Effects of increasing standardized ileal digestible lysine during gestation on reproductive performance and modeled requirements in gilts and sows from a commercial production system

by

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B.S., University of Missouri, 2013
M.S., Kansas State University, 2017

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Animal Sciences and Industry
College of Agriculture

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Abstract

A study was conducted to determine the effects of standardized ileal digestible (SID) lysine (Lys) during gestation on reproductive performance of gilts and sows and effects on piglet birthweight. These data were used to model changes in protein deposition and estimate SID Lys requirements. A total of 936 females were allotted to 1 of 4 dietary treatments (SID Lys intake of 11, 13.5, 16, and 18.5 g/d) on d 5 of gestation. Gilts and sows received 5.3 and 5.8 Mcal NE/d and their respective Lys intake throughout the entire gestation period. Initial BW and backfat were obtained on d 4 of gestation while final BW and backfat were obtained on d 111. Piglet BW was obtained within 12 h of birth. Gestation was divided into 3 stages: d 5 to 39 (early), 40 to 74 (mid), and 75 to 108 (late). Final BW at d 111 of gestation increased (linear, $P < 0.001$) for gilts and sows as SID Lys increased. There was no evidence for differences in final backfat depth. The percentage of pigs born alive increased ($P = 0.006$) with increasing SID Lys intake for sows, but not gilts as a result of a treatment by parity group interaction ($P = 0.043$) for percentage stillborn pigs. In gilts, there was no evidence for differences among treatments in the percentage stillborn pigs but in sows, as dietary SID Lys intake increased, the probability of a pig born as a stillborn decreased (linear, $P = 0.002$). Increasing SID Lys intake during gestation did not affect total born or born alive piglet birthweight. These results suggest that increasing SID Lys intake in gestation increased female BW, without changing backfat depth, suggesting BW gain was in the form of protein and not lipid accretion. To validate this hypothesis, Lys utilization was modeled using daily intake and BW values. The model follows the principle that energy is partitioned between maintenance, growth of conceptus, and maternal protein and lipid deposition. Requirements for SID Lys were estimated based on whole body protein deposition. Regardless of parity group or stage of gestation, as SID Lys increased, whole body protein

deposition increased (linear, $P < 0.001$). For gilts and sows, whole body protein deposition increased ($P < 0.05$) in each sequential stage of gestation. Whole body protein deposition was greater for gilts ($P < 0.05$) in each stage of gestation, compared to sows. Estimated SID Lys balance (intake - requirement) increased with increasing SID Lys (quadratic, $P < 0.054$), and decreased ($P < 0.05$) in each sequential stage of gestation for both gilts and sows. Sow SID Lys balance was greater throughout gestation compared to gilts ($P < 0.05$). Overall, the model shows changes in protein retention of the conceptus and maternal protein deposition differ by parity and stage of gestation. Based on predicted changes in protein deposition, providing females with 13.5 g/d SID Lys adequately meets Lys requirements and ensures gilts do not go into a negative Lys balance at any time during gestation.

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Major Professor
Dr. Robert Goodband

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Chapter 1 - Evaluation of different blends of medium chain fatty acids, lactic acid, and monolaurin on nursery pig growth performance

ABSTRACT: A total of 710 pigs (Line 400 × 200, DNA, Columbus, NE) were used in 2 experiments (Exp. 1, initially 6.3 ± 0.05 kg, Exp. 2 initially 6.8 ± 0.05 kg) to evaluate the effects of two medium chain fatty acid (MCFA) based products on nursery pig growth performance. Following arrival to the nursery facility, pigs were randomized to pens (5 pigs per pen) and allowed a 4-d acclimation period. Thereafter, pens of pigs were blocked by initial weight and randomized to dietary treatment. In Exp. 1, the dietary treatments were a dose titration of: 0, 0.5, 1.0, or 2.0% MCFA-based additive, as well as a diet including 1.0% MCFA from a 1:1:1 blend of C6:0, C8:0, and C10:0. In Exp.2, dietary treatments consisted of a basal diet containing no MCFA (control), the control diet with a 1.0% inclusion of 4 different blends of MCFA, lactic acid, and monolaurin or a diet with 1.0% added MCFA (a 1:1:1 blend of C6:0, C8:0, and C10:0). The 4 blends consisted of 50% C6:0, 20% lactic acid and increasing levels of monolaurin (0, 10, 20, and 30%) at the expense of C12:0 (30, 20, 10, and 0%). Treatment diets were formulated and manufactured in two dietary phases. Data were analyzed as a randomized complete block design with pen as the experimental unit. In Exp. 1, overall (d 0 to 34), increasing CaptiSURE increased (linear, $P \leq 0.014$) ADG and ADFI. Feed efficiency improved (quadratic, $P = 0.002$) with increasing CaptiSURE up to 1.0% of the diet with no benefit thereafter. There was no evidence for differences between pigs fed 1.0% CaptiSURE and pigs fed the 1.0% MCFA blend of C6:0, C8:0, and C10:0. In Exp. 2, overall (d 0 to 35), pigs fed the 1.0% 1:1:1 MCFA blend had increased ($P < 0.034$) ADFI and ADG resulting in 0.9 kg greater final weight ($P = 0.014$)

compared to the control group. There was no evidence that the mean performance of pigs fed the 4 blends of MCFA, lactic acid, and monolaurin were different from the pigs fed the control diet. In summary, the addition of a 1.0% 1:1:1 blend of C6:0, C8:0, and C10:0 in nursery pig diets improved ADG, ADFI, and G:F compared to pigs fed the control diet. In addition, providing nursery pigs with the MCFA product CaptiSURE, up to 2% of the diet, resulted in linear improvements in ADG and ADFI. Altering the C12:0 to monolaurin ratio and adding lactic acid did not improve growth performance compared to pigs fed the control diet.

Key words: Growth, lactic acid, medium chain fatty acid, monolaurin, nursery pig

Introduction

Weaning is a complex transition phase during which pigs experience stress due to social, environmental, and dietary changes (Suiryanrayna and Ramana, 2015). During this time, the intestinal tract and immune system are not yet fully developed (Bailey et al. 2005). Because of these challenges, growth performance can be compromised (Xun et al., 2015). As a result, it has been typical to add feed-grade antimicrobials to weaned pig diets to improve growth performance (Suiryanrayna and Ramana, 2015). Numerous antibiotic alternatives are available; however, research surrounding the efficacy of these products is rarely comparable to that of antibiotics (Close, 2000; Doyle, 2001).

Organic acids, specifically medium chain fatty acids (MCFA) and lactic acid, are receiving attention as feed additives in swine diets as they possess both bacteriostatic and bactericidal properties (Suiryanrayna and Ramana, 2015). Medium chain fatty acids have been shown to reduce infectivity of feed and ingredients containing porcine epidemic diarrhea virus

(PEDV; Cochrane et al. 2016b), as well as improve growth performance in weaned pigs (Gebhardt et al. 2019). In addition, monoglycerides of MCFA, specifically C12:0 (monolaurin), have been shown to have stronger antibacterial property effects than their respective free fatty acids (Dansen, 2016). Previous research with organic acid blends containing lactic acid, found reduced concentrations of Salmonella in feed (Cochrane et al. 2016a) and improvements in growth performance (Tsiloyiannis et al., 2001). Thus, commercial products are becoming available with proprietary blends of MCFA as well as other ingredients. Because of differences in the response to feeding different free fatty acids and MCFA blends (Gebhardt et al. 2019), it is necessary to evaluate products and their impact on growth performance. Therefore, the objectives of these experiments were to evaluate commercial MCFA-blend feed additives on growth performance of nursery pigs.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments. Both studies were conducted at the Kansas State University Segregated Early Weaning Facility in Manhattan, KS. Each pen (1.22 × 1.22 m) contained a 4-hole, dry self-feeder and cup waterer to provide ad libitum access to feed and water. Pens had tri-bar floors and allowed approximately 0.25 m2/pig.

Animals

Pigs were weaned at 21 d of age and transported to the research facility. Upon arrival, pigs were allotted randomly to pens of 5 based on their initial weight and allowed a 4-d acclimation period during which they were provided a commercial starter diet (pelleted)

containing no feed grade antimicrobials. On day 4 after weaning, considered day 0 in the trial, pens of pigs were blocked by weight and assigned randomly to the dietary treatments. In Exp. 1, a total of 350 pigs (Line 200 × 400; DNA, Columbus, NE, initially 6.3 ± 0.05 kg) were used in a 34-d growth study, with 5 dietary treatments, and 14 pens per treatment. In Exp. 2, a total of 360 pigs (Line 200 × 400; DNA, Columbus, NE, initially 6.8 ± 0.05 kg) were used in a 35-d growth study, with 6 dietary treatments, and 12 pens per treatment. In both experiments, pig weights and feed disappearance were measured every 7 d to determine ADG, ADFI, and G:F.

Diets

The same control diet, to which feed additives were added, was used in both experiments 1 and 2 (Table 1). Treatment diets were manufactured in two dietary phases and were formulated to meet or exceed NRC (2012) requirement estimates. In Exp. 1, treatments consisted of a basal diet with increasing amounts (0, 0.5, 1.0, and 2.0%) of a MCFA-based additive composed of primarily C8:0 and C10:0 (CaptiSURE, Kemin Industries, Inc, Des Moines, IA) as well as a diet with 1.0% of added MCFA blend (Sigma Aldrich, St. Louis, MO) composed of a 1:1:1 ratio of C6:0, C8:0, and C10:0 and were guaranteed ≥ 98% purity. In Exp. 2, treatments consisted of a control diet containing no added MCFA, the control diet with 1.0% inclusion of 4 different blends of a MCFA, lactic acid, and monolaurin (monoglyceride form of C12:0) -based additive (Tech Mix, LLC, Stewart, MN) as well as a diet with 1.0% of added MCFA blend (Sigma Aldrich, St. Louis, MO) composed of a 1:1:1 ratio of C6:0, C8:0, and C10:0. The 4 blends consisted of 50% C6:0, 20% lactic acid and increasing amounts of monolaurin (0, 10, 20, and 30%) at the expense of C12:0 (30, 20, 10, and 0%). In both experiments, all feed additives were included at the expense of soy oil on an equal weight basis in an attempt to keep diets similar in NE content.

Chemical Analysis

Diets were manufactured at the K-State O.H. Kruse Feed Technology Innovation Center, Manhattan, KS. Complete diet samples were taken from five feeders per dietary treatment four times throughout the study. Samples were stored at -20°C until they were homogenized, subsampled, and submitted (Ward Laboratories, Inc., Kearney, NE) for analysis of DM (AOAC 934.01, 2006), CP (AOAC 990.03, 2006), ADF (AOAC 978.10, 2006), Ca (AOAC 965.14/985.01, 2006), P (AOAC 965.17/985.01, 2006), and ether extract (AOAC 920.39 A, 2006). In addition, in Exp. 1 MCFA concentration of C8:0 and C10:0 were analyzed (Kemin Industries, Inc; Des Moines, IA) and in Exp. 2 MCFA concentration of C6:0, C8:0, C10:0, and C12:0 (AOCS Ca 5a-40, 2017) were analyzed (University of Missouri Experimental Station Chemical Laboratories, Columbia, MO).

Statistical Analysis

In both experiments, data were analyzed as a randomized complete block design using the GLIMMIX procedure of SAS version 9.4 (SAS Institute, Inc., Cary, NC) with pen as the experimental unit. Weight block was included in the model as a random effect. In Exp.1, within the outcomes described above, linear and quadratic effects of increasing MCFA, as well as a preplanned pairwise contrast comparing MCFA (CaptiSURE) at 1.0% to the 1.0% 1:1:1 MCFA blend treatment were evaluated. Linear and quadratic contrasts were developed using the IML procedure of SAS, generating coefficients for unequally spaced treatments. In Exp. 2, estimated means and corresponding standard errors (SEM) were reported for cell means and pairwise comparisons were conducted on such means using a Tukey adjustment to prevent inflation of Type I error due to multiple comparisons (Stroup, 2013). In addition, linear and quadratic effects of increasing monolaurin, as well as preplanned pairwise contrasts comparing the control group

to the 1:1:1 MCFA blend and the mean of the four MCFA plus acidifier and monolaurin blends. Response variables were each fitted assuming a normal distribution and residual assumptions were checked using standard diagnostics on residuals and were found to be reasonably met. All results were considered significant at $P \leq 0.05$ and marginally significant between $P > 0.05$ and $P \leq 0.10$.

Results

Chemical Analysis

In Exp. 1 and 2, analysis of manufactured diets (Tables 2 and 3) resulted in values consistent with formulation with the exception of ether extract. In Exp. 1, ether extract decreased as MCFA addition increased. Similarly, in Exp. 2, ether extract values for diets containing MCFA or the MCFA, acidifier and monolaurin blends were lower compared to the control diet. Specifically, within the MCFA, acidifier and monolaurin blends, as monolaurin increased (diets 1 to 4), ether extract increased, but remained lower compared to the control diet. Recall, all MCFA products were added to diets at the expense of soybean oil to keep diets isocaloric in both experiments. Thus, we expected to see similar analyzed values for ether extract for all dietary treatments within each experiment; however, the results indicate a reduction in ether extract with the inclusion of MCFA. These findings are similar to analyzed values reported by Gebhardt et al. (2019). Ether extract was determined through an approved method from the American Oil Chemists' Society (AOCS, 2017) utilizing high temperature solvent extraction. These results suggest that the MCFA are not fully detected by this method of fat analysis. Furthermore, in Exp. 1, MCFA analysis results confirmed increasing amounts of C8:0 and C10:0 as CaptiSURE product inclusion increased, but results were lower than formulated values (Table 2). Similarly,

in Exp. 2, analyzed MCFA results were less than formulated values for all dietary treatments containing MCFA (Table 3). These results also suggest that specific free fatty acids are likely not detected by ether extraction.

Experiment 1 Growth Performance

From d 0 to 13 (dietary phase 1), increasing CaptiSURE increased (linear, $P < 0.001$) ADG (Table 4). Feed efficiency increased (linear, $P < 0.001$) up to 1.0% of the diet with marginal benefit observed thereafter. There was no evidence for differences in ADG or ADFI when comparing pigs fed 1.0% CaptiSURE and those fed the 1.0% 1:1:1 MCFA blend; however, there was marginal evidence ($P = 0.091$) for an increase in G:F for pigs consuming the 1.0% CaptiSURE.

From d 13 to 34 (dietary phase 2), pigs fed increasing CaptiSURE had increased (linear, $P < 0.001$) ADG and ADFI, as well as increased (quadratic, $P = 0.013$) G:F. Like d 0 to 13, G:F increased up to 1.0% CaptiSURE with no benefit observed at 2% of the diet. There was no evidence for differences in growth performance between pigs fed 1.0% CaptiSURE and those fed the 1.0% 1:1:1 MCFA blend.

Overall, ADG and ADFI were increased (linear, $P < 0.014$) with increasing CaptiSURE, resulting in a 1.8 kg difference in final BW between the control group and pigs fed the 2.0% inclusion of CaptiSURE (linear, $P < 0.001$; Table 4). Feed efficiency increased from 0 to 1.0% CaptiSURE in the diet (quadratic, $P = 0.002$). Pigs fed 1.0% CaptiSURE and those fed the 1.0% 1:1:1 MCFA blend performed similarly, with no evidence for differences between the two treatment groups.

Experiment 2 Growth Performance

From d 0 to 14 (dietary phase 1), pigs fed the 1.0% 1:1:1 MCFA blend had increased ($P = 0.037$) ADG compared to the control group (Table 5). Feed efficiency was improved ($P < 0.013$) with addition of 1:1:1 MCFA blend and the MCFA, acidifier and monolaurin blends. From d 14 to 35 (dietary phase 2), pigs fed the 1.0% 1:1:1 MCFA blend had increased ($P < 0.057$) ADFI and, subsequently, ADG compared to the control group.

Overall, ADFI and ADG were increased ($P < 0.034$) when the 1.0% 1:1:1 MCFA blend was included in the diet, compared to the control group. This increase in ADG resulted in pigs fed the 1.0% 1:1:1 MCFA blend being 0.9 kg heavier ($P = 0.014$) than the control group on d 35 of the study. There was no evidence for differences between the control group and the 1.0% inclusion of the MCFA, acidifier, and monolaurin blends. In addition, there was no evidence for linear or quadratic effects of increasing monolaurin on nursery pig performance.

Discussion

For the young weaned pig, post-weaning is a critical phase in life often resulting in a reduction in feed intake, causing energy deficiency, changes in the intestinal morphology, reduced absorptive capacity, impaired immune reactivity, and changes in intestinal microbiota (Pluske et al., 1997; Konstantinov and Smidt, 2006; Lallés et al., 2007). Thus, research involving feed additives acting as antibiotic replacements for weaned pigs has been extensive in recent years, with promising results in the use of organic acids (Liu et al., 2018).

Medium chain fatty acids are classified as a type of organic acid which can be considered for use as antibiotic replacers (Decuypere and Dierick, 2003). Medium chain fatty acids are defined as saturated fatty acids with 6 (caproic acid, C6:0), 8 (caprylic acid, C8:0), 10 (capric

acid, C10:0), or 12 (lauric acid, C12:0) carbon atoms. They are found naturally as medium chain triglycerides (MCT) in milk fat and various feed ingredients, including coconut and palm oils (Rossi et al., 2010); however, MCFA as feed additives for swine are commercially available as single MCFA or blends of MCFA. Previous research by Cochrane et al. (2016a, b) observed that the inclusion of a MCFA blend (1:1:1 ratio of C6:0, C8:0, and C10:0) at 1.0 and 2.0% of the diet decreased the presence of Salmonella Typimurium ATCC 14028 and enhanced RNA degradation of PEDV in swine feed and ingredients. They also observed similar results when testing individual fatty acids (C6:0, C8:0, C10:0) at 0.66% of the diet (Cochrane et al., 2017). Because of these desirable antibacterial and antiviral effects, further research by Gebhardt et al. (2019) was conducted to determine the effects on growth performance when feeding nursery pigs diets containing these blends of MCFA, as well individual fatty acids. Gebhardt et al. (2019) reported ADG, ADFI and G:F increased linearly as MCFA (1:1:1 ratio among C6:0, C8:0, and C10:0) increased up to 1.5% of the diet and the addition of individual fatty acids at 0.5% (C6:0, C8:0, or C10:0) resulted in an improvement in ADG and G:F.

In Exp. 1, our results were similar to Gebhardt et al. (2019) in that we observed that feeding up to 2% CaptiSURE and 1.0% of the 1:1:1 MCFA blend, resulted in increased ADG, ADFI, and G:F compared to the control diet. In Exp. 2, pigs fed 1.0% inclusion of the 1:1:1 MCFA blend performed much like those in Exp. 1 and had improved growth performance compared to pigs fed the control diet. These results are consistent with previous literature evaluating the effects of dietary additions of C6:0, C8:0, and C10:0 on growth performance (Zentek et al., 2011; Hanczakowska et al., 2017; Cochrane, 2018). When evaluating individual fatty acids, previous research with C6:0 at 0.5% inclusion showed an improvement in growth performance (Gebhardt et al., 2019); however, in Exp. 2, these benefits were not observed. The

1.0% inclusion of the MCFA blend used in Exp. 2 contained 50% C6:0 and varying amounts of C12:0, and its monoglyceride, monolaurin. Interestingly, Cochrane et al. (2017) reported enhanced RNA degradation of PEDV in swine feed and ingredients for C6:0, C8:0, and C10:0, but not for C12:0. Thus, the MCFA blends included in Exp. 2 with C6:0, C12:0, and monolaurin might be less effective compared to MCFA blends of C6:0, C8:0, and C10:0. Specifically, the inclusion of C12:0 and the impact on growth performance.

Uncertainty still exists about the growth promoting mechanisms of MCFA beyond reducing bacterial or viral load in complete feed (Cochrane et al., 2016a, b; 2017). It is speculated that the antibacterial and antiviral properties of MCFA may reduce the bacterial population within the gut and enhance nutrient absorption in the small intestines, resulting in a healthier pig (Hanczakowska et al., 2017). In a review by Zentek et al. (2011), authors suggest the use of MCFA in swine diets alter the acidification in the stomach of the animal and provide desirable antibacterial effects. Newly weaned pigs appear to have a high capacity to oxidize fatty acids, and MCFA can be used directly by the enterocytes in the upper small intestine for efficient energy production as well as help to support the integrity of the intestinal tissue (Zentek et al., 2011). Specifically, MCFA are thought to work by lowering intestinal pH, stimulating enzyme secretion, and inhibiting pathogenic bacteria, thereby improving nutrient digestibility and retention (Baustadt, 1993; Papatsiros et al., 2012; Decuypere and Dierick, 2003; Upadhaya, 2018). Although research in this area is inconsistent, previous research has also indicated MCFA can influence epithelial function (villus length, crypt depth) in the upper small intestine, thereby increasing uptake and utilization of nutrients through the intestinal wall (Dierick et al., 2004; Hanczakowska et al., 2011; Chwen et al., 2013). However, others have found no evidence for

differences in intestinal morphology when feeding MCFA (Biagi et al., 2006; Ferrara et al., 2016; Hanczakowska et al., 2016).

In addition to supplementing swine diets with MCFA, lactic acid and monolaurin have been considered as antibiotic replacements. Much like MCFA, lactic acid has strong antimicrobial properties and reduces gastric pH, improves pancreatic secretions that increase nutrient digestibility, and reduces the production of harmful microbes, thereby improving pig growth performance (Thompson and Lawrence, 1981). In general, the antimicrobial impact of lactic acid is directed against gram-negative bacteria (Suiryanrayna and Ramana, 2015), whereas most MCFA, specifically C12:0 and its monoglyceride ester monolaurin, target gram-positive bacteria (Ruzin and Novick, 2000; Dansen, 2016). Therefore, the theory behind the development of the MCFA product used in Exp. 2 was that by creating blends of MCFA, other organic acids, and MCFA monoglycerides, different populations of bacteria within the gut would be targeted thereby further reducing microbial populations that may negatively affect pig growth.

In Exp. 2, when pigs consumed the added 1.0% of MCFA, acidifier and monolaurin blends, we observed no evidence for differences in growth performance compared to the control group. These results are similar to those of Zentek et al. (2013) where the authors fed nursery pigs diets with or without 1.05% organic acid product (31.2% lactic acid and 39.8% fumaric acid, with silicium dioxide as a carrier material) and with or without 0.3% MCFA (1:1 ratio C8:0 and C10:0) and found no evidence for differences in ADG, ADFI, or G:F among dietary treatments. However, these results are in disagreement with previous literature where different combinations of organic acids and MCFA had positive effects on growth performance, as well as nutrient digestibility in pigs (Hanczakowska et al., 2013; Upadhaya et al., 2014; Kuang et al., 2015; Long et al., 2018). Inconsistencies in literature surrounding the effects of MCFA and

MCFA blends on nursery pig growth performance can be attributed to many factors, including inclusion level, type of MCFA or blend, basal diet characteristics, and physiological status of the animal (Geng et al., 2016).

The effect MCFA have on feed intake is a specific area of interest. Previous research agrees that free MCFA can produce strong goat-like odors and often lead to a reduction in feed intake (Molimard et al. 1997; Cera et al., 1989; Timmermann, 1993). In addition, MCFA can induce the release of cholecystokinin which can negatively influence the feeling of satiety and lower feed intake (Mabayo et al., 1992; Dierick et al., 2002). However, research in this area is inconsistent. In both experiments herein, free MCFA C6:0, C8:0, and C10:0 produced strong odors both in pure form and in the complete feed, as well as the blended products; however, ADFI increased linearly as added MCFA increased. It is important to note that prior to being provided with the dietary treatments, pigs in both experiments were allowed a 4-d adaptation period during which starter diets were fed to encourage feed intake prior to the start of the trial.

In conclusion, the addition of 1.0% 1:1:1 blend of C6:0, C8:0, and C10:0 in nursery pig diets increased ADG, ADFI, and G:F compared with control-fed pigs. Providing nursery pigs with CaptiSURE, a MCFA-based feed additive made up of predominantly C8:0 and C10:0 fatty acids, improved ADG, ADFI, and G:F up to 2.0% of the diet. Altering the blend of individual fatty acids and adding lactic acid and monolaurin showed similar nursery pig growth performance to those fed the control diet. Additional research is warranted to understand if a blend of MCFA, acidifiers, and monoglycerides can be created to achieve similar benefits in growth performance shown from the 1.0% 1:1:1 MCFA blend and provide a beneficial economic return.

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Table 1.1 Diet composition, Exp. 1 (as-fed basis)[1]

Ingredient, %	Phase 1	Phase 2
Corn	54.43	62.07
Soybean meal, 46.5% CP	26.42	31.63
Whey powder	10.00	---
Enzymatically-treated soybean meal[2]	2.50	---
Soybean oil	2.00	2.00
Calcium carbonate	0.95	1.00
Monocalcium P (21% P)	1.30	1.15
Salt	0.60	0.60
L-Lysine HCl	0.50	0.51
DL-Methionine	0.24	0.23
L-Threonine	0.21	0.21
L-Tryptophan	0.05	0.06
L-Valine	0.15	0.14
Trace mineral[3]	0.15	0.15
Vitamin premix[4]	0.25	0.25
Phytase[5]	0.02	0.02
Zinc oxide	0.25	---
MCFA additive[6]	+/-	+/-
Total	100	100
Calculated analysis		
Standardized ileal digestible (SID) amino acids, %		
Lysine	1.35	1.35
Isoleucine:lysine	55	55
Leucine:lysine	111	113
Methionine:lysine	37.4	37.3
Methionine and cysteine:lysine	58.1	58.1
Threonine:lysine	63.0	62.0
Tryptophan:lysine	20.1	20.3
Valine:lysine	70.2	70.1
Total lysine, %	1.48	1.49
Net energy, kcal/kg	2,529	2,511
SID lysine:NE, g/Mcal	5.69	5.63
Crude protein, %	20.6	21.1
Calcium, %	0.75	0.70
Phosphorus, %	0.68	0.63
Available phosphorus, %	0.51	0.42
STTD P, %[7]	0.54	0.47

[1]Phase 1 and 2 diets were fed from approximately 6.3 to 10.4 and 10.4 to 23.1 kg body weight (BW), respectively.
[2]HP 300 (Hamlet Protein, Findlay, OH).
[3]Provided per kilogram of premix: 22 g Mn from manganese oxide; 73 g Fe from iron sulfate; 73 g Zn from zinc sulphate; 11 g Cu from copper sulfate; 198 mg I from calcium iodate; and 198 mg Se from sodium selenite.
[4]Provided per kilogram of premix: 3,527,360 IU vitamin A; 881,840 IU vitamin B3; 17,637 IU vitamin E; 3,307 mg riboflavin; 1,764 mg menadione; 11,023 mg pantothenic acid; 33,069 mg niacin; and 15.4 mg vitamin B12.
[5]Ronozyme HiPhos 2700 (DSM Nutritional Products, Parsippany, NJ) providing 406.3 phytase units (FTU)/kg and an estimated release of 0.10% STTD P.
[6]Medium chain fatty acids included as a 1:1:1 blend of C6:0, C8:0, and C10:0 (Sigma Aldrich, St. Louis, MO), guaranteed ≥ 98% purity) were added in Exp. 1 and 2. In Exp. 1 CaptiSURE (Kemin Industries, Inc. (Des Moines, IA)), added at the expense of soybean oil. In Exp. 2 the blend of MCFA, lactic acid, and monolaurin-based additive (Tech Mix, LLC, Stewart, MN), added at the expense of soybean oil.
[7]STTD P = Standardized total tract digestible phosphorus.

Table 1.2 Chemical analysis of experimental diets, Exp. 1, (as-fed basis)[1]

	Added MCFA, %				
	CaptiSURE[2]				C6:0:C8:0:C10:0[3]
Analyzed composition, %[4]	0	0.5	1.0	2.0	1.0
Phase 1					
DM	89.73	89.97	89.67	89.19	90.09
CP	20.10	19.85	20.05	20.70	20.10
ADF	3.50	3.45	3.30	3.25	3.70
Ether extract	3.95	3.70	3.10	2.40	3.50
Ca	0.96	0.86	0.92	1.02	1.02
P	0.65	0.63	0.62	0.67	0.68
Total MCFA[5]	---	0.43	0.84	1.60	0.63
Phase 2					
DM	89.46	89.04	89.29	88.54	89.62
CP	20.25	19.85	20.55	21.10	20.20
ADF	3.40	3.70	4.20	3.95	3.45
Ether extract	4.05	4.20	3.80	2.60	3.30
Ca	0.93	1.09	1.01	0.91	0.98
P	0.59	0.61	0.61	0.60	0.64
Total MCFA[5]	---	0.48	0.89	1.89	0.71

[1]Diets were fed from d 0 to 13 and 14 to 34 for phases 1 and 2, respectively.
[2]Kemin Industries, Inc (Des Moines, IA).
[3]Consisted of a 1:1:1 blend of C6:0, C8:0, and C10:0. (Sigma Aldrich, St. Louis, MO).
[4]Complete diet samples were taken from 5 feeders per dietary treatment 4 times throughout the study. Samples were stored at -20°C until they were homogenized, subsamples, and submitted to Ward Laboratories, Inc. (Kearney, NE) for proximate analysis and Kemin Industries, Inc. (Des Moines, IA) for medium chain fatty acids (MCFA) analysis performed in duplicate. Reported values are average of duplicate analysis.
[5]Sum of analyzed C8:0 and C10:0 MCFA.

Table 1.3 Chemical analysis of experimental diets, Exp. 2, (as-fed basis)[1]

		1% MCFA, lactic acid and monolaurin blends[2]				1% MCFA[3]
Analyzed composition, %[4]	Control	1	2	3	4	C6:0:C8:0:C10:0
Phase 1						
DM	90.55	90.51	90.89	90.47	90.79	90.43
CP	20.10	20.50	20.10	20.80	20.75	20.70
ADF	1.80	1.75	1.70	1.95	1.95	1.95
Ether extract	3.85	3.40	3.70	3.70	3.75	3.80
Ca	0.86	0.79	0.85	0.90	0.96	0.82
P	0.64	0.66	0.61	0.71	0.70	0.67
Total MCFA	---	0.45	0.42	0.43	0.33	0.51
Phase 2						
DM	89.97	89.64	90.04	89.99	89.89	89.68
CP	21.65	20.65	22.00	21.70	21.25	21.35
ADF	2.75	1.65	1.95	1.65	1.70	2.10
Ether extract	4.70	2.85	3.35	3.15	3.45	3.90
Ca	0.91	0.72	0.50	0.83	0.68	0.89
P	0.65	0.55	0.52	0.57	0.53	0.64
Total MCFA	---	0.52	0.51	0.48	0.32	0.59

[1]Diets were fed from d 0 to 14 and 14 to 35 for phases 1 and 2, respectively.
[2]Consisted of a blend of C6:0, C12:0, lactic acid, and monolaurin (Tech Mix, LLC, Stewart, MN). The 4 blends consisted of 50% C6:0, 20% lactic acid, and increasing levels of monolaurin (0, 10, 20, and 30%) at the expense of C12:0 (30, 20, 10, and 0%) in products 1 through 4, respectively.
[3]Consisted of a 1:1:1 blend of C6:0, C8:0, and C10:0. Sigma Aldrich (St. Louis, MO).
[4]Complete diet samples were taken from 5 feeders per dietary treatment 4 times throughout the study. Samples were stored at -20°C until they were homogenized, subsampled, and submitted to Ward Laboratories, Inc. (Kearney, NE) for proximate analysis and University of Missouri Experimental Station Chemical Laboratories (Columbia, MO) for medium chain fatty acids (MCFA) analysis performed in duplicate. Reported values are an average of duplicate analysis.
[5]Sum of analyzed C6:0, C8:0, C10:0, and C12:0 MCFA.

Table 1.4 Effect of medium chain fatty acid (MCFA)-based additives on nursery pig growth performance (Exp. 1)[1]

	Added MCFA, %						Probability, <		
	CaptiSURE[2]				C6:0:C8:0:C10:0[3]				
Item	0	0.5	1.0	2.0	1.0	SEM	Linear[4]	Quadratic[4]	1.0% CaptiSURE vs. 1.0% blend
BW, kg									
d 0	6.3	6.3	6.3	6.3	6.3	0.05	0.778	0.927	0.911
d 13	9.9	10.2	10.4	10.4	10.2	0.14	<0.001	0.062	0.288
d 34	21.8	22.8	23.2	23.6	23.1	0.33	<0.001	0.089	0.838
d 0 to 13									
ADG, g	278	301	314	319	303	8.6	<0.001	0.063	0.294
ADFI, g	338	364	353	360	352	9.9	0.149	0.211	0.912
G:F, g/kg	819	827	890	889	860	12.8	<0.001	0.104	0.091
d 13 to 34									
ADG, g	567	600	605	627	615	10.6	<0.001	0.273	0.446
ADFI, g	820	835	839	865	853	14.9	0.013	0.974	0.440
G:F, g/kg	692	719	721	725	722	5.9	<0.001	0.013	0.953
d 0 to 34									
ADG, g	455	486	493	509	496	9.0	<0.001	0.127	0.779
ADFI, g	634	655	652	671	662	12.3	0.014	0.693	0.494
G:F, g/kg	718	742	756	758	750	5.5	<0.001	0.002	0.360

[1]A total of 350 pigs (DNA 400 × 200; initial BW = 6.3 kg) were used in a 34-d experiment with 5 pigs per pen and 14 pens per treatment. Pigs were weaned at approximately 21 d, fed a common starter diet for 4 d postweaning, then placed on experimental diets.
[2]Kemin Industries, Inc. (Des Moines, IA).
[3]Consisted of a 1:1:1 blend of C6:0, C8:0, and C10:0 (Sigma Aldrich, St. Louis, MO).
[4]Linear and quadratic contrast statements include treatments with CaptiSURE (Kemin Industries, Inc, Des Moines, IA) MCFA.

Table 1.5 Effect of medium chain fatty acids (MCFA) on nursery pig growth performance (Exp. 2)[1]

		1% MCFA, lactic acid and monolaurin blends[2]				1% MCFA[3]		Probability, $P <$			
Item	Control	1	2	3	4	C6:0:C8:0:C10:0	SEM	Control vs. 1% C6:0:C8:0:C10:0	Control vs. blends[4]	Linear[4]	Quadratic[5]
BW, kg											
d 0	6.8	6.8	6.8	6.8	6.8	6.8	0.05	0.918	0.943	0.730	0.303
d 14	9.9	10.1	10.2	10.2	10.3	10.4	0.17	0.042	0.132	0.355	0.802
d 35	21.6	21.8	22.0	22.1	22.2	22.5	0.28	0.014	0.134	0.267	0.840
d 0 to 14											
ADG, g	225	239	240	246	254	259	11.2	0.037	0.127	0.304	0.750
ADFI, g	286	280	283	287	300	305	11.3	0.223	0.887	0.204	0.676
G:F, g/kg	788[b]	852[ab]	847[ab]	855[a]	844[ab]	846[ab]	16.2	0.013	0.001	0.838	0.868
d 14 to 35											
ADG, g	554	555	565	564	565	577	8.9	0.057	0.366	0.402	0.600
ADFI, g	772	785	793	792	794	820	14.0	0.015	0.206	0.641	0.822
G:F, g/kg	719	707	713	713	713	705	7.7	0.230	0.416	0.645	0.686
d 0 to 35											
ADG, g	422	427	435	437	441	450	7.7	0.014	0.149	0.202	0.796
ADFI, g	577	581	588	590	597	614	11.9	0.034	0.382	0.359	0.932
G:F, g/kg	733	736	739	741	740	734	6.56	0.932	0.422	0.628	0.713

[1]A total of 360 pigs (DNA 400 × 200; initial body weight (BW) = 6.8 kg) were used in a 35-d experiment with 5 pigs per pen and 12 pens per treatment. Pigs were weaned at approximately 21 d, fed a common starter diet for 4 d postweaning, then placed on experimental diets. Values with different superscripts within a row differ, $P < 0.05$.

[2]Consisted of a blend of C6:0, C12:0, lactic acid, and monolaurin (Tech Mix, LLC, Stewart, MN). The 4 blends consisted of 50% C6:0, 20% lactic acid, and increasing levels of monolaurin (0, 10, 20, and 30%) at the expense of C12:0 (30, 20, 10, and 0%) in products 1 through 4, respectively.

[3]Consisted of a 1:1:1 blend of C6:0, C8:0, and C10:0 (Sigma Aldrich, St. Louis, MO).

[4]Contrast comparing the control group to the average of the four diets including different blends of MCFA, lactic acid, and monolaurin blends included at 1.0% of the diet.

[4]Linear effects of increasing monolaurin, at the expense of C12:0, within the 1% MCFA, lactic acid, and monolaurin blend.

[5]Quadratic effects of increasing monolaurin, at the expense of C12:0, within the 1% MCFA, lactic acid, and monolaurin blend.

Chapter 2 - Nutritional Evaluation of Different Varieties of Sorghum and the Effects on Nursery Pig Performance

ABSTRACT: Five experiments were conducted to determine the standardized total tract digestibility (STTD) of P and Ca, digestible (DE) and metabolizable energy (ME), and standardized ileal digestibility (SID) of AA in three sorghum varieties compared to corn and to determine the effects of sorghum varieties on nursery pig growth. In Exp. 1, 48 barrows (initially 18.6 kg) were housed individually in metabolism crates. Treatments were arranged in a 2 × 4 factorial evaluating 2 levels of microbial phytase (0 or 500 units/kg; Quantum Blue 5G; AB Vista, Marlborough, UK) and 4 grain sources (corn, high-lysine, red, or white sorghum). Added phytase improved ($P \leq 0.05$) STTD of P in all ingredients, but STTD of P was not different among the grains. In Exp. 2, the DE and ME in the 3 sorghum varieties were not different from corn. In Exp. 3, 10 growing barrows (initially 25.9 kg) were surgically fitted with a T-cannula at the terminal ileum. Standardized ileal digestible crude protein (CP), lysine, methionine, threonine, and valine were greater ($P < 0.040$) in corn than the sorghum-based diets with no evidence for differences among the three varieties. In Exp. 4, 160 pigs (initially 6.3 kg) were randomly allotted to 1 of 4 dietary treatments with 5 pigs per pen and 8 replicate pens per treatment in a 20-d experiment. Dietary treatments included corn or the three sorghum varieties, where the varieties of sorghum replaced corn on an SID lysine basis. No differences among treatments were observed in any growth performance parameters. In Exp. 5, treatments consisted of a corn-based diet, a diet based on conventional sorghum (a mixture of red and white sorghum), and 4 diets with high-lysine sorghum containing increasing amounts of feed grade AA, replacing SBM. Overall, there was no evidence for differences in ADG or ADFI among dietary treatments; however, pigs fed the high-lysine sorghum with the greatest amount of added

feed-grade AA had the poorest G:F (P = 0.045) compared with those fed other experimental diets. In summary, no differences in STTD of P or in DE and ME were observed between the grain sources. The SID AA values for the three sorghum varieties were not different; however, they were all lower compared to corn. When swine diets for nursery pigs were formulated on a SID AA basis, there were no differences in ADG between the sorghum sources. These results suggest that these varieties of sorghum can successfully replace corn in nursery pig diets if diets are formulated to account for differences in AA digestibility.

