Feeding and management strategies to enhance sow and litter performance

by

Mikayla Sue Spinler

B.S., Iowa State University, 2021
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AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Animal Science and Industry
College of Agriculture

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Abstract

A series of three experiments were conducted to evaluate the effect of precision feeding lactating sows on sow and litter performance, as described in chapter 1 and 2. In each experiment, sows were offered a high Lys diet (control), or a blend of a low and high Lys diet to target a specific Lys intake based on sow BW, parity, and litter size. In Exp. 1, Lys requirements were based on the NRC and INRA models. Sows fed the NRC and INRA treatment curves had lower Lys intake and litter growth performance compared to sows fed a high Lys diet, with no differences in sow body weight (BW) change over lactation. However, litters from sows fed the NRC treatment curve had higher litter performance compared to the INRA treatment curve. In Exp. 2, the NRC estimated Lys requirements were increased by 20% and similar litter performance was achieved when sows received a blend of the low and high Lys diet compared to the control fed sows receiving the high Lys diet, with no differences in sow BW change. Based on the results of these two experiments, a third experiment was conducted under commercial conditions. Similar to Exp. 2, sow Lys intake targets were based on the NRC model + 20%. Blend fed sows consumed less Lys than targeted due to lower ADFI than predicted, resulting in reduced litter performance compared to control fed sows. However, blend fed sows that met their target Lys intake had similar litter performance compared to control fed sows.

Chapter 3 determined the effects of two split suckling protocols on litter growth performance and mortality pre- and postweaning compared to no split suckling. Three treatments were evaluated: no split suckling (control), or one of two split suckle protocols: split suckling by birth order or body weight. Overall, the split suckling protocols evaluated in this study did not influence pig growth performance or mortality during the pre- or postweaning periods compared to no split suckling.

Chapter 4 evaluated the effect of sow lactation average daily feed intake (ADFI) on litter average daily gain (ADG) and sow BW change over lactation. Lactation ADFI for primiparous and multiparous sows were broken down into five feed intake categories with, 20% of the sows represented in each category. A regression equation was developed to predict litter ADG and sow BW change over change. The analysis indicates that litter ADG is influenced by sow BW loss and lactation feed intake. Results of the regression equations suggest that in primiparous sows, increases in ADFI were associated with a greater improvement in litter ADG compared to multiparous sows, whereas in multiparous sows, ADFI had a stronger effect in reducing BW loss over lactation compared to primiparous sows.

Chapter 5 outlines changes in the nutritional values of corn dried distillers grains with solubles (DDGS) and the development of a tool to determine the most economical feeding levels for grow-finish pigs. Changes in ethanol manufacturing practices have reduced the oil and starch content of DDGS, resulting in lower NE values for DDGS than observed in the past. Recent studies evaluating low-oil DDGS in finishing pig diets have observed decreased growth performance compared with past studies with high-oil DDGS. To support the decision-making process, a tool was developed to help producers determine the most economical levels of DDGS in finishing pig diets, factoring in feed cost savings and income over feed cost on both live and carcass weight basis with varying DDGS oil content.

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Major Professor
Dr. Jason Woodworth

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Chapter 1 - Evaluation of precision feeding standardized ileal digestible lysine and other amino acids to determine and meet the lactating sows's requirement estimate

ABSTRACT

Two experiments evaluated the effects of precision feeding standardized ileal digestible (SID) Lys during lactation. Sows were blocked by parity and allotted to treatment on d 2 of lactation. In both experiments, sow body weight (BW), backfat (BF), loin depth (LD), and estimated N excretion were evaluated as well as litter growth performance. In Exp. 1, 95 sows and litters were used. Three dietary treatments were provided using 2 diets: a low (0.25% SID Lys) and high Lys diet (1.10% SID Lys). Treatments included a control diet (1.10% SID Lys) fed throughout lactation, and NRC or INRA treatment curves. Sows fed NRC or INRA treatment curves received blends of low and high Lys diets using a computerized lactation feeder (Gestal Quattro Opti Feeder, Jyga Technologies, St-Lambert-de-Lauzon, Quebec, CA) to target a specific Lys intake each day of lactation based on NRC and INRA models for parity and litter size. In Exp. 2, 56 sows and litters were used with three treatments, a control diet (1.10% SID Lys fed throughout lactation) and either a static or dynamic blend curve. For both curve treatments, low (0.40% SID Lys) and high Lys (1.10% SID Lys) diets were blended to reach target Lys intake. The difference between the static and dynamic curves was that the dynamic curves were adjusted based on actual Lys intake and static curves were not. Lysine intake curves were based on NRC model estimates, but targets were increased by 20% to target average Lys intake of 60 g/d across parities based on results of Exp. 1. In both experiments, no differences ($P > 0.05$) in sow average daily feed intake or sow BW, BF, or LD change were observed. Sows fed

the control diets had greater Lys intake (g/day; $P < 0.05$) compared to sows fed either of the blended treatment curves. In Exp. 1, pigs from sows fed the control diet had greater ($P < 0.05$) BW at weaning and preweaning average daily gain (ADG) compared to sows fed the INRA treatment curve, with pigs from sows fed the NRC treatment curve intermediate. However, in Exp. 2, no differences ($P > 0.05$) were observed in pig weight at weaning or ADG. In both experiments, sows fed the blended treatment curves had lower ($P < 0.05$) calculated N excretion. Based on these results, for a litter size of 13.5 weaned pigs, 60 g/d of SID Lys is sufficient to maximize litter weight gain and can be achieved through blending low and high Lys diets. Precision feeding reduced N excretion compared to feeding a single diet throughout lactation.

