7	18.1	0.44	0.910	0.951	0.192
Loin depth,[4] mm	66.7	63.7	65.3	65.9	1.14	0.135	0.719	0.349
Lean,[4] %	55.48	55.50	55.24	55.76	0.282	0.389	0.900	0.435
Carcass performance								
HCW ADG, kg	0.63	0.61	0.64	0.62	0.009	0.766	0.173	0.056
HCW G:F	0.272	0.265	0.275	0.267	0.003	0.910	0.432	0.011

[1] A total of 757 pigs (PIC 337 × 1050; initially 27.6 ± 0.05 kg BW) were used in a 117-d experiment with 26 to 28 pigs per pen and 7 replications per treatment.

[2] Tri-basic copper chloride (TBCC; Intellibond C; Micronutrients, Indianapolis, IN).

[3] Refers to a diet containing 30% distillers dried grains with solubles (DDGS) and 15% bakery meal.

[4] Hot carcass weight was used as a covariate.

Table 5-9. Effect of added Cu and diet type on serum glucagon-like peptide 1 (GLP-1) and 2 (GLP-2) concentrations of finishing pigs[1]

Added Cu,[2] mg/kg:	0		150			Probability, *P* <		
Diet type:	Corn-soy	Byproduct[3]	Corn-soy	Byproduct[3]	SEM	Cu × Diet type	Cu	Diet type
Serum Concentrations								
GLP-1, pM	12.97	14.07	14.54	12.24	2.659	0.530	0.960	0.825
GLP-2, ng/mL	1.92	1.67	1.78	1.68	0.354	0.831	0.854	0.616

[1] A total of 84 pigs (PIC 337 × 1050; initially 27.6 ± 0.05 kg BW) were used in a 117-d experiment with 2 pigs per pen and 7 replications per treatment.

[2] Tri-basic copper chloride (TBCC; Intellibond C; Micronutrients, Indianapolis, IN).

[3] Refers to a diet containing 30% distillers dried grains with solubles (DDGS) and 15% bakery meal.

Table 5-10. Effect of added Cu and diet type on small intestine (SI) villus height and crypt depth of finishing pigs, um[1]

Added Cu,[2] mg/kg:	0		150			Probability, *P* <		
Diet type:	Corn-soy	Byproduct[3]	Corn-soy	Byproduct[3]	SEM	Cu × Diet type	Cu	Diet type
Proximal SI								
Villus height	290	277	277	274	9.3	0.625	0.376	0.369
Crypt depth	244	244	214	221	16.7	0.843	0.102	0.874
Villus:crypt ratio	1.25	1.17	1.38	1.27	0.105	0.892	0.253	0.367
Distal SI								
Villus height	412	404	375	400	17.9	0.340	0.230	0.615
Crypt depth	227	223	202	212	7.6	0.330	0.017	0.683
Villus:crypt ratio	1.83	1.83	1.88	1.92	0.106	0.834	0.514	0.823

[1] A total of 84 pigs (PIC 337 × 1050; initially 27.6 ± 0.05 kg BW) were used in a 117-d experiment with 2 pigs per pen and 7 replications per treatment.

[2] Tri-basic copper chloride (TBCC; Intellibond C; Micronutrients, Indianapolis, IN).

[3] Refers to a diet containing 30% DDGS and 15% bakery meal.

Table 5-11. Effect of added Cu and diet type on relative mRNA gene expression of intestinal fatty acid binding protein (iFABP), copper transporter protein-1 (CTR1), and glucagon-like peptide 1 (GLP-1R) in the proximal and distal small intestinal of finishing pigs[1]

Added Cu,[2] mg/kg:	0		150			Probability, $P <$		
Diet type:	Corn-soy	Byproduct[3]	Corn-soy	Byproduct[3]	SEM	Cu × Diet type	Cu	Diet type
Proximal SI[4]								
iFABP	0.289	0.360	0.316	0.325	0.072	0.442	0.870	0.741
CTR1	0.591	0.601	0.661	0.528	0.130	0.363	0.882	0.457
GLP-1R	0.800	0.802	1.364	0.957	0.420	0.623	0.391	0.685
Distal SI								
iFABP	1.143	0.726	0.664	0.571	0.178	0.283	0.032	0.258
CTR1	1.189	0.995	1.028	1.151	0.198	0.713	0.813	0.634
GLP-1R	2.336	1.592	2.088	1.718	0.566	0.575	0.664	0.382

[1] A total of 84 pigs (PIC 337 × 1050; initially 27.6 ± 0.05 kg BW) were used in a 117-d experiment with 2 pigs per pen and 7 replications per treatment.

[2] Tri-basic copper chloride (TBCC; Intellibond C; Micronutrients, Indianapolis, IN).

[3] Refers to a diet containing 30% DDGS and 15% bakery meal.

[4] All values indicate relative expression of genes. Normalized expression (ΔCt) for each sample was determined using ribosomal protein L4 as an endogenous control gene. The average normalized expression of the pooled control sample was used as the calibrator to calculate relative gene expression. For each sample, relative expression was calculated as 2 –ΔΔCt, in which ΔΔCt represents ΔCt sample – ΔCt calibrator (Livak and Schmittgen, 2001).

Chapter 6 - Utilizing linear programming to determine pig flow in a commercial production system

Summary

The systematic approach to raising pigs in a multi-site production system, in terms of where the pigs are housed and how long they are fed, is generally called pig flow. This complex process is most often approached in a segmented fashion, not looking at all barns at the same time in relation to each other. Linear programming, the basis of most nutritional formulation packages and logistics services, provides a mathematical means for characterizing pig flow that allows a producer to look at the entire flow of pigs in a system at the same time. We describe a teaching model that provides the foundation to characterize pig flow in a commercial production system. The model is built in Excel ® and incorporates key components of production such as growth rate, mortality, stocking density, seasonality, packer grid pricing, and marketing. The results from this model are sound and applicable to production, proving this model behaves as expected. The generalizability of the model allows for the inclusion of more barns and a more precise measure of time, needed for direct application in a production system.

Key words: swine, pig flow, linear programming

Introduction

Nutritionists in the livestock industry have utilized linear programming to formulate least cost diets for over 40 years.[1-2] Linear programming is a computer modeling tool for solving optimization problems, such as profit maximization or loss minimization, for a wide array of agricultural, animal science and other areas of interest. A type of linear programming model, known as network flow models, is most often used to determine optimal pathways (e.g., transportation or supply) in a network for a flow of products between different nodes (e.g., producers, consumers, warehouses, barns) optimizing a given objective (e.g., least cost or shortest distance).[3] An area of swine production that can be characterized as a network flow is the movement or flow of pigs from one barn to another within a production system.

Few models have been developed to describe pig flow through a commercial swine production system and of those, to the author's knowledge, the majority have largely been centered upon production within sow farms; not the cycle for a pig from wean-to-market.[4] In addition, such models have not included production characteristics such as growth performance, stocking density, or multiple packer pricing grids. Incorporating these characteristics into a model that determines which barns pigs should be placed in, the duration of their stay, and the density at which they should be stocked could provide significant economic incentives for producers. Therefore, the purpose of this paper is to describe a production tool that can aid producers with decisions concerning pig flow within a swine production system. Specifically, the paper will examine the development of a network flow model for pigs in a swine production system, focusing on the cycle for a pig from wean-to-market. This teaching model will provide the fundamental structure for construction of a model for larger production systems.

Materials and Methods

The model structure follows that of a multi-product network flow over time, with a batch of pigs delivered from the sow farm serving as the product that moves through a designated swine operation. The logic of the model is similar to models examining product movements from manufacturing to distribution to consumers (or retail). The base model is built for a given swine operation with the objective to maximize profit. Temporal pathways, or arcs, in the network structure of the model are established by the length of stay at each barn, or node in the model.[5]

The model then determines the body weight of the pig at the end of each length of stay in a particular barn (i.e. nursery or finisher). In the empirical model developed here, the first stage of the model determines how different batches of pigs from sow farms are housed in 1 of 4 different nurseries for either 6, 7, or 8 weeks (Figure 1). A different ending weight corresponds with each length of stay. The second stage of the model determines which finisher barn pigs are placed in after the length of stay in the nursery is completed (Figure 2). At the finishing barn, the model endogenously determines stocking density by allowing the number of pigs placed in a barn to be determined by the model (Figure 3). The assumed weight gain over the length of time decreases as the number of pigs housed per barn increases.

For the empirical model developed here, a group of pigs has 1,092 different available pathways in the model that can be taken in order to maximize profit; however, the cost per lb of gain is also different for each pathway. Shorter time periods and higher stocking densities may be more profitable than longer periods of low stocking density; depending on the cost of production and marginal revenue per pig. For simplification and demonstration purposes, the time interval used in the model is a week. The mathematical model developed is general in nature and is easily expandable to different size swine operations and time intervals.

General Linear Programming Model Formulation

The mathematical structure of the model is described in Table 1. Decision variables are the decisions that the model changes to optimize the objective function. In this model, the objective function is margin over feed and facilities cost (MOFFC) and is maximized by deciding the number of pigs and durations they are housed in each barn. The majority of swine producers utilize MOFFC as a first-step financial calculation to determine net revenue. The decision variables are subject to a set of constraints which characterize the production system (i.e. number of pigs available, number of usable barns, etc.); and insures solutions are within limits set by the producer; and provides solutions that are plausible. The type of LP model developed is a mixed integer network flow linear programming. That is, some of the decision variables in the model are integer and some are binary.

The model structure provided in Table 1 was made generalizable to allow it to be easily scalable over space and time. The following sub-sections describe the development of the empirical model used to examine the general model formulation; plausibility in an empirical setting; and use for sensitivity analyses. The model was constructed in Excel(R) ® with a built-in user interface to allow for customization across production systems and provide a wide variety of sensitivity analysis.

Input Data and Model Parameters

Data for the empirical modeling exercise was collected from a large commercial production system located in southwest Minnesota that houses 52,000 sows and markets over 1 million pigs per year. This data was compiled to provide valid estimates of seasonality, growth rate, mortality, and stocking densities for pork production in the model. The batch size of 3,000 pigs per week used in the model is based on the average number of pigs weaned from a 6,000 head sow farm; similar to a single sow farm in the production system.

Growth Period Lengths and Seasonality

The different lengths of stay for the nursery periods (6, 7, or 8 weeks) and finishing periods (16, 17, or 18 weeks) were selected around average exit weights and time periods, relative to commercial production. To determine growth patterns and weight gain, growth data was used to create a growth curve using a non-linear mixed model and Gompertz function (Table 2).[6] Fluctuations in mortality and growth due to seasonality were also incorporated by summarizing over 3,700 barn close-outs from the last 4 years of production. Summarizing this data on a week-of-placement basis allowed the model to flow groups of pigs differently during certain times of year; allowing the producer to better understand how pig flow is influenced during different times of the year (i.e., summer vs. fall). Typically, the reduction in growth during the summer months due to heat stress causes barn space to be limited as pigs need more days to reach market weight or the producer is forced to market lighter pigs.

Stocking Density

To allow for the incorporation of different stocking densities, a weight:space ratio termed the k-factor is commonly used to describe the effects the stocking density has on ADG (Table 2).[7] Gonyou et al. (2006) suggested that a k-factor value below 0.0336 was associated with reduced ADG. In our model, when pigs are housed in a finisher facility (800 pigs per barn) at 9.27 ft^2 per pig and weigh on average 235 lb at the first marketing, the *k*-factor is 0.038; therefore, no decrease in ADG should be observed. However, if stocking density is increased (1,200 pigs) in the same barn to only allow 6.81 ft^2 per pig the k-factor is 0.025 and would be associated with a 7% reduction in ADG. A low, medium, and heavy stocking density with 600 to 800, 800 to 1000, and 1000 to 1200 pigs per barn was used, respectively, as the reduction in growth at each stocking density is dramatically different. However, ADG is not improved beyond the growth curve when the k-factor is greater than 0.0336.