Key words: High-lysine sorghum, corn, feed-grade AA, nursery pigs

Introduction

Among the cereal grains, corn is the most commonly used in swine diets in the United States however; sorghum is also an excellent energy source and can be used as a complete or partial replacement (Stein et al., 2016). Previous literature suggests that sorghum can successfully replace corn in nursery pig diets, with minimal differences observed in growth performance (Fialho et al., 2004; Sotak et al., 2014; Goodband et al., 2016). Depending on the variety, crude protein (CP) content of sorghum may vary from 6.8 to 19.6% and can have high concentrations of indispensable amino acids (AA; Hulse et al., 1980; Subramanian et al., 1990). This suggests that specific varieties of sorghum can not only replace corn but can be fed in diets supplemented with feed-grade AA and replace a portion of soybean meal (SBM), potentially lowering diet cost. However, when fed to nonruminants, specific varieties of sorghum may have reduced nutritional value compared with corn (Khoddami et al., 2015), thereby having negative effects on growth performance.

The nutritional value of sorghum is reduced in varieties with high tannin content, because tannins are antinutritional factors. Tannins are plant secondary metabolites, which may inhibit enterocyte metabolism, amylase activity, and have the ability to form complexes with dietary protein, and thereby reduce sugar and AA absorption (Butler et al., 1984; Karasov et al., 1992). Corn and sorghum also contain phytate, which consists of one myo-inositol molecule and six molecules of inorganic phosphate (Birgit et al., 2002). Pigs do not synthesize adequate amounts of endogenous phytase to liberate the P in phytate and the phytate bound P, therefore, P is not available for absorption and is the reason for the low digestibility of Ca and P (Birgit et al., 2002; Liao et al., 2005). If microbial phytase is not provided in the diet, P and Ca absorption and utilization may be compromised (Pallauf et al., 1994).

The breeding of sorghum has generated new varieties, selected to have reduced concentrations of anti-nutritional factors (Stein et al., 2016). One of these new varieties was predicted to have greater concentrations of AA, specifically lysine, compared to conventional varieties. However, there is no data for effects of adding phytase to diets containing sorghum and no data to demonstrate the nutritional value of this specific variety of high-lysine sorghum and the effect of nursery pig growth performance. Therefore, the first objective of this study was to determine the nutritional value of high-lysine sorghum compared to conventional sorghum varieties, and corn based on standardized total tract digestibility (STTD) of P with the inclusion of microbial phytase (Exp. 1), digestible energy (DE) and metabolizable energy (ME) (Exp. 2), and standardized ileal digestibility (SID) of AA (Exp. 3). The second objective was to compare nursery pig growth performance among the different grain sources (Exp. 4) as well as the effect of high-lysine sorghum and increasing additions of feed-grade AA on nursery pig growth performance (Exp. 5).

Materials and Methods

General

The University of Illinois and Kansas State University Institutional Animal Care and Use Committees approved the protocols used in these experiments. Experiments 1, 2, 3, and 4 were conducted at the University of Illinois (Urbana-Champaign) Swine Research Center and Exp. 5 was conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. One batch of corn, high-lysine sorghum, red sorghum, and white sorghum were obtained and ground to 500 microns at Kansas State University and shipped to the Swine Research Center at the University of Illinois at Urbana-Champaign. Multiple samples were collected from each ingredient, homogenized, and then subsampled for analysis (Table 1).

Experiment 1: Phosphorus Digestibility

Experiment 1 was designed to determine the apparent total tract digestibility (ATTD) of Ca and P, as well as STTD of P in corn, high-lysine, red, and white sorghum varieties. A total of 48 growing barrows (initially 18.6 kg; Line 359 × Camborough®; PIC, Hendersonville, TN) were randomly allotted to 1 of 8 dietary treatments in a randomized complete block design with 6 replicate pigs per diet. Dietary treatments were arranged in a 2 × 4 factorial design with 2 levels of microbial phytase (0 or 500 units/kg; Quantum Blue 5G; AB Vista, Marlborough, UK) and 4 grain sources (corn, high-lysine, red, or white sorghum). All diets were formulated to meet or exceed current vitamin and mineral requirement estimates (NRC, 2012), except P (Table 2).

Pigs were placed in individual metabolism crates that were equipped with a self-feeder, a nipple waterer, and slatted floors to allow for total collection of feces. All diets were fed in meal form. Pigs were limit fed at 3 times the energy requirement for maintenance (i.e., 197 kcal/kg ×

BW0.60; NRC, 2012), which was provided each day in 2 equal meals at 0800 and 1700 h. Throughout the study, pigs had free access to water. Feed consumption was recorded daily and diets were fed for 12 d. The initial 5 d was considered the adaptation period to the diet, whereas fecal material was collected during the following 4 d according to standard procedures using the marker to marker approach (Adeola, 2001).

Fecal samples were stored at -20oC immediately after collection. Fecal samples were thawed at the conclusion of the experiment and mixed within pig and diet, and then dried in a 50°C forced air drying oven and ground through a 1-mm screen in a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ) prior to analysis. Fecal and diet samples were analyzed for DM (Method 930.15; AOAC Int., 2007) and ash (Method 942.05; AOAC Int., 2007), and Ca and P were analyzed by inductively coupled plasma optical emission spectrometry using an internally validated method (Method 985.01 A, B, and C; AOAC, 2007) after wet ash sample preparation (Method 975.03 B[b]; AOAC, 2007). Ingredients were analyzed for Ca and P and other minerals as explained for diets. Ingredients were also analyzed for phytic acid (Ellis et al., 1977), and diets were analyzed for phytase activity (method 2000.012; AOAC Int., 2007). The ATTD of P in each source of cereal grain was calculated. By correcting these values for the basal endogenous losses of P (i.e., 190 mg per kg dry matter intake; DMI), values for the STTD of P in each cereal grain both without and with added phytase were calculated (NRC, 2012).

Experiment 2: Energy Measurements

Experiment 2 was conducted to determine the ATTD of GE and the DE and ME in the four grain sources used in experiment 1. A total of 32 growing barrows (initially 18.5 kg; Line 359 × Camborough®; PIC, Hendersonville, TN) were randomly allotted to 1 of 4 dietary treatments in a randomized complete block design with 8 replicate pigs per diet. Dietary

treatments contained either 1 of the four gain sources as the only energy-containing ingredient (Table 3). All diets were formulated to meet or exceed current vitamin and mineral requirement estimates (NRC, 2012).

Pigs were housed individually in metabolism crates that were equipped with a self-feeder, a nipple waterer, and a slatted floor. A screen and a urine pan were placed under the slatted floor to allow for the total, but separate, collection of urine and fecal materials. Pigs were fed at 3 times the energy requirement for maintenance (i.e., 197 kcal/kg × BW0.60), which were provided each day in 2 equal meals at 0800 and 1600 h. Throughout the study, pigs had ad libitum access to water. Each period lasted 12 d. The initial 5 d was considered the adaptation period to the diet, whereas urine and fecal material were collected during 4 d according to standard procedures using the marker to marker approach. Urine was collected in urine buckets over a preservative of 50 mL of hydrochloric acid. Fecal samples and 10% of the collected urine were stored at -20oC immediately after collection. At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet, and a sub-sample was lyophilized before analysis (Kim et al., 2009).

Fecal samples were thawed and mixed within pig and diet, and then dried in a 50°C forced air drying oven prior to analysis. Ingredients and diets were analyzed for DM and ash as explained for Exp. 1. Ingredients, diets, fecal, and urine samples were analyzed for GE using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL). Ingredients were analyzed for CP using the combustion procedure (Method 990.03; AOAC Int., 2007) and for acid hydrolyzed ether extract (AEE) by acid hydrolysis using 3N HCl (Ankom HCl Hydrolysis System, Ankom Technology, Macedon, NY) followed by fat extraction (Ankom XT-15 Extractor, Ankom Technology, Macedon, NY). Ingredients were also analyzed for insoluble dietary fiber (IDF) and

soluble dietary fiber (SDF) according to method 991.43 (AOAC Int., 2007) using the AnkomTDF Dietary Fiber Analyzer (Ankom Technology, Macedon, NY). Total dietary fiber was calculated as the sum of insoluble dietary fiber and soluble dietary fiber. Starch was analyzed in all ingredients using the glucoamylase procedure (Method 979.10; AOAC Int., 2007). Glucose, fructose, maltose, sucrose, stachyose, and raffinose were analyzed in all ingredients by extracting and quantifying the sugars using high-performance liquid chromatograpy (HPLC) and a pulsed amperometric detector (Dionex) as described by Cervantes-Pahm and Stein (2010). Tannic acid was analyzed in high-lysine sorghum, red sorghum, and white sorghum as described by Taylor et al. (2007).

Following analysis, the ATTD of GE and DM was calculated for each diet, and the DE and ME in each diet were calculated as well (Adeola, 2001). The DE and ME of each source of sorghum or of corn were calculated by dividing the DE and ME of the diet by the inclusion rate of sorghum or corn in that diet.

Experiment 3: Ileal Digestibility

The objective of Exp. 3 was to determine the SID of AA in the 4 grain sources. Ten growing barrows (initially 25.9 kg; Line 359 × Camborough®; PIC, Hendersonville, TN) were fitted with a T-cannula in the distal ileum and were randomly allotted to 1 of 5 test diets in a 5-period design with 2 replicate pigs per diet in each period for a total of 10 replicates per diet. The first diet contained 94.0% corn, and the other diets contained 94.2% of a high-lysine, red or white sorghum varieties as the only energy-containing ingredient. In each of these diets, corn or sorghum were the only source of AA (Table 4). The fifth diet was a N-free diet that was used for determining basal AA endogenous losses from the small intestine. All diets were formulated to meet or exceed current vitamin and mineral requirement estimates (NRC, 2012) and contained

0.40% chromic oxide as an indigestible marker. Complete diet samples were obtained and stored for later analysis.

Pigs were housed individually in metabolism crates (1.2 × 1.5 m) equipped with a nipple drinker that allowed for unlimited access to water. Pens had smooth sides and fully slatted tribar floors. A screen and urine pan were placed under the slatted floor to allow for total, but not separate, collection of urine and fecal materials. Each pig was weighed at the beginning of each period before being fed the next dietary treatment to determine the amount of feed needed per day at a level 3.2 times the estimated maintenance requirement (i.e., 197 kcal per kg BW0.6; NRC, 2102) for energy. Pigs were also weighed at the conclusion of the experiment. Daily feed allocation was recorded. Each period consisted of a 5-d adaptation during which a supplemental AA mixture was added to dietary treatments. On d 6 and 7, the supplemental AA mixture was not provided and dietary treatments were the only source of AA. Ileal digesta collection occurred on d 6 and 7 for 8 h each day. Digesta samples were collected by attaching a plastic bag to the cannula barrel and digesta flowing into the bag was collected. The plastic bags were removed every 30 minutes or as soon as they became full. Thereafter, the collected samples were immediately frozen at -20°C to prevent any bacterial degradation of the AA in the digesta. Feed was withdrawn at the end of each period before giving the next experimental diet the following morning to avoid any carryover effects.

At the conclusion of experiment, digesta samples from each pig were thawed, mixed within animal and diet, dried, and sub-sampled for chemical analysis. Digesta samples were lyophilized and finely ground for chemical analysis. Digesta samples, grain ingredient samples, and complete diet samples were analyzed for DM (method 930.15; AOAC Int., 2007), chromium, CP (method 990.03; AOAC Int., 2007), and AA according to the AOAC procedures

(AOAC, 2007) and apparent ileal digestibility (AID) and SID values were calculated based on methods from Stein et al. (2007).

Experiment 4: Growth Performance and Diarrhea Frequency from 6.3 to 10.4 kg

Experiment 4 was designed to determine effects of the 4 grain sources on growth performance and diarrhea frequency of weanling pigs. A total of 160 weaned pigs (initially 6.3 kg; Line 359 × Camborough®; PIC, Hendersonville, TN) were randomly allotted to 4 dietary treatments with 5 pigs per pen and 8 replicate pens per treatment. Treatments consisted of diets formulated based on either corn, red, white, or high-lysine sorghum, where the varieties of sorghum replaced corn on an SID lysine basis (Table 5). Treatment diets were formulated and manufactured in two dietary phases (phase 1 = d 0 to 11; phase 2 = d 11 to 20) and were formulated to meet the current estimates for nutrient requirements (NRC, 2012) for 5 to 7 and 7 to 11 kg pigs, respectively.

Pigs were weighed individually and feed disappearance was recorded at the beginning of the experiment and at the conclusion of each phase to determine ADG, ADFI, and G:F. Diarrhea scores were assessed visually every other day using a score from 1 to 5 (1 = normal feces; 2 = moist feces; 3 = mild diarrhea; 4 = severe diarrhea; and 5 = watery diarrhea). Diarrhea frequency was obtained by totaling the number of pen days with diarrhea scores ≥ 3 divided by the total number of pen days multiplied by 100.

All diets were ground as explained for Exp. 1 prior to chemical analysis. Diets were analyzed for DM, ash, GE, CP, and AEE as explained for Exp. 1 and 2. Diets were also analyzed for AA on a Hitachi AA Analyzer (Model No. L8800; Hitachi High Technologies America, Inc., Pleasanton, CA) using ninhydrin for postcolum derivatization and norleucine as the internal

standard (Method 982.30 E (a, b, c); AOAC Int., 2007), and Ca and P were analyzed as explained for Exp. 1.

Experiment 5: Effect of High-Lysine Sorghum on Nursery Pig Performance from 9.6 to 20.9 kg

Experiment 5 was designed to determine the effect of high-lysine sorghum and increasing additions of feed-grade AA on nursery pig growth. At weaning, approximately 21 d of age, 300 pigs were moved to the nursery and randomly allotted to pen of 5 based on initial BW. Pigs were fed a common diet for 20 d after weaning. On d 20 after weaning, considered d 0 in the trial, a total of 293 pigs (initially 9.7 kg; Line 241 × 600; DNA, Columbus, NE) were enrolled in a 20-d growth trial where pens were randomly assigned to 1 of 6 dietary treatments with 10 replications per treatment. Each pen (1.2 × 1.5 m) contained a 4-hole, dry, self-feeder and a nipple waterer to provide ad libitum access to feed and water.

Experimental treatments included a corn-based diet, a diet based on conventional sorghum, and 4 diets with high-lysine sorghum. The corn-based, conventional sorghum, and the first high-lysine sorghum (low) diets were formulated to contain the same amount of SBM, each with varying amounts of feed-grade AA. The 3-remaining high-lysine diets (low-med, med-high, and high) included incrementally increasing amounts of feed-grade AA, at the expense of SBM. Corn and SBM were analyzed for AA profile in duplicate for total AA (except Trp; method 982.30 e; AOAC 2006), Trp (method 988.15; AOAC 2006), and CP (method 982.30 E(a); AOAC 2006) by the University of Missouri Agricultural Experiment Station Chemical Laboratory (Columbia, MO), and diets were formulated from these values. The conventional sorghum used in this study was a 50:50 blend of red and white and an average of the analyzed AA values were used in formulation. Diets with conventional sorghum varieties and high-lysine

sorghum were formulated based on the SID results obtained in Exp. 3. Corn and SBM in treatment diets were formulated using SID coefficients from NRC (2012). All diets were fed in meal form and formulated to the same Lys:NE ratio (Table 6). Treatments were fed for 20 d. Each pen was equipped with a 4-hole, dry self-feeder and nipple waterer to provide ad libitum access to feed and water. Pens of pigs were weighed and feed disappearance was recorded on d 0, 7, 14, and 20 to determine ADG, ADFI, and G:F.

Experimental diets were manufactured at the Kansas State University O.H. Kruse Feed Technology Innovation Center, Manhattan, KS. Complete diet samples were taken from 5 feeders per dietary treatment 3 times throughout the study. Samples were stored at -20° until they were homogenized, subsampled, and submitted to a commercial laboratory (Ward Laboratories, Inc., Kearney, NE) for analysis of DM (method 935.29; AOAC Int., 2012), CP (AOAC 900.03, 2012), Ca, and P (method 968.08 b; AOAC Int., 2012; for preparation using ICAP 6500, ThermoElectron Corp., Waltham, MA), ether extract (method 920.39 a; AOAC 2012; for preparation and ANKOM XT20 Fat Analyzer; Ankom Technology), and ash (method 942.05 a; AOAC, 2012). In addition, AA analysis was evaluated at the University of Missouri Agricultural Experiment Station Chemical Laboratory (Columbia, MO). Samples were analyzed in duplicate for total AA (except Trp; method 982.30 e; AOAC 2006), Trp (method 988.15; AOAC 2006), and CP (method 982.30 E(a); AOAC 2006).

Statistical Analysis

In Exp. 1 and 2, the data were analyzed as a randomized complete block using the MIXED procedure of SAS (SAS Institute Inc., Cary, NC) with the pig as the experimental unit. In Exp. 1, the model included source of cereal grain, phytase, and the interaction between source of cereal grain and phytase as the main effects. Block and replicate were considered random

effects. In Exp. 2, diet or ingredient was the fixed effect and replicate was the random effect. Least squares means were calculated using an LSD test, and if the model was significant, means were separated using the PDIFF statement. In Exp. 3, the data were analyzed using the PROC MIXED procedure of SAS. The model included grain source as a fixed effect and pigs and period as random effects. In Exp. 4, data were analyzed using the MIXED Procedure of SAS with the pen as the experimental unit. Least squares means were calculated and means were separated as explained for Exp. 1. The chi-squared test was used to analyze frequency of diarrhea among treatments. In Exp. 5, the data were analyzed as a randomized complete block design using the GLIMMIX procedure of SAS, version 9.4, with pen as the experimental unit. Weight block was included in the model as a random effect. Linear and quadratic effects of decreasing CP in high-lysine sorghum diets were evaluated and developed using the IML procedure of SAS, generating coefficients for unequally spaced treatments. Estimated means and corresponding standard errors (SEM) are reported. Pairwise comparisons were conducted using a Tukey adjustment to prevent inflation of Type I error due to multiple comparisons. Degrees of freedom were estimated using the Kenward-Rogers approach. All results were considered significant at $P \leq 0.05$ and marginally significant between $P > 0.05$ and $P \leq 0.10$.

Results

General

The concentration of P in corn and in red and white sorghum varieties was between 0.26 and 0.32%, but high-lysine sorghum contained 0.35% P (Table 1). Concentrations of phytate-bound and nonphytate-bound P were 0.27 and 0.08% in high-lysine sorghum, 0.25 and 0.07% in

red sorghum, 0.23 and 0.07% in white sorghum, and 0.19 and 0.07% in corn, respectively. All cereal grains had intrinsic phytase activity of <70 FTU/kg.

Amino acid analysis of the grain sources indicated that high-lysine sorghum had greater concentrations of most AA, with the exception of lysine, compared to the other varieties of sorghum and corn (Table 1). Crude protein concentration was greatest for high-lysine sorghum, followed by red sorghum, white sorghum, and corn. The lysine in high-lysine sorghum was 0.26%, compared to 0.24, 0.20, and 0.28% in red sorghum, white sorghum, and corn.

Experiment 1: Phosphorus Digestibility

For P digestibility, there was no grain × phytase interaction for any of the response variables (Table 7). Average daily feed intake of pigs fed high-lysine sorghum tended to be less ($P < 0.10$) compared with pigs fed the red sorghum or corn, but was not different compared with pigs fed white sorghum. Pigs fed high-lysine sorghum had greater ($P < 0.05$) P intake compared with pigs fed white sorghum and had greater ($P < 0.05$) P in feces compared with pigs fed the other cereal grains. Pigs fed high-lysine sorghum also tended to have less ($P < 0.10$) basal endogenous P loss compared with pigs fed the red sorghum or corn. Pigs fed red sorghum had greater ($P < 0.05$) fecal and P output compared with pigs fed the other sorghum varieties or corn. However, no differences in ATTD or STTD of P were observed among pigs fed the sorghum varieties or corn. Addition of phytase to diets did not affect ADFI, daily fecal output, or daily P intake. However, pigs fed diets with phytase had less ($P < 0.01$) daily fecal P output and reduced ($P < 0.05$) concentration of P in feces, which resulted in increased ($P < 0.01$) absorption of P, ATTD of P, and STTD of P. There was no effect of phytase addition on daily endogenous P loss.

For Ca intake, Ca in feces, Ca output, and ATTD of Ca, no grain × phytase interaction was observed (Table 7). When phytase was not included in diets, daily amount of Ca absorbed

was less in pigs fed red sorghum compared with pigs fed high-lysine sorghum or corn. However, when phytase was included in diets, pigs fed red sorghum had greater daily Ca absorption compared with pigs fed high-lysine sorghum (interaction; $P < 0.10$). Regardless of phytase addition, pigs fed corn had greater ($P < 0.01$) daily Ca intake compared with pigs fed high-lysine sorghum or white sorghum. Pigs fed high-lysine sorghum had greater ($P < 0.01$) concentration of Ca in feces compared with pigs fed red sorghum, and pigs fed red sorghum tended to have greater Ca output ($P < 0.10$) compared with pigs fed the other sorghum varieties. However, no differences in ATTD of Ca were observed among pigs fed the 3 sorghum varieties or corn. When phytase was added to diets, regardless of grain source, pigs had reduced ($P < 0.01$) concentration of Ca in feces and reduced ($P < 0.05$) daily Ca output, which resulted in an increase ($P < 0.01$) in Ca absorption and in ATTD of Ca.

Experiment 2: Energy Measurements

Pigs fed the red sorghum diet had greater ($P < 0.05$) fecal output and greater ($P < 0.05$) fecal GE output compared with pigs fed the white sorghum or corn diets (Table 8). This resulted in less ($P < 0.05$) DE and ME in the red sorghum diet compared with the high-lysine sorghum and white sorghum diets. The ATTD of GE in high-lysine sorghum and red sorghum (86.7 and 85.0%, respectively) were less ($P \leq 0.01$) than in white sorghum and corn (89.4 and 89.3%, respectively).

The DE and ME, on an as-fed basis, in corn were 3,418 and 3,315 kcal/kg, respectively, and 3,992 and 3,871 kcal/kg DM, respectively (Table 8). On an as-fed basis, these values were not different from the DE and ME values obtained for all sorghum varieties. However, values for DE and ME in red sorghum on an as-fed basis (3,327 and 3,229 kcal/kg, respectively) were less ($P < 0.05$) than in the other sorghum varieties. On a DM basis, values for DE and ME in red

sorghum (3,800 and 3,687 kcal/kg, respectively) were also less ($P < 0.05$) than values for white sorghum, high-lysine sorghum, and corn.

Experiment 3: Ileal Digestibility

Chemical analysis of manufactured diets (Table 9) resulted in values consistent with formulation. There was no evidence for differences between pigs fed high-lysine sorghum and corn in AID values for CP, most total indispensable AA, and total dispensable AA ($P \geq 0.05$; Table 10). The AID values for lysine and methionine were greater ($P < 0.05$) in corn than high-lysine sorghum; however, tryptophan was greater ($P < 0.05$) in high-lysine sorghum. When comparing the different varieties of conventional sorghum, AID of CP was greatest ($P < 0.05$) for high-lysine sorghum compared to red and white varieties of sorghum (Table 10). The AID values for histidine, valine, total indispensable AA, and total dispensable AA were greater ($P < 0.05$) in high-lysine sorghum compared to the other two varieties of conventional sorghum.

When accounting for endogenous N losses to determine SID values, digestibility of CP was greater for corn ($P < 0.05$; Table 11) compared each variety of sorghum. The SID values for most indispensable and dispensable AA were greater ($P < 0.05$; Table 11) for corn compared to each variety of sorghum. There was no evidence for differences in the SID coefficients for CP, leucine, lysine, methionine, phenylalanine, threonine, valine, and most dispensable AA when comparing high-lysine, red, and white sorghum varieties.

Experiment 4: Growth Performance and Diarrhea Frequency from 6.3 to 10.4 kg

No differences were observed in all growth performance parameters among pigs fed diets containing the four grain sources from d 0 to 11, d 11 to 20, or for the entire experimental period (Table 12). Likewise, no differences among dietary treatments were observed in diarrhea scores and frequency of diarrhea.

Experiment 5: Effect of High-Lysine Sorghum on Nursery Pig Performance from 9.6 to 20.9 kg

Analysis of manufactured diets (Table 13) resulted in values consistent with formulation. Overall, there was no evidence for differences in ADG, ADFI, or final BW among dietary treatments for the 20-d study (Table 14). Pigs fed the high-lysine sorghum with the low- and medium-low addition of feed-grade AA had the increased (P = 0.045) G:F compared to pigs fed the high-lysine sorghum with the greatest feed grade AA inclusion, with others intermediate; however, with the Tukey adjustment, these differences are no longer significant.

When evaluating linear and quadratic effects of decreasing CP in high-lysine sorghum diets, ADG tended to decrease with increasing feed grade AA levels (linear, P = 0.055), resulting in marginal evidence for a reduction in final BW (linear, P = 0.096). Lastly, G:F worsened with increasing inclusion levels of feed grade AA (linear, P = 0.003).

Discussion

Grain composition

Chemical analysis results for CP and DM of corn, red sorghum, and white sorghum used in these experiments agree with values previously reported (Sauvant et al., 2002; NRC 2012; Cervantes-Pahm et al., 2014). The analyzed concentrations of ash, Ca, and P in sorghum varieties used in these experiments are in agreement with published values (NRC, 2012; Lopes et al., 2017). The analyzed values for ash, Ca, and P in corn are also in agreement with previous data (NRC, 2012; Li et al., 2014; Huang et al., 2017). Cereal grains have relatively low concentrations of Ca compared with oil seed meals, and, therefore, inclusion of feed ingredients

high in Ca or supplementation with limestone is necessary in diets for pigs. The analyzed values for total P in red sorghum and white sorghum are within the range of total P values for sorghum reported by Selle et al. (2003) and Veum and Liu (2018), and the analyzed values for total P in high-lysine sorghum are in agreement with published values for high digestible sorghum (Nyannor et al., 2007). The observed differences among sorghum varieties may be attributed to differences in varieties and processing conditions (Veum and Liu, 2018).

Analyzed concentrations of indispensable AA and dispensable AA of corn, red sorghum, and white sorghum were like those previously reported (Sauvant et al., 2002; NRC 2012; Cervantes-Pahm et al., 2014). When comparing the chemical analysis results for high-lysine sorghum used in these experiments to reported values for conventional sorghum in the NRC (2012), differences were more obvious. Analyzed CP concentration was 13.9% in high-lysine sorghum, compared to 9.36% in the NRC (2012). On average, analyzed concentrations of indispensable AA were 56% higher in high-lysine sorghum compared to conventional sorghum in the NRC (2012). Specifically, leucine and valine concentrations were 2.08 and 0.71% in high-lysine sorghum, compared to 1.21 and 0.46% in conventional sorghum (NRC, 2012). Differences between dispensable AA were larger than indispensable AA, with the average analyzed concentration of high-lysine sorghum being 108% greater than NRC (2012) conventional sorghum values. This was expected as this is a new variety of sorghum selected for higher AA concentrations compared to conventional sorghum varieties.

Chemical analysis results indicate high-lysine sorghum having increased concentrations of all AA, except lysine, compared to the other varieties of conventional sorghum and corn. Our findings are similar to Goodband et al. (2016) in which the concentration of AA, specifically threonine, tryptophan, and valine, are greater for each variety of sorghum compared to corn.

High-lysine sorghum analyzed lysine concentration was greater compared to conventional sorghum varieties; however, analyzed less compared to corn (0.26 vs. 0.28%). This was disappointing as the previous year, this specific variety of sorghum had an analyzed lysine concentration of 0.33%, compared to 0.26% in the study herein, and 0.20% in the NRC (2012) for conventional sorghum. Thus, this variety of sorghum was named high-lysine based on the previous year's lysine concentration.

Nutritional value of grain sources

The STTD of P in corn without phytase observed in this experiment was slightly greater than values from previous experiments (Almeida and Stein, 2010, 2012; NRC, 2012; Rojas et al., 2013), which may be because of reduced phytate bound P in the corn used in this experiment. The mean STTD of P in all sorghum varieties without phytase was 41.5%, which is in agreement with previous data (Almeida et al., 2017). The addition of microbial phytase increased the ATTD and STTD of P in all ingredients, which indicate that exogenous phytase hydrolyzed some of the ester bonds between P and the inositol ring of phytate which resulted in increased absorption of P (Adeola et al., 1995).

In Exp. 1, all diets contained 0.80% limestone, and because of the very low concentration of Ca in sorghum and in corn, the ATTD of Ca in the diets primarily reflects the ATTD of Ca in limestone. The mean ATTD of Ca in all sorghum varieties without phytase was 61.0%, and this value was not different from the ATTD of Ca in corn, which may indicate that similar proportions of Ca became bound to the phytate complex in the liquid environment of the stomach and small intestine. Addition of microbial phytase improved Ca digestibility in all 4 cereal grains used in this experiment, indicating an increase in Ca absorption by hydrolyzing the Ca-phytate complexes in the gut (Selle et al., 2009). This observation concurs with data

demonstrating that ATTD and STTD of Ca in calcium carbonate increases as microbial phytase is added to diets (González-Vega et al., 2015).

In Exp. 2, the DE and ME values for corn are in close agreement with previous data (Sauvant et al., 2004; NRC, 2012; Espinosa and Stein, 2018). Likewise, DE and ME of the 3 sorghum varieties were close to published values (Pan et al., 2016; 2017). The observation that white sorghum had greater concentration of DE and ME compared with red sorghum is possibly a result of greater concentration of AEE in white sorghum compared with red sorghum (Table 1). White sorghum belongs to type I sorghums that do not have pigmented testa and have low concentration of tannin, whereas red sorghum is a type III sorghum variety , which has greater concentration of tannin in both testa and pericarp (Ramachandra et al., 1977; Dykes and Rooney, 2006). The observation that DE and ME values in high-lysine sorghum were not different from DE and ME in corn and were greater compared with red sorghum is most likely a result of greater concentrations of CP and GE in high-lysine sorghum compared with the other cereal grains. Nevertheless, these data indicate that both high-lysine sorghum and white sorghum will provide the same quantities of ME to diets as corn.

In Exp. 3, the AID of CP for corn, red sorghum, and white sorghum were similar to values reported in the NRC (2012). The AID of CP for high-lysine sorghum was higher (11.3%) than conventional sorghum reported in the NRC (2012). On average, the AID of the indispensable AA for corn and high-lysine sorghum were 3.6 and 8.1% higher than values reported in the NRC (2012). The AID of indispensable AA for red sorghum and white sorghum were similar to values reported in the NRC (2012). Similarly, the AID of dispensable AA of corn and high-lysine sorghum were 6.8 and 18.3% greater than values reported in the NRC (2012). The average AID of dispensable AA for red and white sorghum were 7.4% greater than values

reported in the NRC (2012). Our results were consistent with previous research where AID values for most indispensable and dispensable AA for red and white sorghum varieties were lower than AID values observed in corn (Lin et al., 1987; Mariscal-Landín et al., 2010; Pan et al., 2017). The AID values for high-lysine sorghum were intermediate to corn and the conventional varieties of sorghum, with the exception of tryptophan. When expressing AA digestibility with AID, our results suggest the nutritional value of high-lysine sorghum being greater than that of conventional sorghum varieties and comparable to corn. However, when accounting for endogenous losses and expressing AA digestibility as SID, the 3 varieties of sorghum become very similar.

In Exp. 3, the SID values for most indispensable and dispensable AA for corn were greater than those for high-lysine, red, and white sorghum varieties, which is consistent with previous research (Pedersen et al., 2007; Cervantes-Pahm et al., 2014; Stein et al., 2016; Pan et al., 2017). This is expected as sorghum is known to have lower digestibility of protein and AA compared to corn (Stein et al., 2016) caused by many factors including tannins (Mariscal-Landin et al., 2004; Liu et al., 2013), polyphenols (Liu et al., 2013c, 2016), kafirin (Liu et al., 2013), phytate (Selle et al., 2003; Liu et al., 2013a; Stein et al., 2016), and fiber (Jaworski et al., 2015).

Measures of ileal digestibility are used to estimate AA bio-availability and can be expressed as apparent (AID), true (TID), or standardized (SID) ileal digestibility depending on which proportion of the ileal AA outflow is included in the calculation (Stein et al., 2007). Previous research suggests that the SID values of AA should be calculated to remove the influence of basal endogenous losses of AA on the determined digestibility values and is the suggested measure for ileal digestibility to be used in diet formulations (Stein et al., 2007).

Similar to findings by Cervantes-Pahm et al. (2014), the low SID AA values (Exp. 3) observed in pigs consuming high-lysine, red, or white sorghum compared to pigs consuming corn indicates that when corn is replaced with different varieties of sorghum, more protein or AA supplementation is required to meet AA requirements. This approach was taken in Exp. 4, when feeding each of the cereal grains to nursery pigs.

Nursery pig growth performance

In Exp. 4, the observation that all parameters for growth performance were not different among pigs fed diets containing high-lysine sorghum, red sorghum, white sorghum, or corn indicates that sorghum varieties compare favorably with corn and can partially or fully replace corn in diet formulations. Similarly, the results from Exp. 5 demonstrate that similar growth performance can be achieved in nursery pigs fed either corn or conventional sorghum. These findings are similar to Goodband et al. (2016) where authors summarized 12 nursery studies comparing pigs fed sorghum to corn-based diets and reported the average relative value of sorghum was 99, 100, and 99% of the value of corn for ADG, ADFI, and G:F. The overall performance from this study indicates that the relative value of conventional sorghum (blend of red and white) is 99, 99, and 100% of the value of corn for ADG, ADFI, and G:F. Similarly, the average overall performance for diets containing high-lysine sorghum suggest that the relative value of this specific variety of sorghum is 101, 102, and 99% of the value of corn for ADG, ADFI, and G:F. More recent literature from Pan et al. (2017) evaluated growth performance in weaned pigs fed diets containing either 60% corn, 40% corn and 20% sorghum, 20% corn and 40% sorghum, or 60% sorghum and reported no evidence for differences in ADG or ADFI, but found a reduction in G:F in pigs consuming sorghum. Differences in the G:F response could be the causes of different varieties of sorghum or formulation methods. However, the energy

content of sorghum is believed to be 98 to 99% relative to that of corn due to a reduction in oil concentration (Jaworski et al., 2015) which can result in a reduction in G:F in pigs fed sorghum-based diets compared to those fed corn-based diets (Menegat et al., 2019). Previous research suggests that G:F can be improved by grinding sorghum-based diets to a finer particle size (Owsley et al., 1981; Paulk et al., 2015).

In Exp. 5, in addition to comparing the relative feeding value of different varieties of sorghum to that of corn, the experiment was designed to evaluate the partial replacement of SBM in the diet with a specific variety of high-lysine sorghum. By using feed-grade AA, diets were balanced appropriately as the amount of SBM decreased. The results indicate that increasing the inclusion of high-lysine sorghum and feed grade AA in the diet, nursery pig ADG and G:F were negatively affected. We speculate that dispensable AA may have become limiting as the amount of SBM in the diet decreased, resulting in a reduction in dietary CP. Previous research suggests the ratio of 6.35g SID Lys/g CP as a threshold value, thereafter dispensable AA may limit performance (Millet et al., 2018). In this study, diets formulated with high-lysine sorghum with the med-high and high- feed grade AA had SID Lys:CP ratios exceeding the threshold value, at 6.4 and 7.2 g SID Ly/g CP. In addition, an analysis developed by Cemin et al. (2019) led authors to believe there may be an imbalance in BCAA in the high-lysine sorghum diets contributing to the reduction in ADG and G:F. Specifically, BCAA and other large neutral AA share brain transporters and excess of one BCAA can cause antagonistic effects to the others. However, in diets containing high-lysine sorghum, all BCAA are included well above the requirement, and thus believed to not be the cause for negative effects on growth performance.

Implications

In conclusion, 1) the ATTD and STTD of P of high-lysine sorghum was not different from values obtained for conventional varieties of sorghum or corn when fed to growing pigs; 2) addition of microbial phytase improves the STTD of P in all ingredients, and if 500 FTU of phytase is added to sorghum, the STTD of P is between 60 and 67%; 3) the concentrations of DE and ME in high-lysine sorghum, as well as growth performance of pigs when fed diets based on high-lysine sorghum, were not different from data obtained for corn; 4) there was no evidence the SID AA values for the high-lysine sorghum variety used in this study were different from the red or white sorghum varieties; 5) regardless of the variety of sorghum, corn had the greatest SID AA digestibility coefficient values; 6) pigs fed corn-, conventional sorghum-, or high-lysine sorghum- based diets formulated on an SID AA basis have similar growth performance.

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Table 2.1 Chemical analysis of yellow dent corn and difference sources of sorghum (as-fed basis)[1]

		Sorghum Varieties		
Item	Corn	High-Lysine	Red	White
Dry matter, %	85.65	89.31	87.59	87.41
Gross energy, kcal/kg	3,740	3,959	3,827	3,794
Crude protein, %	6.46	13.92	9.49	8.38
AEE[2], %	4.52	3.50	3.20	4.04
IDF[3], %	11.70	11.90	10.10	10.70
SDF[3], %	0.20	0.10	0.40	0.20
TDF[3], %	11.90	12.00	10.50	10.90
Ash, %	1.18	1.66	1.72	1.33
Calcium, %	0.03	0.02	0.02	0.01
Total phosphorus, %	0.26	0.35	0.32	0.30
Phytic acid, %	0.69	0.97	0.88	0.81
Phytate bound P[4], %	0.19	0.27	0.25	0.23
Nonphytate P[5], %	0.07	0.08	0.07	0.07
Phytase, FTU[6]/kg	<70	<70	<70	<70
Tannic acid, %	-	0.08	0.13	0.11
Carbohydrates				
Glucose, %	0.44	0.34	0.40	0.39
Sucrose, %	1.45	0.77	0.37	0.63
Maltose, %	0.11	0.05	0.14	0.08
Fructose, %	0.25	0.18	0.11	0.12
Stachyose, %	ND[7]	0.06	ND	ND
Raffinose, %	0.15	0.10	ND	0.08
Starch, %	59.12	57.74	62.40	62.46
Minerals				
K, %	0.32	0.39	0.28	0.33
Mg, %	0.10	0.15	0.14	0.13
Na, mg/kg	49.00	35.00	7.00	7.00
S, %	0.11	0.14	0.10	0.09
Cl, %	<0.10	<0.10	<0.10	<0.10
Cu, mg/kg	2.00	5.00	2.00	2.00
Fe, mg/kg	35.00	38.00	38.00	36.00
Mn, mg/kg	8.00	15.00	14.00	16.00
Se, mg/kg	0.40	<0.20	0.60	0.30
Zn, mg/kg	21.00	26.00	20.00	20.00
Indispensable AA, %				
Arginine	0.33	0.43	0.35	0.28
Histidine	0.20	0.31	0.23	0.18
Isoleucine	0.25	0.62	0.41	0.36
Leucine	0.76	2.08	1.29	1.15
Lysine	0.28	0.26	0.24	0.20
Methionine	0.14	0.19	0.16	0.16
Phenylalanine	0.32	0.80	0.52	0.44
Table 1 continued				
Threonine	0.24	0.42	0.32	0.27
Tryptophan	0.07	0.11	0.09	0.09
Valine	0.32	0.71	0.51	0.43

Dispensable AA, %				
Alanine	0.47	1.38	0.89	0.80
Aspartic acid	0.48	0.94	0.65	0.58
Cysteine	0.16	0.24	0.19	0.16
Glutamic acid	1.19	3.16	1.98	1.76
Glycine	0.27	0.38	0.32	0.27
Serine	0.31	0.54	0.40	0.35
Tyrosine	0.19	0.38	0.28	0.22
All AA	6.70	14.39	9.85	8.61

[1]Mulitple samples were collected from each ingredient, homogenized, and then subsampled for analysis at the University of Illinois (Urbana, IL) and the University of Missouri Agricultural Experiment Station Chemical Laboratory (Columbia, MO) for AA analysis performed in duplicate.
[2]AEE = acid hydrolyzed ether extract.
[3]IDF = insoluble dietary fiber; SDF = soluble dietary fiber; TDF = total dietary fiber.
[4]Calculated as 28.2% of phytic acid (Tran and Sauvant, 2004).
[5]Calculated as total P – phytate P.
[6]FTU = phytase units.
[7]ND = not detected.