List of Abbreviations

AA = amino acids

ADG = average daily gain

ADFI = average daily feed intake

BF = backfat

BW = bodyweight

CP = crude protein

LD = loin depth

Lys = lysine

NE = net energy

SID = standardized ileal digestible

WSI = wean to service interval

INTRODUCTION

Amino acid (AA) requirements of lactating sows have increased on a g/d basis due to increased litter size and a greater demand for milk production. Because litter size and growth rate determine Lys requirements during lactation (Tokach et al., 2019), nutrient requirements of lactating sows vary greatly. Differences in Lys requirement estimates between individual sows may be due to parity, mobilization of sow body reserves, and production goals used to determine optimum performance (King et al., 1993). Lysine requirements may vary based on whether the production goal is to maximize litter growth performance or minimize sow body weight (BW) loss. The lactating sow's standardized ileal digestible (SID) Lys requirement is heavily related to total milk protein produced (Gauthier et al., 2019) as nutrient requirements during lactation depend mainly on milk yield (NRC, 2012).

Despite the difference in requirements, sows are commonly fed a single diet during lactation to meet requirements based on the average of the whole herd, not the requirements of an individual sow. This results in either under-feeding or over-feeding nutrients to an individual sow because of differences in, parity, feed intake, litter size, and milk production. Under-feeding nutrients limits sow and litter performance while over-feeding leads to excess nutrient excretion (Gauthier et al., 2022a). Gauthier et al. (2019) reported that the SID Lys requirement of lactating sows vary greatly when using a modeling approach to estimate individual sow Lys requirements. Precision feeding can be defined as giving the right diet with the correct nutrient composition to meet a group or individual animal's needs for their stage of production and can be used to improve feed and nutrient efficiency (Pomar et al., 2009; Gaillard et al., 2021). Precision feeding allows livestock producers to feed on an individual animal level instead of the herd level and can provide an economic advantage because it prevents the wastage of excess nutrients and the associated diet cost (Wathes et al., 2008). Craig et al. (2016) utilized a phase feeding program to precision feed sows during lactation and achieved similar litter growth performance to traditional feeding strategies of a single diet during lactation. However, Gauthier et al. (2022a) observed that litters from sows fed a precision feeding strategy had decreased litter growth performance, likely due to inadequate sow Lys intake.

More research is needed to determine sow Lys requirements to maximize litter growth performance as well as practical application before precision feeding technology can be utilized in commercial swine production. There are limited studies that have specifically evaluated precision feeding Lys utilizing diet blending to meet an individual sow's requirement based on litter size, parity, BW, and feed intake. Both NRC and INRA have models that can be used to estimate a sow's Lys intake requirements for each day of lactation. The NRC and INRA models predict different Lys intake requirements when the same model inputs are used. Therefore, the objective of these studies was to determine the effects of precision feeding a blend of a low and high Lys diet to meet a sow's estimated g/d of SID Lys requirement based on the NRC or INRA model compared to feeding a single diet throughout lactation on sow and litter performance. A second objective was to determine the required Lys intake target for each sow based on parity and litter size to achieve similar litter growth performance to litters from sows fed a conventional high Lys diet. We hypothesized that precision feeding Lys could be used to achieve similar litter growth performance and decrease nitrogen excretion.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in these experiments. These trials were conducted at the Kansas State University Swine Teaching and Research Center (Manhattan, KS, USA).

Animal Facilities

Sows were moved into the farrowing house at approximately d 110 of gestation. Sows were housed in individual farrowing stalls measuring 1.8 × 2.4 m. Sows and pigs had access to a cup waterer. Creep feed was not offered throughout the trial. Feed was delivered using a computerized feeder that can blend two diets and track individual sow feed intake (Gestal Quattro Opti feeders; Jyga Technologies, St-Lambert-de-Lauzon, Quebec, CA).

Exp. 1

A total of 95 mixed parity sows (DNA 241, Columbus, NE) and litters (DNA 241 × 600) were used across four batch farrowing groups. Sows were fed a standard gestation diet until farrowing. On day 2 of lactation, litters were equalized. After equalization, diets were changed from the gestation diet to treatment diets and sows were fed 1 of 3 treatments: a single lactation diet (1.10% SID Lys) fed throughout lactation (control), or blended diets based on either NRC (2012) or INRA (2009) Lys intake estimated requirement curves. In the NRC (2012) and INRA (InraPorc, 2009) models, sow parity, BW, backfat (BF), lactation length, feed intake, litter size, and litter average daily gain (ADG) can be used to estimate Lys (g/d) requirement for each day of lactation, thus creating a precision feeding Lys curve. The INRA treatment curve has a greater requirement than the NRC treatment curve in early lactation but has a flatter curve compared to NRC, with NRC recommending greater Lys intake at the end of lactation (Figure 1-1). However, both the NRC and INRA treatment curves result in Lys intakes that are lower than typically consumed by sows in commercial production (Tokach et al., 2019).

Dietary treatments were fed from d 2 of lactation until weaning and were manufactured in meal form at the O.H. Kruse Feed Technology Innovation Center (Manhattan, KS, USA; Table 1). To create the treatment curves, two corn-soybean meal-based diets were formulated, a low

Lys (0.25% SID Lys) and a high Lys diet (1.10% SID Lys). The two diets were blended to achieve the daily SID Lys target based on either the NRC or INRA model. Sows fed the control diet were fed the 1.10% SID Lys diet with no feed blending. Sows fed the control diet were expected to have the highest Lys intake because they were given access to only the high Lys diet as opposed to sows fed the NRC or INRA treatment curves who were given a blend of the low and high Lys diets to target a specific daily Lys intake during lactation. Sows fed the NRC treatment curve were expected to have a higher overall average Lys intake compared to sows fed the INRA treatment curve due to differences in each of the models' requirement estimates and the shape of the Lys intake curves. Sows were provided ad libitum access to feed and water throughout the study.