Economics and Marketing Strategies

Because pen space becomes limited and the degree of variability in individual pig weight increases towards the end of a finishing period, producers will have multiple marketing events during one finishing turn in a barn. This model uses a marketing strategy consisting of 2 marketing events prior to the barn dump where the heaviest 15 percent of pigs in a barn are sold

4 weeks before the barn dump, followed by the next heaviest 15 percent sold 2 weeks before the full barn dump. All remaining pigs are sold at the end of the time horizon for the model and optimal lengths of stay at the finisher. No reduction in price was given to culls or light weight pigs at the end of a period. To determine the weight of the pigs at each cut, a normal distribution around the average barn weight was calculated using the K-State Swine Weight Variation Calculator, providing an approximate weight of the heaviest pigs at each cut.[8]

Accompanying the growth of the pigs is the marginal revenue and cost that each pig acquires. Marginal revenue is based on market price and the packing grid. Multiple packer grids were incorporated into the model to allow flexibility of determining pig flow based on which packing company the pigs are intended to be marketed to, as this could impact the solution. Marginal revenue was calculated for the weight gain at the nursery and for each cut at the finisher (Table 2).

Feed, facility, and mortality cost were subtracted from marginal revenue in order to determine the margin over feed and facility cost (MOFFC) at the nursery and finisher. An adjusted feed efficiency, according to Goodband et al. (2009), was used to calculate feed cost so that users could input their own feed efficiency information, increasing the flexibility of the model to be incorporated into a multitude of performance scenarios (Table 2).[9] Due to the large range in diet cost per ton between phases in the model, 3 different diet costs were used for each length of stay (6 week nursery turn = \$370.20/ton , 7 week nursery turn = \$354.00/ton, and 8 week nursery turn = \$ 343.20/ton; Table 3). The user also has the ability to change input pricing.

Overall diet cost in the finisher is fairly consistent in relation to nursery diet cost and well represented by a weighted diet cost. The biggest fluctuation in diet cost comes when producers decide to increase the length of the finishing period. Thus, an average diet cost from entry into the finisher until 250 lb ($245.00/ton) and from 250 lb to market ($235.00) is used in the model to calculate total feed cost during the finishing period (Table 3).

Facility cost per pig is used to determine housing cost. This cost typically includes rent or construction of the barn space, water, electricity, maintenance, and labor. This value can certainly change, but in the current model, $0.10 per pig space per day is utilized (Table 2). Mortality cost, however, tends to be determined differently across production systems. In this model, mortality cost is calculated by determining the feed and facility cost that a pig would accrue for half of a nursery or finishing turn; assuming half of the expected mortality occurs before the midpoint of the nursery or finishing point and the other half afterwards. For example, if nursery pigs were housed for 7 weeks and accrued a total input cost of $52.50 that included feed, facility, and the initial cost of the pig, it would be divided across the entire group of pigs for each pig lost. For a nursery group of 3,000 pigs with 2.0% mortality, the total number of pigs lost is 60. The total mortality cost accrued for the 60 pigs lost is the product of $52.50 and 60 pigs divided by 2, or $1,575. Thus, the morality cost per live pig moved out of the nursery is $0.54. This does not account for the lost opportunity or revenue potential from the pig. Weaned pig cost, feed, facility, and mortality costs are all subtracted from the marginal revenue to calculate MOFFC for pigs exiting a nursery. This same calculation is made for finishing pigs marketed at each cut and barn dump.

Building the LP model in Excel ®

The empirical model was developed using Microsoft Excel ® and was solved utilizing the Open Solver ® package available for download from OpenSolver.Org[11]. This solver package can analyze mixed integer linear programming models and handle models with a large number of constraints and decision variables. Given the software package does not provide any sensitivity analysis indicating the largest cost centers of production, sensitivity analyses were completed manually by sequentially solving the model to illustrate how the model solution changes as inputs change. For this model, we look at a flow of 7 batches of pigs (initial size 3,000 weaned pigs) through a production system, which results in a production time period of 33 weeks. Four separate nurseries and 10 separate finishing sites with 2 to 3 barns per site are used in the model. The 4 nurseries were constrained to a capacity of 6,000 pigs at any given time, while the finishing barns were constrained to house between 600 and 1200 pigs per barn. The model and overall structure as it was built in Excel ® is explained further in Appendix 1.

Results and Discussion

Baseline Model Results

The baseline empirical model was run with the input parameters presented in Table 3. These values were chosen based on prices and parameters that would follow a stable and moderate market. The objective function value for the baseline results for MOFFC was $547,568, which equated to $27.38 per pig (Table 4). The average weight of pigs marketed was 290.2 lb with an average nursery turn of 8 weeks and finishing turn of 17.5 weeks. Approximately 9% of the pigs were housed at a low stocking density, while 24% and 65% were housed at either a medium or high stocking density, respectively.

This is very similar to what would be found at an actual production system, with the exception of the percentage of pigs stocked at the low stocking density. Typically, producers inherently would not choose to stock at largely different densities in each barn. However, due to slight amounts of variation in weaned pigs per week from any given sow farm, a producer could certainly have a small amount of variation in stocking density. In the current model, the amount of variation may be inflated by the ranges in stocking density that were chosen for demonstration.

Sensitivity Analysis

Two sets of sensitivity analysis were completed to demonstrate the behavior of the model. Market price and feed cost were chosen as they have the largest impact on profitability. Table 6 shows the effects of changes in market prices on MOFFC when production costs remain constant. The range of \$0.25 to \$1.25 was chosen to demonstrate how the model works over a wide range of prices. When market price increases or decreases, MOFFC per pig responds in the same direction; such that pigs are worth \$0.25 per lb of carcass weight when the MOFFC per pig is (\$79.94), but pigs are worth \$1.50 per lb of carcass weight when the MOFFC per pig is \$145.91. When market price is low, the model chooses to place as many pigs as are available at a high stocking density, while still satisfying minimum capacity constraints for the barns. This flow results because the reduction in ADG from increased stocking density does not impact the overall MOFFC as much as the cost reduction from placing more pigs in a barn.

As price increases past the baseline value, pigs are moved from high stocking densities to medium and low stocking densities. As the value of the live gain increases, there is less savings associated with a high stocking density level. However, placing larger amounts of pigs in low stocking densities begins to become cost effective at prices that are not attainable in current market situations (other sensitivity not shown suggest this happens at prices greater than \$3.00 per lb of carcass). The length of stay for the pigs in the system is increased as well, with the nursery length increasing first and then the finishing period. This finding is most likely because the cost of retaining pigs in the nursery for an extended period of time is less expensive than in the finisher. This implies that a more comprehensive range of stocking density (>3) may be needed.

The other set of sensitivity analyses completed focused on feed costs, which generally accounts for up to 60 to 70% of the total cost of production. The values used are relative percentages of feed cost compared to that used in the base model. Not surprising, as feed cost increases, MOFFC decreases. Similar to decreasing market prices, as feed cost increases and MOFFC decreases, the average weight of pigs marketed reduced as a result of shorter finishing lengths. Also, because the cost of production increases with higher feed costs, the model adjusts by trying to decrease facility costs, placing more pigs at a higher stocking density level.

Conclusion

Overall Summary and Findings

The purpose of this paper was to describe a production tool that can aid producers with decisions concerning pig flow within a swine production system. This LP model developed was successful at describing the characteristics of pig flow through a commercial swine production system and is adaptable to a multitude of scenarios. Although the size and scope of the model is currently limited in Excel ®, the answers produced by OpenSolver provide a learning tool for giving general insight as to lengths of times pigs should be housed, the rate at which they should be stocked in a barn, and which barns in a system should be utilized in a multitude of economic scenarios. The general model framework provides the fundamental structure needed for engineering a much larger model capable of providing guidance for larger operations and different types of systems, which has not been done to the author’s knowledge.

Because of the generalizability of the model, it can easily be expandable over more space (increased numbers of pigs and barns) and time (days, weeks, and months). Potentially, other areas of interest such as health and transportation, as well as a more sophisticated approach to marketing and nutrition could be incorporated; however, this would need to de be completed using a more powerful software package.

Implications

- This teaching model is successful in determining pig flow through linear programming utilizing a multiproduct network flow over time.
- The fully functional teaching model gives insight into how the biggest influences on MOFFC impact pig flow and how pig flow should change to maximize profit of a swine production system.
- Market price and feed cost have a large impact on pig flow through changing MOFFC.
- The model allows the user to see the complexity within the operation and how flows may change.
- The model provides a decision tool for managers to help guide the flow decisions that help to maximize the return to the operation.
- Converting the model to more powerful software will allow the model to deal with scenarios with larger structures and greater number of variables (e.g. more barns, batches of pigs, and finer time scale).

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Table 6-1. General linear programming model formulation

Model Component	Equation	Purpose
Objective function: margin over feed and facility cost (MOFFC)	$\sum_{n}\sum_{b}\sum_{s}\beta y_{nbs}\,NR_s+\sum_{f}\sum_{n}\sum_{b}\sum_{s}\sum_{t}\sum_{q}X_{fnbstq}FR_{bstq}$	The sum of the total MOFFC from the nursery and the finishers for each pig going through the swine operation.
Constraints		
Nursery Capacity Constraint	$\sum_{\{(b,s):b\le k\le b+s-1\}} y_{nbs} \times \beta_{k}^{(1-\varphi_n)} \le c_n, \forall\,(k,n)$	Capacity constraint that determines the number of batches of pigs that can be housed in nursery n for week k. It also incorporates the expected mortality, φ, that would accompany the pigs in each time period s that includes week k.
Pathway Constraint	$\sum_{n}\sum_{s} y_{nbs} \le 1, \forall(b)$	Insures that two batches of pigs cannot take the same exact pathway.
Nursery Flow Constraint	$y_{nbs}\,(1-\varphi_n)^s = \sum_{f}\sum_{t}\sum_{q} X_{fnbstq}, \forall\,(n,b,s)$	Insures that pigs from nursery n and batch β housed for s weeks, minus the pigs lost due to mortality φ_n, are transported to finisher f.
Finisher Capacity Constraint	$\sum_{\{(b,s,t):b+s-1\le k\le b+s+t-1\}} X_{fnbstq}\left(1-\theta_f\right)^{(k-b-s+1)} \le d_f, \forall(f,n,t,q)$	Determines the number of pigs that can be housed at a finisher site f for each week k. It also incorporates the expected mortality θ_f that would accompany the pigs in each week over the time period t the pigs are at the finisher.
Stocking Density Constraint #1	$Z_{fnbstq}\left(min_q+1\right) \le X_{fnbstq} \le Z_{fnbstq}\left(max_q\right), \forall(f,n,b,s,t)$	Determines the minimum, min_q, and maximum, max_q, number of pigs, X_{fnbstq}, that can be put in a finisher barn at site f for each stocking density level q.
Stocking Density Constraint #2	$\sum_{q} Z_{fnbstq} = 1, \forall(f,n,b,s,t)$	Insures that a set of pigs flowing through a barn at finisher site f is stocked at a set density level q in the barn on the site.
Site Constraint	$\sum_{n}\sum_{b}\sum_{s}\sum_{t}\sum_{q} Z_{fnbstq} = \alpha_f, \forall(f)$	Insures the number of groups of pigs moving through the finisher site f is less than α, the absolute number of barns finisher site f has available. For example, the constraint ensures one cannot house

		pigs in 3 finishing barns on a site if there are only 2 available.
Demand Constraint	$\sum_{f}\sum_{n}\sum_{b}\sum_{s}\sum_{t}\sum_{q} \boldsymbol{x_{fnbstq}} \leq \boldsymbol{Demand}$	Pulls the pigs through the system to market. This constraint is important when net return is negative.
Non-Negativity Constraint	$\boldsymbol{X, y, Z \geq 0}$	Prohibits any of the decision variables from taking a negative value.
Integrality Constraint	$\boldsymbol{y, Z}$ ***must be Binary***	Insures the binary variables only take values of 0 or 1.