Table 2.2 Diet composition and chemical analysis, Exp. 1[1]

	No phytase				500 FTU[2]/kg phytase			
		Sorghum Varieties				Sorghum Varieties		
Item	Corn	High-Lysine	Red	White	Corn	High-Lysine	Red	White
Corn	95.65	-	-	-	-	-	-	95.64
Red sorghum	-	-	95.65	-	-	95.64	-	-
White sorghum	-	-	-	95.65	-	-	95.64	-
High-lysine sorghum	-	95.65	-	-	95.64	-	-	-
Soybean oil	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Limestone	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Phytase[2]	-	-	-	-	0.01	0.01	0.01	0.01
Vitamin-mineral premix[3]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Analyzed values[4]								
Dry matter, %	86.32	89.49	87.94	87.65	89.43	87.95	87.92	86.73
Ash, %	2.34	2.75	2.30	2.43	2.64	2.84	2.33	2.30
Calcium, %	0.31	0.34	0.32	0.29	0.36	0.37	0.29	0.36
Phosphorus, %	0.26	0.35	0.32	0.28	0.35	0.31	0.27	0.27
Phytase, FTU/kg	<70	<70	<70	<70	700	670	740	760

[1]A total of 48 growing barrows (initially 18.6 kg; Line 359 × Camborough®; PIC, Hendersonville, TN) were randomly allotted to 1 of 8 dietary treatments in a randomized complete block design with 6 replicate pigs per diet.

[2]The phytase premix (Quantum Blue 5G; AB Vista, Marlborough, UK) contains 5,000 phytase units per gram. At 0.01% inclusion, the premix was calculated to provide 500 units of phytase per kilogram in the complete diet; FTU = phytase units.

[3]Provided the following quantities of vitamins and micro-minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin,6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; $_{D}$-pantothenic acid as $_{D}$-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

[4]Mulitple samples were collected from each diet, homogenized, and then subsampled for analysis at the University of Illinois (Urbana, IL).

Table 2.3 Diet composition and chemical analysis, Exp. 2[1]

		Sorghum Varieties		
Item	Corn	High-Lysine	Red	White
Corn	97.75	-	-	97.75
Red Sorghum	-	-	97.75	-
White Sorghum	-	-	-	-
High-Lysine sorghum	-	97.75	-	-
Dicalcium phosphate	1.10	1.10	1.10	1.10
Calcium carbonate	0.60	0.60	0.60	0.60
Salt	0.40	0.40	0.40	0.40
Vit-mineral premix[2]	0.15	0.15	0.15	0.15
Analyzed values[3]				
Dry matter, %	86.90	89.56	88.31	86.90
GE, kcal/kg	3,828	4,068	3,897	3,828

[1]A total of 32 growing barrows (initially 18.5 kg; Line 359 × Camborough®; PIC, Hendersonville, TN) were randomly allotted to 1 of 4 dietary treatments in a randomized complete block design with 8 replicate pigs per diet.

[2]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride,0.24 mg; vitamin B12, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

[3]Mulitple samples were collected from each diet, homogenized, and then subsampled for analysis at the University of Illinois (Urbana, IL).

Table 2.4 Diet composition, Exp. 3 (as-fed basis) [1,2]

		Sorghum Varieties			
Item	Corn	High-Lysine	Red	White	N-free
Ingredient, %					
Corn	94.00	---	---	---	---
Red sorghum	---	---	94.20	---	---
White sorghum	---	---	---	94.20	---
High-lysine sorghum	---	94.20	---	---	---
Soybean oil	3.00	3.00	3.00	3.00	4.00
Solka floc	---	---	---	---	4.00
Dicalcium phosphate	1.20	1.10	1.10	1.10	1.65
Calcium carbonate	0.70	0.60	0.60	0.60	0.35
Cornstarch	---	---	---	---	68.30
Sucrose	---	---	---	---	20.00
Chromic oxide	0.40	0.40	0.40	0.40	0.40
Magnesium oxide	---	---	---	---	0.10
Potassium carbonate	---	---	---	---	0.40
Salt	0.40	0.40	0.40	0.40	0.40
Vitamin-mineral premix[3]	0.30	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00	100.00

[1]Ten growing barrows (initially 25.9 kg) were fitted with a T-cannula in the distal ileum and were randomly allotted to 1 of 5 test diets in a 5-period design with 2 replicate pigs per diet in each period for a total of 10 replicates per pig diet.
[2]One hundred grams for the following AA mixture (%) was supplemented to dietary treatments daily, during the adaptation period (initial 5 days): 57.92 glycine, 13.51 L-Lysine HCl, 4.44 DL-Methionine, 5.79 L-Threonine, 1.35 L-Tryptophan, 4.25 L-Isoleucine, 4.83 L-Valine, 2.12 L-Histidine, and 5.79 L-Phenylalanine.
[3]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per pound of complete diet: Vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 0.644 mg; thiamin as thiamine mononitrate, 0.109 mg; riboflavin, 2.985 mg; pyridoxine as pyridoxine hydrocloride, 0.109 mg; vitamin B_{12}, 0.014 mg; D-pantothenic acid as D-calcium pantothenate, 10.659 mg; niacin as nicotinamide and niacotinic acid, 19.958 mg; folic acid, 0.717 mg; biotin, 0.199 mg; Cu, 4.536 mg as copper sulfate; Fe, 56.699 mg as iron sulfate; I, 0.572 mg as potassium iodate; Mn, 27.216 mg as manganese sulfate; Se, 0.136 mg as sodium selenite; and Zn, 45.359 mg as zinc oxide.

Table 2.5 Diet composition and chemical analysis, Exp. 4[1]

	Phase 1				Phase 2			
		Sorghum Varieties				Sorghum Varieties		
Item	Corn	High-Lysine	Red	White	Corn	High-Lysine	Red	White
Corn	43.00	-	-	-	48.82	-	-	-
Red sorghum	-	-	43.23	-	-	-	50.20	-
White sorghum	-	-	-	41.80	-	-	-	49.24
High-lysine sorghum	-	46.80	-	-	-	54.50	-	-
Soybean meal, 48% CP[2]	24.25	20.25	24.00	25.50	26.00	20.00	24.50	25.50
Dried whey	20.00	20.00	20.00	20.00	15.00	15.00	15.00	15.00
ESBM[2], HP 300	4.50	4.50	4.50	4.50	5.00	5.00	5.00	5.00
Blood plasma, spray dried	3.00	3.00	3.00	3.00	-	-	-	-
Soybean oil	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Limestone	1.17	1.16	1.20	1.18	1.02	1.04	1.07	1.05
Dicalcium phosphate	0.80	0.85	0.75	0.75	0.90	0.95	0.85	0.85
L-Lysine HCl	0.34	0.50	0.39	0.35	0.34	0.56	0.43	0.41
DL-Methionine	0.20	0.20	0.20	0.19	0.18	0.19	0.20	0.20
L-Threonine	0.09	0.09	0.08	0.08	0.09	0.11	0.10	0.10
Salt	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Vitamin-mineral premix[3]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Analyzed values[4]								
Dry matter, %	88.42	89.36	88.78	88.62	88.85	89.71	89.12	88.82
Ash, %	6.16	6.34	6.38	5.63	5.50	5.68	5.62	5.42
Gross energy, kcal/kg	3,945	4,025	3,990	3,956	4,010	4,082	4,022	4,001
Crude protein, %	23.00	24.07	23.58	24.94	22.09	22.56	22.26	21.97
AEE[5], %	3.04	2.82	2.40	3.12	4.84	3.53	3.26	4.06
Calcium, %	0.82	0.81	0.79	0.78	0.71	0.75	0.70	0.73
Phosphorus, %	0.63	0.66	0.62	0.62	0.59	0.66	0.61	0.61
Indispensable AA, %								
Arginine	1.29	1.27	1.29	1.31	1.23	1.19	1.18	1.20
Histidine	0.55	0.56	0.56	0.54	0.53	0.52	0.49	0.48
Isoleucine	1.00	1.08	1.05	1.05	0.99	1.05	0.97	0.98
Leucine	1.91	2.27	2.02	2.01	1.82	2.24	1.85	1.84
Lysine	1.61	1.62	1.63	1.49	1.44	1.38	1.41	1.44
Methionine	0.48	0.49	0.46	0.46	0.49	0.45	0.51	0.44

Methionine + Cysteine	0.88	0.93	0.86	0.85	0.84	0.81	0.82	0.78
Phenylalanine	1.07	1.19	1.12	1.12	1.05	1.15	1.02	1.02
Threonine	1.03	1.03	1.06	1.03	0.91	0.89	0.87	0.93
Tryptophan	0.31	0.30	0.28	0.32	0.27	0.26	0.26	0.27
Valine	1.12	1.20	1.19	1.17	1.05	1.11	1.00	1.01

[1]A total of 160 weaned pigs (initially 6.3 kg; Line 359 × Camborough®; PIC, Hendersonville, TN) were randomly allotted to 4 dietary treatments with 5 pigs per pen and 8 replicate pens per treatment

[2]CP = crude protein; ESBM = enzyme-treated soybean meal.

[3]Provided the following quantities of vitamins and micro-minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; $_{D}$-pantothenic acid as $_{D}$-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

[4]Mulitple samples were collected from each diet, homogenized, and then subsampled for analysis at the University of Illinois (Urbana, IL).

[5]AEE = acid hydrolyzed ether extract.

Table 2.6 Diet composition, Exp. 5, (as-fed basis) [1]

			Synthetic AA levels in high-lysine diets			
Item	Corn	Sorghum	Low	Low-med	Med-high	High
Ingredient, %						
Corn	59.55	---	---	---	---	---
Conventional sorghum	---	59.10	---	---	---	---
High-lysine sorghum	---	---	59.15	62.30	66.75	73.55
Soybean meal, 46.5% CP	34.70	34.65	34.65	31.70	27.50	21.05
Choice white grease	2.25	2.70	2.73	2.35	1.85	1.00
Calcium carbonate	0.95	0.96	0.96	0.96	0.94	0.93
Monocalcium phosphate, 21%	0.98	0.95	0.95	0.95	1.00	1.08
Salt	0.60	0.60	0.60	0.60	0.60	0.60
L-Lysine HCl	0.30	0.35	0.36	0.45	0.58	0.78
DL-Methionine	0.13	0.16	0.12	0.15	0.18	0.24
L-Threonine	0.12	0.13	0.08	0.12	0.17	0.25
L-Tryptophan	0.02	0.001	---	---	0.02	0.06
L-Valine	0.02	---	---	---	---	0.08
Trace mineral[2]	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[3]	0.25	0.25	0.25	0.25	0.25	0.25
Phytase[4]	0.02	0.02	0.02	0.02	0.02	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis						
Standardized ileal digestible (SID) AA, %						
Lysine	1.30	1.30	1.30	1.30	1.30	1.30
Isoleucine:lysine	64	66	74	71	66	59
Leucine:lysine	128	131	164	161	157	150
Methionine:lysine	33	34	32	33	34	36
Methionine and Cysteine:lysine	56	56	56	56	56	56
Threonine:lysine	63	63	63	63	63	63
Tryptophan:lysine	19.1	19.2	20.1	19.0	19.0	19.1
Valine:lysine	70	69	77	74	70	70
SID lysine:net energy, g/Mcal	5.23	5.23	5.23	5.23	5.23	5.23
SID lysine:crude protein, g/kg	5.9	5.8	5.8	6.0	6.4	7.2
Total lysine, %	1.47	1.46	1.46	1.45	1.44	1.43
Net energy, kcal/kg	2,485	2,485	2,485	2,485	2,485	2,485
Crude protein, %	21.9	22.3	22.5	21.6	20.2	18.1
Calcium, %	0.73	0.73	0.73	0.72	0.71	0.70
Phosphorus, %	0.61	0.61	0.61	0.60	0.59	0.58
Available phosphorus, %	0.38	0.38	0.38	0.38	0.39	0.40

[1]Diets were fed from 9.7 to 20.9 kg BW, respectively.

[2]Provided per kilogram of premix: 22 g Mn from manganese oxide; 73 g Fe from iron sulfate; 73 g Zn from zinc sulphate; 11 g Cu from copper sulfate; 198 mg I from calcium iodate; and 198 mg Se from sodium selenite.

[3]Provided per kilogram of premix:3,527,360 IU vitamin A; 881,840 IU vitamin D3; 17,637 IU vitamin E; 3,307 mg riboflavin; 1,764 mg menadione; 11,023 mg pantothenic acid; 33,069 mg niacin; and 15.4 mg vitamin D12.

[4]HiPhos 2700 (DSM Nutritional Products, Parsippany, NJ) provided an estimated release of 0.10% STTD P.

Table 2.7 Effects of microbial phytase on P and Ca balance, apparent total tract digestibility (ATTD), and standardized total tract digestibility (STTD) of P in high-lysine sorghum, red sorghum, white sorghum, and corn fed to growing pigs, Exp. 1[1,2]

	No phytase				500 FTU[1]/kg phytase[3]							
		Sorghum Varieties				Sorghum Varieties				Probability, *P* <		
Item	Corn	High-Lysine	Red	White	Corn	High-Lysine	Red	White	SEM	Grain	Phytase	Grain × Phytase
ADFI, g	755	657	688	666	712	599	729	662	49	0.061	0.581	0.619
P intake, g/d	2.3	2.5	2.5	2.2	2.2	2.3	2.5	2.1	0.2	0.032	0.389	0.880
Fecal output, g/d	85.7	78.9	109.6	83.5	82.9	66.9	105.8	83.2	7.3	<0.001	0.267	0.783
P in feces %	1.7	2.2	1.7	1.9	0.9	1.6	1.1	1.2	0.1	<0.001	<0.001	0.581
P output, g/d	1.3	1.4	1.7	1.3	0.7	0.9	1.1	0.9	0.1	<0.001	<0.001	0.423
P absorption, g/d	1.0	1.1	0.8	0.9	1.4	1.4	1.4	1.1	0.2	0.182	<0.001	0.563
ATTD of P, %	41.5	41.9	28.1	38.5	66.2	62.3	56.1	53.9	4.8	0.280	<0.001	0.473
Basal EPL[4], mg/d	144	125	131	127	135	114	139	126	9.3	0.061	0.581	0.619
STTD of P[5], %	47.8	46.8	33.4	44.4	72.4	67.1	61.6	60.2	4.8	0.230	<0.001	0.480
Ca intake, g/d	2.8	2.5	2.5	2.2	3.0	2.4	3.0	2.2	0.19	<0.001	0.168	0.218
Ca in feces, %	1.3	1.3	1.1	1.2	0.7	1.1	0.7	0.8	0.09	0.007	<0.001	0.278
Ca output, g/d	0.9	0.8	1.1	0.8	0.5	0.6	0.6	0.6	0.07	0.070	<0.001	0.311
Ca absorption, g/d	1.8	1.6	1.4	1.4	2.4	1.8	2.3	1.6	0.19	0.005	<0.001	0.074
ATTD of Ca, %	65.6	64.7	56.2	62.1	81.5	74.8	79.0	73.4	3.0	0.185	<0.001	0.156

[1]A total of 48 growing barrows (initially 18.6 kg; Line 359 × Camborough®; PIC, Hendersonville, TN) were randomly allotted to 1 of 8 dietary treatments in a randomized complete block design with 6 replicate pigs per diet.

[2]Data are means of 6 observations per treatment.

[3]Phytase: Quantum Blue 5G (5,000 phytase units per gram; AB Vista, Marlborough, UK); FTU = phytase units.

[4]EPL = endogenous P loss. This value was estimated to be at 190 mg/kg DMI (dry matter intake). The daily basal EPL (mg/d) for each diet was calculated by multiplying the EPL (mg/kg DMI) by the daily DMI of each diet (Almeida and Stein, 2010).

[5]Values for STTD were calculated by correcting values for ATTD for the basal endogenous loss of P (NRC, 2012).

Table 2.8 Apparent total tract digestibility (ATTD) of energy, digestible energy (DE), and metabolizable energy (ME) in experimental diets, Exp. 2[1,2]

		Sorghum Varieties				
Item	Corn	High-Lysine	Red	White	SEM	Probability, *P* <
GE[3] intake, kcal/d	3,089	3,303	3,319	3,461	245	0.554
Fecal output, g/d	67[b]	87[ab]	98[b]	71[b]	9	0.019
Fecal GE output, kcal/d	305[b]	396[ab]	458[a]	339[b]	38	0.021
Urine output, g/d	2,161	1,934	2,175	2,543	591	0.913
Urinary GE output, kcal/d	76	82	77	78	12	0.966
ATTD of GE, %	89.3[a]	86.7[b]	85.0[b]	89.4[a]	1.0	0.003
DE, kcal/kg	3,341[ab]	3,433[a]	3,252[b]	3,389[a]	39	0.004
ME, kcal/kg	3,240[ab]	3,324[a]	3,156[b]	3,300[a]	42	0.012
As-fed basis						
DE, kcal/kg	3,418[ab]	3,512[a]	3,327[b]	3,467[a]	40	0.004
ME, kcal/kg	3,315[ab]	3,400[a]	3,229[b]	3,367[a]	43	0.012
Dry matter basis						
DE, kcal/kg	3,992[a]	3,934[a]	3,800[b]	3,968[a]	46	0.007
ME, kcal/kg	3,871[a]	3,809[a]	3,687[b]	3,864[a]	49	0.014

[1]A total of 32 growing barrows (initially 18.5 kg; Line 359 × Camborough®; PIC, Hendersonville, TN) were randomly allotted to 1 of 4 dietary treatments in a randomized complete block design with 8 replicate pigs per diet.
[2]Data are least square means of 8 observations for all treatments except for white sorghum (n = 7).
[3]GE = gross energy.
[a,b]Means within a row that do not have a common superscript differ, $P < 0.05$.

Table 2.9 Chemical analysis of diets, Exp. 3 (%, as- fed basis)[1]

		Sorghum Varieties			
Item	Corn	High-Lysine	Red	White	N-free
Crude protein, %	7.10	13.24	8.78	7.80	0.41
Dry matter, %	87.51	90.12	87.64	88.23	94.45
Indispensable AA, %					
Arginine	0.35	0.40	0.31	0.29	0.01
Histidine	0.21	0.29	0.21	0.17	0.00
Isoleucine	0.26	0.58	0.38	0.33	0.01
Leucine	0.77	1.93	1.19	1.05	0.03
Lysine	0.29	0.24	0.22	0.20	0.01
Methionine	0.15	0.18	0.15	0.14	0.01
Phenylalanine	0.34	0.75	0.48	0.42	0.01
Threonine	0.26	0.40	0.29	0.26	0.01
Tryptophan	0.03	0.11	0.07	0.06	0.01
Valine	0.34	0.66	0.46	0.41	0.01
Dispensable AA, %					
Alanine	0.49	1.29	0.82	0.73	0.02
Aspartic acid	0.54	0.89	0.60	0.54	0.02
Cysteine	0.16	0.22	0.17	0.14	0.00
Glutamic acid	1.24	2.94	1.82	1.60	0.03
Glycine	0.30	0.36	0.30	0.27	0.01
Serine	0.31	0.50	0.37	0.32	0.01
Tyrosine	0.20	0.35	0.24	0.23	0.01
All AA	7.04	13.46	9.03	8.00	0.38

[1]Mulitple samples were collected from each diet, homogenized, and then subsampled for analysis at Ward Laboratories, Inc. (Kearney, NE) for proximate analysis and the University of Missouri Agricultural Experiment Station Chemical Laboratory (Columbia, MO) for AA analysis performed in duplicate.

Table 2.10 Apparent ileal digestibility of AA in yellow dent corn and different varieties of sorghum[1,2,3]

		Sorghum Varieties			
Item	Corn	High-Lysine	Red	White	SEM
Crude protein, %	66.8^{ab}	70.1^{a}	60.4^{bc}	60.0^{c}	2.48
Indispensable AA, %					
Arginine	79.0^{a}	75.4^{ab}	70.7^{bc}	69.8^{c}	1.90
Histidine	80.2^{a}	74.4^{a}	65.0^{b}	65.0^{b}	3.06
Isoleucine	78.2^{a}	77.3^{ab}	71.5^{b}	71.1^{b}	2.60
Leucine	83.6^{a}	81.5^{ab}	75.8^{c}	77.6^{bc}	2.35
Lysine	63.3^{a}	46.1^{b}	42.3^{b}	43.7^{b}	3.72
Methionine	85.6^{a}	78.1^{b}	75.3^{b}	76.3^{b}	2.15
Phenylalanine	80.6^{a}	78.5^{ab}	73.2^{b}	73.9^{b}	2.51
Threonine	67.8^{x}	64.2^{xy}	58.1^{y}	55.8^{y}	3.87
Tryptophan	49.1^{b}	72.8^{a}	69.8^{a}	65.6^{a}	2.94
Valine	74.0^{a}	72.7^{a}	66.2^{b}	66.0^{b}	2.93
Total[4]	78.4^{a}	78.9^{a}	73.0^{b}	73.0^{b}	2.24
Dispensable AA, %					
Alanine	78.3^{x}	78.6^{x}	72.3^{y}	73.4^{xy}	2.28
Aspartic acid	77.3^{a}	73.3^{ab}	68.2^{bc}	66.4^{c}	2.59
Cysteine	75.9^{a}	69.4^{ab}	61.4^{bc}	59.7^{c}	3.34
Glutamic acid	83.8^{a}	81.6^{ab}	75.9^{c}	77.5^{bc}	2.14
Glycine	44.4^{a}	42.6^{a}	35.4^{ab}	26.2^{b}	4.56
Serine	77.7^{a}	75.3^{ab}	71.1^{b}	69.6^{b}	2.48
Tyrosine	77.8^{a}	71.6^{ab}	66.1^{b}	69.1^{b}	2.82
Total[5]	72.8^{a}	70.5^{a}	62.8^{b}	62.5^{b}	2.84
All AA	75.8^{a}	75.1^{a}	68.4^{b}	68.3^{b}	2.50

[1]Ten growing barrows (initially 25.9 kg) were fitted with a T-cannula in the distal ileum and were randomly allotted to 1 of 5 test diets in a 5-period design with 2 replicate pigs per diet in each period for a total of 10 replicates per pig diet.

[2]Values with different superscripts a, b, c differ, $P < 0.05$.

[3]Values with different superscripts x, y differ, $P < 0.10$.

[4]Total indispensable AA (IAA) = [1-(total IAA in the digesta/total IAA in the diet) × (marker in the diet/marker in the digesta)] × 100.

[5]Total dispensable AA (DAA) = [1-(total DAA in the digesta/total DAA in the diet) × (marker in the diet/marker in the digesta)] × 100.

Table 2.11 Standardized ileal digestibility of AA in yellow dent corn and different varieties of sorghum[1,2,3]

		Sorghum Varieties			
Item	Corn	High-Lysine	Red	White	SEM
Crude protein, %	92.8[a]	84.5[b]	81.5[b]	81.9[b]	2.48
Indispensable AA, %					
Arginine	91.8[x]	87.0[x]	85.2[y]	85.4[y]	1.90
Histidine	88.2[a]	80.4[b]	73.1[c]	75.0[bc]	3.05
Isoleucine	87.5[a]	81.6[ab]	77.9[b]	78.5[b]	2.60
Leucine	89.7[a]	83.9[b]	79.7[b]	82.0[b]	2.35
Lysine	82.7[a]	70.2[b]	67.9[b]	72.1[b]	3.72
Methionine	90.4[a]	82.2[b]	80.1[b]	81.4[b]	2.15
Phenylalanine	89.5[a]	82.7[b]	79.5[b]	81.2[b]	2.51
Threonine	86.4[a]	76.7[b]	74.9[b]	74.6[b]	3.87
Tryptophan	84.6	82.7	85.1	83.5	2.94
Valine	87.2[a]	79.6[b]	76.0[b]	77.0[b]	2.93
Total[4]	88.9[a]	84.2[ab]	80.8[b]	81.9[b]	2.24
Dispensable AA, %					
Alanine	91.4[a]	83.7[b]	80.2[b]	82.3[b]	2.28
Aspartic acid	89.9[a]	81.2[b]	79.5[b]	79.0[b]	2.59
Cysteine	86.4[a]	77.2[b]	71.3[b]	71.8[b]	3.34
Glutamic acid	83.8[a]	81.6[b]	75.9[b]	77.5[b]	2.14
Glycine	87.1	79.2	78.2	74.1	4.56
Serine	91.6[a]	84.2[b]	82.8[b]	83.2[b]	2.48
Tyrosine	87.8[a]	77.6[b]	74.5[b]	77.9[b]	2.82
Total[5]	88.2[a]	78.7[b]	74.9[b]	76.2[b]	2.84
All AA	88.6[a]	81.8[b]	78.1[b]	79.3[b]	2.50

[1]Ten growing barrows (initially 25.9 kg) were fitted with a T-cannula in the distal ileum and were randomly allotted to 1 of 5 test diets in a 5-period design with 2 replicate pigs per diet in each period for a total of 10 replicates per pig diet.
[2]Values with different superscripts a, b, c differ, $P < 0.05$.
[3]Values with different superscripts x, y differ, $P < 0.10$.
[4]Total indispensable AA (IAA) = [1-(total IAA in the digesta/total IAA in the diet) × (marker in the diet/marker in the digesta)] × 100.
[5]Total dispensable AA (DAA) = [1-(total DAA in the digesta/total DAA in the diet) × (marker in the diet/marker in the digesta)] × 100.

Table 2.12 Growth performance, diarrhea score, and frequency of diarrhea of pigs fed diets containing high-lysine sorghum, red sorghum, white sorghum, or yellow dent corn, Exp. 4[1,2]

		Sorghum Varieties				
Item	Corn	High-Lysine	Red	White	SEM	Probability, *P* <
BW, kg						
d 0	6.3	6.3	6.3	6.3	0.56	0.516
d 11	7.3	7.4	7.0	7.2	0.65	0.312
d 20	10.5	10.8	10.1	10.3	0.84	0.541
d 0 to 11						
ADG, g	93	100	58	75	0.02	0.308
ADFI, g	170	168	140	148	0.01	0.159
G:F	0.549	0.594	0.414	0.510	0.101	0.522
d 11 to 20						
ADG, g	352	374	348	345	0.03	0.623
ADFI, g	484	485	465	448	0.02	0.738
G:F	0.730	0.772	0.748	0.773	0.022	0.456
d 0 to 20						
ADG, g	208	223	187	198	0.02	0.506
ADFI, g	304	305	280	288	0.02	0.622
G:F	0.687	0.731	0.663	0.683	0.026	0.274
Diarrhea score[3]						
d 0 to 11	2.29	2.17	2.06	2.19	0.127	0.598
d 11 to 20	2.31	2.16	2.25	2.53	0.191	0.563
d 0 to 20	2.30	2.16	2.14	2.33	0.104	0.489
Frequency of diarrhea						
d 0 to 11						
Pen days[4]	48	48	48	48	---	---
Frequency[5]	43.75	41.67	37.50	43.75	---	0.916
d 11 to 20						
Pen days[4]	32	32	32	32	---	---
Frequency[5]	43.75	34.38	40.63	53.13	---	0.495
d 0 to 20						
Pen days[4]	80	80	80	80	---	---
Frequency[5]	43.75	38.75	38.75	47.50	---	0.619

[1]A total of 160 weaned pigs (initially 6.3 kg; Line 359 × Camborough®; PIC, Hendersonville, TN) were randomly allotted to 4 dietary treatments with 5 pigs per pen and 8 replicate pens per treatment.
[2]Data are least square means of 8 observations for all treatments.
[3]Diarrhea score = 1, normal feces; 2, moist feces; 3, mild diarrhea; 4, severe diarrhea; 5, watery diarrhea.
[4]Pen days = number of pens × the number of days assessing diarrhea scores.
[5]Frequency = (number of pen days with diarrhea scores ≥ 3/pen days)*100.

Table 2.13 Chemical analysis and AA analysis of experimental diets fed to nursery pigs (as-fed basis)[1]

			Synthetic AA levels in high-lysine diets			
Analyzed composition, %	Corn	Sorghum	Low	Low-Med	Med-High	High
Dry matter	89.1	89.6	90.4	90.3	89.9	90.4
Crude protein	21.6	22.5	23.9	24.0	22.4	21.0
Calcium	0.84	0.87	0.91	0.80	0.92	0.73
Phosphorus	0.59	0.62	0.65	0.64	0.70	0.63
Ether extract	4.3	4.4	4.9	4.7	4.2	3.9
Ash	4.7	5.4	5.4	5.2	4.8	4.2
Indispensable AA, %						
Arginine	1.38	1.28	1.40	1.34	1.27	1.02
Histidine	0.55	0.52	0.58	0.56	0.54	0.47
Isoleucine	0.94	0.96	1.10	1.06	1.01	0.89
Leucine	1.82	1.87	2.32	2.33	2.27	2.18
Lysine	1.42	1.37	1.40	1.36	1.47	1.41
Methionine	0.44	0.44	0.45	0.47	0.55	0.45
Phenylalanine	1.07	1.07	1.26	1.22	1.18	1.06
Threonine	0.91	0.86	0.88	0.87	0.91	0.83
Tryptophan	0.28	0.28	0.28	0.28	0.28	0.25
Valine	1.06	1.04	1.18	1.14	1.08	1.05
Dispensable AA, %						
Alanine	1.05	1.14	1.40	1.43	1.39	1.36
Aspartic acid	2.09	2.04	2.29	2.18	2.09	1.73
Cysteine	0.37	0.34	0.38	0.37	0.37	0.32
Glutamic acid	3.69	3.68	4.43	4.37	4.20	3.83
Glycine	0.87	0.82	0.89	0.85	0.81	0.68
Serine	0.92	0.87	0.99	0.97	0.94	0.81
Tyrosine	0.76	0.75	0.87	0.85	0.82	0.71
All AA	19.59	19.29	22.06	21.61	21.14	19.00

[1]Complete diet samples were taken from 5 feeders per dietary treatment 3 times throughout the study. Samples were stored at -20°C until they were homogenized, subsamples, and submitted to Ward Laboratories, Inc. (Kearney, NE) for proximate analysis and the University of Missouri Agricultural Experiment Station Chemical Laboratory (Columbia, MO) for AA analysis performed in duplicate. Reported values are average of duplicate analysis.

Table 2.14 Effect of high-lysine sorghum on nursery pig growth performance[1,2]

			Synthetic AA levels in high-lysine diets					Probability, $P <$		
Item	Corn	Sorghum	Low	Low-Med	Med-High	High	SEM	Treatment	Linear[2]	Quadratic[3]
BW, kg										
d 0	9.6	9.7	9.7	9.6	9.7	9.6	0.20	1.000	0.946	0.942
d 20	20.9	20.8	21.3	20.9	21.0	20.7	0.33	0.418	0.096	0.868
d 0 to 20										
ADG, g	560	557	582	565	569	555	9.54	0.262	0.055	0.831
ADFI, g	858	851	881	856	872	898	17.9	0.361	0.259	0.258
G:F	0.654	0.656	0.661	0.662	0.655	0.618	0.0106	0.045	0.003	0.194

[1]A total of 293 pigs (DNA Line 241 × 600; initially 9.7 kg) were used in a 20-d experiment with 5 pigs per pen and 10 replications per treatment.

[2,3]Linear and quadratic effects of increasing high-lysine sorghum.

Chapter 3 - Calculating Breeding Herd Feed Usage and Cost in Commercial Production Systems

ABSTRACT: In most U.S. commercial swine operations, breeding herd gestation and lactation feed cost are commonly reported on a per-weaned-pig basis, based on ingredient cost, feed usage, and the number of pigs weaned. Most producers focus on increasing the number of pigs weaned to reduce feed cost per-weaned-pig; with very little focus on factors affecting breeding herd feed usage. Therefore, the objective of this paper is to describe a production tool to be used by swine producers, veterinarians, and nutritionists, as a method of benchmarking feed usage and feed cost within a production system, including gestation, lactation, and gilt development. The production tool allows for multi-farm comparisons of feed usage and feed cost on a per-weaned-pig and per-inventoried-sow basis, to identify differences in feed usage, aside from the number of pigs weaned.

The model was developed using Microsoft Excel® and includes key variables within the breeding herd affecting feed usage. Data was used from a commercial production system to determine model accuracy as well as demonstrate its use. The results from this production tool provide accurate estimates for feed usage and feed cost within each sub-population of animals in the breeding herd. Due to the complexity of breeding herd variables and the many interrelationships that exist, the model is unable to quantify feed usage and feed cost to specific variables, such as changing farrowing rate or gilt selection rate; however generalized conclusions can be made.

Key words: swine, breeding herd feed usage, feed herd feed cost

Introduction

Feed cost in the swine industry have historically encompassed 65 to 75% of the variable costs of production and because of this, swine producers continually seek ways to reduce feed cost. Although the breeding herd represents a numerically small fraction of the total swine herd, they consume approximately 20% of the total feed produced and can have a large impact on the profitability of a production system[1]. In contrast to other phases of production where body weight is used to derive cost and revenue, breeding herd revenue and production costs are commonly calculated on a per-weaned-pig basis[2]. Historically, the emphasis in reducing feed cost per-weaned-pig has been focused around the factors that increase the number of pigs weaned. Previous literature has developed detailed productivity trees displaying the relationships between factors influencing pigs weaned per-female-per year and models have been developed to quantify changes[3,4,5]. However, little emphasis has been placed on examining factors affecting feed usage and cost in gilt development, gestation, and lactation.

Feed cost per-weaned-pig is affected by feed cost (ingredient cost), feed usage, and the number of pigs weaned. Each variable is influenced by numerous factors, many of which are interrelated within the breeding herd. It is typical for producers to calculate feed cost per-weaned-pig based off of gestation and lactation feed usage and generally do not include feed costs in the gilt development unit (GDU). When farms continue to have replacement rates exceeding 50%, capturing gilt development feed usage and cost is imperative to minimizing feed cost-per-weaned-pig. Therefore, the purpose of this paper is to describe a model that serves as a production tool to internally evaluate factors affecting feed usage-per-weaned-pig, and subsequently feed cost-per-weaned-pig. Specifically, this model partitions feed usage within the

breeding herd among the different female populations allowing for the isolation of feed cost-per-weaned-pig within each population and benchmark or diagnose differences among breeding herds. The model also calculates feed usage and feed cost per-inventoried-sow as another way to report breeding herd feed cost, offering a second means of comparison. Our specific aim was to develop a learning tool to stimulate the complexities of breeding herd feed cost, aside from the factors effecting the number of pigs weaned, through a commercial production system.

Materials and Methods

Description of model

The model was designed with the intent of being used within commercial swine production systems as a form of benchmarking among different breeding herds within and across production systems. This approach allows the producer to enter production data from one or several breeding herds into the model and compare feed usage and cost on a weaned pig and inventoried sow basis for each sub-population within the breeding herd. For most producers, feed usage and feed cost for each sub-population within the breeding herd has not been reported in this fashion, but instead as one value for gestation and one value for lactation. The use of this model allows for not only within system farm comparisons, but also quantifies feed usage within each sub-population and includes GDU.

The mathematical model is reflective of current US swine production practices and is easily expandable to different production systems, assuming a continuous flow within the breeding herd. For simplification and demonstration purposes, the time interval used in the model is reported on a weekly and annual basis.

Data from a commercial productions system with multiple individual sow farms was collected to provide model inputs and validate calculations. The model was developed using Microsoft Excel®. Detailed instructions for model use are outlined in Appendix A.

Determining feed usage

The breeding herd is composed of three primary areas: 1) gestation, 2) lactation, and 3) gilt development (Figure 1). Each of these sections are occupied by females in different stages of their reproductive cycle, and because of this, exhibit differences in feed usage. The model herein is designed to isolate each sub-population of females and determine feed usage specific to each one.

To do this, the model requires a series of inputs based on annual production records and current farm practices. The model estimates feed usage for sub-populations within gestation, lactation, and GDU one of two ways, as outlined in Figure 2 and discussed below.

Methods for estimating feed usage for sub-populations

The user may select to estimate and enter individual feed intakes for each sub-population of animals within gestation, lactation, and GDU (Figure 2). For example, within gestation, the user will enter estimated ADFI values for mated females, females to be serviced within the wean-to-estrus interval, cull sows, and boars. The second and recommended option for estimating feed usage for each sub-population is with actual feed delivery reports for gestation, entry to 1st service, lactation, and GDU feed (Figure 2). The model allows for gilts within the entry-to-first service interval to be fed the same gestation diet as the remaining gestation herd population, or a separate diet. If fed a separate diet, the model will estimate feed usage for gilts within the entry-to-first service interval based on actual feed delivery. However, if gilts are consuming gestation feed, the model requires the user to enter estimated ADFI for gilts within

the entry-to-first service interval. In addition, the model will require the user to enter estimated ADFI values for females in the wean-to-estrus interval, boars, and cull sows within gestation, as well as pre-farrow females in lactation (only if pre-farrow females are limit fed). These estimated ADFI values are needed to partition feed appropriately within each population to the respective sub-population. Without providing any estimated ADFI values, the model would produce ADFI identical for each sub-population within the barn, which we know is not correct. If ADFI for the required sub-populations is unknown, default values can be used and are discussed in detail within each sub-population below.

Gestation

In the model, gestation feed usage is determined separately for each sub-population of females within the gestation barn (Table 1). Female populations in gestation are divided into 1) mated and 2) unmated females, as well as the number of boars used for heat-detection or semen collection. Sub-populations of mated females in gestation include:

- Females who were serviced and died during gestation (mortality),
- Females who were serviced and recycled during gestation (recycles), and
- Females who were serviced and will farrow (gestating sows).

The average day of death is required to estimate feed usage for the mortality sub-population. If the average day of death is unknown, the default value assumes gestating females died on day 58 (midpoint) of gestation. The model assumes mortality occurs only within the mated female gestation population. Female recycles are a function of female services, farrowing rate, and female deaths. Like mortality, the average day of detection of recycles is required to estimate feed usage and if the average day is unknown, a default value assumes recycles were found on day 58 of gestation. Gestating sows are a function of female services and farrowing

rate. The model assumes a continuous flow within the gestation population. For example, as females are serviced and enter the gestation mated population, pregnant females in the gestation mated population enter the farrowing house.