Daily blending of the low and high Lys diets for sows fed the NRC and INRA treatment curves were created based on expected feed intake determined from feed intake data of previous farrowing groups at the Kansas State University Swine Farm. Blends of the low and high Lys diet were then adjusted throughout lactation based on actual sow feed intake to more closely meet targeted Lys intake. Individual sow feed intake was analyzed every 2 days, starting on d 5 of lactation using a 2-d rolling average to determine if a sow was meeting her daily g/d Lys target. Actual feed intake was calculated assuming 5% feed wastage. Changes in diet blends were made by either increasing or decreasing the blend of the high Lys diet by 10% to target a specific sows daily g/d of Lys requirement based on the NRC or INRA model. If a sow was above or below her target g/d Lys by 0 to 10%, no changes to the feed blends were made. Any differences above target g/d of Lys by 10% or greater resulted in a 10% decrease in the diet blend of the high Lys diet. Any differences below target g/d of Lys by 10% or greater resulted in a 10% increase in the diet blend of the high Lys diet.

Exp. 2

A total of 56 mixed parity sows (DNA 241, Columbus, NE) and litters (DNA 241 × 600) were used across two batch farrowing groups. Sows were fed a standard gestation diet until day 113 of gestation and then switched to a 1.10% SID Lys lactation diet until farrowing. Litters were equalized on d 2 of lactation. After equalization, sows were fed their treatment diets until weaning. Sows were fed 1 of 3 treatment diets, a single lactation diet fed throughout lactation (control, 1.10% SID Lys) with no feed blending, a static blend curve, or a dynamic blend curve. The static and dynamic blend curves were set to target a specific Lys intake for each day of lactation based on sow parity and litter size by blending a low and high Lys diet (Figure 1-2). Target Lys intakes were based on NRC (2012) model recommendations for a sow based on weight, parity, and litter size. NRC (2012) estimated Lys intake targets were increased by 20% to target an average of 60 g/d based on the results in Exp. 1. In Exp. 1, sows fed the NRC (2012) requirement curve model were deficient in lysine to achieve maximum performance and had decreased litter growth performance compared to litters from sows fed the 1.10% SID Lys diet throughout lactation. However, litters from sows fed the NRC curve model had better growth performance compared to sows on the INRA curve model, thus we selected the NRC (2012) model for Exp. 2.

Diets were corn-soybean meal-based fed in meal form and were manufactured at the O.H. Kruse Feed Technology Innovation Center (Manhattan, KS, USA; Table 1). Dietary treatments for sows fed the blend treatment curves were formed by blending a low Lys diet (0.40% SID Lys) and the control high Lys diet (1.10% SID Lys) to reach target SID Lys intake. Target Lys intake was the same for each of the blend treatment curves. Sows fed the control diet were fed the 1.10% SID high Lys diet throughout lactation with no feed blending and were expected to have the highest SID Lys intake because they were fed only the high Lys diet. Sows were given ad libitum access to feed and water.

For both blend treatment curves, daily blends of the low and high Lys diets were made based on expected feed intake determined from feed intake data of previous farrowing groups at the Kansas State University Swine Farm. Based on expected feed intake, the correct blend of the low and high Lys diet needed to reach target SID Lys intake predicted by the NRC model was determined. The daily blend of the low and high Lys diet for the static and dynamic blend curve was the same at the start of the trial to target an average SID Lys intake of 60 g/d across parities throughout lactation. However, for sows on the dynamic blend treatment, the feed curve blend of the low and high Lys diet was adjusted every 2 days starting on d 5 of lactation based on actual sow feed intake to meet the target Lys intake more closely. For the static blend treatment curve, the blend of the low and high Lys diet was determined prior to the study starting and was not adjusted during the study.

Sow and Litter Performance

For both Exp. 1 and 2, sow BW, caliper score, BF, and loin depth (LD) measurements were taken at entry into the farrowing house. Caliper score (Knauer and Baitinger, 2015) was taken at the last rib. Backfat and LD measurements were taken 6 cm from the midline on the right side of each sow at the 3rd rib forward from the last rib, using an IBEX Pro ultrasound machine (E.I. Medical Imaging, Loveland, CO). Sow weight was recorded within 24 h after farrowing. At weaning, sow BW, caliper, BF, and LD were recorded again. The wean-to-service interval (WSI) for each sow was recorded for sows that remained in the herd after farrowing.

During lactation, sow feed intake was recorded using the volumetric feeders and feed intake was confirmed by recording the weight of daily feed additions and the weight of any feed removed from the feed pan. Sow average daily feed intake (ADFI) was calculated by taking feed disappearance minus 5% to account for feed wastage. Each week during lactation, 5 random feeders were calibrated and the average calibration value for each diet was used. The calibration value represented the weight of feed dropped in 5 turns of the auger in the feeder.

On d 9 of lactation and at weaning, 10 mL of blood was collected from all sows from the jugular vein using a 1 ½ in x 18 G needle and a Monoject blood collection tube (Covidien, Minneapolis, MN, USA) after a 6-hr fasting period. Whole blood was centrifuged and serum was collected and stored at -20°C until analysis. Serum was analyzed for urea N concentration using a Urea Nitrogen Colorimetric Detection Kit (Arbor Assays, Ann Arbor, MI, USA).

In Exp. 1 only, urine samples were collected using free-catch during the middle of urination on d 9 of lactation and at weaning. Approximately 45 mL of urine was collected and immediately mixed with 0.5 mL of HCl to prevent ammonia volatilization. Samples were stored at -20°C until analysis. Samples were analyzed for creatinine concentration (Creatinine Colorimetric Assay Kit, Cayman Chemical, Ann Arbor, MI, USA).

Nitrogen balance was calculated to determine differences in N utilization among treatments by determining N intake (N content in feed × feed intake) and estimating N content in milk and N mobilized from body reserves. Nitrogen content in milk and N mobilized from body reserves were calculated based on equations in the NRC (2012). Total N excreted was calculated by taking N intake plus N from body reserves minus N in milk.

Litter weight and size were recorded on d 2 of lactation after litters were equalized to 12 to 16 pigs per sow with a similar litter size across treatments and within sow groups. Pre-weaning mortality was calculated by taking the number of pigs weaned divided by the litter size on d 2 of lactation.

Diet Analysis

Complete feed samples were analyzed for DM, CP, and complete AA analysis (AOAC, 2006; Ajinomoto Health & Nutrition North America, Inc., Eddyville, IA, USA).