Decision variables and parameter definitions

b
n = Index for the set of batches from the sow farm;
s = Index for the set of nurseries;
k = Index for the set of weeks of stay options in the nursery;
f = Index for weeks of operation for the period if interest;
t = Index for the set of finisher sites;
q = Index for the length of stay at the finisher sites;
β_k = Index for the stocking density level at a finisher site (e.g. low, medium, high);
= Batch size of incoming pigs from the sow farm that is available to the system in
c_n week *k*;
φ_n = Parameter for the capacity of nursery *n*;
α = Parameter for the mortality rate in nursery *n*;
d_n = Parameter for the number of finishers at site *f*;
θ_f = Parameter for the capacity of finishers at site *f*;
y_{nbs} = Parameter for the mortality rate for finishers at site *f*;
Z_{fnbstq} = Binary variable indicating if pigs from batch *b* are put in nursery *n* for *s* weeks;
= Binary variable indicating if pigs from batch *b* from nursery *n* for *s* weeks are
X_{fnbstq} placed at finisher site *f* for *t* weeks at *q* stocking density level.
= Decision variable deciding the number of pigs at a finisher site *f* for *t* weeks
min_q and at *q* stocking density level from batch *b* from nursery *n* stocked for *s* weeks;
max_q = Minimum number of pigs allowed in a barn at *q* stocking density level;
NR_s = Maximum number of pigs allowed in a barn at *q* stocking density level;
FR_{stq} = Margin over feed and facility cost for a pig from a nursery housed for *s* weeks;
= Margin over feed and facility cost for a pig from a finisher staying *t* weeks at a stocking density *q* from a nursery where the pig stayed *s* weeks.

Table 6-2. Input equations used in empirical model development

Title	Equation	Source
Growth curve	$Weight, lb = 482.86e^{-e^{-\frac{(d-132.50)}{85.92}}}$*, where d is the day of age*	KSU Swine Research
***k*-factor**	$k = \frac{(Area, m^2 \; \times 0.0929 m/ft^2\;)}{(BW, lb^{0.667} \; \div \; 2.2046 \; lb/kg)}$	Gonyou et al., 2006[7]
***k*-factor reduction**	$If \; k < 0.0336, \% \; reduction \; in \; ADG = 817 \; \times k + 72.55$	Gonyou et al., 2006[7]
Marginal revenue	$= (final \; wt., lb \times carcass \; yield, \% \times carcass \; price, \$/lb) - (initial \; wt., lb \times 75\% \times \; carcass \; price, \$/lb)$	KSU Swine Research
Adjusted feed efficiency	$= input \; F{:}G + (initial \; input \; BW, lb - initial \; model \; BW, lb) \times 0.005 + (final \; input \; BW, lb - final \; model \; BW, lb) \times 0.005$	Goodband et al., 2009[9]
Nursery feed cost	$= (final \; BW, lb - initial \; BW, lb) \times adjusted \; F{:}G \times diet \; cost/lb$	KSU Swine Research
Finisher feed cost	$= (total \; feed \; to \; 250 \; lb \; \times early \; finishing \; diet \; cost) + (total \; feed \; from \; 250 \; lb \; to \; market \times late \; finishing \; diet \; cost)$	KSU Swine Research
Facility cost	$= Pig \; days \; \times \$0.10$	KSU Swine Research
Nursery MOFFC	*= marginal revenue – facility cost –feed cost –mortality cost – weaned pig cost*	KSU Swine Research
Finisher MOFFC	*= marginal revenue – facility cost – feed cost – mortality cost*	KSU Swine Research

Table 6-3. Parameters and input values for baseline empirical model

Parameter	Input value[1]
Market prices	
Weaned pig cost, $/pig	$33.20
Market price, $/lb carcass	$0.75
Diet cost, $/ton	
6 week nursery turn	$370.20
7 week nursery turn	$354.00
8 week nursery turn	$343.20
Early finishing	$245.00
Late finishing	$235.00
Feed efficiency	
Nursery F:G	1.68
Finishing F:G	2.89
Mortality, %	
Nursery	2.0%
Finishing	2.5%
Facility cost, $/pig space/day	$0.10
Initial start date of flow	January 1st

[1] Values above were chosen based on prices and parameters that would be seen in a stable and moderate market place, as well as characteristics of the commercial production system from which the model structure was developed.

Table 6-4. Baseline Model Results[1]

Batch	Finishing group	Nursery length, wk	Nursery #	Finisher length, wk	Finishing site #	Stocking density	# of pigs housed
1	A	8	2	17	10	Medium	801
1	B	8	2	17	8	High	1001
1	C	8	2	18	4	High	1130
2	A	8	1	17	8	Low	601
2	B	8	1	18	5	High	1200
2	C	8	1	18	4	High	1131
3	A	8	3	18	10	Medium	801
3	B	8	3	18	6	High	1130
3	C	8	3	17	1	High	1001
4	A	8	4	17	6	High	1131
4	B	8	4	18	2	High	1200
4	C	8	4	16	2	Low	601
5	A	8	1	18	7	Medium	801
5	B	8	1	18	5	High	1001
5	C	8	1	18	3	High	1130
6	A	8	4	18	10	High	1130
6	B	8	4	16	9	Medium	801
6	C	8	4	16	1	High	1001
7	A	8	3	18	9	Medium	801
7	B	8	3	18	7	High	1001
7	C	8	3	18	3	High	1130

[1] The objective function (margin over feed and facility cost; MOFFC) for the results above was $547,568 for the entire system, which equated to $27.38/pig or $7.08/cwt (initial flow of 21,000 pigs over a 33 week period with an initial weight of 12.5 lb). The average weight of marketed pigs was 290.2 lb.

Table 6-5. Effect of market price on margin over feed and facility cost (MOFFC), market weight, length of turn, and stocking density of finishing pigs[1]

Market price, $/lb carcass	$ 0.25	$ 0.50	$ 0.75[2]	$ 1.00	$ 1.25
Objective function MOFFC, $	$ (1,611,148)	$ (562,222)	$ 547,568	$ 1,703,339	$ 2,915,820
MOFFC, $/pig	$ (79.94)	$ (28.06)	$ 27.38	$ 85.18	$ 145.91
Average market wt., lb	257.3	270.2	290.2	291.6	301.3
Length of barn turn, wk					
Nursery	6	8	8	8	8
Finisher	16.00	16.00	17.47	17.52	18.00
Stocking density[3]					
Low	1	0	2	3	0
Medium	6	7	5	6	21
High	14	14	14	12	0

[1] All other cost and parameters were held constant with the baseline model

[2] Baseline model price.

[3] These values indicate the count or number of barns at each stocking density (Low = 600 to 800 pigs; Medium = 800 to 1,000 pigs; High = 1,000 to 1,200 pigs).

Table 6-6. **Effect of relative feed cost on margin of feed and facility cost (MOFFC), market weight, length of turn, and stocking density of finishing pigs[1]**

Relative feed cost, %	50%	75%	100%[2]	125%	150%
Objective function MOFFC, $	$ 1,509,966	$ 1,012,672	$ 547,568	$ 105,054	$ (329,193)
MOFFC, $/pig	$ 75.56	$ 50.64	$ 27.38	$ 5.24	$ (16.42)
Average market wt., lb	300.8	290.0	290.2	274.4	274.4
Length of barn turn, wk					
Nursery	8	8	8	8	8
Finisher	18.00	17.47	17.41	16	16
Stocking density[3]					
Low	0	2	2	0	1
Medium	20	6	5	7	6
High	1	13	14	14	14

[1] All other cost and parameters were held constant with the baseline model.

[2] Baseline model cost.

[3] These values indicate the count or number of barns at each stocking density (Low = 600 to 800 pigs; Medium = 800 to 1,000 pigs; High = 1,000 to 1,200 pigs).