The second division in the gestating category is the unmated female population. This further subdivides gilts within the entry-to-first service interval and non-productive sows. The unmated gilts within the entry-to-first service interval captures the cost associated with these females as they enter the breeding herd. The model assumes the population of unmated gilts within the entry-to-first service interval are eligible for breeding (>200 d of age). From this population, gilts are subdivided into:

- Gilts serviced and entering the mated population (serviced gilts),
- Gilts who skip a heat and are serviced 21 days later, before entering the mated population (skipped gilts),
- Gilts culled and removed from the breeding herd (culled gilts).

The unmated non-productive sow population include all remaining sows consuming gestation feed. The two unmated non-productive sow populations include:

- Sows yet to be serviced (weaned females and recycles to be serviced)
- Sows to be culled (females culled)

The model requires an input for ADFI for non-productive sows to be serviced and non-productive cull sows. If ADFI values are unknown, default values of 3.6 and 5.2 kg are used[7,8,9,10]. The model assumes unmated non-productive sows to be serviced are within the wean-to-estrus interval and include sows weaned from the farrowing house as well as recycles to be serviced. Total non-productive cull sow inventory is a function of annual culling rate. Lastly, in

addition to entering non-productive cull sow intake, the average number of cull sow days on the farm is needed to estimate feed usage for this population.

Lactation

Lactation feed usage is determined separately for each sub-population of females within the farrowing house. Female populations in lactation include:

- Pregnant females who have not yet farrowed (pre-farrow sows),
- Females that farrow and wean a litter (normal lactating sows),
- Females that farrow and wean >1 litter (nurse sows),
- Females that farrow but do not wean a litter of pigs, i.e., females that farrow and pigs are transferred onto another sow (weaned without a litter sows).

Pregnant females loaded into the farrowing house who have not yet farrowed is estimated based on female services and farrowing rate. The same calculation is used to estimate the number of normal lactating females while also accounting for nurse sows and those farrowed but did not wean a litter of pigs (weaned without a litter sows). The model allows for pregnant females loaded into the farrowing house who have not yet farrowed to be fed ad libitum, in which ADFI will be determined using the model, or the user can input estimated ADFI if they are not on full-feed. The model also allows for an option if lactation feed is fed to unmated non-productive sows to be serviced (wean-to-service interval).

Gilt development unit

The model is designed to capture gilt development feed usage, and the associated feed cost, starting at entry into the breeding herd. For producers purchasing or producing weaned replacement gilts, nursery feed usage and the associated feed cost, mortality, and selection rates should be included with GDU inputs. The user enters the annual average days gilts are in the

GDU before entering the breeding herd population (average days in GDU). For example, if replacement gilts are purchased at weaning, the average days entered would include days from purchase to entry into the breeding herd population (nursery + GDU). If females are purchased at selection (> 200 days of age) and thereafter directly enter the breeding herd, the resulting days in the GDU would be zero. Thus, the model allows for flexibility among productions systems to tailor GDU inputs specific to their system.

Female populations within the GDU include:

- Replacement gilts eligible to enter the gilt pool (replacement gilt pool),
- Gilt mortality (GDU mortality),
- Non-select gilts (GDU non-selects).

Replacement gilt inventory is a function of replacement rate and total female inventory (>200 days of age) accounting for gilt death loss and selection rate in the GDU. Gilt mortality is a function of GDU mortality rate. If the average day of death within the GDU is unknown, a default value equivalent to half the days in GDU is used to determine how much feed was consumed before death. Non-select gilts are a function of GDU selection rate and if the average days of feed consumed before non-select females are removed from the herd is unknown, a default value equivalent to half the days in GDU is used.

Practical Application

The efficacy of the model was determined using data from a large commercial production system with multiple sow farms. Data was compiled from production records and farm managers based on current farm practices. The goal was not only to evaluate the accuracy of the model, but also determine the accessibility of obtaining all required model inputs and demonstrate model

use. The model calculates feed usage and feed cost for each sub-population within gestation, lactation, and GDU on a per-weaned-pig and per-inventoried-sow basis. In addition, the model also calculates a system weighted average (weighted by breeding herd female inventory) that can be used to help with benchmarking and identify farms that are greater than one standard deviation from the average.

Annual breeding herd productivity records were obtained from 4 breeding herds within a large production system. to evaluate the model (sow farms 1 to 4, Table 2). All 4 farms house gestating females in conventional gestation stalls and are fed via feed drops. Females across all 4 farms are fed in gestation stalls during the wean-to-estrus period and provided feed ad libitum. Cull sows are housed in pens or gestation stalls and provided feed ad libitum before being sold. Upon loading into the farrowing house (day 113 of gestation) females are limit fed until farrowing. Thereafter, the feeders in lactation allow for ad libitum feed intake during lactation. Replacement gilts enter an off-site nursery at weaning, spend 50 d in the nursery, and are then transported to the GDU. Gilts enter into the unmated breeding herd population at approximately 200 days of age. Gilts are provided feed ad libitum in the nursery and GDU.

Model calculated mated female (gestation) ADFI for farms 1 through 4 are 2.2, 2.1, 2.3, and 2.4 kg, respectively (Table 3). The producer estimated mated female ADFI at 2.0 kg. On average, mated females consume 0.2 kg more feed per day than the producers estimate. The mated female population consumes the greatest quantity of feed among female sub-populations within gestation. Thus, discrepancies between model calculations and producer estimates, can have a large financial impact and it is important to understand why differences exist. Factors possibly contributing to the increase in ADFI for mated females could be feed wastage, thin females requiring more feed, or inaccurate feed drops.

Model calculated lactation ADFI for farms 1, 2, 3, and 4 were 5.6, 6.6, 6.4, and 6.2 kg, respectively, compared to the producer's estimate for lactation feed intake at 5.9 kg (Table 3). On average, lactating females consume 0.3 kg more per day than producer estimates. Within this production system, pre-farrow females in a lactation stall are provided 2.7 kg of feed per day until farrowing, in which females are provided with ad libitum feed. Speculation for differences in model calculated and producer estimated lactating female ADFI could be the pre-farrow females are receiving more than the allotted 2.7 kg per day. Other possibilities include poor feeder management (wastage) or differences in parity structure.

Model calculated ADFI for GDU (from weaning to 200 days), using feed delivery, for farms 1, 2, 3, and 4 were 2.0, 2.0, 3.3, and 1.8 kg, respectively (Table 3). Feed delivery records include nursery and GDU. Within this system, nursery and GDU sites commonly supply gilts for multiple sow herds. Therefore, nursery and GDU feed deliveries were partitioned appropriately in an attempt to accurately reflect gilt flow among the breeding herds.

Model calculated feed usage and feed cost per-weaned-pig are presented in Figures 3 and 4 and per-inventoried-sow in Figures 5 and 6. Gestation, lactation, and GDU diet costs differ among the breeding herds due to different feed mills manufacturing the feed. Average gestation, lactation, and GDU feed usage and feed cost per-weaned-pig for all 4 farms were 54.3 kg and $10.71. Similarly, average gestation, lactation, and GDU feed usage and feed cost per-inventoried-sow for all 4 farms were 1,336 kg and $263.76.

The use of this model within this production system highlights differences in feed usage and feed cost between the 4 farms. Weaned-pig feed usage and feed cost are greatest in farm 3 and lowest in farm 4 (Figures 3 and 4). These differences are influenced by the number of pigs weaned as well as differences in feed usage in gestation, lactation, and GDU, with farm 3 feed

usage being the greatest in almost all sub-populations. When evaluating differences in feed usage and feed cost on a per-inventoried-sow basis, farm 3 was still the greatest, however the magnitude of differences in feed usage and feed cost within each sub-population were smaller. This showcases the reduction in the number of pigs weaned in farm 3 compared to remaining farms.

The model calculated notable differences in feed usage and in turn feed cost in gestating females, recycles, serviced gilts, weaned females to be serviced, and cull sow sub-populations within gestation. Gestation diet cost was $0.18 per kg for farms 1 and 2 and $0.17 per kg for farms 3 and 4. Based on delivery data, estimated ADFI for gestating females from farm 4 was 0.2 kg greater than the average for the remaining 3 farms, contributing to the increase in feed cost per-inventoried-sow of $12.77 (Table 4). Gestating females on farm 2 had the lowest feed cost per-inventoried-sow; however, feed usage per-inventoried-sow for females that recycle was the greatest at 50.3 kg, compared to the average of the other 3 farms at 27.1 kg. This can be partially explained by a lower farrowing rate and greater days from 1st service to found open for farm 2 compared to the average of the other farms. This contributes to the increased feed cost per-weaned-pig and per-inventoried-sow of $0.18 and $4.37 for farm 2 compared to the average of farms 1, 3, and 4 (Table 4). Similarly, farm 2 feeds cull sows for an additional 4 days compared to other farms and has a higher culling rate, contributing to the increase in feed cost per-weaned-pig and per-inventoried-sow of $0.09 and $2.08 (Table 4). Lastly, serviced gilts from farm 3 have the greatest feed usage per-weaned-pig and per-inventoried-sow (Table 4). This can be partially explained by an increase in the entry-1st-service interval for gilts within farm 3 by 27 days, contributing to an increase in feed cost per-weaned-pig and per-inventoried-sow of $0.30 and $5.54. Thus, within gestation, the model indicates there are numerous sub-

populations of females with differences in feed usage and cost. Using the model allows for the user to further diagnose and understand where opportunities exist to reduce breeding herd feed usage and, subsequently, feed cost.

Differences in feed usage and feed cost were observed in lactation sub-populations as well. Lactation diet cost for farms 1, 2, and 3 were $0.23 per kg and $0.22 per kg for farm 4. In farm 3, feed cost per-weaned-pig and per-inventoried-sow was increased by $0.80 and $7.29 for normal lactating sows and $0.20 and $3.79 for nurse sow sub-populations compared to the average of the other farms (Table 4). These differences are attributed to numerous factors, including increased ADFI in lactation, increased lactation length, and increased percentage of nurse sows in farm 3.

In addition to gestation and lactation, the model also highlighted differences in feed usage and feed cost per-weaned-pig and per-inventoried-sow for GDU sub-populations. Within this system, diet cost per kg was $0.21 for farms 1, 2, and 3 and $0.20 for farm 4. Feed cost per-weaned-pig and per-inventoried-sow for replacement gilts was $1.45 and $23.99 greater in farm 3 compared to the average of the other farms (Table 4). Similarly, non-select gilt feed cost per-weaned-pig and per-inventoried-sow were $0.25 and $4.20 greater in farm 3 compared to farms 1, 2, and 4 (Table 4). These differences in feed cost can be explained by increased gilt ADFI in farm 3 compared to farms 1, 2, and 4 (Table 3), as well as difference in pigs weaned and female inventory.

Conclusions

Overall summary

The purpose of this paper was to describe a production tool that can be used a resource to swine producers to understand differences in feed usage and subsequently feed cost, within the breeding herd. Specifically, the model focused on capturing feed usage within each sub-population of the breeding herd, including GDU, to quantify and understand feed usage within each these areas, instead of focusing solely on factors that increase the number of pigs weaned. The model developed was successful at partitioning feed usage and feed cost among sub-populations within gestation, lactation, and GDU within multiple farms from a commercial swine production system.

When demonstrating model use, feed usage and subsequently feed cost per-weaned-pig and per-inventoried-sow was determined, illustrating the variability that can exist within systems and how to rationalize and make sense of these differences. The model identifies sub-populations with feed usage greater than 1 standard deviation of the average for the system, providing the user with an opportunity to diagnose what factors are contributing to these differences. Due to the complexity of the response variable, the model cannot quantify financial impacts of individual variables; however, the model remains useful for benchmarking and highlighting differences among the different farms.

Implications:

- This model determines feed usage and feed cost per-weaned-pig and per-inventoried-sow for each sub-population of animals within the breeding herd.

- The model allows the user to see the complexity of feed usage within the breeding herd and quantifies feed usage and feed cost for each sub-population within the breeding herd, including GDU.
- The use of this model provides managers and producers with a tool that allows them to compare farms internally or externally and diagnose other factors affecting breeding herd feed usage.
- Demonstrating model use utilizing data from a commercial production system provides evidence that although the number of pigs weaned is a large factor affecting feed cost per-weaned-pig, it is not the only factor other opportunities exist to reduce feed cost.

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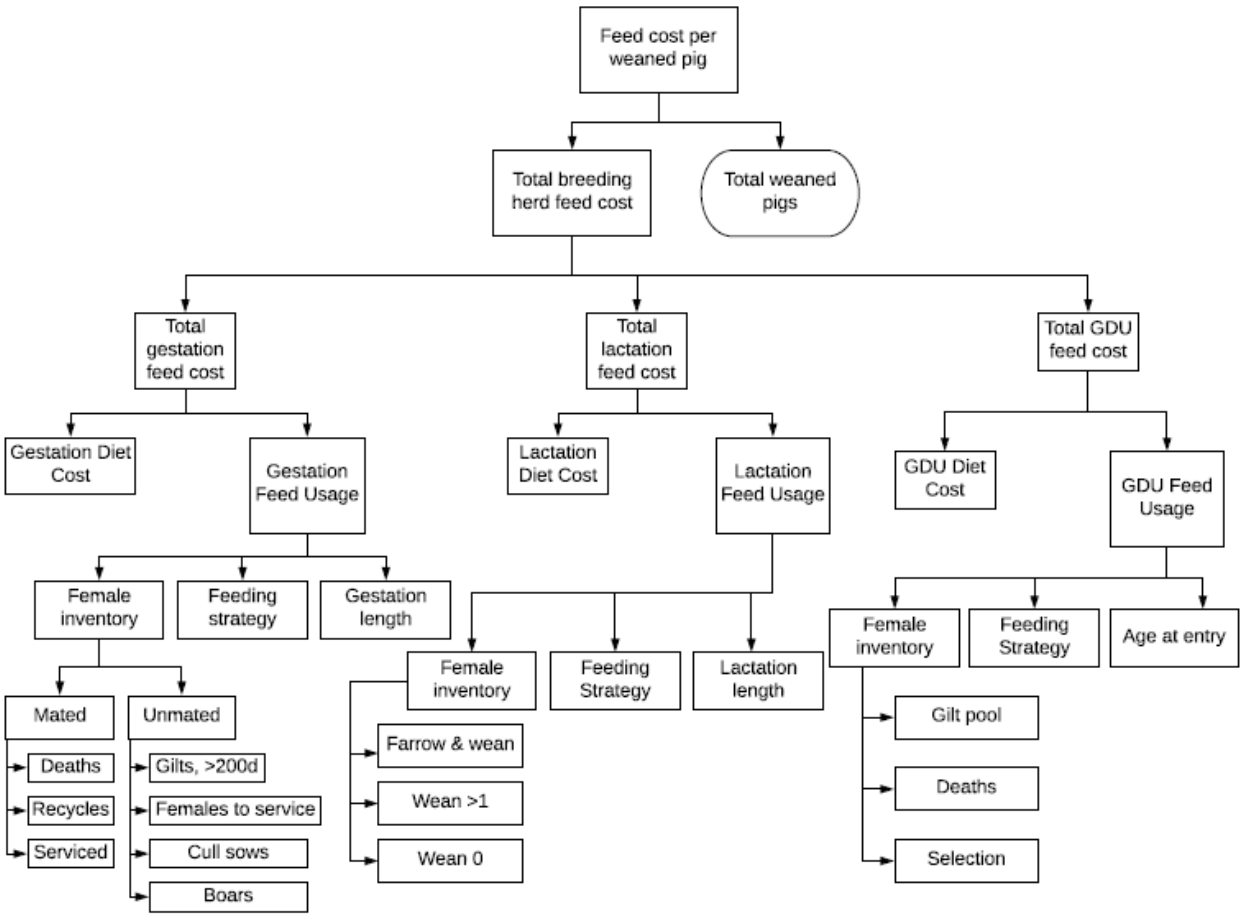

Figure 3.1 Representation of the feed cost per-weaned-pig separated into gestation, lactation, and GDU sub-populations. Within each area of the breeding herd, feed cost is composed of diet cost and feed usage. Feed usage is further divided among female populations, feed allowance, and days on feed.

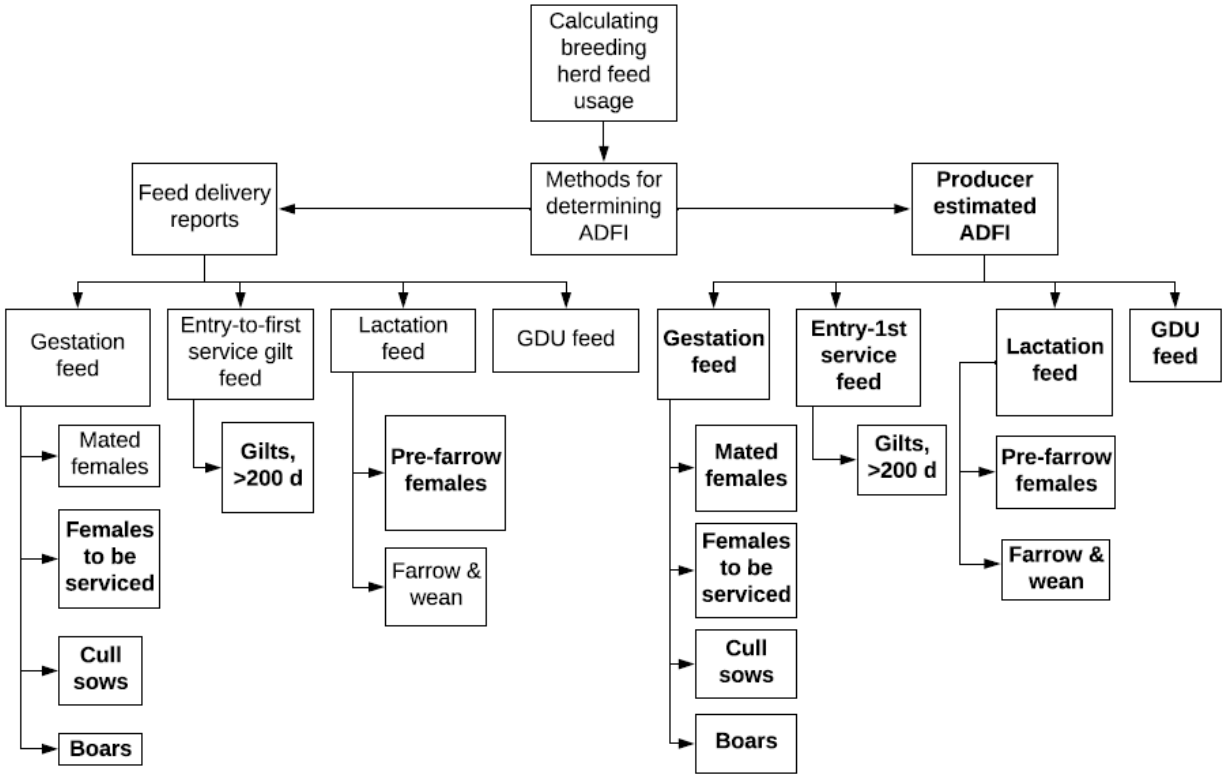

Figure 3.2 Different methods for determining feed usage. Regardless of method, the model requires (bold text in figure above) estimated ADFI values for females to be serviced, cull sows, gilts >200 d (only if consuming gestation feed), and boars consuming gestation feed and pre-farrow females consuming lactation feed (only if pre-farrow sows are limit fed).

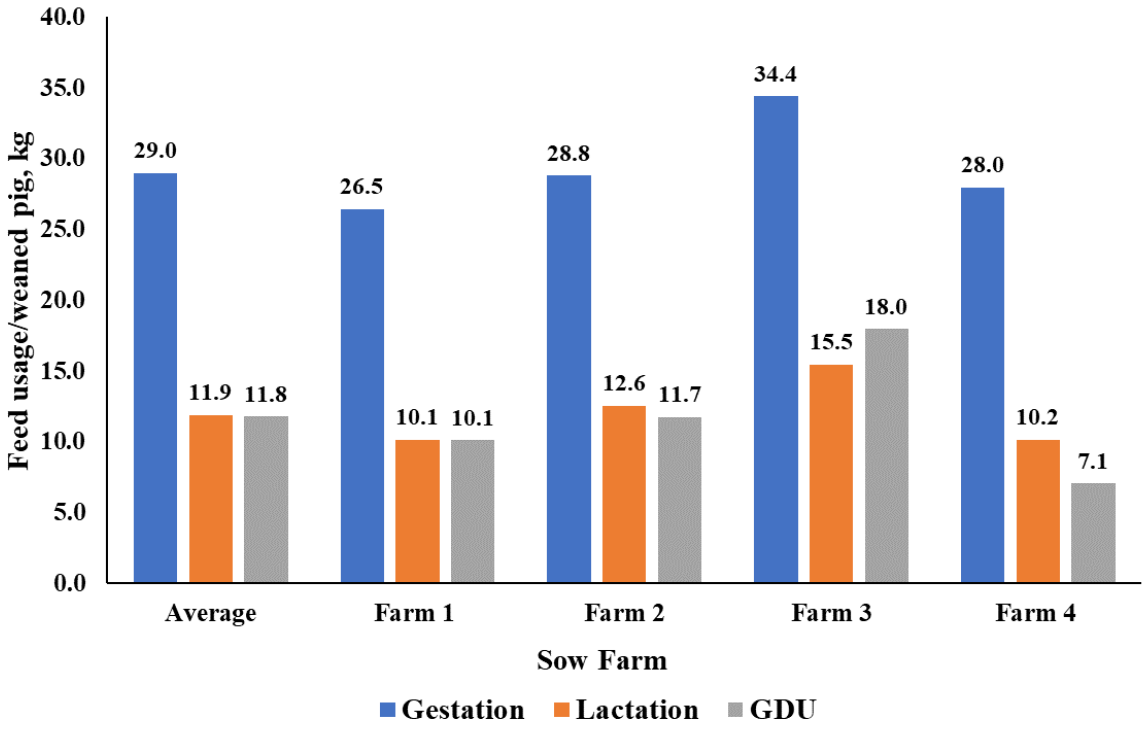

Figure 3.3 Model calculated annual feed usage per-weaned-pig for each segment of the breeding herd for each of the 4 farms.

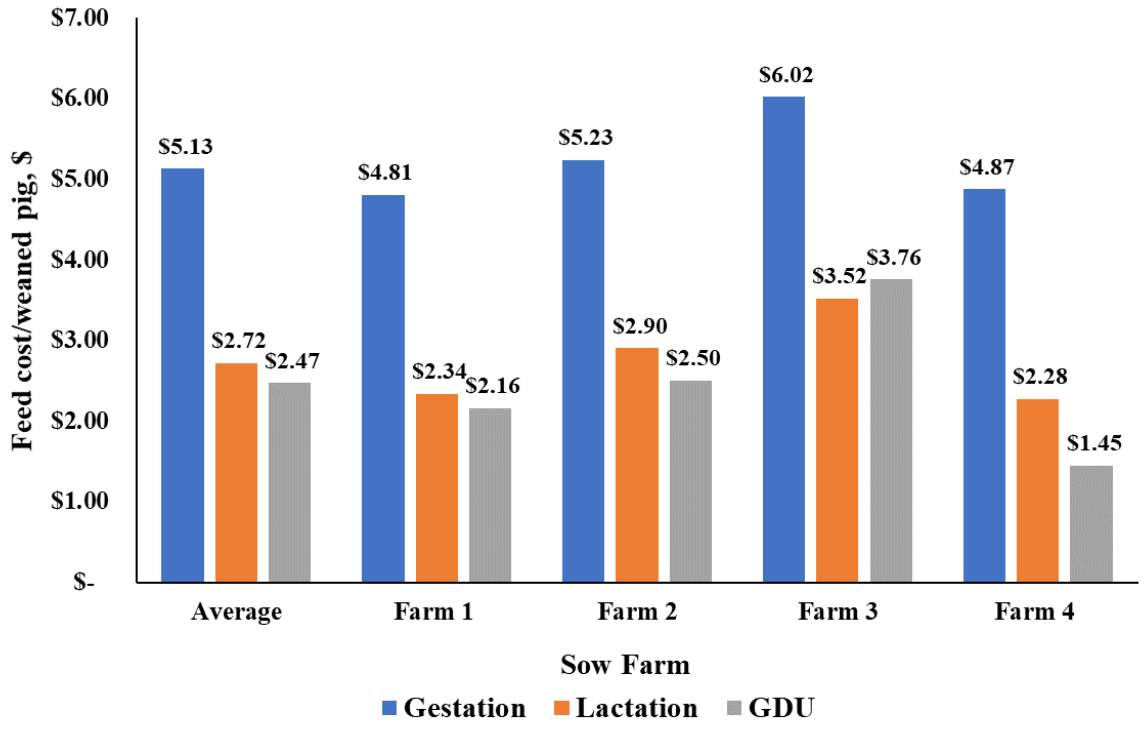

Figure 3.4 Model calculated annual feed cost per-weaned-pig for each segment of the breeding herd for each of the 4 farms.

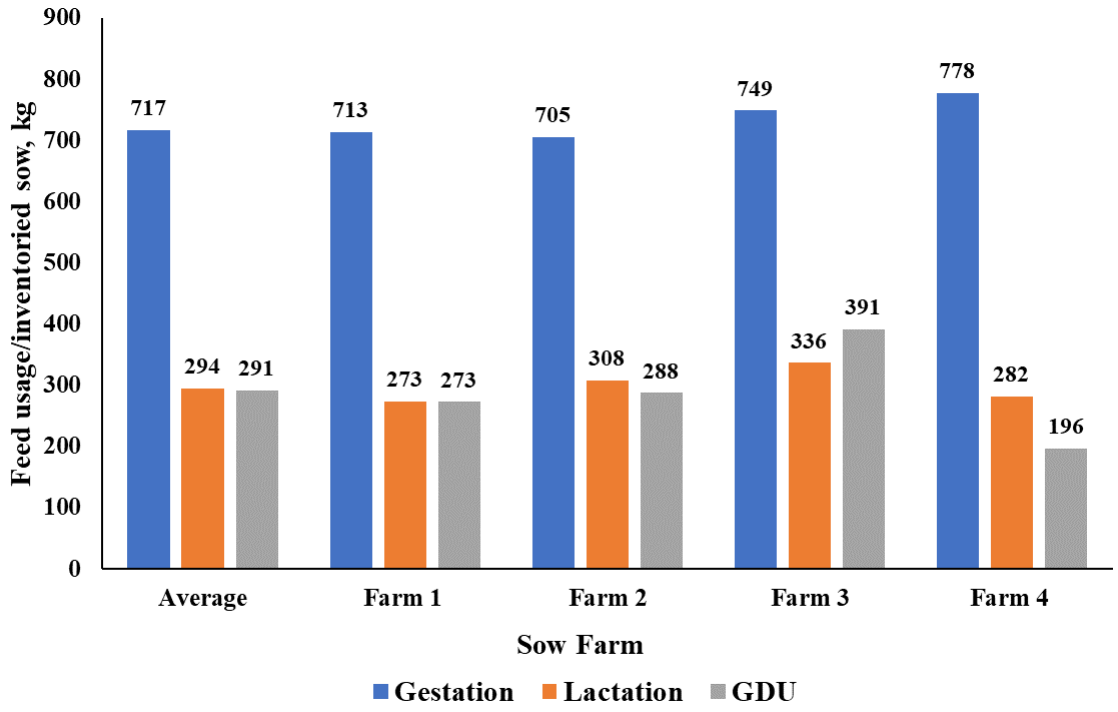

Figure 3.5 Model calculated annual feed usage per-inventoried-sow for each segment of the breeding herd for each of the 4 farms.

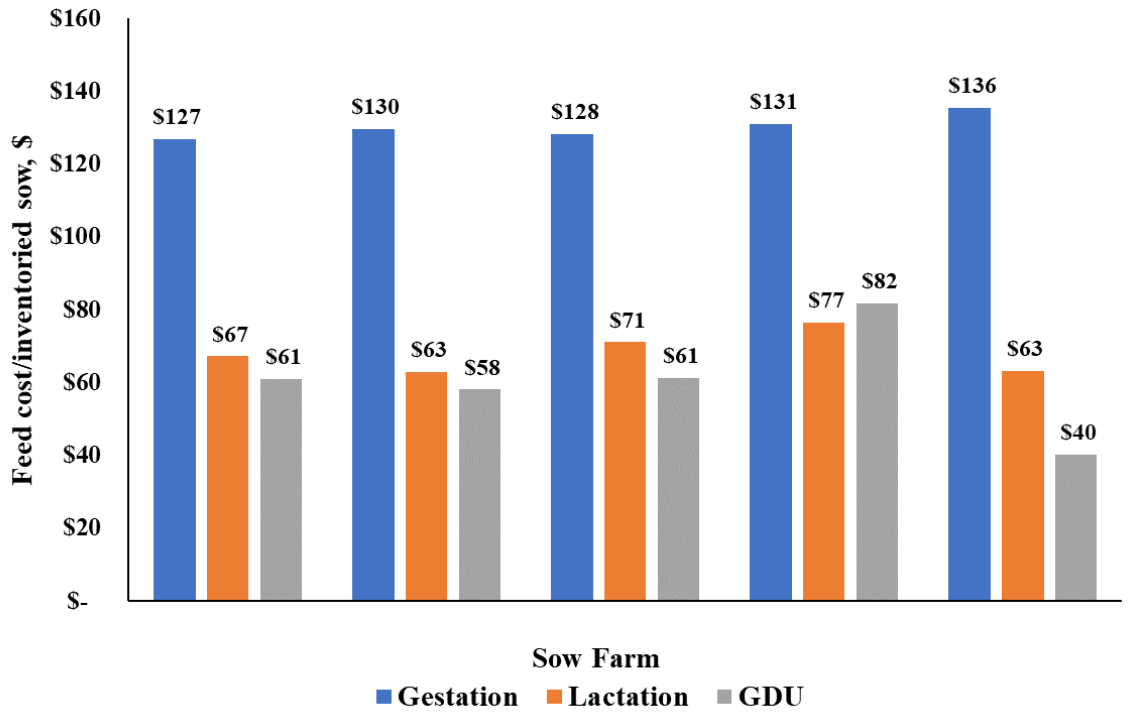

Figure 3.6 Model calculated annual feed cost per-inventoried-sow for each segment of the breeding herd for each of the 4 farms.

Table 3.1 Equations used in the estimation of female inventories per week for each breeding herd population[1]

Population	Equation
Gestation	
Mated females	
Mortality[2]	= (total female inventory × avg. mortality rate, %) / (365.25/7)
Recycles	= (avg. services per wk. × (1-avg. farrowing rate, %)) – mortality per wk.
Gestating sows	= avg. services per wk. × farrowing rate, %
Unmated females	
Entry-to-first service interval[3]	
Serviced gilts	= (gilts available per week × gilts bred, %)
Skipped gilts[4]	= (gilts available per week - gilts serviced per week) × gilts skipped, %
Culled gilts[5]	= (gilts available per week - gilts serviced per week) × (1-gilts skipped, %)
Non-productive sows	
Weaned females to be serviced[6]	= (females that farrow and wean per wk + nurse sows weaned per wk) × weaned females bred, %
Weaned without a litter to be bred[7]	= weaned zero females per week × weaned zero females bred, %
Recycles to be serviced	= recycles per week × recycles bred, %
Females culled	= (total female inventory × avg. culling rate, %) / (365.25/7)
Lactation	
Pre-farrow sows	= avg. services per wk. × farrowing rate, %
Normal lactating sows	= (avg. services per wk. × farrowing rate, %) × (1 – nurse sow, % + weaned zero females, %)
Nurse sow	= (avg. services per wk. × farrowing rate, %) × nurse sow, %
Weaned without a litter sows[7]	= (avg. services per wk. × farrowing rate, %) × weaned zero females, %
GDU	
Replacement gilt pool	= (((((total female inventory × replacement rate, %) + ((total female inventory × replacement rate, %) × (avg. GDU mortality rate, %)) + ((total female inventory × replacement rate, %) × (1- avg. GDU selection rate, %))) / 365.25) ×7) – (GDU mortality) – (GDU selection)
GDU mortality	= ((total female inventory × replacement rate, %) × avg. GDU mortality rate, %) / 365.25) ×7
GDU non-selects[8]	= (((total female inventory × replacement rate, %) × (1- avg. GDU selection rate, %)) / 365.25) ×7

[1]The model was designed assuming farrowing's are uniformly distributed through the week (continuous flow).
[2]The model assumes mortality occurs within the gestation population to mated females only.
[3]Gilts available/week are defined as gilts >200 d of age, within the entry-to-first service interval, eligible to bred.
[4]Gilts skipped are defined as gilts who skip a heat and are serviced 21 days later.
[5]The model assumes if the eligible gilt is not bred or skipped, she is culled.
[6]Weaned females to be serviced includes females that farrow and wean a litter and females that farrow and wean>1 litter (nurse sow).
[7]Females who weaned without a litter are defined as females who farrow, and pigs are transferred onto another sow.

[8]GDU selection is defined as gilts not selected to enter the replacement gilt pool and are removed from the breeding herd.

Table 3.2 Selected model inputs from 4 sow farms to demonstrate model use[1]

Input variable	Farm 1	Farm 2	Farm 3	Farm 4
Female inventory, >200 d[2]	1583	4109	2772	1480
Boar inventory	3	10	17	4
Avg. services (sows & gilts)/wk	80	213	142	77
Recycles serviced, %	43	63	99	70
Avg. d found open, d[3]	40	58	37	42
Wean to estrus interval, d	5.9	6.8	7.7	6.9
Avg. farrow rate, %	87.6	80.1	79.0	85.8
Avg. culling rate, %	46.4	48.0	35.3	40.5
Avg. cull sow days, d[4]	24	27	24	22
Avg. mortality rate, %	9.9	12.8	16.0	10.6
Entry to 1st service interval, d	23.4	15.3	46.7	21.7
Entry to removal interval, d	41	51	71	11
Avg. lactation length, d	20.1	21.6	24.6	18.9
Avg. nurse sows weaned, %[5]	3.5	5.0	8.5	3.8
Avg. sows weaned zero, %[6]	0.3	7.4	3.6	4.3
Avg. number of pigs weaned/wk	818	1929	1156	789
Avg. replacement rate, %	58.6	62.3	49.4	45.7
Unmated females to be serviced ADFI, kg[7]	3.4	3.4	3.4	3.4
Unmated females culled ADFI, kg[7]	3.0	3.0	3.0	3.0
Boar ADFI, kg[7]	2.0	2.0	2.0	2.0
Unmated (gilts) entry-1st service ADFI, kg[7]	3.0	3.0	3.0	3.0
Pre-farrow ADFI, kg	2.7	2.7	2.7	2.7

[1]Averages are reported on an annual basis unless otherwise specified.
[2]Total female inventory includes gilts and sows, >200 days of age.
[3]Average days from 1st service to found open.
[4]Average days cull sows remain on the farm after classified as a cull sow.
[5]Females that farrow and wean >1.
[6]Females that farrow and wean zero.
[7]Producer estimated ADFI based off farm observation.

Table 3.3 Model calculated ADFI for each sow farm[1]

Input variable	Farm 1	Farm 2	Farm 3	Farm 4
Calculated mated female ADFI, kg	2.2	2.1	2.3	2.4
Calculated lactation ADFI, kg[2]	5.6	6.6	6.4	6.2
Calculated GDU ADFI, kg[3]	2.0	2.0	3.3	1.8

[1]Model calculated ADFI was derived based off feed delivery inputs for females in gestation and lactation (using the optimization tool to separate deliveries to gestation, entry-to-first service interval, and lactation), and feed budget inputs for GDU.
[2]Females are provided with ad libitum feed at farrowing.
[3]Gilts are produced internally and enter the breeding herd population at 200 d of age.

Table 3.4 Breeding herd populations having the greatest effect on feed usage- and feed cost per-weaned-pig[1,2]

Parameter	Farm 1	Farm 2	Farm 3	Farm 4
Gestation				
Gestating sows				
Days on feed, d	114	113	113	114
Yearly inventory	3,649	8,885	5,834	3,444
Yearly intake, metric ton	894	2,136	1,510	9,366
Yearly feed cost, $	162,484	388,153	264,194	163,185
Feed usage/weaned pig, kg	21.0	21.2	25.0	22.8
Feed cost/weaned pig, $	3.81	3.86	4.38	3.97
Feed usage/inventoried sow, kg	565	520	545	633
Feed cost/inventoried sow, $	102.64	94.46	95.32	110.25
Recycles				
Days on feed, d	40	58	37	42
Yearly inventory	360	1,681	1,107	413
Yearly intake, metric ton	31	207	93	42
Yearly feed cost, $	5,654	37,602	16,195	7,275
Feed usage/weaned pig, kg	0.7	2.1	1.5	1.0
Feed cost/weaned pig, $	0.13	0.37	0.27	0.18
Feed usage/inventoried sow, kg	20	50	33	28
Feed cost/inventoried sow, $	3.57	9.15	5.84	4.91
Serviced gilts, > 200 days				
Days on feed, d	23	15	47	22
Yearly inventory	835	2,304	1,232	609
Yearly intake, metric ton	59	106	173	40
Yearly feed cost, $	10,652	19,221	30,204	6,905
Feed usage/weaned pig, kg	1.4	1.1	2.9	1.0
Feed cost/weaned pig, $	0.25	0.19	0.50	0.17
Feed usage/inventoried sow, kg	37	26	62	27
Feed cost/inventoried sow, $	6.73	4.68	10.90	4.67
Females culled				
Days on feed, d	24	27	24	22
Yearly inventory	735	1,972	978	599
Yearly intake, metric ton	53	161	70	39
Yearly feed cost, $	9,609	29,261	12,183	6,880
Feed usage/weaned pig, kg	1.2	1.6	1.2	1.0
Feed cost/weaned pig, $	0.23	0.29	0.20	0.17
Feed usage/inventoried sow, kg	33	39	25	27
Feed cost/inventoried sow, $	6.07	7.12	4.40	4.65
Lactation				
Normal lactating sows				
Days on feed, d	20	22	25	19
Yearly inventory	3,511	7,878	5,125	3,165
Yearly intake, metric ton	394	1,110	804	372
Yearly feed cost, $	90,921	256,119	182,896	83,397
Feed usage/weaned pig, kg	9.2	11.0	13.3	9.0
Feed cost/weaned pig, $	2.13	2.54	3.03	2.03
Feed usage/inventoried sow, kg	249	270	290	251
Feed cost/inventoried sow, $	57.4	62.3	66.0	56.3

Table 7 continued

Nurse sows				
Days on feed, d	26	27	28	26
Yearly inventory	127	443	498	130
Yearly intake, metric ton	18.1	77.5	87.3	20.6
Yearly feed cost, $	4,172	17,889	19,852	4,615
Feed usage/weaned pig, kg	0.4	0.8	1.5	0.5
Feed cost/weaned pig, $	0.10	0.18	0.33	0.11
Feed usage/inventoried sow, kg	11	19	31	14
Feed cost/inventoried sow, $	2.64	4.35	7.16	3.12
GDU				
Replacement gilt pool				
Days on feed, d	199	199	199	199
Yearly inventory	928	2,560	1,369	676
Yearly intake, metric ton	363	994	912	245
Yearly feed cost, $	77,383	211,800	190,563	50,136
Feed usage/weaned pig, kg	8.5	9.9	15.1	5.9
Feed cost/weaned pig, $	1.81	2.10	3.16	1.22
Feed usage/inventoried sow, kg	229	242	329	165
Feed cost/inventoried sow, $	48.88	51.54	68.76	33.87
GDU non-selects				
Days on feed, d	99.5	99.5	99.5	99.5
Yearly inventory	325	896	479	237
Yearly intake, metric ton	64	174	160	43
Yearly feed cost, $	13,542	37,065	33,349	8,774
Feed usage/weaned pig, kg	1.5	1.7	2.6	1.0
Feed cost/weaned pig, $	0.32	0.37	0.55	0.21
Feed usage/inventoried sow, kg	40	42	58	29
Feed cost/inventoried sow, $	8.55	9.02	12.03	5.93

[1]Diet cost for gestation, lactation, and GDU were the same across farms.