Statistical Analysis

Performance data were analyzed using the lmer function of R software, version 1.4.171, as a randomized complete block design. Sow and litter were considered the experimental unit. Treatment was a fixed effect and block (sow parity) and group were considered random effects. An analysis of variance was performed and pairwise comparisons were used to detect differences among treatments. Pre-weaning mortality and percentage of N excreted were analyzed using a binomial distribution. Serum urea N and urinary creatinine were analyzed as a repeated measure using the lmer function of R software with treatment, sample timepoint, and their interaction included as fixed effects. Plate and group were included as a random effect. Results are considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

RESULTS

Exp. 1

Over the entire lactation period (18.8 d , standard deviation = 1.2`) Lys intake was 102% of the targeted g/d of Lys intake for sows fed the NRC treatment curve and 98% of the targeted Lys intake for sows fed the INRA treatment curve. These results indicate that the blending strategy with adjustments made every other day was successful in meeting the targeted Lys intake throughout lactation.

There were no differences among treatments in sow BW at entry, farrowing, or weaning as well as BW changes ($P > 0.05$; Table 2) at any time point. No differences in sow BF, LD, and caliper score were observed at entry, weaning, or changes from entry to weaning ($P > 0.05$).

A tendency was observed ($P = 0.093$) where sows fed the NRC treatment curve had greater ADFI from d 2 to weaning than sows fed the control diet or INRA curve. As expected, sows fed the high Lys diet with no feed blending had greater ($P < 0.05$) average Lys intake compared to sows fed either the NRC or INRA treatment curves. Sows fed the NRC treatment curve had greater ($P < 0.05$) Lys intake than sows fed the INRA treatment curve, which was expected based on the model assumptions because the INRA modeled Lys intake is lower than the NRC model. Although a tendency ($P < 0.092$) for differences in WSI was observed for sows fed the NRC treatment curve to have a higher WSI, values only ranged from 4.1 to 4.4 d.

Nitrogen balance was calculated for each sow based on equations in NRC (2012). As expected, sows fed the control treatment had the highest ($P < 0.05$) N intake followed by sows fed the NRC treatment curve, with sows fed the INRA treatment curve having the lowest. Sows fed the control treatment had greater ($P < 0.05$) milk N output compared to sows fed the INRA treatment curve, with sows fed the NRC treatment curve intermediate. No differences ($P > 0.05$) in N mobilization from body reserves were observed between treatments. Calculated N excretion (g/d) and percentage of N excreted was greatest ($P < 0.05$) for sows fed the control treatment followed by sows fed the NRC treatment curve with sows fed the INRA treatment curve lowest ($P < 0.05$).

No differences ($P > 0.05$) in litter size were observed at d 2, 9, or weaning (Table 3). Litter weight was similar ($P > 0.05$) between all treatments at d 2. However, at d 9 and weaning, litters from sows fed the control treatment had greater ($P < 0.05$) litter weight than litters from sows fed the NRC or INRA treatment curves. There were no differences ($P > 0.05$) observed for pig BW at d 2. At d 9, a tendency ($P = 0.085$) for differences among treatments was observed, but at weaning, pigs from sows fed the control treatment had greater ($P < 0.05$) BW compared to pigs from sows fed the INRA treatment curves, with pigs from sows fed the NRC treatment curve intermediate. Litters and pigs from sows fed the control treatment had a greater ($P < 0.05$) ADG compared to litters and pigs from sows fed the INRA treatment curve with those fed the NRC treatment curve intermediate. Sows fed the control treatment had greater ($P > 0.05$) Lys intake per kg of litter weight gain than sows fed the NRC treatment curve with sows on the INRA treatment having the lowest Lys intake per kg of litter weight gain. No differences ($P > 0.05$) were observed in preweaning mortality.

There was no interaction ($P = 0.786$) between day and treatment for serum urea N (Table 4). Sows fed the control treatment had higher ($P < 0.05$) serum urea N concentration compared to sows fed the NRC and INRA treatment curves and no differences were observed between sows fed either the NRC or INRA treatment curves. There were no differences ($P > 0.05$) in urinary creatinine concentration among treatments.

Exp. 2

Over the lactation period, actual SID Lys intake for sows fed the static blend treatment curve was 97% of the targeted intake and sows fed the dynamic blend treatment curve was 96% of the targeted Lys intake. No differences were observed in sow BW at entry, after farrowing, and weaning, caliper score, BF, or LD at entry or weaning ($P > 0.05$; Table 5). There were no differences in ADFI among treatments throughout the trial ($P > 0.05$), although sows fed either of the blend treatments had a numerically greater feed intake compared to sows fed the control treatment. As expected, sows fed the control treatment had the greatest average Lys intake because they were fed only the high Lys diet throughout lactation ($P < 0.05$). Sow Lys intake was similar between the static blend curve and dynamic blend curve. A tendency for differences ($P = 0.092$) in WSI was observed with sows fed the static blend having a higher WSI compared to the control and dynamic blend. However, WSI only varied from 4.1 to 4.4 d. Differences in WSI interval were not expected because no differences in ADFI or BW loss during lactation were observed.

Sows fed the control diet had a higher N intake compared to sows fed either of the blend treatment curves ($P < 0.05$). Sows fed the static blend treatment curve had higher N intake than sows fed the dynamic blend treatment curve ($P < 0.05$); however, there was only a 1.7 g difference. No differences were observed among treatments for N in milk or N from body reserves ($P > 0.05$) because no changes in litter gain or sow body tissue mobilization were observed. Thus, sows fed the control diet had greater ($P < 0.05$) calculated N excretion, and therefore lower N utilization compared to sows fed either of the blend treatment curves with the two blend treatment curves having similar ($P > 0.05$) N excretion. Sows fed the control diet had the highest ($P < 0.05$) percentage of N excreted relative to intake, followed by sows fed the static blend curve, with sows fed the dynamic blend curve the lowest.