Figure 6-1. Nursery flow diagram

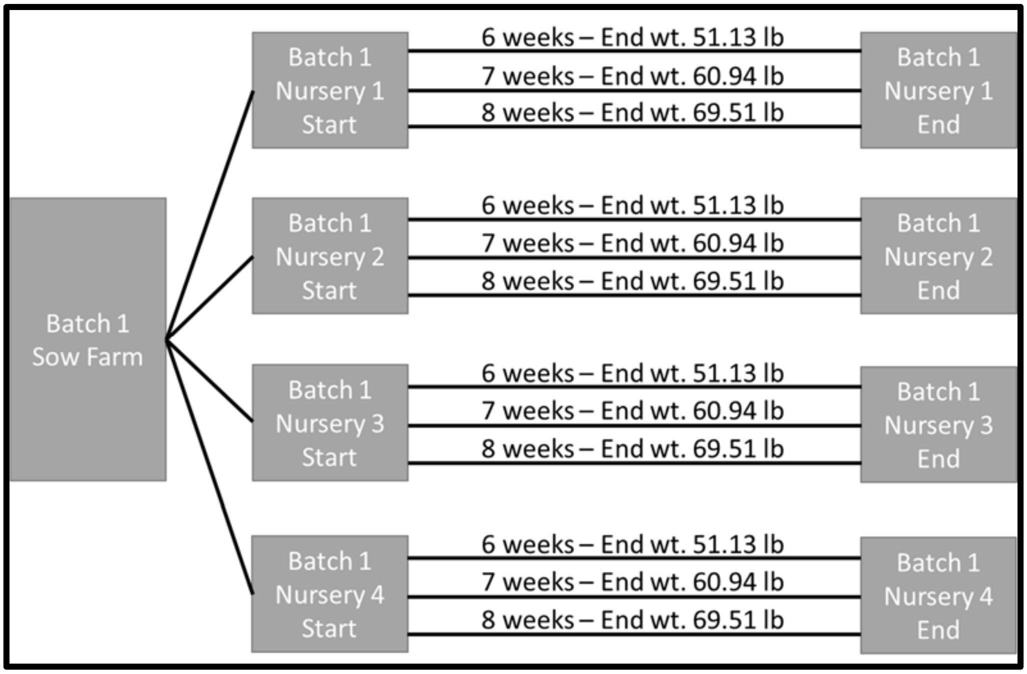


Figure 6-2. Finisher flow diagram

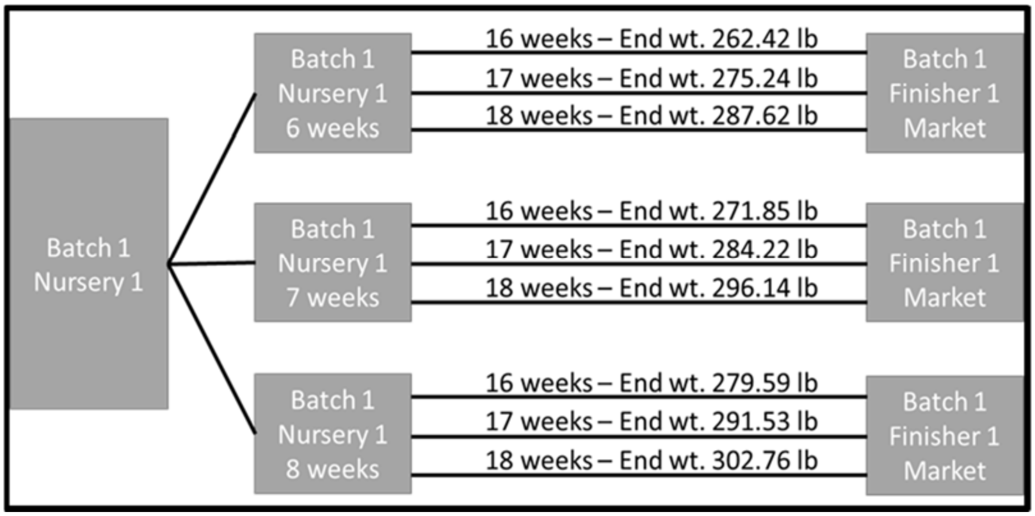
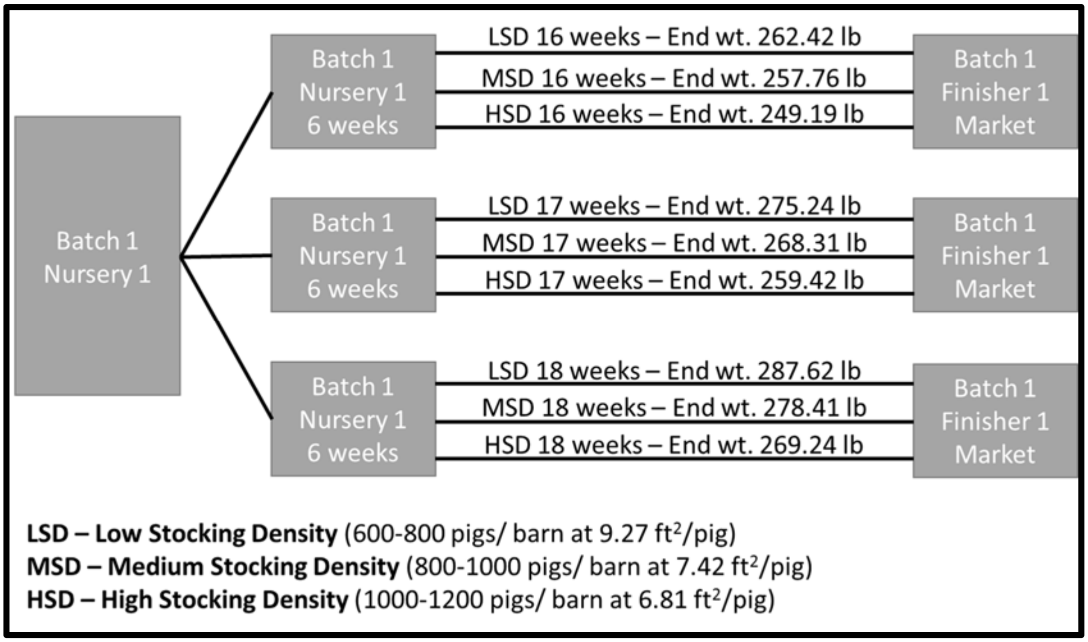


Figure 6-3. Stocking density flow diagram



Appendix A - Chapter 6: Utilizing Linear programming to determine pig flow in a commercial production system

Purpose

This appendix describes the layout of the model described in “Chapter 6 - Utilizing linear programming to determine pig flow in a commercial production system”.

Building the Model in Excel ®

The model using the mathematical structure and parameterization in Chapter 6 was developed using Microsoft Excel ® and was solved utilizing the Open Solver ® package available for download from OpenSolver.Org[11]. This solver package analyzes mixed integer linear programming models and can handle models with a large number of constraints and decision variables. Given the software package does not provide any sensitivity analysis indicating the largest cost centers of production, sensitivity analyses were completed manually by sequentially solving the model to illustrate how the model solution changes as inputs change. For this model, we look at a flow of 7 batches of pigs (initial size 3,000 piglets) through the system, over a production period of 33 weeks. Four separate nurseries and 10 separate finishing sites with 2 to 3 barns per site are used in the model. The 4 nurseries were constrained to a capacity of 6,000 pigs at any given time, while the finishing barns were constrained to house between 600 and 1200 pigs per barn. The following sections describe each part of the model and overall structure as it was built in Excel ®. These sections help identify each individual calculation in specific detail.

User Input Page

The user input page allows the model to be flexible across multiple types of production systems (Figure 1). In this model, the user can put their own information for feed efficiency, diet cost, nursery and finishing length, packer grid, live or carcass price, carcass yield, and mortality rates. While the model was only built to handle 7 weeks of production, the intention is to describe the underlying structure for building a more robust model. The limits in this model were created by the software of choice, Excel®, for this type of programming. However, using an alternative type of program would allow for a with more complexity and scope.

Nurseries Structure

The nurseries and finishers are designated as nodes in the network flow model and were built with the same underlying structure (Figure 2). In the Excel® model, each respective column is used to identify a calculation while each row is associated with a particular pathway or arc in the network flow. For example, row 5 identifies the pathway for pigs in batch 1 with a 6 week nursery stay, whereas row 25 identifies the pathway for pigs in batch 7 and an 8 week stay in nursery 1. As described earlier, binary decision variables are used at this stage of the model to determine which pathways are chosen (represented for nursery 1 in column C and cells C5:C25; Nursery flow constraint). If the model choses to use a pathway, the binary variable will equal 1 and the cell in column D will allow a batch to enter into the nursery; which happens to be 3,000 pigs, the set batch size, β. Column M is the calculated MOFFC for each pig that flows through that particular pathway.

To incorporate the capacity constraints for each barn, a matrix was built to calculate the number of pigs in a nursery during each week (Figure 3). Since batch number signifies the week that a group of pigs enters the network flow, the matrix follows a tiered design. The beginning column in the matrix for a batch in the barn is the same regardless of the length of stay, but the ending column is associated directly with the length of stay. For example, batch 1 in nursery 1 for each length of stay (6, 7, or 8 weeks) all begin in column N. However, a 6, 7, or 8 week length of stay ends in column S, T, and U respectively. This matrix design is consistent throughout the entire model in all nurseries and all finishers.

Row 26 (N26:AA26) is the sum total of all the pigs in the nursery during each week. This is the left hand side (LHS) of the nursery capacity constraint. Row 27 (N27:AA27) is the set capacity of the barn or the right hand side of the nursery capacity constraint (RHS). Row 28 (N28:AA28) is the percent utilization of the barn on a per week basis and calculated by dividing the number of pigs in the barn by the capacity. The number of pigs decreases by a few pigs each week because of the weekly mortality factor. Column AB is the total number of pigs left after the nursery phase that will be transported to the finisher, taking into account morality.

Finisher Structure

For the finisher, 3 levels of stocking density were incorporated into the model (Figure 4). Column AI distinguishes the level of stocking density that each path designates. The next column (AJ) sets the minimum number of pigs that can be in the barn for the stocking density while column AM sets the maximum number. Column AL is the binary decision variable that helps to ensure that only one stocking density is chosen. The difference in the finisher structure from that of the nursery however, is that each pathway also has a second set of decision variables for the number of pigs entering the barn at each stocking density, designated in column AK. A binary variable (1 = yes, 0 = no) is used to signify which stocking density the model chooses to use within each time length in a given finisher. When the binary variable for that stocking density equals 1, the minimum and maximum binary constraints (Stocking Density Constraint; columns AN and AO) insures the number of pigs allocated (column AK) is between the minimum and maximum capacity for that stocking density level.

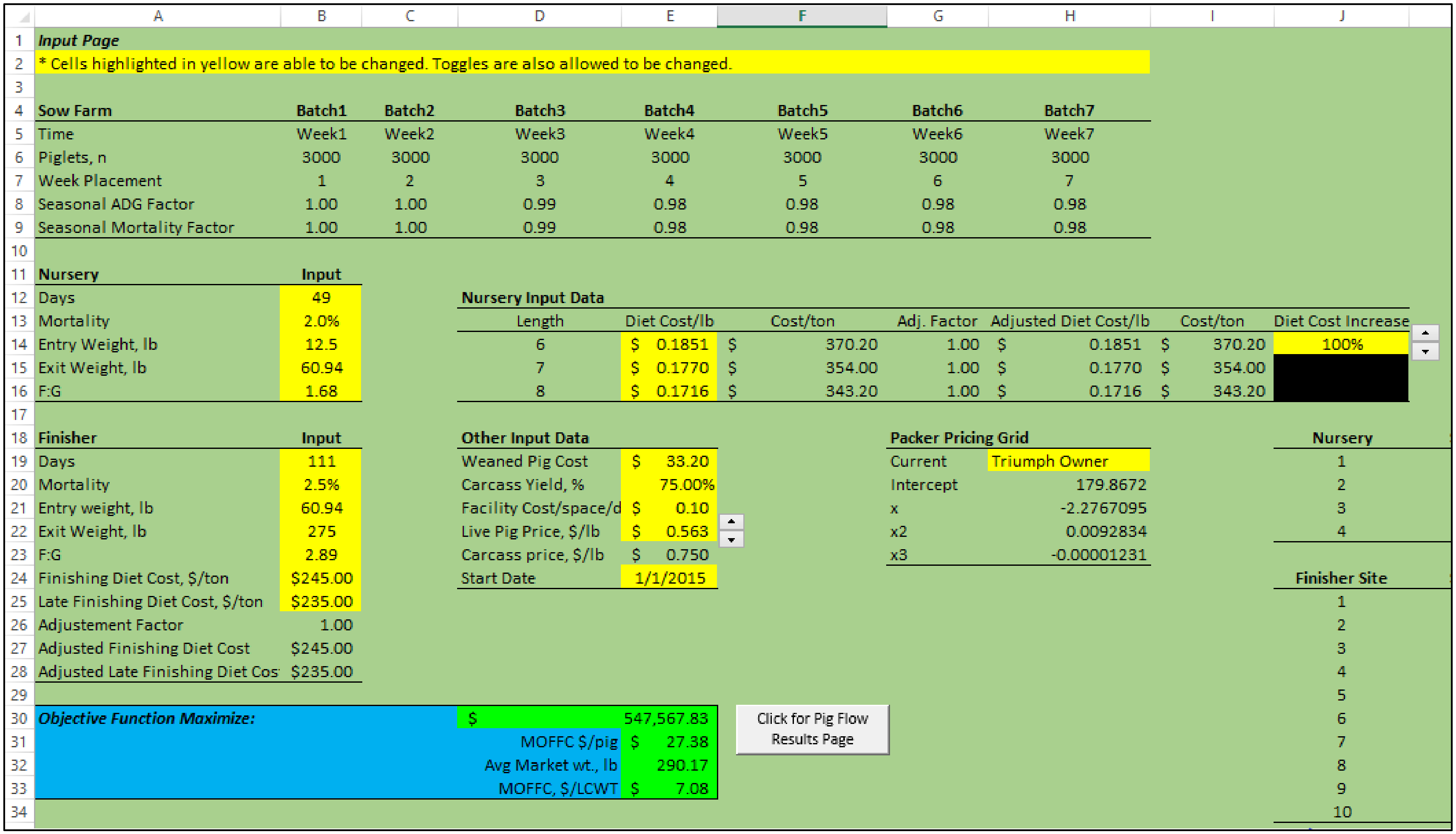
The *k*-factor adjustments in columns AQ to AS are the associated reductions in ADG for the pigs from entry until cut 1 (*k*-factor adjustment 1), cut 1 to cut 2 (*k*-factor adjustment 2), and from cut 2 until the barn dump (*k*-factor adjustment 3; Figure 5). Columns AT through AV are the average barn weight at each of those marketing events, while columns AW through AY are the barn average weight with seasonality taken into account. The values in columns AZ through BB are the average weights of the pigs marketed at each marketing event with the seasonality adjustments (Figure 6). The columns highlighted in blue are the cells indicating the number of pigs that are marketed at each event, taking into account the mortality factor for the finisher.

Cost and marginal revenue for each of these pathways are shown in Figure 7. Columns BJ through BK are the feed cost per pig for those sold at each marketing event (BJ: BL). The facility and mortality cost are calculated on a total per pig basis (column BN and BO) and subtracted from the marginal revenue. The marginal revenue is calculated on a per pig basis, similar to the feed cost, for each pig at their respective market weight (BP: BR). The MOFFC for each pig marketed is then calculated in column BS through BU. For example, to calculate MOFFC for those marketed in the first barn cut, the sum of cells BJ5, BN5 and BO5 all multiplied by BF5 (equal to marginal cost for pigs in this pathway) are subtracted from the sum-product of pigs marketed and their respective marginal revenue (cells BF5:BP5). This is the total net profit from the first cut of pigs, not taking into account the nursery cost or revenue.