[2]Inventory, intake, and feed costs are reported on an annual basis unless otherwise specified.

Appendix A - Detailed Instructions for Use

Purpose

This appendix describes the layout of the model described in "Calculating breeding herd feed usage and cost in commercial production systems".

Building the Model in Excel®

The model was designed using basic functions with Microsoft Excel®. The purpose of the model was to calculate feed usage and cost per-weaned-pig for each breeding herd to establish production benchmarks for the system. By benchmarking, producers can quantify what is "normal" or "optimal" for their production system and further identify herds that deviate from this population. The model will bring light to the differences among the breeding herds, allowing for the producer to diagnosis why differences exist and determine if intervention is possible. The limitation of this model is the inability to quantify financial impacts of individual variables. The model was not designed as an optimization, because of the complexity of the variable of interest (feed cost per-weaned-pig and feed cost per-inventoried-sow).

The current model assumes farrowing's are uniformly distributed through the week; therefore, modeling efforts cannot be directly applied to herds that batch farrow. The model can easily be expanded to include multiple breeding herds within or across production systems. The following sections describe each worksheet of the model and overall structure as it was built in Excel®.

User Input Worksheet

The user input page allows the model to be flexible across multiple types of production systems. In the Excel® model, each respective column is used to identify a specific breeding herd. Annual averages are the preferred input values, and this can be specified when generating the report of interest. Input cells are gold. The input worksheet is divided into three categories: 1) Performance Summary Inputs, 2) Productivity Summary Inputs, and 3) Miscellaneous Reports and Manager Inputs.

1. Performance summary inputs: Twelve performance variables are listed within this category. Performance summary reports show service, farrowing, and weaning performance variables and inventory changes in the breeding herd. These required inputs can be generated in Porcitec and PigChamp in reports titled “Performance Analysis Summary” and “Performance Analysis Report”.

2. Productivity summary inputs: Four productivity variables are listed within this category and may require the user to calculate depending on the report generated. Productivity summary inputs can be obtained through a variety of reports, two of which are discussed here.

    a. Productivity reports: These reports show a breakdown of productive and non-productive female days per time period. Productive days are any day a female is either gestating or lactating. In the report, the days are calculated per female per year. Examples of this report in Porcitec and PigChamp are “Productivity Summary Report” and “Productivity Analysis Report”. The model requires non-productive days for recycles (days from first service to found open), mortality (days from first service to found dead), cull sows (days from first service to removal), and days from entry to removal for gilts who have never been serviced. To obtain model required non-productive day inputs for each of these variables, the user must utilize the non-

productive days listed in the report for the specific variable of interest, the corresponding yearly sum of females for the specific variable of interest, and total female inventory. The user will likely not know the yearly sum of females for the specific variable of interest, however; the model will calculate this value following completion of miscellaneous reports (see next section) and manager inputs and the yearly sum value can be found at the bottom of the input page. An example calculation is provided below.

- Entry to removal (no service) non-productive sow days = 2.4 (from productivity summary report)
- Yearly sum of culled gilts = 93 (model calculated value based on user inputs)
- Total female inventory (user input) = 1,583

$$\frac{\text{(Entry to removal (no service) non-productive sow days} * \text{Total female inventory)}}{\text{Yearly sum of culled gilts}}$$

$$= \frac{(2.4 \text{ days} * 1{,}583 \text{ females})}{93 \text{ culled gilts}} = 40.9 \text{ days (model input)}$$

b. Farrowing analysis reports: These reports show the number of females served per user defined time period, then tracks gestation fall out by days of gestation. The user can filter the reasons and occurrences of gestation fall-out and select for returned to estrus, pregnancy check negative, aborted, found open, deaths, and removed. The report shows the total for each gestation period. Utilizing farrowing analysis reports, the user can calculate a weighted average for each variable and directly input into the model productivity summary inputs.

If values for days from first service to found open or day of gestation females are found dead are unknown, default values can be used (default values are equivalent to half the course of gestation). Lastly, to improve the accuracy of the model, it should be understood how cull sows are recorded within the production system. One of the objectives of this model is to capture the cost associated with feeding the cull sow population, thus cull sows should be entered as removed from the system when they are sold and not when they are deemed as a cull sow.

3. Miscellaneous reports and manager inputs: Fifteen input variables are required within the miscellaneous reports and manager inputs section. Several variables can be obtained indirectly through production records, such as the percentage of returns bred. The performance analysis report provides the number of returns, total services, and the percentage of repeat services. With this information, you can determine the percentage of returns that were bred. This same thought process can be applied to obtain other necessary inputs, and comments are added to cells to provide further details. Farm managers can estimate many of these values with great accuracy as well.

It is important to specifically define the average days gilts are in the GDU. If the model calculates ADFI for gilts based on GDU feed delivery, the average days gilts are in GDU becomes very important. The user can choose to enter only GDU feed delivery or may enter nursery and GDU feed delivery as one total value. If this is done, be sure the average days for gilts in the GDU includes the average days gilts are in the nursery.

User Feed Input Worksheet

Input cells are seen in gold. The user must first answer five questions regarding current feeding practices for each farm. Thereafter, the feed input worksheet is divided into four categories:

1. **Period:** Enter the beginning and end period in which feed deliveries were obtained. For best results, feed delivery periods should be greater than or equal to 6 months.
2. **Feed delivery:** Enter feed delivery for gestation, entry to first service interval gilts (if selected and available), lactation, and GDU.
3. **Feed cost:** Enter annual average feed cost for gestation, entry to first service interval gilts (if selected and available), lactation, and GDU.
4. **Required producer estimates for feed intake:** Based on the selected method for calculating feed usage per-weaned-pig, the user is required to enter ADFI estimates for specific sub-populations.

User output worksheet

There are four worksheets that contain model calculated outputs titled: 1) Feed cost per-weaned-pig, 2) Feed usage per-weaned-pig, 3) Feed cost per-inventoried-sow, and 4) Feed usage per-inventoried-sow. Within each specific worksheet, model calculated values are provided for each sub-population within the breeding herd. Sub-populations are divided within gestation (green), lactation (orange), and GDU (blue). Total (purple) values are also provided including the sum of all gestation, lactation, and GDU sub-populations. Total values also include the sum of gestation and lactation, as well as the sum of gestation, lactation, and GDU. Within each row (sub-population), values displayed in red are greater than one standard deviation from the mean

for that specific sub-population. Each worksheet also contains a bar chart where total sub-populations can be selected from the drop-down list.

Much like the input page, each column represents a breeding herd (except for column C). Column C is a weighted average (weighted by breeding herd female inventory) for each sub-population and includes all breeding herds. The weighted average serves as a reference point to determine where each farm stands compared to the average of the system.

Column D within each output worksheet is the first breeding herd entered in the input page. The user will need to expand the output to include all breeding herds (each column is a breeding herd). To do this (within each output worksheet), first highlight cells 3 through 27 in the final column (select the last column that is generating output, if starting with a new workbook, this will be column D). Once highlighted, place the cursor on the square at the bottom right of the highlighted area (the cursor will appear as a "+" sign) and drag to the right, until all breeding herds are included in the worksheet (Figure 7).

As mentioned above, each output worksheet includes a bar chart. The bar chart is designed to include up to 25 breeding herds. If the user enters more than 25 breeding herds, the bar chart will need to be expanded to include the remaining breeding herds. To do this, follow the below steps within each worksheet (Figure 8).

1. Unprotect worksheet (review > unprotect sheet)
2. Click anywhere on the bar chart. This will select row 3 in the worksheet. These are the breeding herds currently included in the bar chart.
3. Place the cursor at the bottom right corner of the selected area and drag to the right to include all remaining breeding herds.
4. Protect worksheet (review > protect sheet)

Printing

Output pages can be printed following these steps within each worksheet:

1. Select (highlight) the cells to print.

2. File > Print > Settings > Print Selection

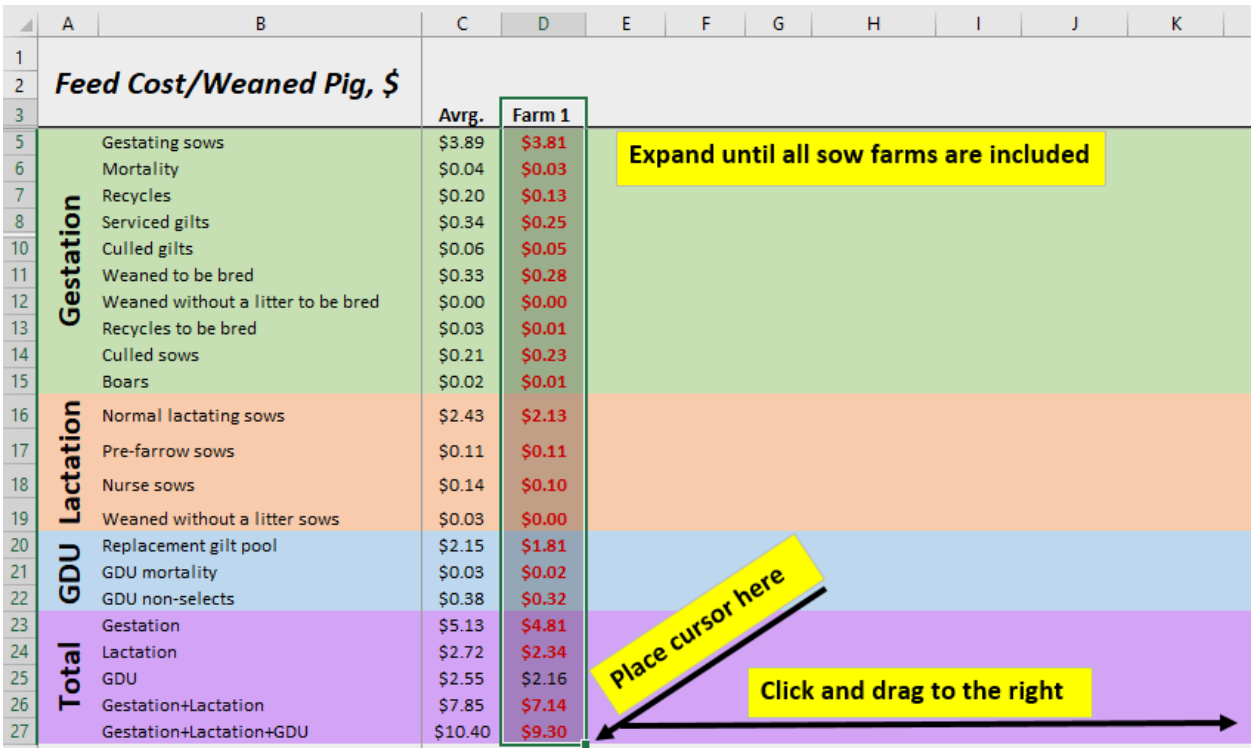

Figure A.1 Instructions on how to expand output within each output worksheet to include all breeding herds. Column D within each output worksheet is the first breeding herd entered in the input page. Within each output worksheet, highlight cells 3 through 27 in the final column (select the last column that is generating output, if starting with a new workbook, this will be column D). Once highlighted, place the cursor on the square at the bottom right of the highlighted area (the cursor will appear as a "+" sign) and drag to the right, until all breeding herds are included in the worksheet.

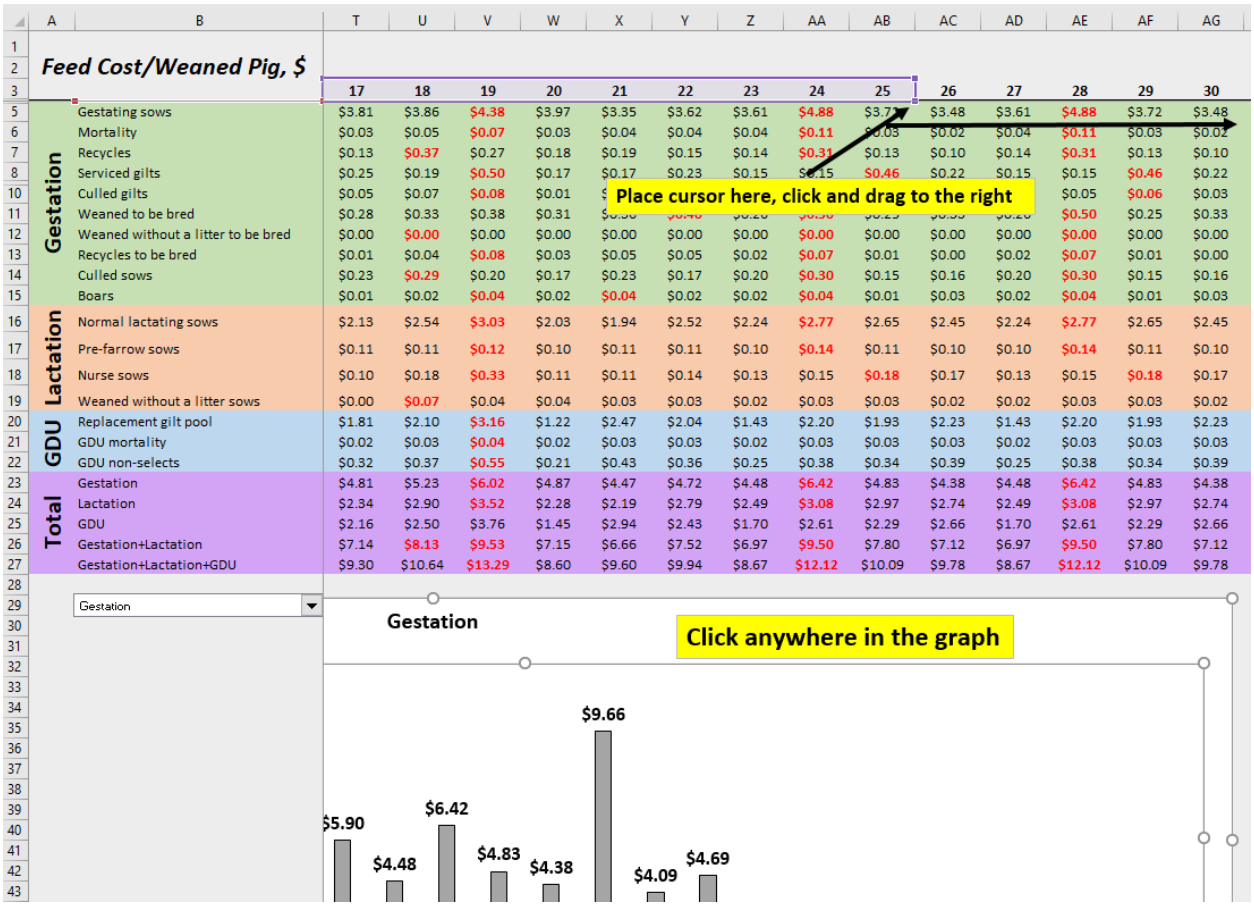

Figure A.2 Instructions on how to expand bar charts within each output worksheet in cases when the user has entered more than 25 breeding herds into the input page. To do this, 1) Unprotect worksheet (review > unprotect sheet); 2) Click anywhere on the bar chart. This will select row 3 in the worksheet. These are the breeding herds currently included in the bar chart; 3) Place the cursor at the bottom right corner of the selected area and drag to the right to include all remaining breeding herds; 4) Protect worksheet (review > protect sheet).

Chapter 4 - Effects of Increasing Standardized Ileal Digestible Lysine During Gestation on Reproductive Performance of Gilts and Sows

ABSTRACT: The objective of this study was to evaluate the effects of increasing standardized ileal digestible (SID) lysine (Lys) during gestation on piglet birthweight and reproductive performance of gilts and sows. A total of 936 females (498 gilts, 438 sows; Camborough®, PIC, Hendersonville, TN) were group-housed (approximately 275 females per pen) and individually fed with electronic sow feeders (ESF). A scale was located in the alleyway after sows left individual feeding stations. Females were moved from the breeding stall to pens on d 4 of gestation and allotted to 1 of 4 dietary treatments on d 5. Dietary treatments included increasing SID Lys intake (11, 13.5, 16, and 18.5 g/d). Gilts (parity 1) and sows (parity 2 +) received 2.1 and 2.3 kg (5.3 and 5.8 Mcal NE/d) of feed throughout the entire gestation period. Dietary treatments were achieved by different blends of low (0.48% SID Lys) and high (0.88% SID Lys) Lys diets via ESF based on the females set feed allowance. Initial BW and backfat were obtained on d 4 of gestation while final BW and backfat were obtained on d 111 of gestation. Individual piglet BW was obtained within 12 h of birth on litters from 895 females. Final BW, maternal BW, body lipid, and body lean at d 111 of gestation increased (linear, $P < 0.001$) for gilts and sows as SID Lys increased. There was no evidence for differences in final backfat depth. Average total born for gilts and sows was 15.3 and 16.0 pigs with no evidence for differences among treatments. The percentage of pigs born alive increased ($P = 0.006$) with increasing SID Lys intake for sows, but not in gilts as a result of a treatment by parity group interaction ($P = 0.043$) for percentage of stillborn pigs. Increasing SID Lys intake during gestation did not affect

the percentage of mummified fetuses, total born, or born alive piglet birthweight in this study. In addition, increasing SID Lys intake during gestation did not affect subsequent reproductive performance. In conclusion, increasing dietary SID Lys intake in gestation increased female BW, without changing backfat depth. The minimal effects on female reproductive performance and piglet birthweight suggests that 11 g/day of SID Lys intake appears to be adequate for gestating gilts and sows; however, providing sows with 18.5 g/d SID reduced stillbirth rate by 2.3 percentage points.

Key words: gilt, gestation, lysine, reproduction, sow

Introduction

Sow herds continue to increase in reproductive productivity, with some of today's most prolific females producing over 35 pigs per sow per year. One of the major concerns with this increase in litter size is the resulting decrease in piglet birth weight (Quiniou, 2015). This has led to a growing emphasis on redefining nutrient requirements for sows, specifically dietary Lys.

Lysine is the first limiting AA in corn-soybean meal-based diets and is essential for protein deposition in maternal and fetal tissues (Kim et al., 2009; Jang et al., 2017). Literature agrees that the requirements for Lys and other AA for sows increase twofold over the course of gestation, as the metabolic focus of the sow changes from maternal body tissue recovery in early to mid-gestation to development of fetal and mammary tissue in late gestation (Ji et al., 2005; Srichana, 2006; Samuel et al., 2012). In addition, requirements of young females (gilts and parity 1 sows) are greater than older sows due in part to greater protein retention (Dourmad et al.,

1999). The NRC (2012) estimates SID Lys requirements based on these principles, suggesting that a parity-segregated, phase-feeding approach better meets the requirements of gestating sows.

Previous research has suggested an increase in dietary Lys during mid to late gestation increased litter birth weight (Yang et al., 2008; Zhang et al., 2011); however, total born from these studies ranged from 9.7 to 10.9 pigs per litter. A more recent study conducted with sows having 14.5 pigs total born, indicated that increasing SID Lys intake (10.7 vs 20 g/d) from d 90 of gestation until farrowing did not affect piglet birth weight (Goncalves et al., 2016). The variation in the results of these studies indicate the need for a better understanding of the effects of increased dietary Lys throughout gestation on sow reproductive performance, and specifically piglet birth weight. Therefore, the objective of this study was to evaluate the effect of SID Lys intake during gestation on weight gain and reproductive performance of gilts and sows.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. The experiment was conducted at a commercial sow farm in central Nebraska using electronic sow feeding. Further detail is provided by Thomas et al. (2018a). In brief, following weaning, sows were individually housed in stalls (0.61 × 2.3) until 4 d after breeding (d 4 of gestation). Similarly, gilts were moved to individual gestation stalls (0.56 × 2.1 m) following first heat detection and bred on subsequent cycle. Heat detection and artificial insemination were performed utilizing direct boar exposure and females were inseminated with two doses of semen, 24 h apart. Four days after breeding, d 4 of gestation, females were moved to group housing and remained in pens until d 111 of gestation. Pens for sows provided 2.04 m^2

per sow and those for gilts provided 1.95 m^2 per gilt. Each pen was equipped with 6 electronic feeding stations (Nedap Velos, Gronelo, Netherlands) allowing for up to 45 females per station and 28 nipple waterers to provide ad libitum access to water. Each feeding station was 2.0 m long × 0.56 m wide. Females were group-housed in dynamic groups (275 females per pen), meaning serviced sows were entering the group (approximately d 4 of gestation) as sows due to farrow were exiting (approximately d 111 of gestation). This occurred over a 3 to 4-wk period, thereafter, the pen remained static (no movement of newly bred sows into the pen) until the sows reached d 111 of gestation and the process repeated. Each pen was equipped with a scale (1.74 m long × 1.07 m wide, Nedap Velos, Gronelo, Netherlands) located in the alleyway following the feeding stations and prior to returning to the pen for individual sow weight collection every time the sow exited the feeding station (Thomas et al., 2018a).

Animals and Diets

The study was conducted over a 159-day period, from early March to late August 2017. A total of 1,091 females (Camborough®, PIC, Hendersonville, TN) were enrolled in the study, of which 936 (498 gilts, 438 sows) completed and farrowed. At d 4 of gestation, as females were moved from the breeding stall to pens, females were weighed, and backfat was measured at the P2 position (last rib, 7 cm from the center line of the back) using a Lean-Meater (RENCO, Minneapolis, MN). Females were blocked by BW within each day of enrollment and were randomly assigned to 1 of 4 dietary treatments within block. Dietary treatments began on d 5 of gestation. Dietary treatments were corn-soybean meal-based and consisted of increasing SID Lys intake (11, 13.5, 16, and 18.5 g/d). Gilts and sows were offered 2.1 and 2.3 kg/d, respectively, of feed throughout the entire study following standard practice at this commercial farm (Thomas et al., 2018a). This feeding level provided daily NE intake of 5.3 and 5.8 Mcal for gilts and sows,

respectively. Dietary treatments were achieved by blending a low (0.48% SID Lys) and high (0.88% SID Lys) Lys diet via the ESF based on the females set feed allowance (Table 1). Low and high Lys diets were achieved by changing the amounts of corn and soybean meal. Dietary energy (NE, kcal/kg) was the same across the low and high Lys diets and all other nutrients met or exceeded the NRC (2012) requirement estimates. Diets were formulated using nutrient values and SID AA coefficients from the NRC (2012) for corn, SBM, and DDGS (Table 1). Experimental diets were manufactured at the Thomas Livestock Feed Mill in Merna, NE and presented in meal form.

On d 111 of gestation, as females were moved from the pens to the farrowing house, they were weighed and backfat measurements were collected at the P2 position (last rib, 7 cm from the center line of the back). Upon entry into the farrowing house, females were provided ad libitum access to a lactation diet containing 1.20% SID Lys. Of the 936 females that completed the study, individual piglet BW was obtained within 12 h of birth on litters from 895 females. Although 24-h observation was provided, pigs on some litters were transferred or cross-fostered before they could be weighed. Thus, these litters were not included in piglet BW data. Piglets born alive, stillborn, and mummified fetuses were identified and weighed. Litter birth weight was then calculated with and without the inclusion of stillborns and mummified fetuses. The coefficient of variation (CV) of birth weight within litter was calculated by dividing the individual piglet birth weight standard deviation (SD) by the average piglet birth weight of that specific litter for both total piglets born and piglets born alive. In addition, the percentage of litters with one or more stillborn pigs was calculated. Due to the commercial setting, cross fostering occurred regardless of dietary treatment immediately after piglets were weighed. Thus, the number of pigs reported in this study as weaned is a measure of nursing pressure exhibited on

the sow. The wean-to-estrus interval (WEI) was also determined as the number of days between weaning and when sows were first serviced. The percentage bred by 7 d after weaning were also calculated.

During the subsequent gestation cycle, no dietary treatments were applied, and all females were fed a common diet formulated to 0.60% SID Lys based on body condition and parity. To evaluate subsequent female performance, farrowing rate, total born, number born alive, mummies, stillborns, and piglets weaned were collected from sows remaining in the herd on their subsequent parity using the PigCHAMP Knowledge Software (Ames, IA). Adjusted farrowing rate was reported and excludes bred females that died or were removed for non-reproductive reasons.

Definitions and Calculations

Female body lipid, protein, and lean content were estimated using initial and final BW and backfat depth as outlined by the NRC (2012):

Maternal EBW (empty body weight) (kg) = 0.96 × maternal BW, kg

Maternal body lipid (kg) = -26.4 + 0.221 × maternal EBW, kg + 1.331 × P2 backfat, mm;

Maternal body protein (kg) = 2.28 + 0.178 × maternal EBW, kg – 0.333 × P2 backfat, mm;

Maternal body lean (kg) = Maternal body protein, kg × 2.55.

The equations for maternal body lipid and maternal body protein were developed by Dourmad et al. (1997). Maternal body protein was converted to maternal body lean using a conversion factor reported in the NRC (1998). Maternal body predictions do not include the products of conceptus, defined as the fetus, placenta, and fluids. Thus, to determine maternal BW needed for the above equations, conceptus weights were estimated. The NRC (2012) provides an

equation to predict the weight of conceptus using natural logarithmic values as a function of time and litter size at farrowing:

Weight of conceptus (kg/d) = (exp (8.621 - 21.02 × exp (-0.053 × gestation, d) + 0.114 × total born, n))/1000.

As described in detail by Thomas et al., (2018b), the equation was developed and reported by Dourmad et al. (1999), where authors combined a set of regression equations from previous research (Noblet et al., 1985) to generate an equation that included all of the products of conceptus (fetus, placenta, and fluids). The equation should be used with caution as it was developed based on data from over 30 years ago in a small population of gilts with a range in litter size of 9 to 14 (Noblet et al., 1985). Therefore, it is necessary to account for changes in litter size with a correction ratio, as suggested by NRC (2012), using litter birth weight as the numerator portion of the ratio and the litter birth weight equation reported by Dourmad et al. (1999) as the denominator portion of the ratio:

Ratio = (total born, n × (average piglet birth weight, kg × 1000)) / (exp (9.095 – 17.69 exp (-0.0305 × gestation length, d) + 0.0878 × total born, n)).

On average, initial BW was obtained on d 4 (SD 0.4) and final BW was obtained on d 111 (SD 0.9) of gestation. Thus, conceptus weight was required at each of these time points to determine the corresponding maternal BW needed for body composition calculations. However, the above ratio can only be used to correct for conceptus weight on d 114 of gestation because piglet birth weights are only known at farrowing. Similarly, Thomas et al. (2018b) sought to determine conceptus weight at each day of gestation. Authors reviewed the data from Dourmad et al. (1999) and determined the regression equation calculated for a litter size of 12. With this, the authors determined conceptus weight from d 4 through d 114 of gestation for a litter size of

12. The authors then calculated the percent of final conceptus weight for each d of gestation. Multiplying these percentages by the corrected final conceptus weight at d 114 of gestation generated a value for each d of gestation. We followed the same steps as outlined above to determine conceptus weight corresponding to the d of gestation when initial and final BW were obtained for each female:

Weight of conceptus (kg) = Final conceptus weight at d 114, kg × % of final conceptus weight corresponding to d of gestation when initial or final BW were obtained.

Diet Sampling and Analysis

Low and high dietary treatment samples were taken from ESF every wk during feeder calibration. In addition, dietary samples were collected for each treatment. This was done by designating a known RFID transponder to each of the dietary treatments for both the gilt and sow daily feed allowances. The total diets were dispensed by the ESF into the feeder bowl, mixed, and samples were then collected. All samples were analyzed weekly at a commercial laboratory (Ward Laboratories, Inc., Kearney, NE) for DM (method 935.29; AOAC Int., 2012), CP (AOAC 900.03, 2012), Ca, and P (method 968.08 b; AOAC Int., 2012 for preparation using ICAP 6500 [ThermoElectron Corp., Waltham, MA]; Table 2). At the conclusion of the trial, 6 composite samples of the low and high dietary treatments were analyzed for complete AA profile (University of Missouri Experimental Station Chemical Laboratories, Columbia, MO; Table 1).

Statistical Analysis

Prior to data analysis, descriptive statistics in the form of means were generated using the PROC MEANS statements in SAS (Version 9.4, SAS Institute Inc., Cary, NC). Data were analyzed using generalized linear mixed models (GLMM) whereby the linear predictor included dietary treatment, parity group (gilts and sows) and all interactions as fixed effects, as well as the

random effect of block. As specified, models recognized the individual female as the experimental unit for this study. Within these outcomes, linear and quadratic contrasts were generated to determine the effects of increasing SID Lys.

Day 4 BW, d 111 BW, BW gain, d 4 backfat depth, d 111 backfat depth, backfat depth gain, total born piglet BW, total born litter weight, born alive piglet BW, born alive litter weight, WEI, conceptus weight, maternal BW, EBW, body lipid, body lipid gain, body lean, and body lean gain were each fitted assuming a normal distribution of the response variable. In these cases, residual assumptions were checked using standard diagnostics on residuals and were found to be reasonably met. Total number of pigs born, number of pigs born alive, and number weaned were fitted assuming a negative binomial distribution on the response. The percentage of piglets born alive, stillborns, mummified fetuses, the percentage of litters with one or more stillborns, females bred by 7 d after weaning, farrowing rate, farrowing rate farm, farrowing rate farm adjusted farrowing rate, and removal rate were each analyzed using a binomial distribution. Two sows were deleted from the data set with 9 and 10 stillborns. These two observations generated studentized residuals more extreme than +/- 3 standard deviations and were thus deemed as outliers and consequently removed from the data set. Furthermore, the CV of birth weight within the litter considering total piglets born and piglets born alive were approximated with a β distribution, as all observed values lay between 0 and 1. Overdispersion was assessed using a maximum-likelihood-based Pearson χ^2/degrees of freedom statistic and accounted for as needed (Stroup, 2012). The final models used for inference were fitted using restricted maximum likelihood estimation. Degrees of freedom were estimated using the Kenward-Rogers approach. Results were considered significant at $P \leq 0.05$ and marginally significant at $0.05 > P \leq 0.10$.

Results

General

Chemical analyses of DM, CP, Ca, and P for each dietary treatment are presented in Table 2. The values reported for the complete feed reasonably met formulated values and aligned similarly with values reported in NRC (2012). Gilts and sows consumed 5.3 and 5.8 Mcal NE/d based on their feed allowances. The NRC (2012) suggests 5.4 and 6.4 Mcal NE/d for gilts before and after d 90 of gestation. For sows, the NRC (2012) suggests 5.2 and 6.2 Mcal NE/d before and after d 90 of gestation. Thus, caloric intake provided to both gilts and sows in the present study were similar to recommendations from the NRC (2012) prior to d 90 of gestation and were lower than recommendations in late gestation. Analyzed total AA concentrations were similar to formulated values and are reported in Table 1. The average parity for sows within this study was 4.3.

Of the 1,091 females enrolled in the study, 155 females did not complete the study due to death (6 females), reproductive failure (27 females), relocation within the gestation barn (49 females), a change in feeding strategy due to body condition (19 females), or removal from experimental pen where reason is unknown (54 females). There was no evidence for differences in removal rate among dietary treatments ($P > 0.05$). Removal rates for gilts consuming 11, 13.5, 16, and 18.5 g/d SID Lys was 15.5, 12.7, 9.2, and 12.0%. Removal rates for sows consuming 11, 13.5, 16, and 18.5 g/d SID Lys was 11.5, 18.0, 14.7, and 20.6%.

Female Body Composition

There was no evidence for differences ($P > 0.05$) among dietary treatments on d 4 sow BW, which validates the randomization of females to treatment (Table 3). In addition, we found no evidence for differences ($P > 0.05$) in d 4 maternal BW, EBW, body lipid, or body lean

estimates among dietary treatments. There was no evidence for differences ($P > 0.05$) among dietary treatments for backfat depth on d 4 of gestation.

There was no evidence for an interaction between treatment and parity for d 111 BW ($P > 0.05$, Table 3). Body weight at d 111 increased (linear, $P < 0.001$) as SID Lys increased within each parity group. Gilts and sows consuming 18.5 g/d SID Lys gained 6.9 and 5.0 kg BW more (linear, $P < 0.001$), respectively, than gilts and sows consuming 11 g/d SID Lys (Figure 1). There was no evidence for differences in conceptus weight among dietary treatments ($P > 0.05$; Table 3); however, final maternal BW and EBW increased (linear, $P < 0.001$) as SID Lys increased within each parity group. Thus, after accounting for conceptus weight, gilts and sows consuming 18.5 g/d SID Lys gained 6.3 and 4.8 kg more maternal BW (linear, $P < 0.001$) than gilts and sows fed 11 g/d SID Lys (Figure 2). Maternal body lipid on d 111 of gestation increased (linear, $P = 0.001$) as SID Lys increased with gilts and sows fed 18.5 g/d SID Lys gaining 1.3 and 1.4 kg more (linear, $P = 0.001$), than those provided 11 g/d (Figure 3). Similarly, maternal body lean on d 111 of gestation increased (linear, $P < 0.001$) as SID Lys increased with gilts and sows fed 18.5 g/d SID Lys gaining 2.8 and 1.9 kg more (linear, $P < 0.001$), than those fed 11 g/d (Figure 4). There was no evidence for differences ($P > 0.05$) in d 111 backfat depth, and subsequently backfat gain, among dietary treatments for gilts or sows (Table 3 and Figure 5).

Average BW gain was greater in gilts compared to sows (55.3 ± 0.81 and 41.6 ± 0.84 kg, respectively; $P < 0.001$); however, final conceptus weight was greater in sows than gilts (31.8 ± 0.38 and 28.7 ± 0.37 kg, respectively; $P < 0.001$). Like BW gain, maternal BW gain was greater in gilts compared to sows (26.6 ± 0.80 and 9.7 ± 0.83 kg, respectively; $P < 0.001$). Maternal body lipid gain was also greater in gilts compared to sows (7.9 ± 0.29 and 6.7 ± 0.30 kg, respectively; $P = 0.003$); however, backfat gain showed the opposite, with gilts gaining less

backfat in gestation than sows (1.7 ± 0.14 and 3.5 ± 0.15 mm, respectively; $P < 0.001$). Maternal body lean gain was greater for gilts compared to sows 10.1 ± 0.33 and 1.3 ± 0.34 kg, respectively; $P < 0.001$).

Farrowing Rate and Litter Size

There was no evidence for differences ($P > 0.05$) in farrowing rate or adjusted farrowing rate among dietary treatments (Table 4). Similarly, there was no evidence for differences ($P > 0.05$) in total piglets born or piglets born alive among dietary treatments (Table 4). Although no evidence for statistical differences, across diets, sows had numerically more total piglets born than gilts (16.0 ± 0.19 and 15.3 ± 0.18, respectively) as well as more piglets born alive (15.0 ± 0.19 and 14.5 ± 0.18, respectively; Table 4). The percentage of piglets born alive increased ($P = 0.006$) with increasing SID Lys intake among sows, with no evidence for differences observed in gilts. This can be explained by a treatment × parity group interaction ($P = 0.043$) identified for the percentage of stillborn pigs, whereby increasing SID Lys intake in sows reduced ($P = 0.002$) the percentage, with no evidence for differences observed in gilts. The percentage of stillborn pigs tended to be lower for gilts compared to sows (2.7 ± 0.21 and 3.3 ± 2.5, respectively; $P = 0.063$). There was no evidence for differences ($P > 0.271$) for the probability of litters having one or more stillborns or mummified fetuses between dietary treatments.

Piglet Birth Weight

There was no evidence ($P > 0.05$) for differences among dietary treatments for individual total born piglet birth weight or litter weight (Table 4). Individual piglet birth weight and litter weight was heavier in sows than in gilts ($P = 0.001$; 1.30 ± 0.011 and 1.25 ± 0.011 kg, respectively and 20.4 ± 0.19 and 18.7 ± 0.18 kg, respectively). Similarly, within-litter birth weight CV was also greater in sows than gilts (25.1 ± 0.44 and 21.8 ± 0.40 %, respectively; $P <$

0.001). There was marginal evidence for a treatment × parity group interaction ($P = 0.073$) for the within-litter birth weight CV for total piglets born. For gilts, within-litter birth weight CV decreased then increased (quadratic, $P > 0.029$) with increasing SID Lys intake, though no evidence for difference was observed in sows.

When considering piglets born alive, there was no evidence ($P > 0.05$) for differences among dietary treatments on individual piglet birth weight, litter weight, or within-litter birth weight CV (Table 4). Individual piglet birth weight and litter weight were greater in sows than in gilts ($P = 0.001$; 1.32 ± 0.011 and 1.27 ± 0.010 kg, respectively and 19.5 ± 0.19 and 18.1 ± 0.18 kg, respectively) and within-litter birth weight CV was greater in sows than gilts ($P < 0.001$; 22.5 ± 0.35 and 18.8 ± 0.30 %, respectively).

Piglets weaned, Wean-to-Estrus Interval, Percentage Bred by 7 d, and Subsequent Female Performance

There was no evidence for differences ($P > 0.05$) among treatment groups for the number of piglets weaned or in the percentage of females bred by d 7 after weaning (Table 4). There was marginal evidence that increasing gestation SID Lys intake influenced (quadratic, $P = 0.096$) WEI, with WEI increasing as SID Lys intake increased from 11.0 to 13.5 g/d and then decreasing as SID Lys intake increased from 13.5 to 18.0 g/d. For all dietary treatments, WEI was greater ($P < 0.001$) for gilts compared with sows (5.0 ± 0.12 and 4.3 ± 0.13 d, respectively). For the subsequent reproductive cycle, there was no evidence for any effects of dietary treatment on farrowing rate, adjusted farrowing rate, total number of piglets born, number of piglets born alive, percentage of piglets born alive, percentage of stillborn pigs, percentage of mummified fetuses, or piglets weaned. However, the percentage of piglets born alive for gilts was greater ($P = 0.051$) in the subsequent litter compared with sows (95.5 ± 0.34 and 94.5 ± 0.39%,

respectively), and this was partially explained by a decreased (P = 0.020) percentage of stillborn pigs (2.0 ± 0.23 and 2.9 ± 0.30%, respectively).

Discussion

Historical research surrounding Lys requirements for gestating females is limited, with previous requirements estimated by the NRC (1998) being generated from data utilizing growing pigs. For gestating sows, most research was conducted in late gestation to determine AA requirements through nitrogen balance studies (Rippel et al., 1965; Salmon-Legagneur and Duee, 1972), with no reports of AA requirements in early to mid- gestation. The NRC (1998) estimates SID Lys requirements ranging 8.4 to 9.7 g/d throughout the course of gestation. However, requirements have evolved as modern sows are more productive, leaner, and heavier than those raised over two decades ago (Dourmad and Étienne, 2002).