There were no differences in litter size among treatments at d 0, 2, 9, or weaning ($P > 0.05$; Table 6). Litter and mean pig BW as well as litter and pig ADG were not different among treatments at any time point during the study ($P > 0.05$). Sows fed the control treatment had higher Lys intake per kg of litter gain ($P < 0.05$) compared to sows fed either blend treatment curve with no differences among sows fed either of the blended treatment curves ($P < 0.05$). No differences ($P = 0.444$) were observed in preweaning mortality among treatments.

There was no interaction ($P = 0.786$) between day and treatment for serum urea N (Table 7). Sows fed the control diet had higher ($P < 0.05$) serum urea N concentration compared to sows fed both blend treatment curves and no differences were observed between sows fed either blend treatment curves.

DISCUSSION

Precision feeding in swine has been studied more extensively in finishing pigs. A review by Pomar and Remus (2019) summarized that precision feeding in finishing pigs can reduce production cost by 8% and N and P excretion by 40%. Andretta et al. (2014) determined that precision feeding can be used to achieve similar growth performance to traditional feeding strategies while decreasing N and P excretion. Numerous other studies and reviews have found that precision feeding can reduce nutrient excretion in grow-finish pigs (Andretta et al., 2016; Remus et al., 2020; 2021) and reduce diet cost (Pomar et al., 2010; 2021).

Gaillard et al. (2020) compared precision feeding vs conventional feeding strategies in gestating gilts using a modeling approach and estimated that precision feeding reduced feed cost by 3.6% per sow and reduced N and P excretion. Gaillard and Dourmad (2022) then applied the model in an experimental trial and observed decreased feed cost, an 18.5% reduction in N excretion, an 8% reduction in P excretion, and no differences in litter size and weight at farrowing. When precision feeding gestating sows Lys and energy, Hansen et al. (2021) observed improved growth performance in the nursery for offspring from precision fed sows but no differences in the finisher phase.

Gauthier et al. (2022a) conducted a study looking at the effect of precision feeding sows and utilized a decision support system that automatically determined the blend of a low and high AA and mineral diet to meet an individual sow's specific requirement based on sow feed intake and pig ADG. The authors predicted pig ADG based on sow parity and litter size to estimate the protein and energy content put into the milk, calculated each sows estimated nutrient requirement, and estimated a sow's feed intake for each day based on the previous day's feed intake for that sow. Based on these assumptions, a computer system automatically determined the blend of the 2 diets. This was compared to conventional feeding strategies of feeding a single diet during lactation. A 3% decrease in pig weaning weight was observed for sows fed the precision feeding treatment, similar to the 5% reduction observed in pig weight at weaning in Exp. 1 for sows fed the NRC treatment curve. The authors attributed this reduction in pig weaning weight to insufficient AA intake, which is likely the cause of the lower litter growth performance in Exp. 1.

If sows are not meeting their nutritional requirements through feed consumption, they will mobilize lipid and protein tissue from body reserves to meet their nutrient needs. Numerous studies have observed that increasing dietary Lys concentration leads to reduced body reserve mobilization (Touchette et al., 1998; Xue et al., 2012; Gourley et al., 2017; Hojgaard et al., 2019). Gourley et al. (2017) observed that increasing dietary Lys intake from 48.8 to 70.6 g/d decreased protein catabolism. Touchette et al. (1998) observed no differences in sow BF loss as dietary digestible Lys increased from 27 to 48 g/d but did observe a reduction in sow BW and LD loss. In both Exp. 1 and 2, no differences in BW composition changes over lactation were found, indicating that adequate Lys was consumed to minimize body weight loss throughout lactation. It would also suggest that even though sows on the blend diets were consuming less Lys and had lower litter growth performance in Exp. 1, they were not mobilizing more body protein compared to control sows for milk production to make up for lower dietary Lys intake. The lack of difference in body tissue mobilization suggests that modern sows may be utilizing dietary nutrients and body reserves differently than observed in past research.

Excess dietary N will increase N excretion, resulting in a negative environmental impact. Pomar and Remus (2019) estimated that for every 1% reduction in protein intake, N excretion can be decreased by 1.5%. Everts and Dekker, (1994) observed that only 40% of dietary N was utilized by both pregnant and lactating sows and 60% excreted, which is in line with the results observed in control sows in both experiments herein, with an estimated N excretion rate of 66.6% in Exp. 1 and 63.9% in Exp. 2. However, when dietary N intake was decreased in sows on the blend treatment curves, dietary N excretion was decreased. Gauthier et al. (2022) observed a 28% reduction in N excretion when sows were provided blended diets to meet individual nutrient requirements vs conventional feeding strategies. In Exp. 1, estimated N excretion was decreased by 20.1% for the NRC treatment blend and 36.5% for the INRA blend treatment compared to the control treatment. In Exp. 2, a 31.3% reduction was observed for the static curve treatment and a 37.9% reduction for the dynamic blend compared to the control treatment. This would indicate that precision feeding sows can decrease N excretion, having a positive environmental impact.

Sows fed the blend treatments in both Exp. 1 and 2 had lower Lys intake per kg of litter gain compared to control fed sows. Improvements in Lys utilization seem to be related to decreased Lys intake during lactation for sows on the blend curves, with sows fed the blend treatment being more efficient at utilizing Lys toward litter gain than sow fed the control treatments. The results of Exp. 2 indicate that sows fed either of the blend treatment curves were able to wean pigs that had similar growth performance compared to pigs from sows fed the control treatment, even though they had decreased Lys intake throughout lactation. Sows fed the control treatment were likely overfed Lys during the study.

Blood urea N is a waste product from the breakdown of amino acids that are not used and reflects dietary N intake and utilization (Whang and Easter, 2000). It can also be used to indicate protein mobilization from body reserves (Coma et al., 1996) and is directly related to protein intake and inversely related to protein quality (Orok and Bowland, 1975). In both Exp. 1 and 2, sows fed the control treatment had higher serum urea N concentrations at d 9 and weaning, indicating that control sows were consuming more protein than required for maintenance and milk production. Because no differences in sow body composition were observed among treatments in both experiments, the differences in serum urea N concentration are reflective of differences in circulating N due to higher N intake for control sows. Higher serum urea N levels are correlated with poorer feed efficiency (Whang and Easter, 2000) which is reflective of the results observed for Lys efficiency with control fed sows having a higher Lys intake per kg of gain and higher serum urea N levels. This could indicate that the current practice of feeding one diet throughout lactation provides amino acids in excess of the sows' needs and therefore precision feeding strategies could help provide a more efficient and sustainable solution for feeding lactating sows.