Network Flow Constraints

In addition to the barn structure, the constraints are also built into Excel®. The batch supply constraint insures each batch takes a unique pathway though the nursery (Figure 8).The nursery supply balance constraints insures that all of the pigs alive at the end of the nursery period are placed into a finisher (Figure 9).The demand and site constraints insure that all of the pigs available to the model are pulled through (i.e. raised) and that only the available barns on a site have the option of filling, respectively (Figure 10). The constraints that are not visible in the spreadsheet, such as the capacity constraints for the nursery and finisher, are programmed into the OpenSolver platform. The objective function cell, where MOFFC from the nursery and finisher are summed together, is on the user input page.

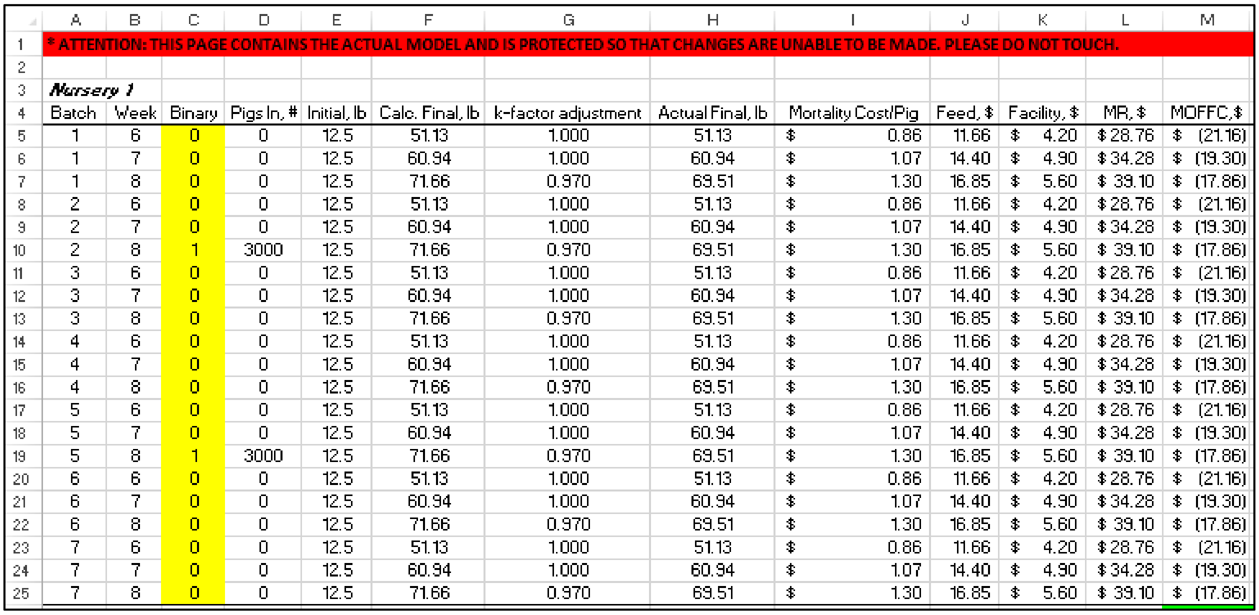
Figure A. 1. Objective Function Cell and User Page. Below is the user input page where the inputs and parameters in the model can be changed. Cells that are highlighted in yellow can be changed to influence the model results. The objective function is located in cell E30. The gray toggle button can be clicked to open up the results page.



	A	B	C	D	E	F	G	H	I	J
1	***Input Page***									
2	* Cells highlighted in yellow are able to be changed. Toggles are also allowed to be changed.									
3										
4	**Sow Farm**	**Batch1**	**Batch2**	**Batch3**	**Batch4**	**Batch5**	**Batch6**	**Batch7**		
5	Time	Week1	Week2	Week3	Week4	Week5	Week6	Week7		
6	Piglets, n	3000	3000	3000	3000	3000	3000	3000		
7	Week Placement	1	2	3	4	5	6	7		
8	Seasonal ADG Factor	1.00	1.00	0.99	0.98	0.98	0.98	0.98		
9	Seasonal Mortality Factor	1.00	1.00	0.99	0.98	0.98	0.98	0.98		
10										
11	**Nursery**	**Input**								
12	Days	49		**Nursery Input Data**						
13	Mortality	2.0%		Length	Diet Cost/lb	Cost/ton	Adj. Factor	Adjusted Diet Cost/lb	Cost/ton	Diet Cost Increase
14	Entry Weight, lb	12.5		6	$ 0.1851	$ 370.20	1.00	$ 0.1851	$ 370.20	100%
15	Exit Weight, lb	60.94		7	$ 0.1770	$ 354.00	1.00	$ 0.1770	$ 354.00	
16	F:G	1.68		8	$ 0.1716	$ 343.20	1.00	$ 0.1716	$ 343.20	
17										
18	**Finisher**	**Input**		**Other Input Data**			**Packer Pricing Grid**			**Nursery**
19	Days	111		Weaned Pig Cost	$ 33.20		Current	Triumph Owner		1
20	Mortality	2.5%		Carcass Yield, %	75.00%		Intercept	179.8672		2
21	Entry weight, lb	60.94		Facility Cost/space/d	$ 0.10		x	-2.2767095		3
22	Exit Weight, lb	275		Live Pig Price, $/lb	$ 0.563		x2	0.0092834		4
23	F:G	2.89		Carcass price, $/lb	$ 0.750		x3	-0.00001231		
24	Finishing Diet Cost, $/ton	$245.00		Start Date	1/1/2015					**Finisher Site**
25	Late Finishing Diet Cost, $/ton	$235.00								1
26	Adjustement Factor	1.00								2
27	Adjusted Finishing Diet Cost	$245.00								3
28	Adjusted Late Finishing Diet Cos	$235.00								4
29										5
30	***Objective Function Maximize:***			$	547,567.83	Click for Pig Flow Results Page				6
31				MOFFC $/pig	$ 27.38					7
32				Avg Market wt., lb	290.17					8
33				MOFFC, $/LCWT	$ 7.08					9
34										10

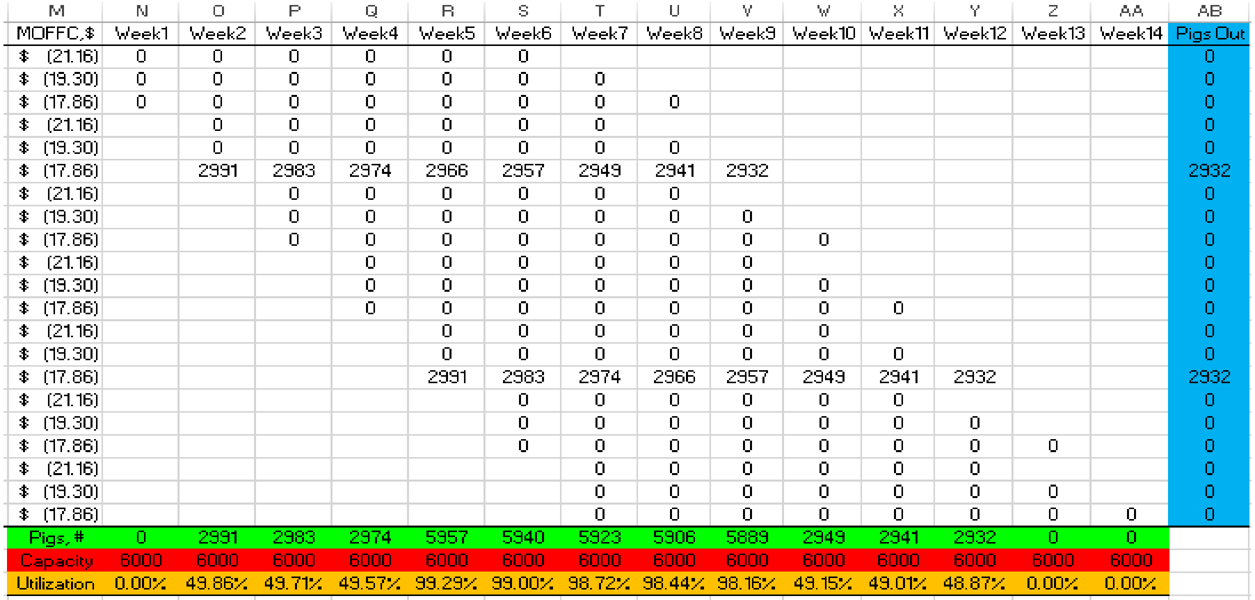
Figure A. 2. Model Structure of Nurseries, Part 1.

This figure describes the structure used to build each nursery in the spreadsheet. Each respective column is used to identify a calculation while each row is associated with a particular pathway or arc in the network.



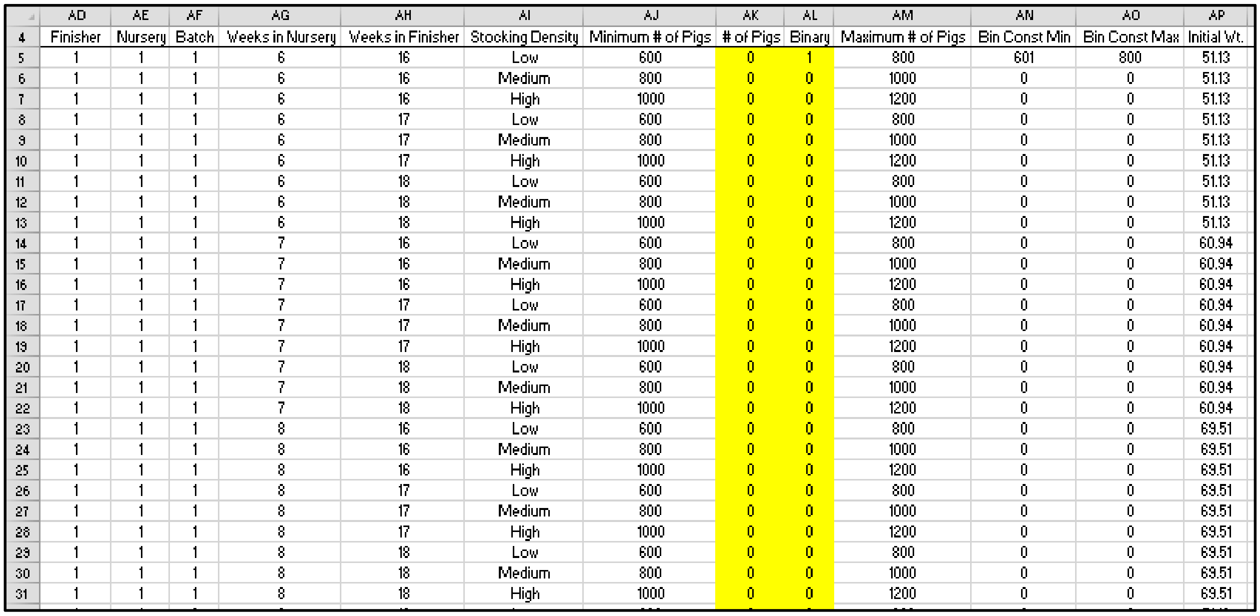
	A	B	C	D	E	F	G	H	I	J	K	L	M
1	* ATTENTION: THIS PAGE CONTAINS THE ACTUAL MODEL AND IS PROTECTED SO THAT CHANGES ARE UNABLE TO BE MADE. PLEASE DO NOT TOUCH.												
2													
3	*Nursery 1*												
4	Batch	Week	Binary	Pigs In, #	Initial, lb	Calc. Final, lb	k-factor adjustment	Actual Final, lb	Mortality Cost/Pig	Feed, $	Facility, $	MR, $	MOFFC, $
5	1	6	0	0	12.5	51.13	1.000	51.13	$ 0.86	11.66	$ 4.20	$ 28.76	$ (21.16)
6	1	7	0	0	12.5	60.94	1.000	60.94	$ 1.07	14.40	$ 4.90	$ 34.28	$ (19.30)
7	1	8	0	0	12.5	71.66	0.970	69.51	$ 1.30	16.85	$ 5.60	$ 39.10	$ (17.86)
8	2	6	0	0	12.5	51.13	1.000	51.13	$ 0.86	11.66	$ 4.20	$ 28.76	$ (21.16)
9	2	7	0	0	12.5	60.94	1.000	60.94	$ 1.07	14.40	$ 4.90	$ 34.28	$ (19.30)
10	2	8	1	3000	12.5	71.66	0.970	69.51	$ 1.30	16.85	$ 5.60	$ 39.10	$ (17.86)
11	3	6	0	0	12.5	51.13	1.000	51.13	$ 0.86	11.66	$ 4.20	$ 28.76	$ (21.16)
12	3	7	0	0	12.5	60.94	1.000	60.94	$ 1.07	14.40	$ 4.90	$ 34.28	$ (19.30)
13	3	8	0	0	12.5	71.66	0.970	69.51	$ 1.30	16.85	$ 5.60	$ 39.10	$ (17.86)
14	4	6	0	0	12.5	51.13	1.000	51.13	$ 0.86	11.66	$ 4.20	$ 28.76	$ (21.16)
15	4	7	0	0	12.5	60.94	1.000	60.94	$ 1.07	14.40	$ 4.90	$ 34.28	$ (19.30)
16	4	8	0	0	12.5	71.66	0.970	69.51	$ 1.30	16.85	$ 5.60	$ 39.10	$ (17.86)
17	5	6	0	0	12.5	51.13	1.000	51.13	$ 0.86	11.66	$ 4.20	$ 28.76	$ (21.16)
18	5	7	0	0	12.5	60.94	1.000	60.94	$ 1.07	14.40	$ 4.90	$ 34.28	$ (19.30)
19	5	8	1	3000	12.5	71.66	0.970	69.51	$ 1.30	16.85	$ 5.60	$ 39.10	$ (17.86)
20	6	6	0	0	12.5	51.13	1.000	51.13	$ 0.86	11.66	$ 4.20	$ 28.76	$ (21.16)
21	6	7	0	0	12.5	60.94	1.000	60.94	$ 1.07	14.40	$ 4.90	$ 34.28	$ (19.30)
22	6	8	0	0	12.5	71.66	0.970	69.51	$ 1.30	16.85	$ 5.60	$ 39.10	$ (17.86)
23	7	6	0	0	12.5	51.13	1.000	51.13	$ 0.86	11.66	$ 4.20	$ 28.76	$ (21.16)
24	7	7	0	0	12.5	60.94	1.000	60.94	$ 1.07	14.40	$ 4.90	$ 34.28	$ (19.30)
25	7	8	0	0	12.5	71.66	0.970	69.51	$ 1.30	16.85	$ 5.60	$ 39.10	$ (17.86)