Most U.S. gestation diets and feeding levels provide 10 to 12 g/d SID Lys through the entire gestation period (Goodband et al., 2013). This feeding strategy aligns with the NRC (1998) in that AA requirements are constant throughout gestation; however, more recent literature suggest AA requirements differ among females of different parities and stages of gestation (Kim et al., 2009; Moehn and Ball, 2013; Kraeling and Webel, 2015). The NRC (2012) adopted this concept of a parity-segregated, phase feeding program in gestation with SID Lys requirements ranging from 10.6 to 16.7 g/d SID Lys for gilts and 6.3 to 15.1 g/d SID Lys for sows across different stages of gestation. The NRC (2012) AA requirements suggest that a single diet feeding strategy, like used in the present study, provides gilts and sows with excess SID Lys in early and mid- gestation whereas a deficiency is likely occurring in late gestation (Quiniou, 2015).

Cooper et al. (2001), fed females a gestation diet containing either 10.6 or 13.2 g/d total Lys (9.0 and 11.2 g/d calculated SID Lys, respectively) from breeding to d 110 of gestation and concluded that total Lys intakes greater than 10.6 g/d did not improve female productivity. Specifically, authors reported Lys level in gestation did not affect gestation BW gain or backfat depth. The results from the study herein are similar to Cooper et al. (2001) in that we found no evidence for differences in backfat depth among dietary treatments; however, BW gain increased with increasing SID Lys. Aside from differences in Lys level between the two studies, females from Cooper et al. (2001) gained more BW (4.6 kg), but less backfat (0.6 mm) even though initial BW and backfat were similar between their and our studies. Interestingly, Cooper et al. (2001) also reported a parity × gestation diet interaction where parity 2 sows fed the low Lys diet gained more backfat than parity 2 sows consuming the high Lys diet, suggesting that BW gain was in the form of protein and not lipid deposition.

Like Cooper et al. (2001), leanness was not directly measured in the study herein and we also hypothesized that because backfat depth remained relatively constant through gestation, regardless of dietary treatment, and female BW increased with increasing SID Lys, BW gain was in the form of protein and not lipid deposition. However, using prediction equations from Dourmad et al. (1997) to estimate maternal body composition, we found a linear increase in both body lipid and body lean gain as SID Lys level increased. If we assume the prediction equations are accurate, these results suggest that measuring backfat depth may not be a sensitive enough measurement to detect changes in body lipid accretion.

In contrast, when applying these same prediction equations to data reported by Cooper et al. (2001), average maternal body lipid and lean gain were 8.8 and 10.5 kg for females fed the low Lys diets and 8.5 and 11.1 kg for females consuming the high Lys diet, indicating that

females increased leanness and reduced body fat as Lys level increased. Thus, the prediction equations support their hypothesis that as SID Lys increased, lean tissue accretion increased, and body lipid decreased.

The main differences responsible for the predicted changes in body composition between Cooper et al. (2001) and the present study are found in differences in litter size and backfat gain. Total born in the present study was 3.6 pigs greater than reported by Cooper et al. (2001) and consequently average total born piglet birth weight is 0.2 kg lighter. Initial and final maternal BW were similar between the two studies, but the increase in total born resulted in an increase in conceptus weight, generating maternal BW estimates that were less in the present study than those estimated for Cooper et al. (2001). In addition, although not statistically significant, in the present study there is a numeric increase in backfat gain within sows as SID Lys level in the diet increases with little change observed in gilts, compared to Cooper et al. (2001) where average backfat gain decreased by 0.3 mm as Lys increased. Research in gestating sows as presented in the current study and by Cooper et al. (2001) is particularly unique in that it encompasses most of gestation, and females were fed the same amount of feed throughout pregnancy, which differs from most gestation research (Zhang et al., 2011; Magnabosco et al., 2013; Ampaire, 2017).

Shi et al. (2015) fed 5 levels of dietary SID Lys (8.6, 10.4, 12.0, 14.0, and 16.0 g/d) from d 1 to 80 of gestation then increased feed intake to provide 12.9, 15.6, 18.0, 21.0, and 24.0 g/d SID Lys from d 80 to 110 of gestation. Their results agree with the present study in that authors found no evidence for differences in final backfat, total born, born alive, or litter birth weight; however, unlike the present study, authors also reported no evidence for differences in final BW across dietary treatments from d 1 to 80. Authors did find an increase in BW gain from d 80 to 110 of gestation with increasing SID Lys up 21.0 g/d SID Lys. Lastly, the authors reported a

reduction in birthweight CV with increased SID Lys up to 14.0 and 21.0 g/d SID Lys before and after d 80 of gestation. These results agree with the present study where birthweight CV decreased with increasing SID Lys intake in gilts only, up to intake of 16.0 g/d. Dietary energy provided by Shi et al. (2015) was much greater compared to the present study, which is reflective in large differences in BW gain and backfat depth between the two studies, possibly contributing to differences in response to dietary Lys.

Zhang et al. (2011) evaluated different levels of dietary Lys from mid to late gestation and reported that increasing SID Lys to 12.2 g/d from d 30 to 80 of gestation, followed by an increase in feed intake providing 16.6 g/d SID Lys from d 80 to 110 of gestation, increased sow BW and backfat gain, and increased piglet birthweight by 0.18 kg. Similarly, Yang et al. (2008) reported that increasing total dietary Lys from 0.62 to 0.82% (15.8 and 20.9 g/d calculated SID Lys, respectively) in late gestation increased female BW, backfat thickness, and increased litter birth weight by 1.82 kg. Results from both Zhang et al. (2011) and Yang et al. (2008) should be interpreted with caution in relation to the present study due to large differences in trial design and female genetics. Specifically, dietary treatments in the previous studies were not fed throughout the full duration of gestation and total born was much lower, ranging from 9.7 to 10.9 pigs per litter.

Often, feed allowance is increased in late gestation to account for the increase in fetal and mammary growth, but diet composition doesn't change (Goodband et al., 2013). This is generally referred to as bump feeding and the literature surrounding the effectiveness is variable (Oliviero et al., 2010; Goncalves et al., 2016; Mallman et al., 2019). Using the population of females from the study herein, Thomas et al. (2019) modeled daily female nitrogen retention to

estimate SID Lys requirements from d 5 to 108 of gestation and concluded that gilts and sows were able to meet requirements in all stages of gestation when consuming 13.5 g/d SID Lys.

Goncalves et al. (2016), observed no evidence for differences in total born or born alive piglet birth weight for both gilts and sows consuming high Lys diets (10.7 and 20.0 g/d SID Lys) in late gestation. However, the authors reported a reduction in the percentage of stillborn pigs for gilts and sows consuming high Lys diets. Magnabosco et al. (2013) also observed a reduction of 1.1% percentage points in stillborn rate for gilts fed high Lys in late gestation. In the present study, the reduction in percentage of stillborns observed in sows and is suggested to be the result of changes in body composition (lean-to-fat ratio), which in turn, positively impacts muscle tone and reduces dystocia (Almond et al. 2006). The absence of a reduction in stillborns within gilts could be attributed to the relationship between higher parities having an increased percentage for stillborns, of which is thought to be related to poorer uterine muscle tone (Leenhouwers et al., 1999; Borges et al., 2005). In the present study, the average percentage of a pig being born as a stillborn for gilts was lower compared to Goncalves et al. (2016) and Magnabosco et al. (2013), and final BW was also heavier. It is unknown if differences in gilt body composition are responsible for the differences observed in stillborn rate as affected by dietary Lys level or other unknown factors.

The prediction equations used in the present study to estimate maternal body lipid and lean gain were generated from a small population of sows at different physiological stages (Dourmad et al., 1997). The prediction equations were obtained from genotypes selected for increased leanness at that time and literature suggests that these prediction equations are relatively inaccurate for genetic lines with less lean and greater lipid composition (Gill, 2006). However, leanness within the breeding herd has continued to evolve, with modern sows being

selected for increased protein deposition at rates greater than those in previous decades (Lewis and Southern, 2000; Bortolozzo et al., 2009; Kraeling and Webel, 2015). Thus, although the prediction equations were obtained on lean sows, they were likely less lean than current genetic lines within the breeding herd. Literature surrounding backfat depth in relation to body condition suggests that sows in the present study are likely thin to ideal, with gilts being over-conditioned (Boyd et al., 2010; Houde et al., 2010; Quiniou, 2014). Based on this information and changes in sow body composition, it is hypothesized that maternal body lipid predictions are likely overestimated, and sows are leaner than predicted. Hansen et al. (2014) reported similar findings using the same equations to model changes in body composition throughout gestation and upon validation found that the body composition prediction equations overestimate maternal weight and fat gain.

Recent literature has provided evidence that the NRC (2012) may underestimate the NE value for SBM. Li et. al. (2017) used indirect calorimetry and reported an NE value of 2,709 kcal/kg for SBM, which is significantly greater than the NRC (2012) SBM NE value. Growth data in growing pigs reported by Cemin et al. (2019) estimated the NE value for SBM be between 105 and 125% of corn energy, or 2,816 and 3,332 kcal/kg NE. The SBM value reported for sows in the InraPorc model is similar to the NRC (2012) estimate, at 2,079 kcal/kg (INRA, 2000). In the present study, diets were formulated to be isocaloric using NRC (2012) NE values for SBM. However, dietary treatments were achieved by increasing SBM in the diet. Thus, as SID Lys increased, SBM increased in the diet. Because of this, dietary energy may have also increased if these recent estimates of SBM NE are correct. Based on the amount of maternal weight gain observed in this study, the NE value for SBM was estimated between 106 and 110% of corn NE. This results in differences in NE of 260 kcal/d from the low to high SID Lys dietary

treatments. The increase in weight gain as Lys increased may be at least partially attributed to increased dietary energy intake if the NE value for SBM was underestimated.

While previous research has challenged the traditional single-phase gestation feeding program, suggesting that females are above their requirement in early gestation and under their requirement in late gestation (NRC, 2012; Moehn and Ball, 2013), observations from the present study provide evidence that a parity-segregated, phase feeding approach may not be necessary to obtain high performance.

In conclusion, 1) increasing SID Lys intake from 11 to 18.5 g/d throughout the full duration of gestation increased female BW and predicted maternal BW, body lipid, and body leanness; 2) for sows, the percentage of piglets born alive increased with increasing SID Lys intake, as a result of a reduction in the percentage of stillborn piglets; and 3) there was no evidence for differences in individual piglet birth weight as a result of dietary treatment. Therefore, the results from this study suggest that 11 g/d of SID Lys intake appears to be adequate for gestating gilts and sows for most reproductive traits; however, greater amounts of SID Lys could reduce the percentage of stillborn pigs within sows.

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Table 4.1 Diet composition of low- and high-lysine diets (as-fed basis)[1]

	Standardized ileal digestible lysine, %	
Ingredient	0.48	0.88
Corn	71.80	53.20
Soybean meal, 46.5% crude protein	4.20	20.80
DDGS[2], 8.0% oil	20.00	20.00
Beef tallow	---	2.10
Monocalcium phosphate, 21% P	1.10	1.00
Limestone	1.60	1.50
Salt	0.50	0.50
Liquid lysine, 50%[3]	0.28	0.28
L-Threonine	---	0.09
L-Tryptophan	0.01	---
Methionine hydroxyl analogue	---	0.02
Vitamin and trace mineral premix[4]	0.38	0.38
Choline chloride, 60%	0.11	0.11
Dye[5]	0.05	0.05
Total	100	100
Calculated analysis		
Standardized ileal digestibly (SID) amino acids, %		
Lysine	0.48	0.88
Isoleucine:lysine	85	77
Methionine:lysine	47	35
Threonine:lysine	77	77
Tryptophan:lysine	21	21
Valine:lysine	108	88
Total lysine, %	0.60	1.05
ME, kcal/kg	3,226	3,311
NE, kcal/kg	2,502	2,500
CP, %	13.8	20.2
Ca, %	0.85	0.85
P, %	0.60	0.65
Available P, %	0.47	0.47
Standardized total tract digestible P, %	0.38	0.40
Ca:P	1.41	1.31
Total amino acid analysis, %[6]		
Lysine	0.66	1.10
Isoleucine	0.54	0.85
Leucine	1.50	1.89
Methionine	0.25	0.33
Methionine and cysteine	0.53	0.70
Threonine	0.49	0.82
Tryptophan	0.11	0.20
Valine	0.67	0.98
Histidine	0.37	0.53
Phenylalanine	0.68	1.00

[1]Diets were fed from d 4 to 112 of gestation. Dietary treatments were achieved by different blends of a low (0.48% SID Lys) and high (0.88% SID Lys) Lys diet via the ESF based on the females set feed allowance.
[2]DDGS = distillers dried grains with solubles.
[3]ADM (Decatur, IL).
[4]Provided per kg of diet: 110 mg Zn from zinc sulfate, 110 mg Fe from ferrous sulfate, 33 mg Mn from manganese oxide, 17 mg Cu from copper sulfate, 0.30 I mg calcium iodate, 0.30 Se from sodium selenite, 0.08 mg Cr from chromium picolinate, 1,134 IU vitamin A, 142 IU Vitamin D, 6.35 IU Vitamin E, 0.45 mg Vitamin K, 40 µg vitamin B_{12}, 5.10 mg Niacin, 2.83 mg pantothenic acid, 0.85 mg riboflavin, 0.02 biotin, 0.14 folic acid, 0.41 mg pyridoxine, 153.4 mg choline, and 4.08 mg carnitine.
[5]Different colored dyes were added to distinguish among diets at the farm.
[6]Diets were collected weekly and pooled to make composite samples. Six composite samples for the low and high dietary treatments were used for analysis University of Missouri Experimental Station Chemical Laboratories, Columbia, MO.

Table 4.2 Chemical analysis of experimental diets (as-fed basis)[1]

	Standardized ileal digestible lysine, g/d			
Item, %	11	13.5	16	18.5
Dry matter	86.50	88.89	89.06	89.13
Crude protein	14.70	16.37	17.96	19.86
Calcium	0.93	0.92	0.96	0.93
Phosphorus	0.62	0.61	0.63	0.64

[1]Diets were collected weekly and analyses were conducted by Ward Laboratories (Kearney, NE).

Table 4.3 Effects of increasing standardized ileal digestible (SID) lysine (Lys) in gestation on gilt and sow body composition[1]

	Gilts				Sows					Probability, *P* <			
	SID Lys, g/d				SID Lys, g/d							SID Lysine	
Item	11.0	13.5	16.0	18.5	11.0	13.5	16.0	18.5	SEM	Trt × Parity	Parity	Linear	Quadratic
N	112	118	125	118	107	107	106	102	---	---	---	---	---
Parity	1.0	1.0	1.0	1.0	4.4	4.4	4.3	4.3	---	---	---	---	---
Initial													
Backfat depth, mm	17.9	17.8	17.9	18.0	11.7	11.7	11.8	11.9	0.28	0.979	<0.001	0.482	0.583
BW, kg	161.9	161.6	161.8	162.2	213.2	211.8	213.1	213.1	1.87	0.911	<0.001	0.663	0.375
Maternal BW, kg[2]	161.9	161.6	161.8	162.2	213.2	211.8	213.1	213.1	1.87	0.911	<0.001	0.663	0.375
Maternal EBW, kg[3]	155.5	155.1	155.3	155.7	204.7	203.3	204.6	204.6	1.80	0.911	<0.001	0.663	0.375
Maternal body lipid, kg[4]	32.0	31.7	31.9	32.2	34.3	34.2	34.5	34.5	0.61	0.985	<0.001	0.402	0.528
Maternal body lean, kg[5]	61.2	61.2	61.2	61.2	88.7	87.9	88.5	88.5	0.81	0.790	<0.001	0.999	0.515
Final													
Backfat depth, mm	19.6	19.7	19.6	19.7	15.0	15.2	15.3	15.5	0.32	0.852	<0.001	0.430	0.914
BW, kg	214.4	216.6	218.8	221.5	252.2	250.2	255.8	257.2	1.72	0.342	<0.001	<0.001	0.269
Weight of conceptus, kg[6]	28.2	28.8	28.8	28.9	31.6	31.7	32.4	31.6	0.69	0.887	<0.001	0.484	0.412
Maternal BW, kg[2]	186.1	187.7	189.9	192.7	220.7	218.6	223.4	225.4	1.72	0.485	<0.001	<0.001	0.123
Maternal EBW, kg[3]	178.6	180.2	182.3	185.0	211.8	209.8	214.4	216.3	1.65	0.485	<0.001	<0.001	0.123
Maternal body lipid, kg[4]	39.2	39.6	40.0	40.7	40.4	40.3	41.3	42.1	0.63	0.900	0.003	0.001	0.485
Maternal body lean, kg[5]	70.3	70.9	71.9	73.1	89.0	88.0	90.1	90.8	0.75	0.441	<0.001	<0.001	0.141

[1]A total of 895 females (473 gilts, 422 sows; Camborough, PIC, Hendersonville, TN) were used in a 159-d trial. Reproductive performance and individual piglet birth weights were obtained from litters and maternal body composition values were estimated from these observations.

[2]Maternal BW (kg) = BW, kg – weight of conceptus on day when BW was obtained, kg.

[3]Maternal EBW (kg) = 0.96 × maternal BW, kg.

[4]Maternal body lipid (kg) = -26.4 + 0.221 × maternal EBW, kg + 1.331 × backfat, mm.

[5]Maternal body lean (kg) = Maternal body protein, kg × 2.55, where maternal body protein (kg) = 2.28 + 0.178 × maternal EBW, kg – 0.333 × backfat, mm.

[6]Weight of conceptus (fetus, placenta, and fluids) (kg) = Final conceptus weight at d 114, kg × % of final conceptus weight, where final conceptus weight at d 114 (kg) = ((average piglet birth weight, kg × 1000) × total born, n) / (exp((9.095 - 17.69 × exp(-0.0305 × 114) + 0.0878 × total born, n))) × ((exp(8.621 – 21.02 × exp(-0.053 × 114) + 0.0114 × total born, n)) / 1000)

Table 4.4 Effects of increasing standardized ileal digestible (SID) lysine (Lys) in gestation on litter characteristics and reproductive performance[1]

	Gilts				Sows					Probability, $P <$			
	SID Lys, g/d				SID Lys, g/d							SID Lysine	
Item	11.0	13.5	16.0	18.5	11.0	13.5	16.0	18.5	SEM	Trt × Parity	Parity	Linear	Quadratic
Farrowing rate, %[2,3]	84.5	86.6	90.8	88.0	88.5	82.0	85.3	79.4	6.56	0.192	0.085	0.885	0.549
Farrowing rate farm, %[2,4]	94.4	95.1	96.5	95.1	94.6	92.5	97.8	90.8	2.52	0.691	0.678	0.747	0.402
Adjusted farrowing rate farm, %[2,5]	94.4	97.1	96.5	95.1	94.6	94.6	97.8	92.3	2.35	0.719	0.685	0.941	0.310
Total born, n[6]	15.3	15.3	15.3	15.3	15.8	16.2	15.9	16.0	0.40	0.953	0.231	0.839	0.835
Born alive, n[6]	14.3	14.5	14.5	14.5	14.7	15.1	14.9	15.3	0.38	0.917	0.284	0.573	0.758
Born alive, %[2,7]	94.0	95.3	94.8	94.5	92.8	93.6	93.8	95.2	0.66	0.152	0.110	0.030	0.538
Stillborn, %[2,8]	2.8	2.2	3.0	2.9	4.6	3.3	3.5	2.3	0.54	0.043	0.063	0.109	0.762
Litters with stillborn, %[2,9]	33.9	26.3	33.6	31.3	44.9	36.4	40.0	30.4	4.85	0.553	0.048	0.271	0.709
Mummified fetuses, %[2]	3.2	2.4	2.2	2.6	2.5	3.1	2.6	2.5	0.45	0.311	0.776	0.221	0.661
Total born													
Litter birth weight, kg	18.4	18.9	18.8	18.8	20.2	20.2	20.7	20.3	0.34	0.704	<0.001	0.323	0.288
Piglet birth weight, kg	1.23	1.25	1.25	1.26	1.31	1.28	1.32	1.28	0.02	0.328	0.001	0.823	0.700
Birth weight CV, %[10,11]	23.5	21.6	20.3	21.8	24.3	25.8	24.9	25.6	0.89	0.073	<0.001	0.346	0.229
Born alive													
Litter birth weight, kg	17.7	18.3	18.1	18.1	19.1	19.3	19.9	19.6	0.34	0.695	<0.001	0.125	0.222
Piglet birth weight, kg	1.26	1.27	1.26	1.27	1.33	1.30	1.35	1.30	0.02	0.307	<0.001	0.955	0.725
Birth weight CV, %[11]	19.6	18.9	17.8	18.9	21.8	22.9	22.2	23.3	0.66	0.194	<0.001	0.826	0.249
Piglets weaned, n[6]	13.3	13.5	13.3	13.4	12.7	12.8	13.0	12.9	0.36	0.965	0.261	0.810	0.838
Wean-to-estrus interval, d[12]	4.8	5.5	5.0	4.8	4.3	4.5	4.2	4.1	0.27	0.851	<0.001	0.297	0.096
Females bred by 7 d after weaning, %[2]	95.1	91.5	96.1	97.1	97.5	94.7	98.9	98.8	2.71	0.927	0.329	0.362	0.548
Subsequent performance													
Farrowing rate, %	88.0	94.5	89.3	90.3	91.6	92.5	89.9	94.2	3.65	0.705	0.538	0.886	0.814
Adjusted farrowing rate, %	90.4	94.5	90.3	91.3	91.6	94.6	92.1	94.3	3.34	0.961	0.483	0.997	0.599
Total born, n	15.0	15.1	15.7	15.0	16.1	16.0	16.7	16.1	0.44	0.980	0.173	0.564	0.476
Born alive, n	14.3	14.3	15.0	14.4	15.2	15.1	15.8	15.1	0.43	0.996	0.211	0.530	0.482

Born alive, %	95.5	95.0	95.7	95.9	94.2	94.9	94.7	94.3	0.72	0.629	0.051	0.547	0.814
Stillborn, %	1.8	2.3	1.8	2.3	3.1	2.4	3.0	3.2	0.55	0.402	0.020	0.544	0.434
Mummified fetuses, %	2.8	2.8	2.8	2.0	3.0	3.1	2.6	2.8	0.49	0.672	0.399	0.174	0.569
Piglets weaned, n	12.9	12.9	13.0	13.0	12.5	12.1	12.5	12.3	0.40	0.898	0.252	0.869	0.888

[1]A total of 936 females (498 gilts, 438 sows; Camborough, PIC, Hendersonville, TN) were used in a 159-d trial. Individual piglet birth weights were obtained on litters from 895 females.
[2]Variables were analyzed using a binomial distribution.
[3]Farrowing rate = females that farrowed that completed the study / females that were serviced and enrolled in the study. This is reflective of female removal rate.
[4]Farrowing rate farm = females that farrowed / females that were serviced and enrolled in the study. This is reflective of the farms farrowing rate and includes females that were removed from dietary treatment but still farrowed.
[5]Adjusted farrowing rate farm excludes bred females that diet or were removed for non-reproductive reasons.
[6]Variables were analyzed using a negative binomial distribution.
[7]Linear, $P = 0.006$ for treatment within sows.
[8]Linear, $P = 0.002$ for treatment within sows.
[9]If a female had greater than or equal to 1 stillborn pig, this variable was recorded as 1. If the female didn't have any stillborn pigs, this variable was recorded as 0.
[10]Quadratic, $P = 0.029$ for treatment within gilts.
[11]Variable analyzed using a beta distribution.
[12]Quadratic, $P = 0.090$ for treatment within gilts.

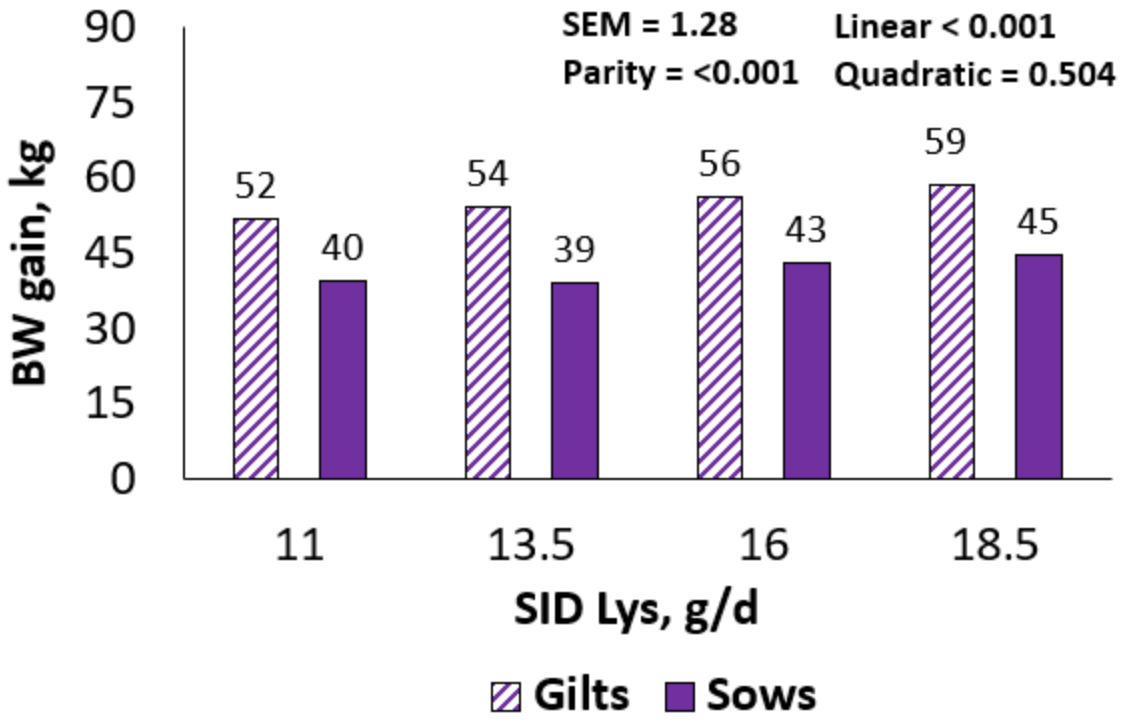

Figure 4.1 Mean BW gain of gilts and sows fed increasing SID Lys from d 4 to 112 of gestation. Other AA met or exceeded the NRC (2012) recommendations as a ratio to Lys.

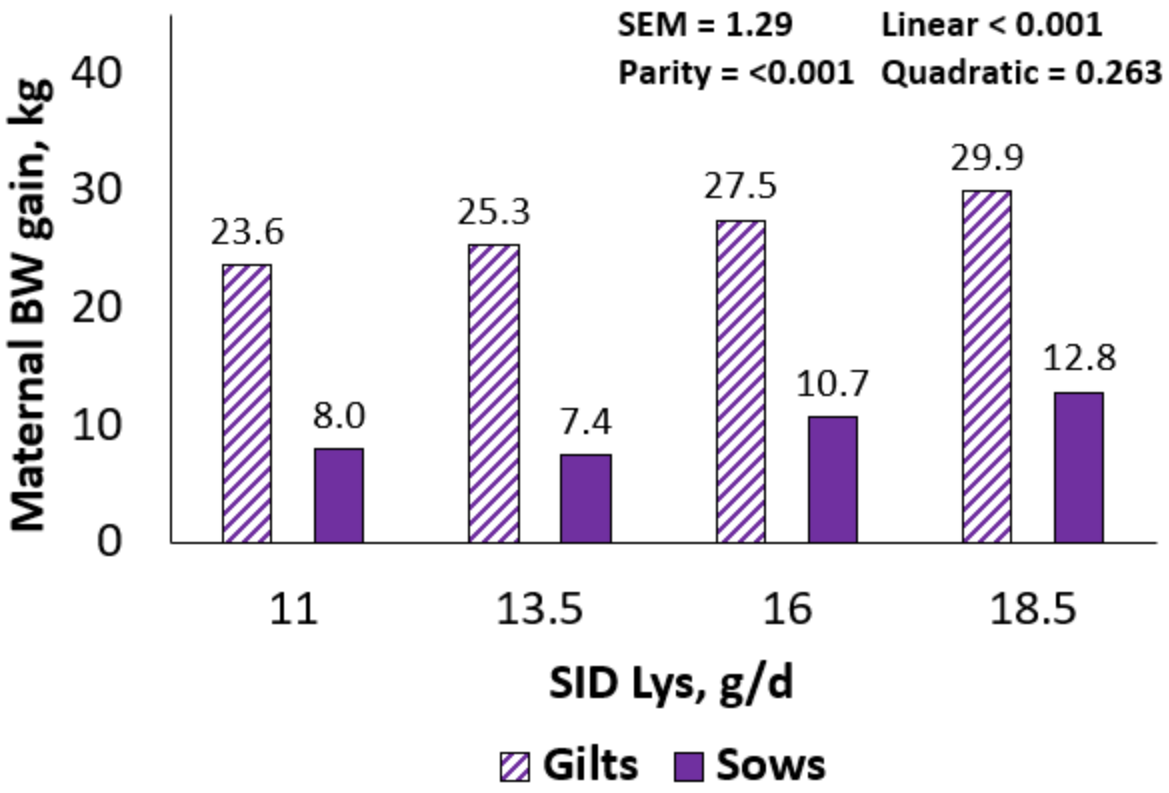

Figure 4.2 Estimated mean maternal BW gain of gilts and sows fed increasing SID Lys from d 4 to 112 of gestation using prediction equations from Dourmad et al. (1997). Other AA met or exceeded the NRC (2012) recommendations as a ratio to Lys.

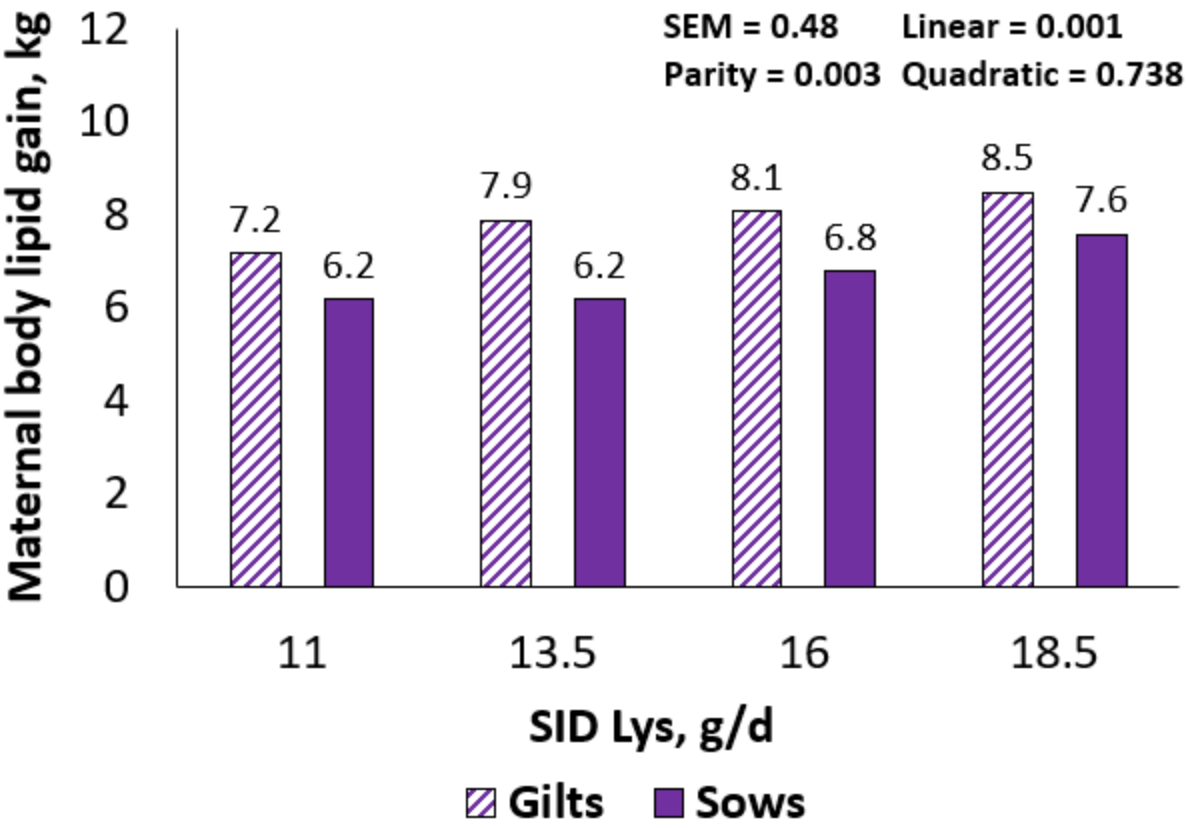

Figure 4.3 Estimated mean maternal body lipid gain of gilts and sows fed increasing SID Lys from d 4 to 112 of gestation using prediction equations from Dourmad et al. (1997). Other AA met or exceeded the NRC (2012) recommendations as a ratio to Lys.

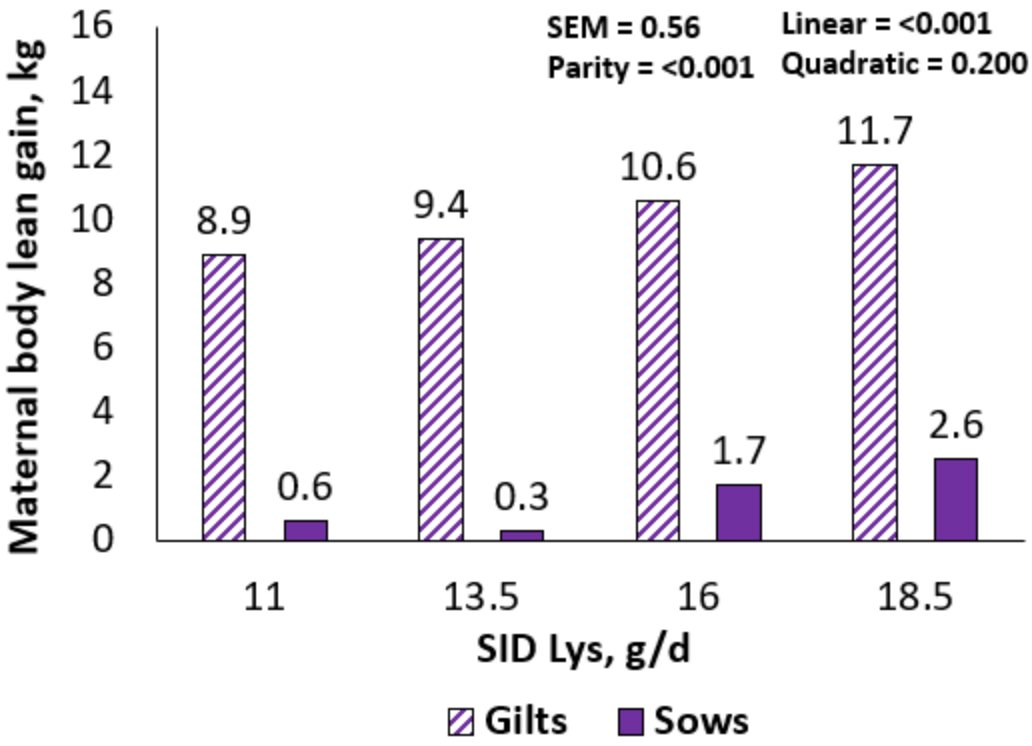

Figure 4.4 Estimated mean maternal body lean gain of gilts and sows fed increasing SID Lys from d 4 to 112 of gestation using prediction equations from Dourmad et al. (1997). Other AA met or exceeded the NRC (2012) recommendations as a ratio to Lys.

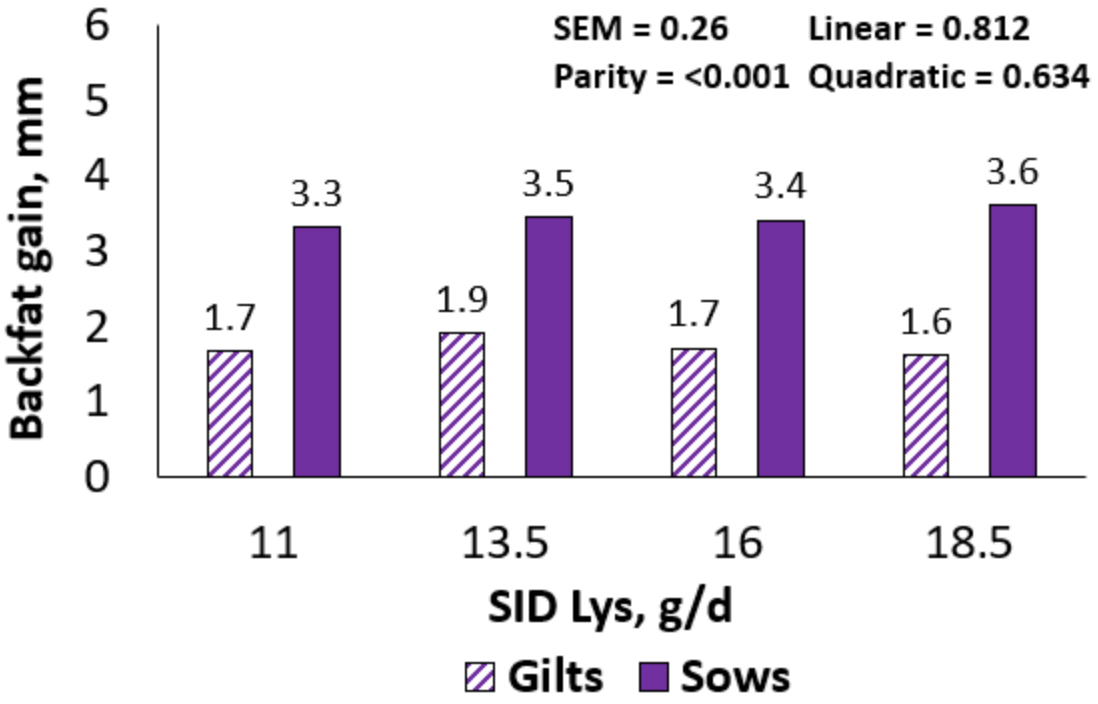

Figure 4.5 Mean backfat gain of gilts and sows fed increasing SID Lys from d 4 to 112 of gestation. Other AA met or exceeded the NRC (2012) recommendations as a ratio to Lys.