Creatinine is used as a marker for body protein catabolism (Gourley et al., 2020). A study by Yang et al. (2009) observed higher circulating levels of creatinine in sows fed a 1.0% total Lys diet compared to a 1.3% total Lys diet. This would indicate that sows fed the lower Lys diet had greater muscle breakdown because they were deficient in Lys. In the current study, no differences in urinary creatinine concentration were observed, indicating that treatment did not influence body protein catabolism, which was further confirmed by no changes in LD during lactation. This is an interesting finding that warrants additional research because the lower litter weight gain of sows fed the NRC and INRA treatments would indicate that intake of Lys, and other amino acids, was not sufficient to maximize litter performance. Why sows fed these treatments did not mobilize more body protein in order to overcome the amino acid deficiency that resulted in poorer litter weight gain is unknown.

Differences in litter growth performance among treatments in Exp. 1 indicate that sows fed the NRC and INRA treatment curves were deficient in Lys to maximize litter growth performance. Based on the results in Exp. 1, the NRC Lys intake recommended target was increased by 20% for Exp. 2. In Exp. 2, when sows fed the blend treatments reached an average SID Lys intake of 60 g/d, they had similar litter growth performance compared to litters from control sows. This would indicate that an average SID Lys intake of at least 60 g/d is needed to maximize litter growth performance for a litter size of 13.5 at weaning. A regression equation developed by Greiner et al. (2020) predicted that the Lys requirement for gilts to be 64 g/d and 73 g/d for parity 3+ sows to achieve a litter growth rate of 2.16 and 2.64 kg/d. To achieve the same litter growth rate both the NRC and INRA models estimated a lower Lys requirement that was used as the target Lys intake in Exp.1. The additional Lys intake that the control sows consumed was not used toward additional litter growth or sow BW gain compared to sows fed the blend treatments. In Exp. 1, the sows were likely deficient in Lys, resulting in lower litter growth performance. Control fed sows were likely over fed Lys in both Exp. 1 and 2 because blend and control fed sows had similar litter growth performance in Exp. 2, even though blend fed sows had lower Lys intake. Additionally, because sows fed the control treatment in Exp. 2 consumed more N and had a higher estimated N excretion, but not greater litter growth performance, they were meeting the N intake requirements to maximize litter growth requirement and any additional N consumed was being excreted as waste.

Both the NRC and INRA models estimated Lys requirement increased as litter size increased for parity 1, 2, and 3+. Average Lys intake requirements increased by 1.8, 2.3, and 2.4 g/d for the INRA model and 1.7, 2.2, and 2.2 g/d for the NRC model as litter size increased by 1 pig for parity 1, 2 and 3+ sows respectively. Both models underestimated Lys intake needed to maximize litter growth performance for each parity and litter size combination. The 20% increase in the NRC suggested curve applied in Exp. 2 led to similar litter growth performance.

The Lys requirement for a lactating sow will change based on whether the production goal is to minimize sow BW loss, maximize litter growth performance, or decrease feed cost. Touchette et al. (1998) observed that sow BW loss was minimized at a digestible Lys intake of 45 and 48 g/d. King et al. (1993) suggested that Lys intake needed to minimize BW loss is higher than Lys intake needed to support lactation because sows will mobilize body reserves to support lactation, but this was not observed in the current study. Hojgaard et al. (2019) determined that SID Lys intake of 52.5 g/d was needed to maximize litter growth and 58.1 g/d was needed to minimize sow BW loss. The results of this study and others demonstrate that the Lys requirements of sows in lactation will change based on production goals, but overall, literature would suggest that estimations of lactating sows nutrient requirements are predominantly based on milk production (Noblet and Etienne, 1989; NRC, 2012; Gauthier et al., 2019). As indicated by the results of Exp. 1, the NRC and INRA models estimated Lys requirements on a g/d basis are insufficient to maximize litter growth performance. A potential explanation for this is that modern sows are producing more milk or mobilizing less body protein, therefore having a higher g/d Lys requirement than sows used to develop these models.

The results of Exp. 2 indicate that adjusting the blend of the two diets for sows fed the dynamic blend treatment did not result in average Lys intake being closer to the target vs. the static blend curve that was not adjusted throughout lactation. Expected feed intake based on past farrowing groups in the same facility was close to actual feed intake resulting in similar Lys intake between the dynamic and static blend curves. This is an important finding because implementation of this research to commercial farms will be easier if dynamic adjustments to feeding curves by farm staff is not needed to prevent the under-feeding of nutrients. However, accurate expected feed intake estimates are needed to reach target Lys if dynamic adjustments of dietary blends are not done based on actual feed intake.

An important component of precision feeding and a current challenge is accurately predicting nutrient requirements of lactating sows. Gauthier et al. (2021; 2022b) compiled large databases to obtain reliable predictions of sow and litter performance. For precision feeding technology to be effective, it is important to have accurate information to predict sow requirements and feed intake to avoid underfeeding nutrients during lactation and having a negative impact on milk production and litter growth performance. Technology should be utilized to automatically adjust diet blends to meet the sow's requirement based on actual feed intake and litter growth vs predicted values.