Figure A. 3. Model Structure of Nurseries, Part 2. This figure illustrates the matrix that was built to calculate the number of pigs in a nursery during each week. Cell T26 is the sum of T6:T25 (LHS-Left hand side) and row 27 is the capacity constraint for this particular nursery (RHS-Right hand side).



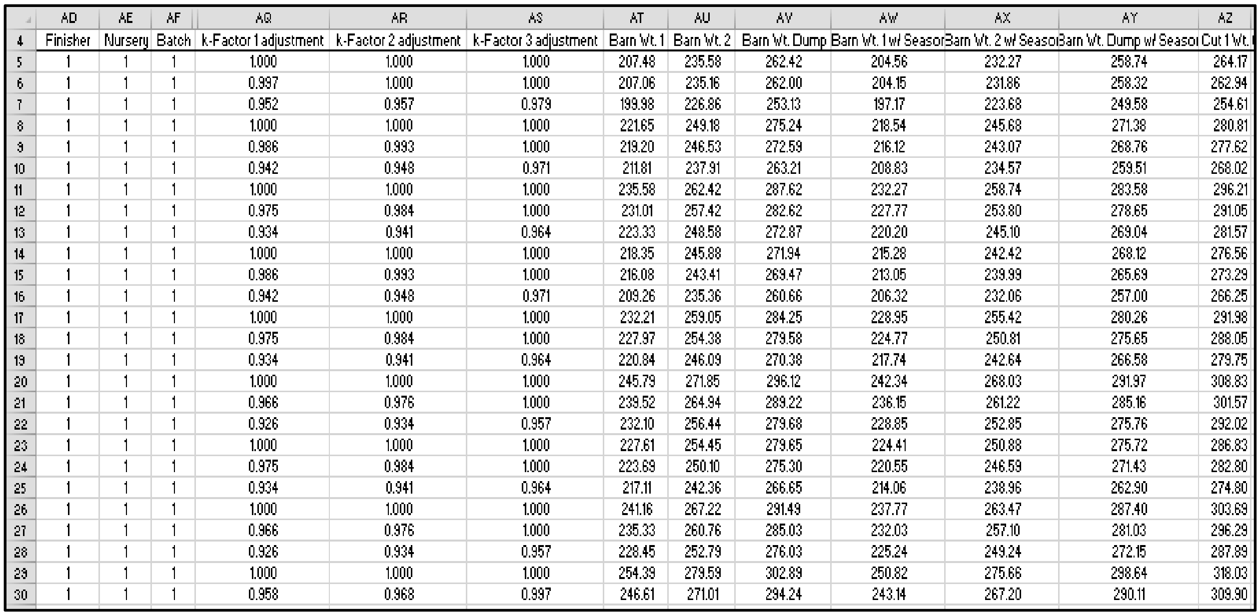
M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
MOFFC, $	Week1	Week2	Week3	Week4	Week5	Week6	Week7	Week8	Week9	Week10	Week11	Week12	Week13	Week14	Pigs Out
$ (21.16)	0	0	0	0	0	0									0
$ (19.30)	0	0	0	0	0	0	0								0
$ (17.86)	0	0	0	0	0	0	0	0							0
$ (21.16)		0	0	0	0	0	0								0
$ (19.30)		0	0	0	0	0	0	0							0
$ (17.86)		2991	2983	2974	2966	2957	2949	2941	2932						2932
$ (21.16)			0	0	0	0	0	0							0
$ (19.30)			0	0	0	0	0	0	0						0
$ (17.86)			0	0	0	0	0	0	0	0					0
$ (21.16)				0	0	0	0	0	0						0
$ (19.30)				0	0	0	0	0	0	0					0
$ (17.86)				0	0	0	0	0	0	0	0				0
$ (21.16)					0	0	0	0	0	0					0
$ (19.30)					0	0	0	0	0	0	0				0
$ (17.86)					2991	2983	2974	2966	2957	2949	2941	2932			2932
$ (21.16)						0	0	0	0	0	0				0
$ (19.30)						0	0	0	0	0	0	0			0
$ (17.86)						0	0	0	0	0	0	0	0		0
$ (21.16)							0	0	0	0	0	0			0
$ (19.30)							0	0	0	0	0	0	0		0
$ (17.86)							0	0	0	0	0	0	0	0	0
Pigs, #	0	2991	2983	2974	5957	5940	5923	5906	5889	2949	2941	2932	0	0	
Capacity	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	
Utilization	0.00%	49.86%	49.71%	49.57%	99.29%	99.00%	98.72%	98.44%	98.16%	49.15%	49.01%	48.87%	0.00%	0.00%	

Figure A. 4. Model Structure of Finishers, Part A. In addition to the basic structure, three levels of stocking density are available within each length of time. For example, row 5 to 7 is a 16 week finishing turn, but has three different levels of stocking density.



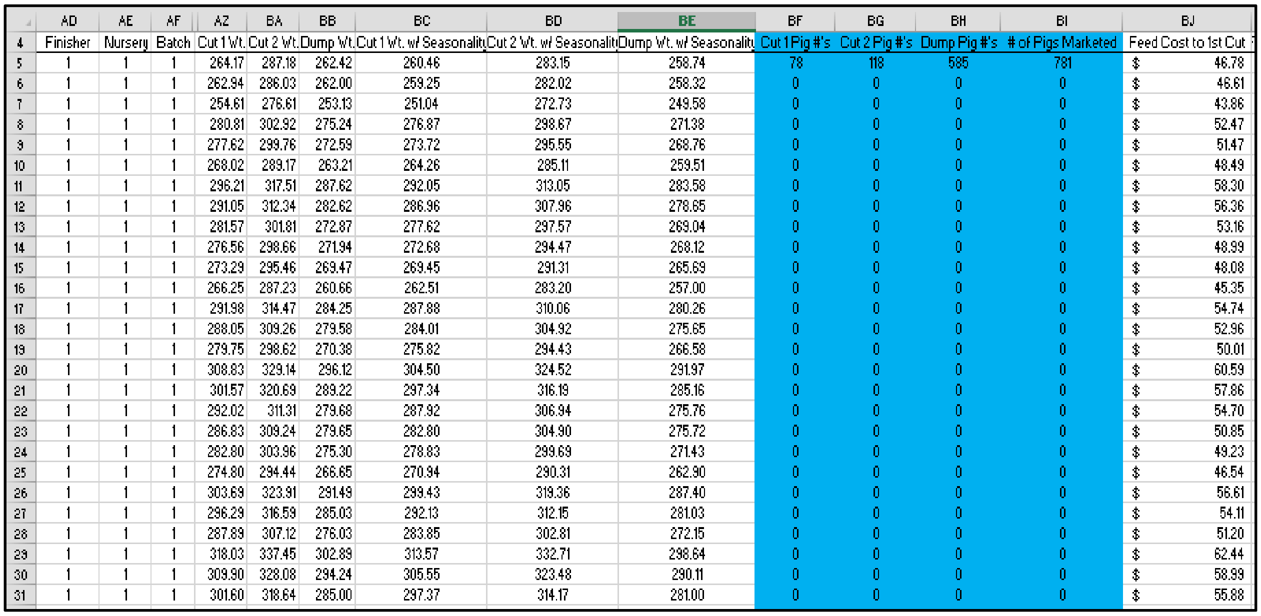
	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP
4	Finisher	Nursery	Batch	Weeks in Nursery	Weeks in Finisher	Stocking Density	Minimum # of Pigs	# of Pigs	Binary	Maximum # of Pigs	Bin Const Min	Bin Const Max	Initial Wt.
5	1	1	1	6	16	Low	600	0	1	800	601	800	51.13
6	1	1	1	6	16	Medium	800	0	0	1000	0	0	51.13
7	1	1	1	6	16	High	1000	0	0	1200	0	0	51.13
8	1	1	1	6	17	Low	600	0	0	800	0	0	51.13
9	1	1	1	6	17	Medium	800	0	0	1000	0	0	51.13
10	1	1	1	6	17	High	1000	0	0	1200	0	0	51.13
11	1	1	1	6	18	Low	600	0	0	800	0	0	51.13
12	1	1	1	6	18	Medium	800	0	0	1000	0	0	51.13
13	1	1	1	6	18	High	1000	0	0	1200	0	0	51.13
14	1	1	1	7	16	Low	600	0	0	800	0	0	60.94
15	1	1	1	7	16	Medium	800	0	0	1000	0	0	60.94
16	1	1	1	7	16	High	1000	0	0	1200	0	0	60.94
17	1	1	1	7	17	Low	600	0	0	800	0	0	60.94
18	1	1	1	7	17	Medium	800	0	0	1000	0	0	60.94
19	1	1	1	7	17	High	1000	0	0	1200	0	0	60.94
20	1	1	1	7	18	Low	600	0	0	800	0	0	60.94
21	1	1	1	7	18	Medium	800	0	0	1000	0	0	60.94
22	1	1	1	7	18	High	1000	0	0	1200	0	0	60.94
23	1	1	1	8	16	Low	600	0	0	800	0	0	69.51
24	1	1	1	8	16	Medium	800	0	0	1000	0	0	69.51
25	1	1	1	8	16	High	1000	0	0	1200	0	0	69.51
26	1	1	1	8	17	Low	600	0	0	800	0	0	69.51
27	1	1	1	8	17	Medium	800	0	0	1000	0	0	69.51
28	1	1	1	8	17	High	1000	0	0	1200	0	0	69.51
29	1	1	1	8	18	Low	600	0	0	800	0	0	69.51
30	1	1	1	8	18	Medium	800	0	0	1000	0	0	69.51
31	1	1	1	8	18	High	1000	0	0	1200	0	0	69.51

Figure A. 5. Model Structure of the Finishers, Part B. This figure illustrates the calculations of the barn weight at the end of each length of time, taking the *k*-factor into account. Columns AT:AV have the adjusted barn weight after the *k*-factor adjustment for each marketing event. Columns AW:AY includes seasonality into the weight.