Chapter 5 - Modeling Standardized Ileal Digestible Lysine Requirements During Gestation on Gilts and Sows from a Commercial Production System

ABSTRACT: The objective of this study was to model daily standardized ileal digestible (SID) lysine (Lys) requirements in gestating sows. Data from 877 females (459 gilts, 418 sows; Camborough®, PIC, Hendersonville, TN) was collected and modeled using Dourmad et al. (2008) equations. Individual feed intake and BW were recorded daily throughout gestation via electronic sow feeders and a scale located in the alleyway after sows left feeding stations. Dietary treatments included 11, 13.5, 16, and 18.5 g/d SID Lys intake throughout gestation. Gilts (parity 1) and sows (parity 2 +) received 5.3 and 5.8 Mcal NE/d for the entire gestation period. Data were divided into 2 parity groups: gilts and sows, and gestation was divided into 3 stages: d 5 to 39 (early), 40 to 74 (mid), and 75 to 108 (late). The model follows the principle that energy is partitioned between maintenance, growth of conceptus (fetus, placenta, and fluids), and maternal protein and lipid deposition. Requirements for SID Lys were estimated based on predicted whole body protein deposition. The differences between SID Lys intake and SID Lys requirements is defined as SID Lys balance. After dividing energy requirements into tissue pools for maintenance, products of conceptus, and maternal reserves, the greatest portion of the energy requirement was for maintenance. Estimated protein retention of the conceptus increased in each sequential stage of gestation ($P < 0.05$) but there were no differences ($P > 0.05$) among treatments. Regardless of parity or stage of gestation, increasing SID Lys increased estimated maternal protein deposition (linear, $P < 0.001$), but it decreased in each sequential stage of

gestation ($P < 0.001$). Estimated maternal lipid deposition increased with increasing SID Lys (linear, $P = 0.076$) and decreased in each sequential stage of gestation ($P < 0.05$), with gilts having to mobilize maternal lipid in late gestation. For gilts and sows, estimated SID Lys requirements increased in each sequential stage of gestation ($P < 0.05$). Estimated SID Lys balance increased with increasing SID Lys in the diet (quadratic, $P < 0.054$), and decreased ($P < 0.05$) in each sequential stage of gestation. Overall, the model shows how changes in protein retention of the conceptus and maternal protein deposition differ by parity and stage of gestation. Based on predicted changes in protein deposition, and SID Lys balance, providing females with 11.0 g/d SID Lys throughout gestation adequately meets Lys requirements for most of gestation for prolific gilts and sows; however, gilts and sows were in a negative SID Lys balance for the last 5- to 10 d of gestion and this can be prevented by providing gilts and sows with 13.5 g/d SID Lys.

Key words: gilt, gestation, lysine requirement, model, sow

Introduction

Genetic selection continues to make sows leaner and more prolific and with these changes, nutrient requirements must be redefined. Lysine continues to receive attention, as the first limiting AA in corn-soybean-meal-based diets, with requirements during pregnancy defined based on total protein deposition in gestation (Dourmad et al., 2008; NRC, 2012). Current SID Lys requirements suggest a parity-segregated, phase feeding program for optimal performance within a breeding herd (Kim et al., 2009; NRC, 2012; Ball and Moehn, 2013). The challenge with this approach is with implementation, in that most commercial farms are constrained by

their current feeding system (Trottier et al., 2015) and as a result, are feeding a single diet in gestation (Goodband et al., 2013).

Thomas et al. (2019) evaluated the effects of SID Lys intake during gestation on weight gain and reproductive performance of gilts and sows from a prolific commercial herd. Authors observed a significant increase in female BW with increasing SID Lys intake; however, backfat remained relatively constant. These results suggest weight gain was in the form of protein deposition and the potential need for dietary Lys to support protein reserves. Protein accretion was not directly measured, but the authors collected daily intake and BW data, allowing for tissue pools to be modeled to further understand changes in body composition across dietary treatments.

Mathematical models are available to estimate nutrient requirements of gestating sows by partitioning energy intake between energy for maintenance, energy for growth of the conceptus, and energy for maternal protein and lipid deposition (Dourmad et al., 2008; NRC, 2012). Through this process, AA requirements are estimated based on the amount of total body protein deposition. Further, the models can be used to determine the impact of SID Lys intake on female body composition for gilts and sows at various time points in gestation. Therefore, the objective of this study was to use daily intake and BW observations collected by Thomas et al. (2019) to predict protein deposition, and subsequently SID Lys requirements, for a population of gilts and sows to further understand changes in female body composition due to increasing SID Lys intake.

Materials and Methods

The data used to model SID Lys requirements in this analysis were from a study by Thomas et al. (2019) that was conducted at a commercial sow farm in central Nebraska. Females were housed individually in stalls (gilts 0.56 × 2.1 m and sows 0.61 × 2.3 m) from breeding to d 4 of gestation and then were group-housed from d 4 to d 111 of gestation. Pens for sows provided 2.04 m^2 per sow and those for gilts provided 1.95 m^2 per gilt. Each pen was equipped with 6 electronic feeding stations (Nedap Velos, Gronelo, Netherlands) allowing for up to 45 females per station and 28 nipple waterers to provide ad libitum access to water. Each feeding station was 2.0 m long × 0.56 m wide. Females were group-housed in dynamic groups (275 females per pen), meaning serviced sows were entering the group (approximately d 4 of gestation) as sows due to farrow were exiting (approximately d 111 of gestation). This occurred over a 3 to 4-wk period, thereafter, the pen remained static (no movement of newly bred sows into the pen) until the sows reached d 111 of gestation and the process repeated. Each pen was equipped with a scale (1.74 m long × 1.07 m wide, Nedap Velos, Gronelo, Netherlands) located in the alleyway following the feeding stations and prior to returning to the pen for individual sow weight collection every time the sow exited the feeding station.

There were 1,091 females (Camborough®, PIC, Hendersonville, TN) enrolled in the study, of which 936 (498 gilts, 438 sows) completed (Thomas et al., 2019). At d 4 of gestation, females were weighed and backfat was measured at the P2 position (last rib, 7 cm from the center line of the back) using a Lean-Meater (RENCO, Minneapolis, MN). Females were blocked by BW within each d of enrollment and randomly assigned to 1 of 4 dietary treatments within block. Dietary treatments began on d 5 of gestation. Dietary treatments were corn-soybean meal-based and consisted of increasing SID Lys intake (11, 13.5, 16, and 18.5 g/d).

Gilts and sows were offered 2.1 and 2.3 kg/d, respectively, of feed throughout the entire study following standard practice at this commercial farm. This feeding level provided daily NE intake of 5.3 and 5.8 Mcal for gilts and sows, respectively. Dietary treatments were achieved by blending a low (0.48% SID Lys) and high (0.88% SID Lys) Lys diet via the ESF based on the females set feed allowance (Thomas et al., 2019). Low and high Lys diets were achieved by changing the amounts of corn and soybean meal. Dietary energy (NE, kcal/kg) was the same across the low and high Lys diets and all other nutrients met or exceeded the NRC (2012) requirement estimates. Diets were formulated using nutrient loading values and SID AA coefficients from the NRC (2012) for corn, SBM, and DDGS (Thomas et al., 2019).

On d 111 of gestation, as females were moved from the pens to the farrowing house, they were weighed and backfat measurements were collected at the P2 position (last rib, 7 cm from the center line of the back). Of the 936 females that completed the study, individual piglet BW was obtained within 12 h of birth on litters from 895 females.

The study was conducted over a 159-d period, from early March to late August 2017. Feed intake data was manually extracted daily through Nedap Velos software. The Nedap Velos system reported 1 total intake value per d of gestation and it was assumed that the feed which was dispensed was consumed by the sow before leaving the feeding station. Feed intake failed to download on 3 d (1.9%) during the trial and in the model herein it was assumed that feed intake equaled feed allowance on d when intake data was not available.

Sows had to walk across a scale as they moved from the feeding station back into the pen and as a result, sow BW was automatically recorded (Nedap Velos, Gronelo, Netherlands). The process of preparing BW data for analysis was much like that described by Thomas et al. (2018a), however; scales had been replaced and the new software included an algorithm (Nedap

Velos, Gronelo, Netherlands) providing the user with daily BW values compared to the previous system where raw data was provided. With this improvement, the process of removing outliers from the BW data set was dramatically reduced. However, the model required BW values for each d of gestation and the new algorithm provided BW values on average for 90 d, out of the 107 d the sow was in the gestation pen. Thus, 15.9% of BW were estimated using the closest surrounding measured BW and the ADG obtained from the 2 manual weights collected on d 4 and 111 of gestation. If the most recent observed weight was prior to the missing weight, the ADG for each missing d was added to the most recent observed weight. If the most recent observed weight was after the missing weight, the ADG was subtracted from the observed weight. The scale was validated using the PROC TTEST statement in SAS (Version 9.4, SAS Institute Inc., Cary, NC) testing the manual weights obtained on d 4 and 111 of gestation to weights recorded by the scale corresponding to those d and we found no evidence ($P > 0.256$) for differences.

Descriptive statistics in the form of means, histograms and scatterplots were generated using the PROC MEANS, PROC GPLOT, and PROC SGPLOT statements in SAS (Version 9.4, SAS Institute Inc., Cary, NC) for the daily observations. To be included in the data set, sows had to have daily intake and BW values from d 5 to 111 of gestation, as well as have piglet birth weights. Of the 895 females with piglet birth weights, 877 were used in the modeling. Four females were removed from the data set due to extreme observations found for female ADG, based on a critical *t*-score using a Bonferroni adjustment (0.05/ number of observations; Stroup, 2013). Five females were removed from the data set due to inconsistencies observed in ADFI. Specifically, these females had greater than 10 no feed events recorded for intake throughout gestation, suggesting that they were removed from the gestation pen to individual stalls. The

remaining 9 females were removed due to large variability in daily BW. Lastly, intake values on d 109, 110, and 111 of gestation were recorded as no feed events for a large population of sows in the data set. Based on farm practices, this was determined to be the result of females being removed from the gestation pen and loaded into farrowing. Thus, these d of gestation were removed for all sows from the data set. Following these removals, the data set included 877 females (459 gilts and 418 sows), generating a total of 91,183 observations (Table 1).

Definitions and Calculations

Standardized ileal digestible Lys intake was calculated from feed delivery and dietary SID Lys. Standardized ileal digestible Lys requirements were predicted for each female for each day of gestation using the InraPorc model, detailed by Dourmad et al. (2008), much like that reported by Thomas et al. (2018b), where the main nutrient flows considered were energy and AA. The model partitions energy between maintenance, products of conceptus (fetus, placenta, and fluids), and maternal body protein and lipid deposition as outlined by Dourmad et al. (1999). Priority is given to maintenance requirements and requirements for products of conceptus with nutrients in excess contributing to the constitution of the sow's body protein and lipid reserves (Dourmad et al. 1999). Conversely, when nutrient supplies are not sufficient, body reserves will be mobilized to support maintenance requirements and conceptus growth. The model is reported on an ME basis as presented by Dourmad et al. (2008). Diets formulated by Thomas et al. (2019) were on an NE basis and constant across the low and high Lys diets, but dietary treatments were not isocaloric on an ME basis (Table 2).

Dourmad et al. (2008) predict energy content of conceptus using natural logarithmic values as a function of time and litter size at farrowing. Dourmad et al. (2008) do not report the equation for predicted conceptus weight, which is needed to estimate maternal BW. However,

the equation used to predict the energy content of the conceptus was developed by Dourmad et al. (1999) and authors also report conceptus weight in the same manner, using logarithmic values as a function of time and litter size at farrowing:

Weight of conceptus (kg/d) = (exp (8.621 - 21.02 × exp (-0.053 × gestation, d) + 0.114 × total born, n))/1000;

Energy content of conceptus (kJ/d) = (exp (11.72 – 8.62 × exp (-0.0138 × gestation, d) + 0.0932 × total born, n))

Dourmad et al. (1999) developed the equations by combining a set of regression equations, developed by Noblet et al. (1985), generating 1 equation for both weight and energy content of the conceptus (fetus, placenta, and fluids). The equations allow for estimations of conceptus weight and energy content at any given d of gestation. The equations should be used with caution as they were developed over 30 years ago from a small population of gilts (Large White breed) with a range in litter size of 9 to 14 (Noblet et al., 1985). Total born in the current study ranged from 4 to 25, with an average of 15.6 pigs. Therefore, it is necessary to account for these changes in litter size with a correction ratio using litter birth weight as the numerator portion of the ratio and the litter birth weight equation reported by Dourmad et al. (1999) as the denominator portion of the ratio:

Ratio = (total born, n × (average piglet birth weight, kg × 1000)) / (exp (9.095 – 17.69 exp (-0.0305 × gestation length, d) + 0.0878 × total born, n)).

Daily predictions were required for modeling purposes for each of these variables, and the ratio can only be used to determine weight and energy content of the conceptus on d 114 of gestation because piglet birth weights were obtained after farrowing. This was resolved by Thomas et al. (2018b) where authors reviewed the data from Dourmad et al. (1999) and

determined the regression equations calculated for a litter size of 12. Authors then determined weight and energy content of the conceptus from d 4 through d 114 of gestation for a littler size of 12. Using this information, authors then calculated the percent of final weight and energy content of conceptus at each d of gestation. These percentages can then be multiplied by the corrected final weight and energy content of conceptus at d 114 of gestation and generate a value for each d of gestation. Thus, the equations used to predict weight and energy content of conceptus at each d of gestation, while correcting for mean piglet birth weight on d 114, are:

Weight of conceptus on each d (kg/d) = ((average piglet birth weight, kg × 1000) × total born, n) / (exp((9.095 - 17.69 × exp(-0.0305 × 114) + 0.0878 × total born, n))) × ((exp(8.621 – 21.02 × exp(-0.053 × 114) + 0.0114 × total born, n)) / 1000) × % of final weight of conceptus;

Energy content of conceptus on each d (kJ/d) = ((average piglet birth weight, kg × 1000) × total born, n) / (exp((9.095 - 17.69 × exp(-0.0305 × 114) + 0.0878 × total born, n))) ×(exp (11.72 – 8.62 × exp (-0.0138 × 114) + 0.0932 × total born, n)) × % of final energy content of conceptus.

Energy retention of the conceptus (ERc, kJ) was determined by calculating the difference in energy content of conceptus between each d of gestation.

The gestation sow model proposed by Dourmad et al. (2008) suggests ME for maintenance (MEm) under thermoneutral conditions with moderate physical activity ranges from 400 to 460 kJ per kg $BW^{0.75}$ based on observations by Noblet and Etienne (1987) and Everts (1994). The equation used to predict female maintenance requirement per d of gestation is:

MEm (kJ/d) = 440 × $BW^{0.75}$.

Our estimations assume that temperature conditions were thermoneutral throughout the duration of this study and that females spent no more than 4 h per d standing. The staff monitored temperature daily and the set point for ventilation control was 18° C to ensure environmental temperature was at or above the thermoneutral zone. Quantitative physical activity measures were not recorded but visual observations and inspection of feeding time records suggested that females likely spent no more than 4 h per d standing.

Nitrogen retention in the pregnant sow was estimated to determine maternal protein deposition, and subsequently SID Lys requirements. Nitrogen retention was calculated considering N retained in the conceptus (NR_c) by first determining protein content of conceptus. The equation to predict protein content of the conceptus (Dourmad et al., 2008) originated from Dourmad et al. (1999):

Protein content of conceptus (g/d) = (exp (8.090 – 8.71 × exp (-0.0149 × gestation, d) + 0.0872 × total born, n)).

It is necessary to account for changes in litter size by correcting for mean piglet birth weight, just as described for determining weight and energy content of the conceptus. Thus, the correction ratio was applied to the above equation to determine final protein content of conceptus on d 114 of gestation. Further, the corrected final protein content of the conceptus at d 114 of gestation can then be multiplied by the percentage of final protein content at each d of gestation to generate a value for each d. Thus, the equation used to predict protein content of conceptus at each d of gestation is:

Protein content of conceptus on each d (g/d) = ((average piglet birth weight, kg × 1000) × total born, n) / (exp((9.095 - 17.69 × exp(-0.0305 × 114) + 0.0878 × total born, n))) × (exp (8.090 – 8.71 × exp (-0.0149 × 114) + 0.0872 × total born, n))

Protein content of the conceptus (Dourmad et al., 2008) can be divided by 6.25, yielding N content of conceptus:

Nitrogen content of conceptus (g/d) = Protein content of conceptus, g / 6.25.

Nitrogen retained in the conceptus (NRc) was then determined by calculating the difference in daily N content of conceptus.

Whole body N retention was calculated based on the quantity of N retained in the conceptus (NRc) and N retention in maternal tissues which depends on parity, stage of pregnancy, and the supply of ME above the maintenance requirement (Dourmad et al., 1999). Thus, whole body N retention was calculated using the following equation (Dourmad et al., 2008):

$$NR\ (g/d) = 0.85 \times (NR_c - 0.4 + 45.9 \times (\text{gestation, d}/100) - 105.3 \times (\text{gestation, d}/100)^2 + 64.4 \times (\text{gestation, d}/100)^3 + a \times (ME - MEmm) / 1000).$$

Where NR_c = N retention in conceptus (g), a = 0.571 in the first pregnancy and a = 0.366 for other parities, ME= kJ per d ME intake, and MEmm = maintenance requirement at d 5 of gestation, kJ. Whole body protein retention was calculated by multiplying whole body N retention by 6.25:

Whole body protein retention (g/d) = NR, g × 6.25.

The amount of energy available to be deposited as protein in maternal tissues (ERmp) was calculated from whole body N retention (Dourmad et al., 2008):

$$ERmp\ (kJ/d) = 23.8 \times 6.25 \times (NR - NR_c).$$

In this model, priority is given to satisfy energy requirements for body maintenance functions, and growth of conceptus, with the remaining nutrients available for maternal body

accretion. Priority is given to maternal body protein deposition with the remaining nutrients available for lipid deposition (ERmf; Dourmad et al., 2008).

ERmf (kJ/d) = (Intake, kJ/d – (MEm + ERc / kc + ERmp / kp)) × kf.

Where kc, kp, and kf are the efficiencies of ME for uterine growth, protein deposition and fat deposition. Efficiencies of 0.50, 0.60, and 0.80 were used for kc, kp, and kf, respectively, in this study as reported by Dourmad et al. (2008). If energy intake was insufficient to support maintenance requirements and growth of conceptus, maternal body reserves were mobilized and used as an energy source (Dourmad et al., 2008) with an efficiency of energy mobilization of 0.80 (kr).

Maternal protein and lipid deposition were determined in terms of female BW (Dourmad et al., 2008):

Maternal protein deposition (g/d) = (ERmp / 23.8);

Maternal lipid deposition (g/d) = (ERmf / 39.7).

Total maternal protein and maternal lipid deposition were predicted by calculating the sum of each, for each individual sow.

Maternal BW gain from d 5 to 108 of gestation was determined by subtracting conceptus weight (fetus, placenta, and fluids), correcting for mean piglet birth weight, on d 108 of gestation from BW gain:

Maternal BW gain (kg) = (BW at d 108 of gestation, kg – BW at d 5 of gestation) – weight of conceptus on d 108 of gestation, kg.

Daily SID Lys intake was determined using daily intake values, generated from feed delivery reports, and dietary Lys based on respective treatment:

SID Lys intake (g/d) = feed intake, g × SID Lys, %.

Where the inclusion of SID Lys was 0.52, 0.64, 0.76, and 0.88% for gilts and 0.48, 0.59, 0.70, and 0.80% for sows, providing 11.0, 13.5, 16.0, and 18.5 g/d SID Lys.

Standardized ileal digestible Lys requirements were calculated assuming 6.5% Lys in retained protein with an efficiency of retention of 65% (Dourmad et al., 2008 and 2017):

SID Lys requirement (g/d) = $(0.036 \times BW^{0.75} + 6.25 \times NR \times 0.065) / 0.65$.

Standardized ileal digestible Lys balance was calculated as the differences between SID Lys intake and requirement:

SID Lys balance (g/d) = SID Lys intake, g - SID Lys requirement, g.

Statistical Model

Daily intake and weight values were recorded for each sow from d 5 to 108 of gestation. Data were divided into 2 parity groups (gilts and sows) and gestation was divided into three 5-wk intervals (d 5 to 39 (early), 40 to 74 (mid), and 75 to 108 (late)). Female maintenance requirement, energy retention of conceptus, protein retention of conceptus, whole body protein retention, energy used for maternal protein deposition, maternal protein deposition, energy used for maternal lipid deposition, maternal lipid deposition, SID Lys intake, SID Lys requirement, and SID Lys balance were analyzed using generalized linear mixed models (GLMM) whereby the linear predictor included dietary treatment, parity group (gilts and sows), stage of gestation (early, mid, late), and all interactions as fixed effects, as well as the sow(trt) random effect, accounting for the covariance structure of the observed responses. So specified- models recognized the individual female as the experimental unit for this study and stage within female as the observational unit. Within these outcomes, linear and quadratic contrasts were generated to determine the effects of increasing SID Lys. Response variables were fitted assuming a normal distribution and residual assumptions were checked using standard diagnostics on

residuals and were found to be reasonably met. The final models used for inference were fitted using restricted maximum likelihood estimation. Degrees of freedom were estimated using the Kenward-Rogers approach.

Estimated means and corresponding standard errors (SEM) are reported for all least square means. Pairwise comparisons were conducted on such means using a Tukey-Kramer adjustment to prevent inflation of Type I error due to multiple comparisons. Statistical models were fitted using the GLIMMIX procedure of SAS. Results were considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

Results and Discussion

The NRC (2012) gestating sow model was initially attempted for use in the study herein as it is very similar to the principles outlined by Dourmad et al. (2008); however, 6 different protein pools are identified in NRC (2012) including the fetus, placenta and fluids, uterus, mammary tissue, time-dependent maternal protein deposition, and energy intake-dependent maternal protein deposition. The model requires an adjustment factor on energy intake-dependent maternal protein deposition to achieve a reasonable fit between observed and estimated changes in the sow's body composition across parities. The adjustment allows for the user to change the composition of maternal BW, specifically the ratio between body protein and lipid accretion; however, the adjustment is not clearly defined and as a result, unrealistic estimates for maternal protein deposition were generated. Following these findings, the decision was made to use the model proposed by Dourmad et al. (2008).

Descriptive statistics from the predicted data are presented in Table 3. There was no evidence ($P > 0.10$) for a dietary treatment × parity group × stage of gestation interaction for any

of the response variables, thus LS-means were compared on two-way interactive terms (Tables 4, 5, and 6).

Predicted Protein Deposition of the Conceptus

There was no evidence ($P > 0.05$; Table 4) for an interaction between treatment and parity group or between treatment and stage of gestation for protein deposition of the conceptus (Table 5). In addition, there was no evidence for differences in protein deposition of the conceptus across dietary treatments ($P > 0.05$; Tables 4 and 5). Regardless of parity, protein content of the conceptus increased in each sequential stage of gestation ($P < 0.05$; Table 6). Protein content of the conceptus was greater for sows compared to gilts ($P < 0.05$; Figure 1) in early, mid, and late gestation.

Protein deposition of the conceptus was determined based on litter size, piglet birth weight, and d of gestation. Protein deposition of the conceptus in early, mid, and late gestation averaged 2.6, 16.7, and 43.0 g/d. Thus, there is a substantial increase in protein deposition in the last 1/3 of gestation, with a 16.6-fold increase from early to late gestation. These results are similar to those reported by McPherson et al. (2004) where authors observed an 18.5-fold increase in the rates of fetal tissue protein gain between early and late gestation. Because of this large increase in protein deposition of the conceptus, literature suggests an increase in AA in later gestation to meet the growing demands of the conceptus (Kim et al., 2009; Jang et al., 2017). However, differences were not observed as SID Lys increased in the diet which is the result of similar total born and piglet birthweights among dietary treatments (Thomas et al., 2019). Thomas et al. (2019) did find differences in total born and piglet birth weight between sows and gilts, resulting in an increased demand for protein deposition of the conceptus observed in sows.

Predicted Whole Body Protein Deposition

There was no evidence ($P > 0.05$; Table 4) for an interaction between treatment and parity group or between treatment and stage of gestation for whole body protein deposition (Table 5). Regardless of parity group or stage of gestation, as SID Lys level in the diet increased, whole body protein deposition increased (linear, $P < 0.001$). For gilts and sows, whole body protein deposition increased ($P < 0.05$; Table 6) in each sequential stage of gestation. Whole body protein deposition was greater for gilts ($P < 0.05$; Figure 2) in each stage of gestation compared to sows.

The equation used to determine whole body protein deposition was developed by Dourmad et al. (1999) where authors combined data from several experiments to fit a relationship for the prediction of whole body protein deposition, based on energy intake, female BW or parity, stage of gestation, and litter size (Williams and Close, 1985; Dourmad et al., 1996; Dourmad et al., 1999). Previous research suggests that whole body protein deposition is linearly affected by energy supply (Dourmad et al., 1996), however; the effect of stage of gestation complicates this relationship (Dourmad et al., 1999). Specifically, whole body protein deposition does not appear to be constant over gestation and research suggests a quadratic relationship between whole body protein deposition and stage of gestation (Dourmad et al., 1996), possibly independent of energy intake (Miller et al., 2016) and is thought to be driven through hormonal regulation.

In the present study, the proposed quadratic relationship for whole body protein deposition and stage of gestation can be visualized in Figures 3 and 4 for gilts and sows. Average whole body protein deposition in early, mid, and late gestation was 45.9, 52.2, and 73.8 g/d, respectively, similar to values reported in previous literature (Dourmad et al., 1996; Thomas et

al., 2018b). Literature agrees that the observed increase in whole body protein deposition in early gestation is maternal, since deposition in the products of conceptus is only 1 to 2 g/d during this time (Dourmad et al., 1996; NRC, 2012, Miller et al., 2016). However, the plateau observed in early to mid-gestation is harder to conceptualize, but was observed by Dourmad et al. (1996), and in a more recent nitrogen retention study by Miller et al. (2016) and is thought to reflect lower total nutrient requirements during a period when neither maternal or conceptus requirements are particularly high. Gilts and sows are still depositing maternal protein during this period, but at a reduced rate compared to early gestation as protein deposition in the products of conceptus is starting to increase at a rapid rate (Noblet et al., 1985; Ji et al., 2005; Jang et al., 2017). Higher whole body protein deposition is found in gilts compared to older parity sows which is explained partially by lower energy requirements for maintenance relative to their lower BW (Pettigrew and Yang, 1977). As gilts and young sows mature, maternal protein deposition decreases and is focused on replenishing protein reserves that were depleted in the previous lactation (Whittemore, 1998, Dourmad et al., 1996; Jagger, 2011).

As noted, whole body protein deposition is linearly affected by energy supply. In this model, the ME content of the diet and intake were reported rather than NE because the model from Dourmad et al. (2008) was reported on an ME basis. As reported previously, dietary treatments were achieved by blending a low and high Lys diet based on females set feed allowance. The low and high Lys diets were achieved by changing the amounts of corn and SBM, balancing for dietary energy on an NE basis. On an ME basis, dietary energy increased with increasing SID Lys, as a result of increasing SBM. Thus, in this model, the increase in predicted whole body protein deposition with increasing SID Lys is the result of an increase in ME.

Thomas et al. (2019) observed that the NE value used for SBM in formulation is likely underestimating the actual energy value. Thus, responses to increasing SID Lys may be a response to increasing energy from SBM. Authors estimated the NE value for SBM to be between 106 and 110% of corn energy, based on maternal weight gain, compared to 76% used in formulation. These estimates are similar to Cemin et al. (2019) where authors estimated the NE value for SBM in growing pigs between 105 and 125% of corn energy. In the present study, differences in NE for SBM generate differences in NE of 260 kcal/d from the low to high SID Lys dietary treatments (Thomas et al., 2019). Therefore, differences in predicted whole body protein deposition across dietary treatments may also be affected by differences in NE.

Predicted Maternal Protein Deposition

There was no evidence ($P > 0.05$; Table 4) for an interaction between treatment and parity group or between treatment and stage of gestation for maternal protein deposition (Table 5). Regardless of parity group or stage of gestation, as SID Lys level in the diet increased, maternal protein deposition increased (linear, $P < 0.001$). For gilts and sows, maternal protein deposition decreased ($P < 0.05$; Table 6) in each sequential stage of gestation. Maternal protein deposition was greater for gilts ($P < 0.05$; Figure 5) in each stage of gestation compared to sows.

In the present model, average maternal protein deposition in early, mid, and late gestation was 43.3, 35.6, and 30.9 g/d and includes the empty uterus and mammary tissue. Nutrients available above maintenance and growth of the conceptus are utilized for maternal gain, starting with protein synthesis (Dourmad et al., 2008). Maternal protein deposition was determined indirectly as the difference between whole body protein deposition and conceptus protein deposition. Thus, maternal protein deposition is also affected by energy intake, parity, stage of gestation, and litter size because of the relationship with whole body protein deposition.

Maternal protein deposition decreases as females progress through gestation and conceptus protein retention increases (Dourmad et al., 1999; Moehn and Ball, 2013). Maternal protein deposition in early to mid-gestation is suggested to be used for replenishing protein reserves depleted in the previous lactation (Dourmad et al., 1996, Boyd et al., 2000). In late gestation, maternal protein deposition is used to support the gain of the empty uterus and largely mammary development (Noblet et al., 1985; Ji et al., 2006; Feyera and Theil, 2016). The dynamics of protein deposition as it relates to the gradual transition of maternal protein deposition into conceptus protein deposition is poorly understood (Miller et al., 2016). This relationship is influenced by the degree of restoration needed in maternal protein reserves and if the reserves can be restored before conceptus protein demands rapidly increase. Thus, there is a physiological competition for protein between maternal and products of conceptus (Close et al., 1984; Shields et al., 1985; Miller et al., 2016).

Predicted Maternal Lipid Deposition

There was no evidence ($P > 0.05$; Table 4) for an interaction between treatment and parity group or between treatment and stage of gestation for maternal lipid deposition (Table 5). There was marginal evidence (linear, $P = 0.076$) suggesting an increase in maternal lipid deposition with increased dietary SID Lys. For gilts and sows, maternal lipid deposition decreased ($P < 0.05$; Table 6) in each sequential stage of gestation. Maternal lipid deposition was greater for sows ($P < 0.05$) compared to gilts for most of gestation (Figure 6).

Maternal lipid deposition is given the lowest priority for nutrient utilization and is the first to be mobilized when nutrient supplies are not sufficient (Dourmad et al., 1999; 2008). Like maternal protein reserves, maternal lipid reserves are important during lactation when females are not consuming enough nutrients to meet the demands of milk production and in turn mobilize

maternal reserves (Strathe, 2019). The challenge in gestation is to increase maternal lipid reserves without making females fat, as this can predispose them to dystocia at farrowing, decrease sow longevity, and reduce appetite during lactation causing excessive mobilization of body reserves (Dourmad et al., 1994; Boyd et al., 2000; Quiniou, 2014).

Average maternal lipid deposition in early, mid, and late gestation was 106, 68, and 0.3 g/d. For gilts, average maternal lipid deposition was -4.4 g/d in late gestation, signifying tissue mobilization was required to support fetal and mammary growth. This agrees with previous literature suggesting that maternal reserves will be mobilized in late gestation to meet the growing demands of the conceptus if energy intake is not sufficient (Pluske et al., 1995; Bee, 2004).

Predicted Maintenance Requirement

There was no evidence ($P > 0.05$; Table 4) for an interaction between treatment and parity group; however, there was evidence for a treatment by stage interaction for predicted maintenance requirements ($P < 0.001$; Table 5). In early and mid-gestation, there was no evidence for differences in maintenance requirements across dietary treatments; however, in late gestation, females consuming 18.5 g/d SID Lys had greater maintenance ($P < 0.05$) requirements than females consuming 11.0 g/d SID Lys. This is explained by greater differences in BW across dietary treatments in late gestation, compared to early and mid-gestation. Regardless of parity, maintenance requirements increased ($P < 0.05$; Table 6) in each sequential stage of gestation. Maintenance requirements for sows were greater ($P < 0.05$) in each stage of gestation compared to gilts within the same stage.

Maintenance requirements were estimated from BW, assuming constant environmental conditions and physical activity. Thus, differences in BW directly impact predicted differences in

maintenance requirements. Thomas et al. (2019) report an increase in final BW as SID Lys increased. This explains the increase in maintenance requirements with increasing SID Lys. Further, initial and final BW for sows were greater compared to gilts, therefore maintenance requirements were greater as well (Thomas et al., 2019). In the present study, maintenance requirements for gilts and sows accounted of 79 and 82% of their daily caloric intake. Thus, most of the energy provided to gilts and sows was used to maintain BW and composition (Trottier and Johnston, 2001).

Deviations between predicted and actual maintenance requirements have a large impact on the ME that is available for energy deposition above maintenance. In a recent study by Knauer et al. (2019; preliminary data, personal communication), gestating sows were fed from 80 to 110% of the energy allowance for maintenance only (Dourmad et al. 2008; NRC, 2012), and sows gained BW across dietary treatments, suggesting that current maintenance requirements are likely overestimating the actual requirements. If this is true in the study herein, more energy will be available than predicted for maternal protein and lipid deposition.

Predicted Energy Retention of the Conceptus

There was no evidence ($P > 0.05$; Table 4) for an interaction between treatment and parity group or between treatment and stage of gestation for energy retention of the conceptus (Table 5). There was also no evidence for differences in energy retention of conceptus across dietary treatments ($P > 0.05$). Regardless of parity, energy retention of the conceptus increased ($P < 0.05$; Table 6) in each sequential stage of gestation. There was no evidence for differences between gilts and sows in energy retention of the conceptus in early gestation ($P > 0.05$); however, energy retention of the conceptus was greater ($P < 0.05$) for sows in mid- and late gestation.

Energy retention of the conceptus was determined based on litter size, piglet birth weight, and d of gestation. Thomas et al. (2019) reported increased total born and piglet birth weight in sows compared to gilts, contributing to differences observed in energy retention of the conceptus in mid and late gestation. Energy retention of the conceptus in early, mid, and late gestation represent 0.3, 1.9, and 5.0% of total daily caloric intake, which aligns with previous research (Noblet et al., 1990; Thomas et al., 2018b).

Predicted Energy Used for Maternal Protein and Lipid Deposition

There was no evidence ($P > 0.05$; Table 4) for an interaction between treatment and parity group or between treatment and stage of gestation for the energy used for maternal protein deposition (Table 5). Regardless of parity group or stage of gestation, as SID Lys level in the diet increased, the energy used for maternal protein deposition increased (linear, $P < 0.001$). For gilts and sows, the energy used for maternal protein deposition decreased in each sequential stage of gestation ($P < 0.001$; Table 6). When comparing the energy used for maternal protein deposition in each stage of gestation, gilts were greater compared to sows ($P < 0.05$).

Similarly, there was no evidence ($P > 0.05$; Table 4) for an interaction between treatment and parity group or between treatment and stage of gestation for the energy used for maternal lipid deposition (Table 5). Regardless of parity group or stage of gestation, the energy used for maternal lipid deposition increased with increasing SID Lys (linear, $P = 0.076$). Regardless of parity group, the energy used for maternal lipid deposition decreased with each sequential stage of gestation ($P < 0.05$; Table 6). There was no evidence for differences in the energy used for maternal lipid deposition in early gestation for gilts or sows ($P > 0.05$); however, the energy used for maternal lipid deposition was greater for gilts compared to sows in mid and late gestation ($P < 0.05$).

After prioritizing nutrients to meet maintenance requirements, and the demands of the products of conceptus, the remaining nutrients available are for maternal deposition, with priority given to protein deposition (Dourmad et al.,1999; 2008). Gilts and sows in this study were provided with the same feed allowance throughout gestation. Predicted model estimates indicate an increase in maintenance requirements and energy retention of the conceptus as gestation progresses, thereby reducing the energy available for deposition into maternal reserves.

Thomas et al. (2018b) modeled nutrient requirements on a population of gilts and sows from the same farm as herein, only two years prior to the collection of this data. Authors found that gilts in late gestation were in a negative energy balance, mobilizing 26 g/d of maternal lipid. Our results also suggest that feed intake was insufficient in late gestation and gilts were mobilizing 4.4 g/d of maternal lipid. Although gilts in the present study had greater BW, and subsequently greater maintenance requirements, and 0.5 more pigs in total born, contributing to an increase in energy retention of the conceptus, caloric intake was greater compared to Thomas et al. (2018b), thereby reducing the negative energy balance in late gestation. The opposite was observed when comparing sows from the two studies. Like gilts, sows in the present study had greater BW, and 1.1 more pigs, however; average caloric intake was less in the present study, resulting in even less maternal protein and lipid deposition than sows in the previous trial.

Lysine Requirement

There was no evidence ($P > 0.05$; Table 4) for an interaction between treatment and parity group or between treatment and stage of gestation for SID Lys intake, predicted requirement, or balance (Table 5).

Regardless of parity or stage of gestation, SID Lys intake increased with increasing SID Lys in the diet (quadratic, $P < 0.001$; Table 5). In gilts, SID Lys intake was greater in early and

mid-gestation, compared to late gestation ($P < 0.05$; Table 6). In sows, SID Lys intake was greatest in mid and late gestation, compared to early gestation ($P < 0.05$). Regardless of stage of gestation, SID Lys intake was greater for sows compared to gilts ($P < 0.05$).

Daily feed delivery was used to determine daily SID Lys intake based off dietary Lys. Feed allowance for gilts and sows was set at 2.1 and 2.3 kg/d and blends of high and low dietary Lys diets were used to achieve the same dietary treatments for both gilts and sows. Average SID Lys intake for gilts was 10.7, 13.2, 15.6, and 18.0 g/d and 10.9, 13.5, 16.0, and 18.3 g/d for sows. Dietary treatments were designed to be equally spaced, with a difference of 2.5 g SID Lys between treatment groups. However; females did not always consume their full feed allowance, which resulted in differences in SID Lys intake between dietary treatments that are no longer equally spaced. Thus, variability in feed intake resulted in the quadratic response of SID Lysine intake observed as SID Lys increased.

Thomas et al. (2018c) observed a reduction in feed intake during early gestation for both gilts and sows housed in group pens utilizing ESF. The authors also observed variability in feed intake throughout gestation, predominantly in gilts, with females consuming less than their daily feed allowance. These results are similar to the present study (Figures 7 and 8). Results indicate SID Lys intake for each treatment were greater for sows, compared to gilts, reflecting the increased variability in feed consumption for gilts.

Regardless of parity or stage of gestation, predicted SID Lys requirements increased with increasing SID Lys intake (linear, $P < 0.001$; Table 5). For gilts and sows, SID Lys requirements increased in each sequential stage of gestation ($P < 0.05$; Table 6). Regardless of stage of gestation, SID Lys requirements for gilts were greater compared to SID Lys requirements for sows ($P < 0.05$; Figure 9).

Requirements for SID Lys were determined based on predicted whole body protein deposition, and because of this, the estimated requirements increase with increasing SID Lys intake in each stage of gestation and are greater for gilts, compared to sows. Previous research suggests daily SID Lys requirements for gilts range from 10 to 13 g/d in early gestation and increase to 17 to 18 g/d in late gestation (Ji et al., 2005; Samuel et al., 2012; NRC, 2012). For sows, SID Lys requirements are reduced significantly with parity, ranging from 6 to 9 g/d in early gestation and 11 to 15 g/d in late gestation (Samuel et al., 2012; NRC, 2012). In comparison to these studies, the estimated SID Lys requirements generated herein are lower for both gilts and sows. These requirements are similar to those predicted by Dourmad et al. (2017) where authors applied the same model to a large population of gilts and sows, with growth and reproductive performance comparable to values reported herein.

Regardless of parity or stage of gestation, SID Lys balance (SID Lys intake – SID Lys requirement) increased with increasing SID Lys (quadratic, $P < 0.054$; Table 5*)*. Regardless of parity group, SID Lys balance decreased in each sequential period of gestation ($P < 0.05$; Table 6). Sow SID Lys balance was greater in each stage of gestation compared to gilts ($P < 0.05$; Figure 10).