There is large variability between Lys requirements for sows during lactation. Precision feeding can be used to meet an individual sow's requirement and avoid the under or over-feeding of nutrients compared to traditional feeding strategies of a single diet during lactation regardless of parity or litter size. The results of these studies indicate that a low and high Lys diet can be blended to target a specific Lys intake target for an individual sow and decrease N excretion while maintaining similar pig growth performance compared to feeding a standard high Lys diet. This data would also suggest that SID Lys intake of approximately 60 g/d is sufficient to maximize litter weight gain with a litter size of approximately 13.5 weaned pigs. However, more research is needed to accurately predict an individual sow's requirement on a daily basis and determine how affordable technology can be used to automatically adjust diet blends based on actual sow feed intake and milk production

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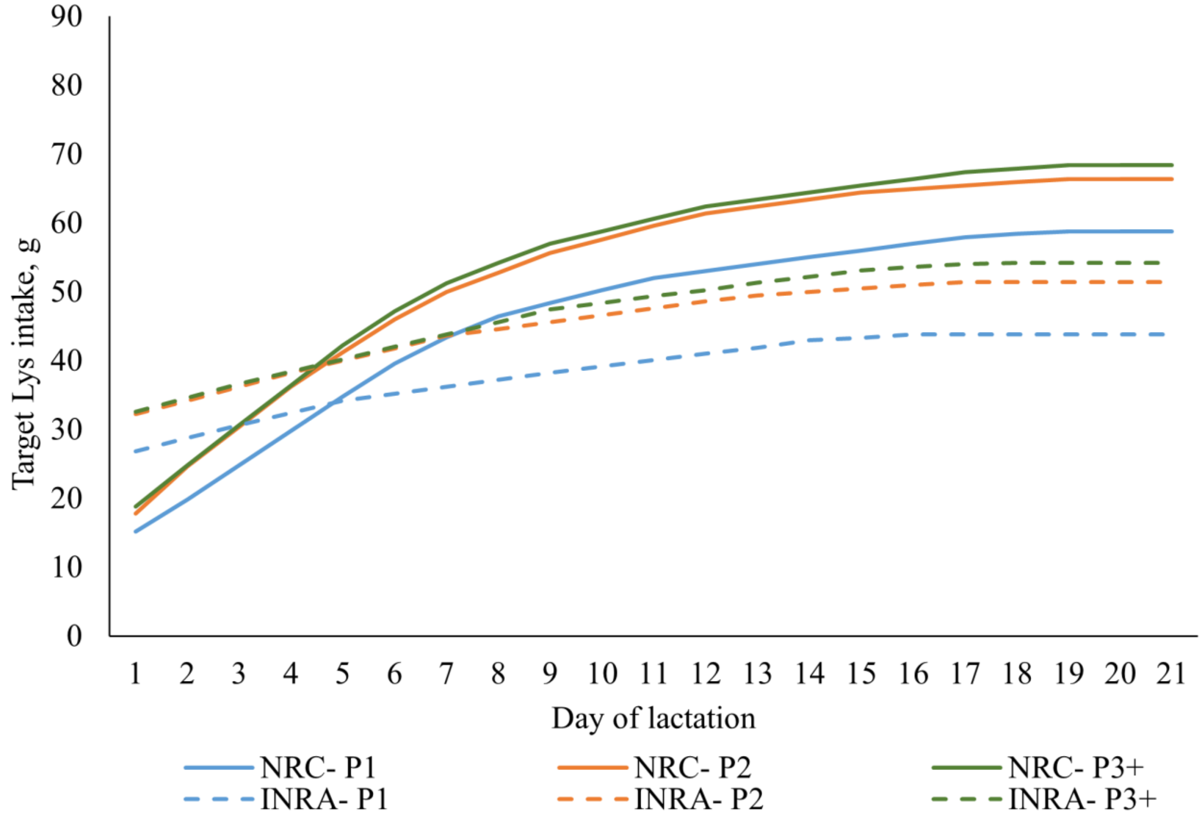

Figure 1-1. Target Lys intake by parity (P) with a litter size of 14 for NRC and INRA treatment curves in Exp. 1.

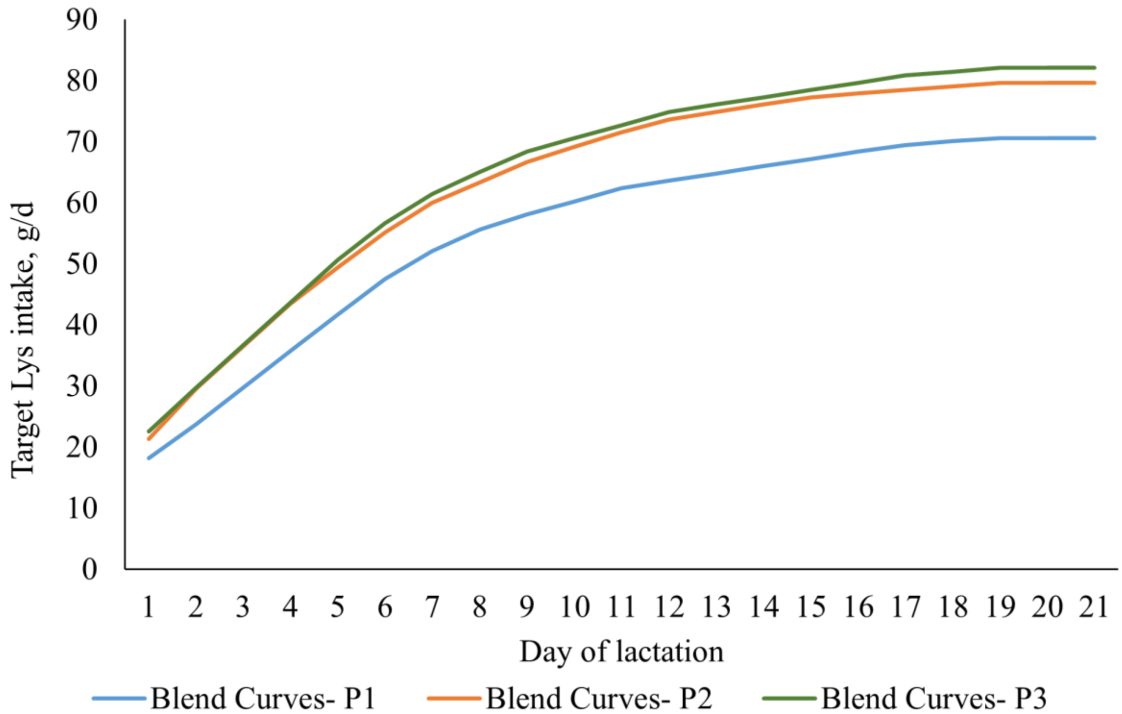

Figure 1-2. Target Lys intake by parity (P) with a litter size of 14 for the static and dynamic treatment curves in Exp. 2.