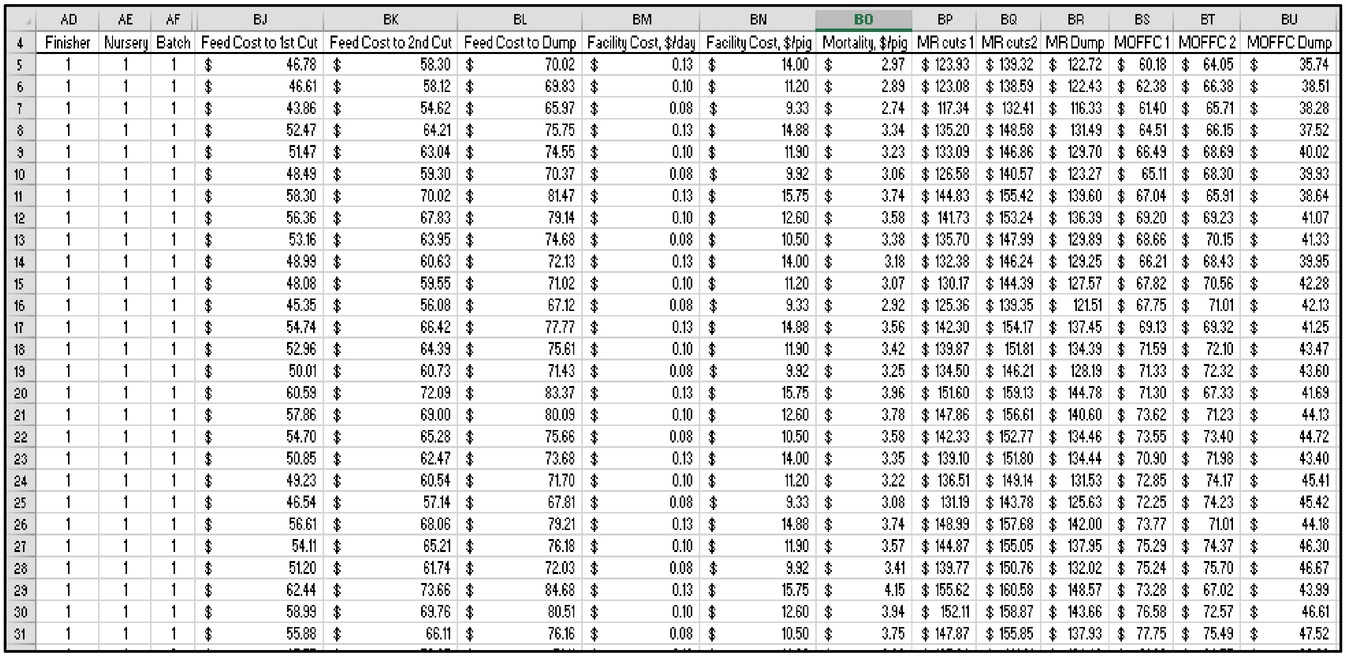
	AD	AE	AF	AQ	AR	AS	AT	AU	AV	AW	AX	AY	AZ
4	Finisher	Nursery	Batch	k-Factor 1 adjustment	k-Factor 2 adjustment	k-Factor 3 adjustment	Barn Wt. 1	Barn Wt. 2	Barn Wt. Dump	Barn Wt. 1 w/ Seasor	Barn Wt. 2 w/ Seaso	Barn Wt. Dump w/ Seaso	Cut 1 Wt.
5	1	1	1	1.000	1.000	1.000	207.48	235.58	262.42	204.56	232.27	258.74	264.17
6	1	1	1	0.997	1.000	1.000	207.06	235.16	262.00	204.15	231.86	258.32	262.94
7	1	1	1	0.952	0.957	0.979	199.98	226.86	253.13	197.17	223.68	249.58	254.61
8	1	1	1	1.000	1.000	1.000	221.65	249.18	275.24	218.54	245.68	271.38	280.81
9	1	1	1	0.986	0.993	1.000	219.20	246.53	272.59	216.12	243.07	268.76	277.62
10	1	1	1	0.942	0.948	0.971	211.81	237.91	263.21	208.83	234.57	259.51	268.02
11	1	1	1	1.000	1.000	1.000	235.58	262.42	287.62	232.27	258.74	283.58	296.21
12	1	1	1	0.975	0.984	1.000	231.01	257.42	282.62	227.77	253.80	278.65	291.05
13	1	1	1	0.934	0.941	0.964	223.33	248.58	272.87	220.20	245.10	269.04	281.57
14	1	1	1	1.000	1.000	1.000	218.35	245.88	271.94	215.28	242.42	268.12	276.56
15	1	1	1	0.986	0.993	1.000	216.08	243.41	269.47	213.05	239.99	265.69	273.29
16	1	1	1	0.942	0.948	0.971	209.26	235.36	260.66	206.32	232.06	257.00	266.25
17	1	1	1	1.000	1.000	1.000	232.21	259.05	284.25	228.95	255.42	280.26	291.98
18	1	1	1	0.975	0.984	1.000	227.97	254.38	279.58	224.77	250.81	275.65	288.05
19	1	1	1	0.934	0.941	0.964	220.84	246.09	270.38	217.74	242.64	266.58	279.75
20	1	1	1	1.000	1.000	1.000	245.79	271.85	296.12	242.34	268.03	291.97	308.83
21	1	1	1	0.966	0.976	1.000	239.52	264.94	289.22	236.15	261.22	285.16	301.57
22	1	1	1	0.926	0.934	0.957	232.10	256.44	279.68	228.85	252.85	275.76	292.02
23	1	1	1	1.000	1.000	1.000	227.61	254.45	279.65	224.41	250.88	275.72	286.83
24	1	1	1	0.975	0.984	1.000	223.69	250.10	275.30	220.55	246.59	271.43	282.80
25	1	1	1	0.934	0.941	0.964	217.11	242.36	266.65	214.06	238.96	262.90	274.80
26	1	1	1	1.000	1.000	1.000	241.16	267.22	291.49	237.77	263.47	287.40	303.69
27	1	1	1	0.966	0.976	1.000	235.33	260.76	285.03	232.03	257.10	281.03	296.29
28	1	1	1	0.926	0.934	0.957	228.45	252.79	276.03	225.24	249.24	272.15	287.89
29	1	1	1	1.000	1.000	1.000	254.39	279.59	302.89	250.82	275.66	298.64	318.03
30	1	1	1	0.958	0.968	0.997	246.61	271.01	294.24	243.14	267.20	290.11	309.90

Figure A. 6. Model Structure of the Finishers, Part C. This figure shows the weight of the pigs marketed at each cut and the number of pigs sold. These values account for mortality and are used to calculate marginal revenue for the group.



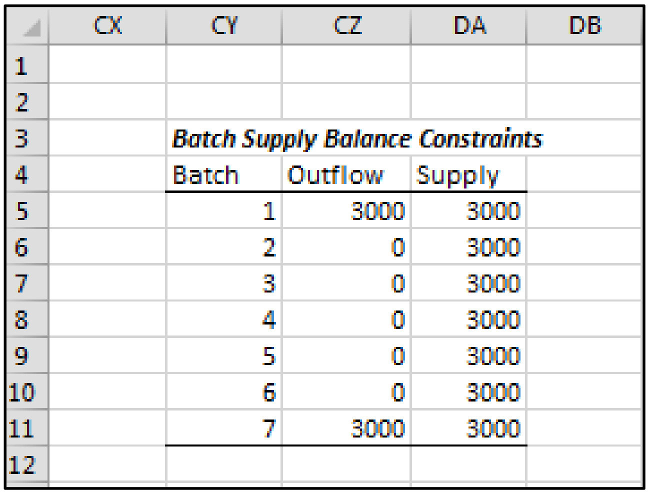
	AD	AE	AF	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ
4	Finisher	Nursery	Batch	Cut 1 Wt.	Cut 2 Wt.	Dump Wt.	Cut 1 Wt. w/ Seasonality	Cut 2 Wt. w/ Seasonality	Dump Wt. w/ Seasonality	Cut 1 Pig #'s	Cut 2 Pig #'s	Dump Pig #'s	# of Pigs Marketed	Feed Cost to 1st Cut
5	1	1	1	264.17	287.18	262.42	260.46	283.15	258.74	78	118	585	781	$ 46.78
6	1	1	1	262.94	286.03	262.00	259.25	282.02	258.32	0	0	0	0	$ 46.61
7	1	1	1	254.61	276.61	253.13	251.04	272.73	249.58	0	0	0	0	$ 43.86
8	1	1	1	280.81	302.92	275.24	276.87	298.67	271.38	0	0	0	0	$ 52.47
9	1	1	1	277.62	299.76	272.59	273.72	295.55	268.76	0	0	0	0	$ 51.47
10	1	1	1	268.02	289.17	263.21	264.26	285.11	259.51	0	0	0	0	$ 48.49
11	1	1	1	296.21	317.51	287.62	292.05	313.05	283.58	0	0	0	0	$ 58.30
12	1	1	1	291.05	312.34	282.62	286.96	307.96	278.65	0	0	0	0	$ 56.36
13	1	1	1	281.57	301.81	272.87	277.62	297.57	269.04	0	0	0	0	$ 53.16
14	1	1	1	276.56	298.66	271.94	272.68	294.47	268.12	0	0	0	0	$ 48.99
15	1	1	1	273.29	295.46	269.47	269.45	291.31	265.69	0	0	0	0	$ 48.08
16	1	1	1	266.25	287.23	260.66	262.51	283.20	257.00	0	0	0	0	$ 45.35
17	1	1	1	291.98	314.47	284.25	287.88	310.06	280.26	0	0	0	0	$ 54.74
18	1	1	1	288.05	309.26	279.58	284.01	304.92	275.65	0	0	0	0	$ 52.96
19	1	1	1	279.75	298.62	270.38	275.82	294.43	266.58	0	0	0	0	$ 50.01
20	1	1	1	308.83	329.14	296.12	304.50	324.52	291.97	0	0	0	0	$ 60.59
21	1	1	1	301.57	320.69	289.22	297.34	316.19	285.16	0	0	0	0	$ 57.86
22	1	1	1	292.02	311.31	279.68	287.92	306.94	275.76	0	0	0	0	$ 54.70
23	1	1	1	286.83	309.24	279.65	282.80	304.90	275.72	0	0	0	0	$ 50.85
24	1	1	1	282.80	303.96	275.30	278.83	299.69	271.43	0	0	0	0	$ 49.23
25	1	1	1	274.80	294.44	266.65	270.94	290.31	262.90	0	0	0	0	$ 46.54
26	1	1	1	303.69	323.91	291.49	299.43	319.36	287.40	0	0	0	0	$ 56.61
27	1	1	1	296.29	316.59	285.03	292.13	312.15	281.03	0	0	0	0	$ 54.11
28	1	1	1	287.89	307.12	276.03	283.85	302.81	272.15	0	0	0	0	$ 51.20
29	1	1	1	318.03	337.45	302.89	313.57	332.71	298.64	0	0	0	0	$ 62.44
30	1	1	1	309.90	328.08	294.24	305.55	323.48	290.11	0	0	0	0	$ 58.99
31	1	1	1	301.60	318.64	285.00	297.37	314.17	281.00	0	0	0	0	$ 55.88

Figure A. 7. Model Structure of the Finishers, Part D. This figure illustrates the segment of the finisher structure where calculations for feed, facility, and mortality cost are calculated as well as marginal revenue (MR) and further margin over feed and facility cost (MOFFC).