These results are reflective of both SID Lys intake and estimated SID Lys requirements, suggesting that if the model is correct, regardless of dietary treatment, both gilts and sows are above their SID Lys requirements throughout gestation (Figures 11 and 12). Estimated SID Lys balance reflects SID Lys requirements, which was estimated based on whole body protein deposition. As gilts and sows progress through gestation, SID Lys intake remains relatively constant, but SID Lys requirement is changing and is progressively increasing, resulting in an

SID Lys balance that is slowly decreasing. By the end of gestation, SID Lys intake is very close to requirement, resulting in SID Lys balances close to zero.

In gilts and sows, SID Lys balance was negative from d 100 to 108 and d 104 to 108 of gestation for those consuming the lowest SID Lys intake at 11 g/d (Figures 13 and 14). For gilts and sows receiving 13.5 g/d SID Lys, balance remained positive through gestation but was very low at d 108 of gestation, estimated at 0.2 and 1.1 g/d. This suggests that gilts and sows provided with 13.5 g/d SID Lys were provided with adequate concentrations to meet requirements for protein deposition. However, Thomas et al. (2019) observed an increase in female BW gain up to 18.5 g/d SID Lys, with no evidence for differences in backfat depth. Authors speculated that BW gain was in the form of protein and not lipid deposition, potentially increasing the requirement for SID Lys. However, the model suggests 13.5 g/d SID Lys was adequate to meet the demands of protein deposition throughout gestation.

The constant feeding level throughout gestation chosen by Thomas et al. (2019) is criticized because females are above their AA requirements in early gestation and under their AA requirements in late gestation (NRC, 2012; Moehn and Ball, 2013). However, Quiniou (2014) suggests excess of AA in early gestation is beneficial and allows for sows to reconstitute muscle for those who have over mobilized protein reserves in the previous lactation. This is supported by Moehn et al. (2011) where authors suggest adjusting AA intake in gestation based on weight loss in the previous lactation. Specifically, authors recommend increasing SID Lys by 1.5 g/d throughout gestation for each 10 kg of BW lost during lactation, as recommended by GfE (2008).

Thomas et al. (2019) did not report BW or backfat changes in lactation; however, differences in final maternal BW and backfat reported at d 111 of gestation for gilts and initial

BW and backfat reported at d 5 of gestation parity 2 sows can be used to estimate changes in body composition in lactation. Final maternal BW and backfat for gilts was 189.6 kg and 19.7 mm and initial maternal BW and backfat for parity 2 sows was 179.7 kg and 11.9 mm (Thomas et al., 2019). This suggests that gilts on this farm lose BW and considerable backfat in lactation.

Changes in body composition in lactation are commonly reported in research to indicate the degree to which maternal reserves were mobilized (Dourmad et al., 1998). Modern females are challenged in lactation to consume enough nutrients to meet demands for milk production, and as a result, mobilize maternal reserves (Strathe et al., 2019). Previous research has demonstrated that females are susceptible to a negative energy balance at any time during lactation (Koketsu et al., 1996; Zak et al., 1997). Literature has reported weight loss in lactation ranging from 15 to 40 kg (Beyer et al., 2007; Cools et al., 2014); however, Boyd et al. (2000) reported normal weight loss for a 21-d lactation to be less than 10 kg. The actual BW and backfat losses in lactation are unknown for the population of females reported by Thomas et al. (2019); thus, additional research is warranted to determine if young females from this herd would benefit from additional SID Lys in early gestation to replenish maternal body protein reserves.

The results from this model further explain changes in body composition reported by Thomas et al. (2019). Maternal protein deposition increases with increasing SID Lys. Maternal lean tissue deposition (maternal protein deposition × 2.55; NRC, 2012) is greater compared to maternal lipid deposition, especially in late gestation when females are in a negative energy balance and are having to mobilize maternal lipid reserves. The model also suggests that maternal protein reserves were mobilized in the last 5 to 10 days of gestation for both gilts and sows. However, SID Lys intake was greater than SID Lys requirements for most of gestation, especially early gestation, suggesting that ample maternal protein reserves were available for

mobilization in late gestation. Previous research suggests that mobilization of maternal reserves prior to farrowing can have negative effects during lactation (Trottier et al., 2015) and should be minimized, however; over-feeding can have negative effects in lactation as well (Boyd et al., 2000; Kraeling and Webel, 2015). This suggests a balance between the two is necessary to achieve optimal performance. Overall, the model agrees with conclusions made by Thomas et al. (2019) suggesting that 11 g/d SID Lys intake appears adequate to meet requirements for protein deposition for gilts and sows throughout gestation; however, providing 13.5 g/d SID Lys will prevent females from entering a negative SID Lys balance in late gestation.

In conclusion, 1) the present model demonstrates that SID Lys requirements increase through gestation; 2) gilts and sows were overfed SID Lys in early to mid-gestation; and 3) gilts and sows consuming 11 g/d SID Lys were below predicted SID Lys requirements in the last 5 to 10 d of gestation and gilts and sows consuming 13.5 g/d SID Lys were above predicted SID Lys requirements throughout gestation.

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Table 5.1 Descriptive statistics for data included in the study[1]

Item	Mean	SD	Minimum	Maximum
Parity	2.6	2.30	1	13
Final BW, kg	235.3	25.3	183.7	315.0
BW gain, kg	49.0	14.0	2.0	115.0
Total born	15.6	3.13	4	25
Birth weight, kg	1.27	0.207	0.68	2.05
Born alive	14.7	2.94	4	23
Birth weight, kg	1.29	0.202	0.68	2.02
Stillbirths	0.49	0.811	0	6
Mummies	0.42	0.747	0	5
Gestation Length	115.9	1.10	112	118

[1]Values from a total of 877 females (Camborough, PIC, Hendersonville, TN) are used.

Table 5.2 Energy and crude protein content of the diet for gilts and sows[1]

	SID Lys, g/d			
	11.0	13.5	16.0	18.5
Gilts (2.1 kg/d)				
CP, %	14.4	16.4	18.2	20.2
NE, kcal/kg	2,504	2,504	2,503	2,503
ME, kcal/kg	3,235	3,261	3,286	3,311
Sows (2.3 kg/d)				
CP, %	13.7	15.5	17.2	19.0
NE, kcal/kg	2,504	2,504	2,504	2,503
ME, kcal/kg	3,226	3,249	3,272	3,295

[1]A total of 877 females (Camborough, PIC, Hendersonville, TN) were fed increasing levels of SID Lys from d 4 to d 111 of gestation. Diets were formulated to be isocaloric on an NE basis. On an ME basis, energy increases as SID Lys inclusion increases.

Table 5.3 Descriptive statistics for predicted data[1]

Item	Mean	SD	Minimum	Maximum
Final weight of conceptus, kg[2]	29.9	7.07	7.5	58.2
Final maternal BW, kg[3]	203.9	23.12	154.8	279.6
Maternal weight gain, kg[4]	17.7	15.02	-24.6	56.4
Total maternal protein deposition, kg[5]	3.8	0.79	1.9	5.5
Total maternal lipid deposition, kg[6]	6.1	3.06	-3.8	16.6

[1]A total of 877 females (Camborough, PIC, Hendersonville, TN) were used to predict the above variables from d 5 to d 108 of gestation.
[2]Weight of conceptus (fetus, placenta, and fluids) at d 108 of gestation (kg) = Final conceptus weight at d 114, kg × % of final conceptus weight at d 108, where final conceptus weight at d 114 (kg) = ((average piglet birth weight, kg × 1000) × total born, n) / (exp((9.095 - 17.69 × exp(-0.0305 × 114) + 0.0878 × total born, n))) × ((exp(8.621 – 21.02 × exp(-0.053 × 114) + 0.0114 × total born, n)) / 1000).
[3]Maternal BW at d 108 of gestation (kg) = BW at d 108, kg – weight of conceptus on d d 108, kg.
[4]Maternal weight gain from d 5 to 108 of gestation (kg) = (BW on d 108, kg – BW at d 5, kg)- weight of conceptus at d 108, kg.
[5]Total protein deposition (kg) = Sum of protein deposition for each sow given by, (energy available to be deposited as protein in maternal tissue, kJ/23.8)/1000; Dourmad et al. (2008)
[6]Total lipid deposition (kg) = Sum of lipid deposition for each sow given by, (energy available to be deposited as lipid in maternal tissue, kJ /39.7)/1000; Dourmad et al. (2008)

Table 5.4 Effects of increasing standardized ileal digestible (SID) lysine (Lys) and parity on predicted model parameters[1]

	Gilts				Sows					Probability, $P <$			
	SID Lys, g/d				SID Lys, g/d							SID Lys	
Item	11.0	13.5	16.0	18.5	11.0	13.5	16.0	18.5	SEM	Trt × Parity	Parity	Linear	Quadratic
N	109	112	121	117	106	107	104	101	---	---	---	---	---
Parity	1.0	1.0	1.0	1.0	4.4	4.4	4.3	4.3	---	---	---	---	---
Deposition, g													
Conceptus	19.6	20.1	19.9	20.1	21.5	21.5	22.0	21.4	0.36	0.605	<0.001	0.427	0.421
Whole body protein	60.8	62.3	62.7	62.8	51.1	51.8	52.5	52.6	0.56	0.897	<0.001	<0.001	0.183
Maternal protein	41.2	42.2	42.8	42.7	29.6	30.3	30.5	31.1	0.47	0.848	<0.001	<0.001	0.326
Maternal lipid	54.1	56.6	58.0	55.7	54.9	61.5	60.1	64.5	2.92	0.512	0.037	0.076	0.373
Energy requirement, kcal ME													
Maintenance	5,277	5,327	5,346	5,376	6,051	6,043	6,098	6,119	36.7	0.877	<0.001	0.010	0.923
Conceptus	158.9	162.7	161.5	163.3	175.4	175.3	179.3	174.6	3.4	0.653	<0.001	0.470	0.450
Protein deposition	234	240	244	243	168	173	173	177	2.65	0.807	<0.001	<0.001	0.326
Lipid deposition	513	537	550	529	521	584	571	612	27.7	0.512	0.037	0.076	0.373
SID Lys, g													
Intake	10.7	13.2	15.6	18.0	10.9	13.5	16.0	18.3	0.02	0.557	<0.001	<0.001	<0.001
Requirement	8.0	8.2	8.2	8.3	7.2	7.3	7.4	7.4	0.05	0.761	<0.001	<0.001	0.204
Balance[2]	2.6	5.0	7.4	9.7	3.7	6.2	8.6	10.9	0.05	0.630	<0.001	<0.001	0.054

[1]Daily intake and BW values from d 4 to 108 of gestation on 877 females (459 gilts, 418 sows; Camborough, PIC, Hendersonville, TN) were used to model gestation nutrient utilization with females receiving increasing levels of SID Lys. Values represent an average for the gestation period and were predicted as described by Dourmad et al. (2008).

[2]SID Lys balance (g) = SID Lys intake, g - SID Lys requirement, g.

Table 5.5 Effects of increasing standardized ileal digestible (SID) lysine (Lys) and stage of gestation on predicted model parameters[1]

	Early gestation, d 5 to 39				Mid gestation, d 40 to 74				Late gestation, d 75 to 108					Probability, *P* <	
	SID Lys, g/d				SID Lys, g/d				SID Lys, g/d					SID Lys	
Item	11.0	13.5	16.0	18.5	11.0	13.5	16.0	18.5	11.0	13.5	16.0	18.5	SEM	Linear	Quadratic
Deposition, g															
Conceptus	2.6	2.6	2.6	2.6	16.5	16.7	16.8	16.7	42.6	43.0	43.3	43.0	0.52	0.427	0.421
Body protein[2]	44.8	45.7	46.3	46.8	51.0	52.1	52.9	53.0	72.3	73.8	74.8	74.5	0.57	<0.001	0.183
Mat. protein[3]	42.2	43.1	43.7	44.2	34.4	35.4	36.1	36.3	29.7	30.7	31.5	31.5	0.35	<0.001	0.326
Mat. lipid[4]	101.4	106.3	106.0	110.2	64.3	68.8	69.3	69.4	-2.3	2.0	1.7	-0.2	2.3	0.076	0.373
Energy requirement, kcal ME															
Maintenance[5]	5,324^{d}	5,334^{d}	5,336^{d}	5,346^{d}	5,649^{c}	5,665^{c}	5,683^{c}	5,711^{c}	6,003^{b}	6,031^{ab}	6,061^{ab}	6,104^{a}	27.8	0.010	0.923
Conceptus	21.5	21.7	21.8	21.7	131.4	132.9	133.6	132.7	348.1	352.0	353.8	351.3	4.84	0.470	0.450
Protein dep.[6]	240	245	248	251	196	201	206	206	169	175	179	179	2.0	<0.001	0.326
Lipid dep.[7]	962	1008	1006	1046	610	653	657	659	-21	19	16	-2	21.7	0.076	0.373
SID Lys, g															
Intake	10.8	13.3	15.7	18.1	10.8	13.4	15.9	18.2	10.8	13.3	15.8	18.1	0.03	<0.001	<0.001
Requirement	6.4	6.5	6.6	6.6	7.1	7.2	7.3	7.3	9.4	9.5	9.6	9.6	0.05	<0.001	0.204
Balance[8]	4.4	6.8	9.2	11.5	3.7	6.2	8.6	10.9	1.4	3.8	6.2	8.5	0.06	<0.001	0.054

[1]Daily intake and BW values from d 4 to 108 of gestation on 877 females (459 gilts, 418 sows; Camborough, PIC, Hendersonville, TN) were used to model gestation nutrient utilization with females receiving increasing levels of SID Lys. Values represent an average for the gestation period and were predicted as described by Dourmad et al. (2008). Values with different superscripts within a row differ, $P < 0.05$. There was no evidence for Trt × Stage interaction for any variable except for maintenance requirement. Stage <0.0001 for all variables.

[2]Body = Wole body protein

[3]Mat. protein = Maternal protein

[4]Mat. lipid = Maternal lipid

[5]Trt × stage interaction = <0.001

[6]Protein dep.= Protein deposition

[7]Lipid dep. = Lipid deposition

[8]SID Lys balance (g) = SID Lys intake, g – SID Lys requirement, g

Table 5.6 Effects of parity and stage of gestation on predicted model parameters[1].

	Gilts			Sows				Probability, $P <$		
	Stage of Gestation			Stage of Gestation						
Item	d 0 to 39	d 40 to 74	d 75 to 109	d 0 to 39	d 40 to 74	d 75 to 109	SEM	Parity × Stage	Parity	Stage
Deposition, g										
Conceptus	2.5^{f}	16.0^{d}	41.3^{b}	2.7^{e}	17.4^{c}	44.8^{a}	0.37	<0.001	<0.001	<0.001
Whole body protein	51.4^{a}	57.3^{b}	77.9^{c}	39.9^{d}	46.7^{e}	69.4^{f}	0.41	<0.001	<0.001	<0.001
Maternal protein	48.9^{a}	41.2^{b}	36.6^{c}	37.2^{c}	29.3^{d}	24.6^{e}	0.25	0.405	<0.001	<0.001
Maternal lipid	108.8^{a}	64.1^{c}	-4.4^{e}	102.9^{a}	72.3^{b}	5.5^{d}	1.58	<0.001	0.037	<0.001
Energy requirement, kcal ME										
Maintenance	4,920^{e}	5,340^{d}	5,737^{c}	5,790^{c}	6,047^{b}	6,394^{a}	19.9	<0.001	<0.001	<0.001
Conceptus	20.8^{f}	127.2^{d}	336.9^{b}	22.7^{f}	138.6^{c}	367.1^{a}	3.33	<0.001	<0.001	<0.001
Protein deposition	278^{a}	235^{b}	208^{c}	211^{c}	167^{d}	140^{e}	1.43	0.405	<0.001	<0.001
Lipid deposition	1,032^{a}	608^{c}	-41^{e}	977^{a}	686^{b}	52^{d}	15.5	<0.001	0.037	<0.001
SID Lys, g										
Intake	14.5^{cd}	14.5^{c}	14.4^{d}	14.6^{b}	14.7^{a}	14.6^{ab}	0.02	0.162	<0.001	<0.001
Requirement	7.0^{a}	7.7^{b}	9.9^{c}	6.0^{d}	6.8^{e}	9.1^{f}	0.04	<0.001	<0.001	<0.001
Balance[2]	7.5^{a}	6.8^{b}	4.6^{c}	8.5^{d}	7.9^{e}	5.5^{f}	0.04	<0.001	<0.001	<0.001

[1]Daily intake and BW values from d 4 to 108 of gestation on 877 females (459 gilts, 418 sows; Camborough, PIC, Hendersonville, TN) were used to model gestation nutrient utilization with females receiving increasing levels of SID Lys. Values represent an average for the gestation period and were predicted as described by Dourmad et al. (2008). Values with different superscripts within a row differ, P <0.05.

[2]SID Lys balance (g) = SID Lys intake, g – SID Lys requirement, g

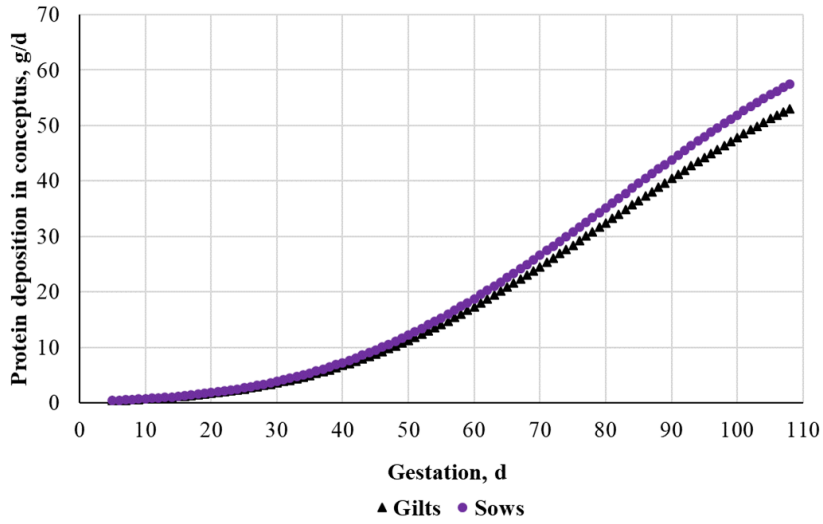

Figure 5.1 Predicted protein deposition of the conceptus (g/d) for gilts and sows from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for the specified parity group.

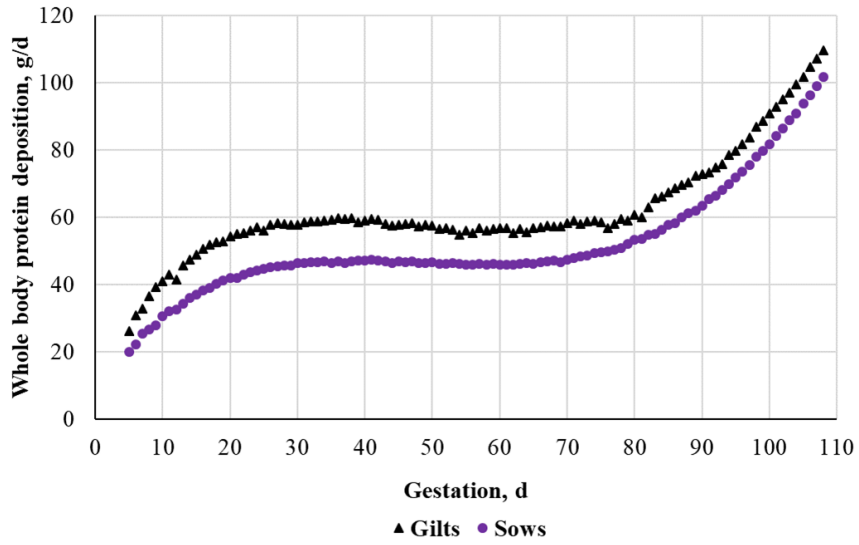

Figure 5.2 Predicted whole body protein deposition (g/d) for gilts and sows from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for the specified parity group.

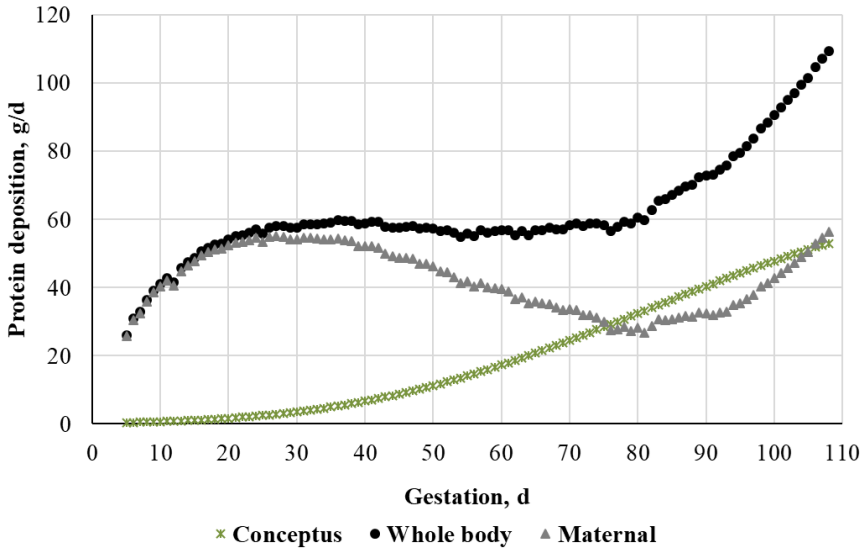

Figure 5.3 Predicted whole body, maternal, and conceptus protein deposition (g/d) for gilts from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for the specified protein pool.

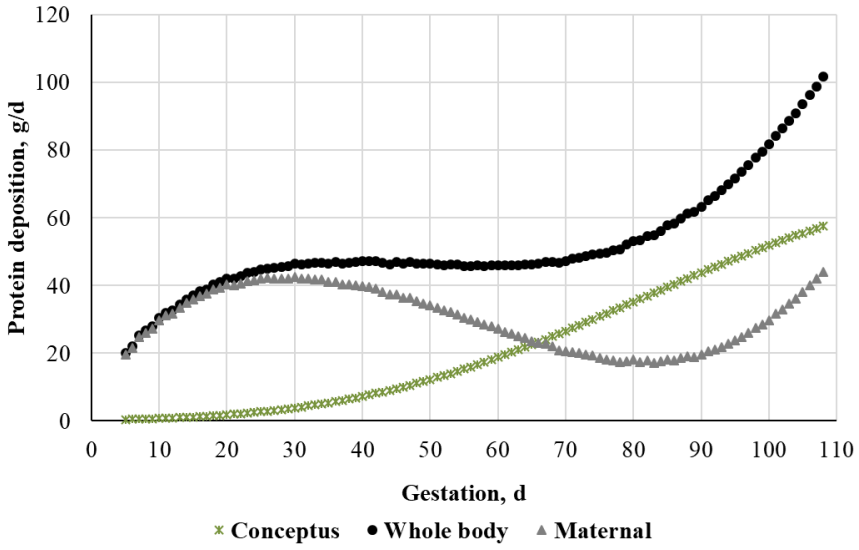

Figure 5.4 Predicted whole body, maternal, and conceptus protein deposition (g/d) for sows from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for the specified protein pool.

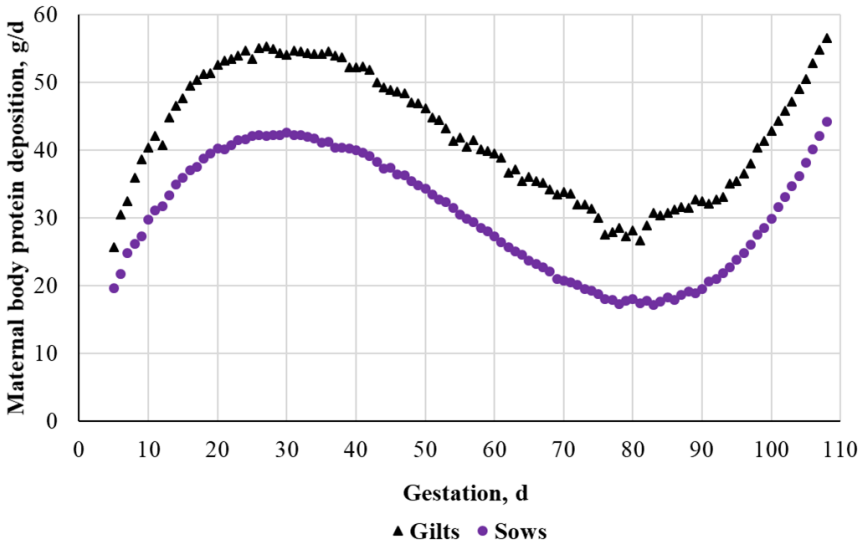

Figure 5.5 Predicted maternal protein deposition (g/d) for gilts and sows from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for the specified parity group.

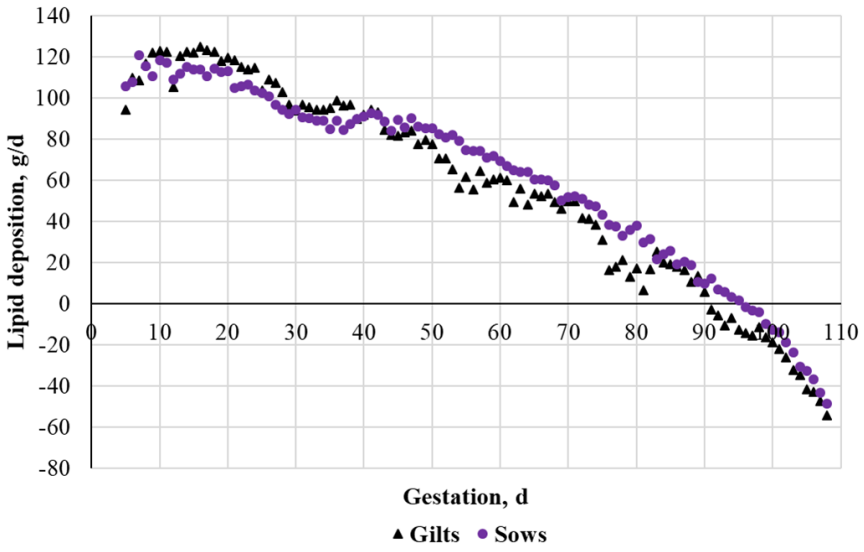

Figure 5.6 Predicted maternal lipid deposition (g/d) for gilts and sows from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for the specified parity group.

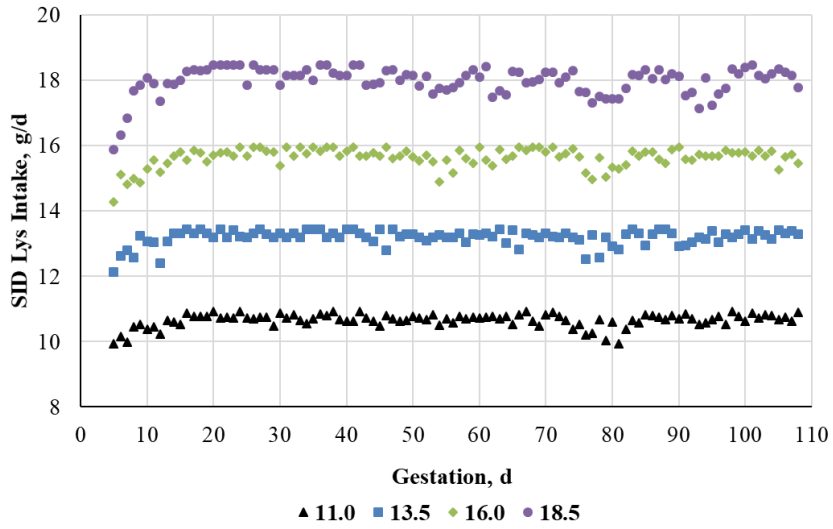

Figure 5.7 Predicted SID Lys intake (g/d) for gilts fed increasing SID Lys from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for the specified treatment (11.0, 13.5, 16.0, or 18.5 g/d SID Lys).

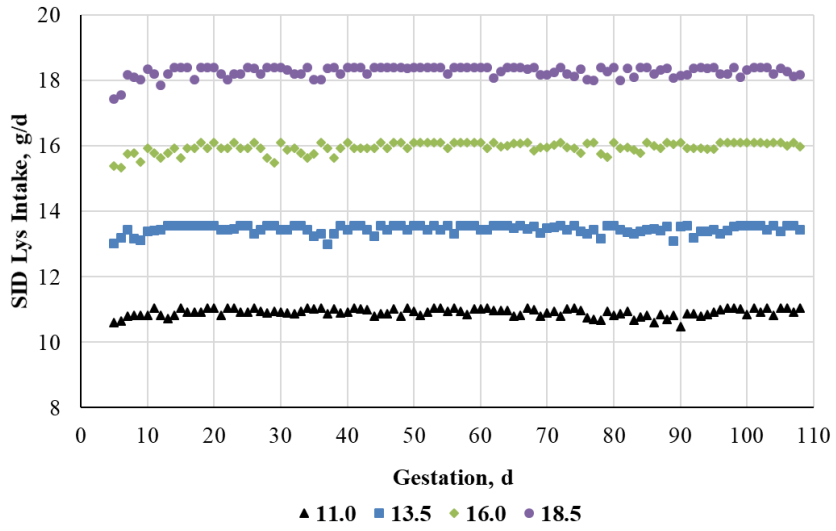

Figure 5.8 Predicted SID Lys intake (g/d) for sows fed increasing SID Lys from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for the specified treatment (11.0, 13.5, 16.0, or 18.5 g/d SID Lys).

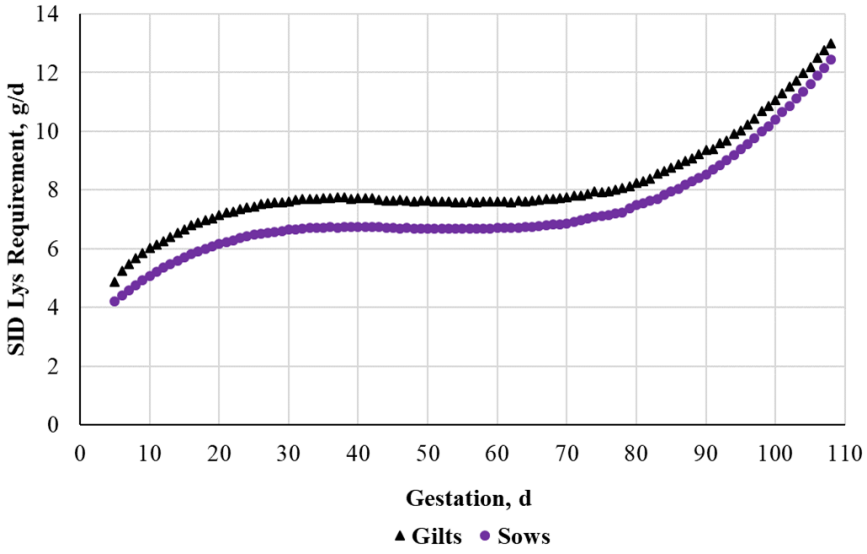

Figure 5.9 Predicted SID Lys requirements (g/d) for gilts and sows from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for the specified parity group.

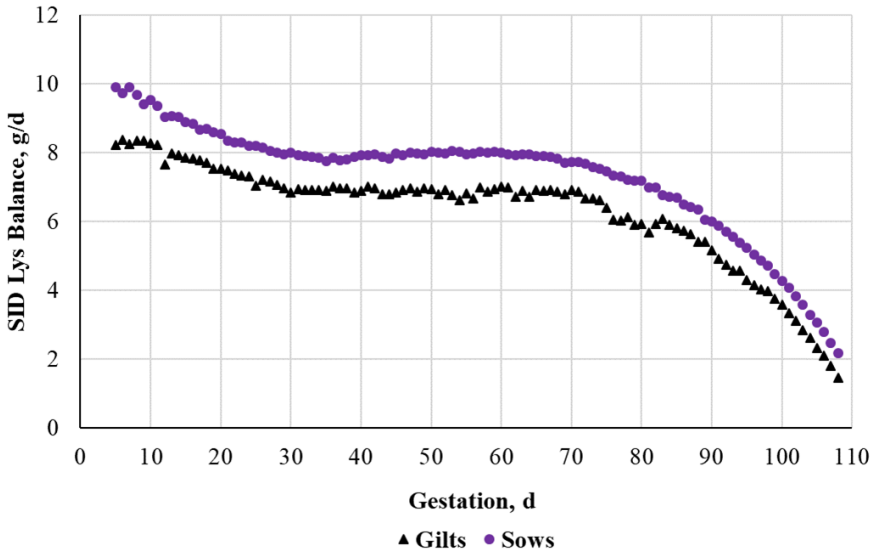

Figure 5.10 Predicted SID Lys balance (g/d) for gilts and sows from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for the specified parity group.

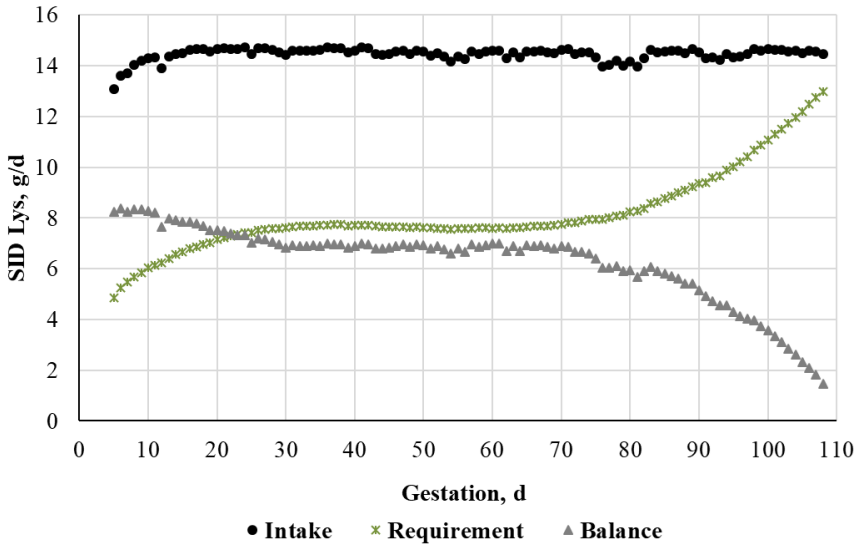

Figure 5.11 Predicted SID Lys intake, requirement, and balance (g/d) for gilts from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for all dietary treatments for the specified SID Lys variable.

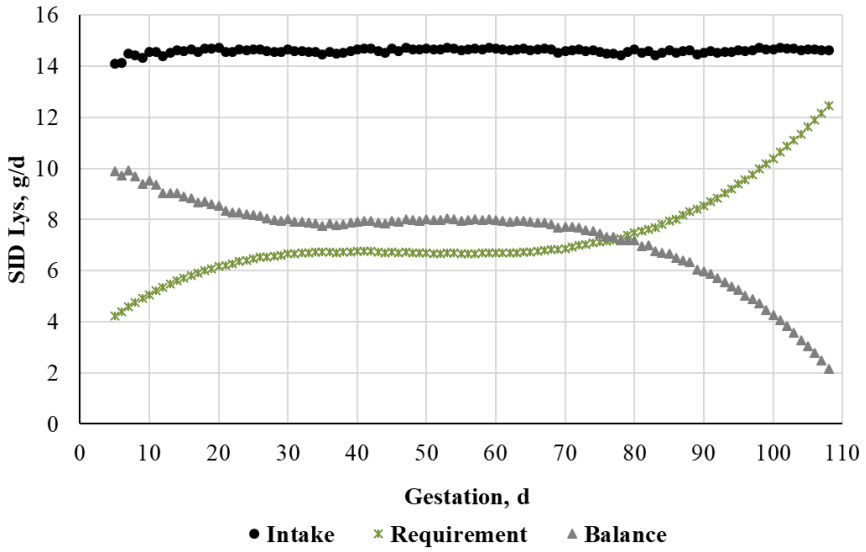

Figure 5.12 Predicted SID Lys intake, requirement, and balance (g/d) for sows from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for all dietary treatments for the specified SID Lys variable.

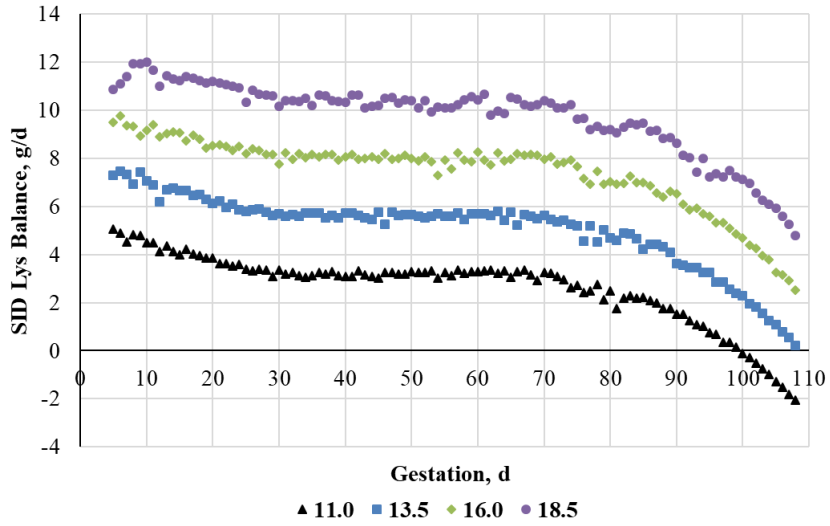

Figure 5.13 Predicted SID Lys balance (g/d) for gilts fed increasing SID Lys from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for the specified treatment (11.0, 13.5, 16.0, or 18.5 g/d SID Lys).

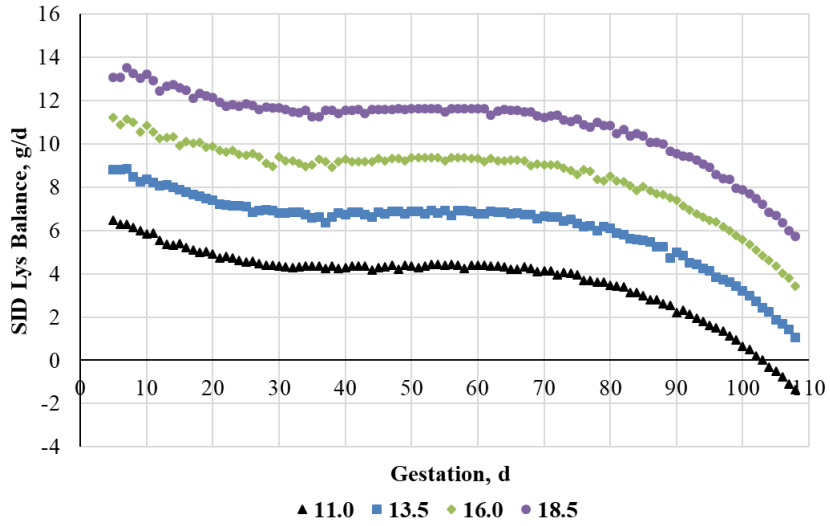

Figure 5.14 Predicted SID Lys balance (g/d) for sows fed increasing SID Lys from d 5 to 108 of gestation. For each day of gestation, the symbol represents the average for the specified treatment (11.0, 13.5, 16.0, or 18.5 g/d SID Lys).