	AD	AE	AF	BJ	BK	BL	BM	BN	BO	BP	BQ	BR	BS	BT	BU
4	Finisher	Nursery	Batch	Feed Cost to 1st Cut	Feed Cost to 2nd Cut	Feed Cost to Dump	Facility Cost, $/day	Facility Cost, $/pig	Mortality, $/pig	MR cuts 1	MR cuts2	MR Dump	MOFFC 1	MOFFC 2	MOFFC Dump
5	1	1	1	$ 46.78	$ 58.30	$ 70.02	$ 0.13	$ 14.00	$ 2.97	$ 123.93	$ 139.32	$ 122.72	$ 60.18	$ 64.05	$ 35.74
6	1	1	1	$ 46.61	$ 58.12	$ 69.83	$ 0.10	$ 11.20	$ 2.89	$ 123.08	$ 138.59	$ 122.43	$ 62.38	$ 66.38	$ 38.51
7	1	1	1	$ 43.86	$ 54.62	$ 65.97	$ 0.08	$ 9.33	$ 2.74	$ 117.34	$ 132.41	$ 116.33	$ 61.40	$ 65.71	$ 38.28
8	1	1	1	$ 52.47	$ 64.21	$ 75.75	$ 0.13	$ 14.88	$ 3.34	$ 135.20	$ 148.58	$ 131.49	$ 64.51	$ 66.15	$ 37.52
9	1	1	1	$ 51.47	$ 63.04	$ 74.55	$ 0.10	$ 11.90	$ 3.23	$ 133.09	$ 146.86	$ 129.70	$ 66.49	$ 68.69	$ 40.02
10	1	1	1	$ 48.49	$ 59.30	$ 70.37	$ 0.08	$ 9.92	$ 3.06	$ 126.58	$ 140.57	$ 123.27	$ 65.11	$ 68.30	$ 39.93
11	1	1	1	$ 58.30	$ 70.02	$ 81.47	$ 0.13	$ 15.75	$ 3.74	$ 144.83	$ 155.42	$ 139.60	$ 67.04	$ 65.91	$ 38.64
12	1	1	1	$ 56.36	$ 67.83	$ 79.14	$ 0.10	$ 12.60	$ 3.58	$ 141.73	$ 153.24	$ 136.39	$ 69.20	$ 69.23	$ 41.07
13	1	1	1	$ 53.16	$ 63.95	$ 74.68	$ 0.08	$ 10.50	$ 3.38	$ 135.70	$ 147.99	$ 129.89	$ 68.66	$ 70.15	$ 41.33
14	1	1	1	$ 48.99	$ 60.63	$ 72.13	$ 0.13	$ 14.00	$ 3.18	$ 132.38	$ 146.24	$ 129.25	$ 66.21	$ 68.43	$ 39.95
15	1	1	1	$ 48.08	$ 59.55	$ 71.02	$ 0.10	$ 11.20	$ 3.07	$ 130.17	$ 144.39	$ 127.57	$ 67.82	$ 70.56	$ 42.28
16	1	1	1	$ 45.35	$ 56.08	$ 67.12	$ 0.08	$ 9.33	$ 2.92	$ 125.36	$ 139.35	$ 121.51	$ 67.75	$ 71.01	$ 42.13
17	1	1	1	$ 54.74	$ 66.42	$ 77.77	$ 0.13	$ 14.88	$ 3.56	$ 142.30	$ 154.17	$ 137.45	$ 69.13	$ 69.32	$ 41.25
18	1	1	1	$ 52.96	$ 64.39	$ 75.61	$ 0.10	$ 11.90	$ 3.42	$ 139.87	$ 151.81	$ 134.39	$ 71.59	$ 72.10	$ 43.47
19	1	1	1	$ 50.01	$ 60.73	$ 71.43	$ 0.08	$ 9.92	$ 3.25	$ 134.50	$ 146.21	$ 128.19	$ 71.33	$ 72.32	$ 43.60
20	1	1	1	$ 60.59	$ 72.09	$ 83.37	$ 0.13	$ 15.75	$ 3.96	$ 151.60	$ 159.13	$ 144.78	$ 71.30	$ 67.33	$ 41.69
21	1	1	1	$ 57.86	$ 69.00	$ 80.09	$ 0.10	$ 12.60	$ 3.78	$ 147.86	$ 156.61	$ 140.60	$ 73.62	$ 71.23	$ 44.13
22	1	1	1	$ 54.70	$ 65.28	$ 75.66	$ 0.08	$ 10.50	$ 3.58	$ 142.33	$ 152.77	$ 134.46	$ 73.55	$ 73.40	$ 44.72
23	1	1	1	$ 50.85	$ 62.47	$ 73.68	$ 0.13	$ 14.00	$ 3.35	$ 139.10	$ 151.80	$ 134.44	$ 70.90	$ 71.98	$ 43.40
24	1	1	1	$ 49.23	$ 60.54	$ 71.70	$ 0.10	$ 11.20	$ 3.22	$ 136.51	$ 149.14	$ 131.53	$ 72.85	$ 74.17	$ 45.41
25	1	1	1	$ 46.54	$ 57.14	$ 67.81	$ 0.08	$ 9.33	$ 3.08	$ 131.19	$ 143.78	$ 125.63	$ 72.25	$ 74.23	$ 45.42
26	1	1	1	$ 56.61	$ 68.06	$ 79.21	$ 0.13	$ 14.88	$ 3.74	$ 148.99	$ 157.68	$ 142.00	$ 73.77	$ 71.01	$ 44.18
27	1	1	1	$ 54.11	$ 65.21	$ 76.18	$ 0.10	$ 11.90	$ 3.57	$ 144.87	$ 155.05	$ 137.95	$ 75.29	$ 74.37	$ 46.30
28	1	1	1	$ 51.20	$ 61.74	$ 72.03	$ 0.08	$ 9.92	$ 3.41	$ 139.77	$ 150.76	$ 132.02	$ 75.24	$ 75.70	$ 46.67
29	1	1	1	$ 62.44	$ 73.66	$ 84.68	$ 0.13	$ 15.75	$ 4.15	$ 155.62	$ 160.58	$ 148.57	$ 73.28	$ 67.02	$ 43.99
30	1	1	1	$ 58.99	$ 69.76	$ 80.51	$ 0.10	$ 12.60	$ 3.94	$ 152.11	$ 158.87	$ 143.66	$ 76.58	$ 72.57	$ 46.61
31	1	1	1	$ 55.88	$ 66.11	$ 76.16	$ 0.08	$ 10.50	$ 3.75	$ 147.87	$ 155.85	$ 137.93	$ 77.75	$ 75.49	$ 47.52

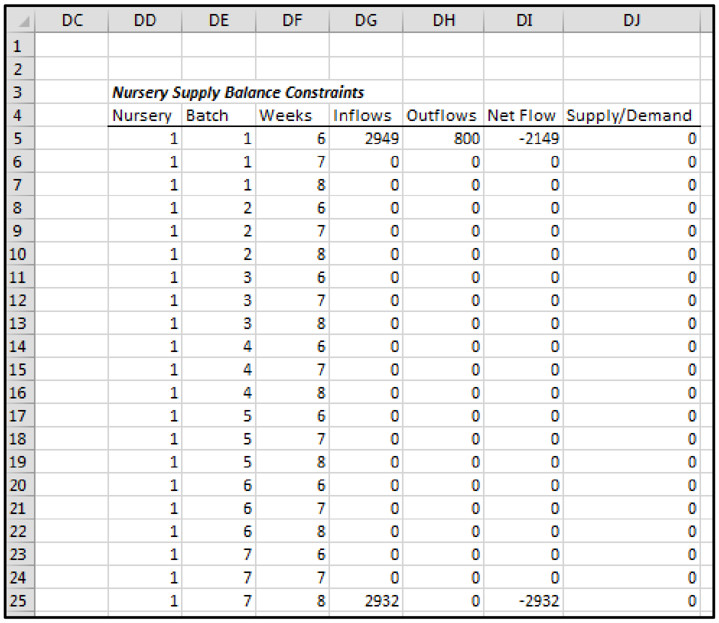
Figure A. 8. Batch Supply Constraint. The constraint below insures that all of the batches available to the model each week are used in the flow.



Batch Supply Balance Constraints

Batch	Outflow	Supply
1	3000	3000
2	0	3000
3	0	3000
4	0	3000
5	0	3000
6	0	3000
7	3000	3000

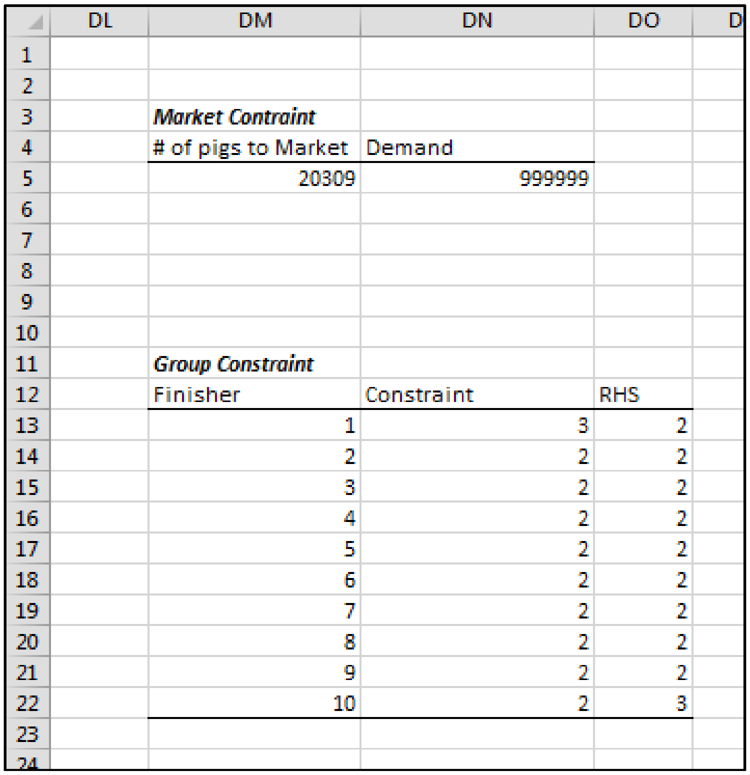
Figure A. 9. Nursery Supply Constraint. This figure shows the constraints responsible for insuring that all of the pigs that went through the nurseries are transported to the finishers.



Nursery Supply Balance Constraints

Nursery	Batch	Weeks	Inflows	Outflows	Net Flow	Supply/Demand
1	1	6	2949	800	-2149	0
1	1	7	0	0	0	0
1	1	8	0	0	0	0
1	2	6	0	0	0	0
1	2	7	0	0	0	0
1	2	8	0	0	0	0
1	3	6	0	0	0	0
1	3	7	0	0	0	0
1	3	8	0	0	0	0
1	4	6	0	0	0	0
1	4	7	0	0	0	0
1	4	8	0	0	0	0
1	5	6	0	0	0	0
1	5	7	0	0	0	0
1	5	8	0	0	0	0
1	6	6	0	0	0	0
1	6	7	0	0	0	0
1	6	8	0	0	0	0
1	7	6	0	0	0	0
1	7	7	0	0	0	0
1	7	8	2932	0	-2932	0

Figure A. 10. Demand and Site Constraint. The market constrain below in cells DM5:DN5 helps pull pigs through the system. The site constraint below the market constraint insures only the absolute number of batches that can be handled at a finishing site are allowed to flow through the site.



	DL	DM	DN	DO	D
1					
2					
3		***Market Contraint***			
4		# of pigs to Market	Demand		
5		20309	999999		
6					
7					
8					
9					
10					
11		***Group Constraint***			
12		Finisher	Constraint	RHS	
13		1	3	2	
14		2	2	2	
15		3	2	2	
16		4	2	2	
17		5	2	2	
18		6	2	2	
19		7	2	2	
20		8	2	2	
21		9	2	2	
22		10	2	3	
23					
24					