Table 1.1. Composition of lactation diet (as-fed basis)[1]

Item	Low Lys- Exp. 1	Low Lys- Exp. 2	High Lys- Exp. 1 and 2
Ingredient, %			
Corn	91.05	84.96	63.40
Soybean meal, 46.5% CP	3.20	9.49	30.70
Corn oil	2.00	2.00	2.00
Calcium carbonate	1.20	1.30	1.30
Monocalcium P,21% P	1.40	1.25	1.00
Sodium chloride	0.50	0.50	0.50
L-Lys-HCl	-	-	0.25
DL-Met	-	-	0.07
L-Thr	-	-	0.12
L-Trp	-	-	0.01
L-Val	-	-	0.15
Vitamin and trace mineral premix[2]	0.50	0.50	0.50
Total	100	100	100
Calculated Analysis			
SID amino acids, %			
Lys	0.25	0.40	1.10
Ile:Lys	106	90	62
Leu:Lys	342	247	130
Met:Lys	62	45	31
Met & Cys:Lys	125	92	56
Thr:Lys	98	81	65
Trp:Lys	25	24	20
Val:Lys	138	112	85
His:Lys	85	66	40
Total Lys, %	0.32	0.49	1.24
NE, kcal/kg	2,650	2,619	2,507
SID Lys:NE, g/Mcal	0.94	1.53	4.39
CP, %	9.0	11.5	20.4
Ca, %	0.86	0.83	0.85
P, %	0.56	0.56	0.60
STTD P, %[3]	0.47	0.47	0.47
Analyzed values			
CP, %	9.1	10.0	19.4
Total Lys, %	0.34	0.44	1.17

[1]Feed was manufactured by a commercial feed mill (Hubbard Feeds: Beloit, KS, USA) for Exp. 1 and Kansas State University O.H. Kruse Feed Technology Innovation Center (Manhattan, KS, USA) for Exp. 2.

[2]Ronozyme HiPhos GT 2700 (DSM Nutritional Products, Parsippany, NJ) provided 396,007 FYT/kg and a STTD P release of 0.12%. Provided per kg of premix: 1,653,468 IU vitamin A; 330,693 IU vitamin D; 2,722 IU vitamin E; 661 mg vitamin K; 6.6 mg

vitamin B12; 9,921 mg niacin; 5,512 mg pantothenic acid; 1,653 mg riboflavin; 44 mg biotin; 441 mg folic acid; 198 mg pyridoxine; 110,231 mg choline; 9,921 mg carnitine; 39.7 mg Cr from Cr picolinate; 22.1 g Zn from Zn sulfate; 22.1 g Fe from ferrous sulfate; 6.6 g Mn from manganese oxide; 3.3 g Cu from copper sulfate; 59.5 g I from Ca iodate; 59.5 mg Se from sodium selenite.

[3]Standardized total tract digestibility

Table 1.2. The effect of precision feeding SID lysine to lactating sows on sow performance, Exp. 1[1]

Item	Control[2]	NRC	INRA	SEM	$P =$
Sows, n	31	32	32		
Parity	2.0	2.0	2.0	0.35	0.985
Lactation length, d	19.1	18.7	18.6	0.25	0.375
Sow BW, kg					
Entry	255.0	258.7	261.6	9.26	0.389
Farrow	234.3	237.2	238.1	8.97	0.697
Wean	224.2	227.5	227.9	8.44	0.691
Sow BW change, kg					
Entry to farrow	-20.0	-20.6	-22.0	2.49	0.589
Farrow to wean	-10.6	-9.93	-10.6	2.42	0.954
Entry to wean	-29.9	-30.7	-32.7	3.41	0.590
Sow back fat, mm					
Entry	15.2	15.0	14.6	0.47	0.655
Wean	13.9	14.4	13.6	0.46	0.412
Change (entry to wean)	-1.3	-0.6	-1.0	0.30	0.248
Sow caliper score					
Entry	16.4	16.6	16.2	0.34	0.494
Wean	15.2	15.4	14.8	0.39	0.414
Change (entry to wean)	-1.2	-1.2	-1.3	0.32	0.841
Sow loin depth, mm					
Entry	47.9	47.3	47.6	0.85	0.830
Wean	46.8	46.4	45.9	0.77	0.587
Change (entry to wean)	-1.1	-0.8	-1.5	0.57	0.673
Sow ADFI, kg					
d 2 to 9	5.1	5.3	4.8	0.31	0.122
d 9 to wean	7.9	8.3	7.8	0.30	0.270
d 2 to wean	6.7	7.0	6.6	0.27	0.093
Lys intake, g/d	76.7[a]	53.1[b]	42.8[c]	2.22	< 0.001
Wean-to-service interval, d	4.2	4.4	4.1	0.14	0.092
N balance, g/d					
Intake[3]	231.1[a]	155.8[b]	114.7[c]	14.05	< 0.001
In milk[4]	90.0[a]	84.2[ab]	80.4[b]	2.47	0.004
From body reserves[5]	11.8	12.6	12.2	3.37	0.975
Excreted[6]	154.2[a]	84.2[b]	48.0[c]	12.51	< 0.001
Excreted, %[7]	66.6[a]	53.2[b]	42.3[c]	2.28	< 0.001

[,a, b, c] Means in the same row that do not have a common superscript differ ($P < 0.05$).

[1]A total of 95 mixed-parity sows (Line 241, DNA, Columbus NE) and litters were used from day 2 of lactation (the day after farrowing) until weaning.

[2]Sows were allotted to 1 of 3 treatments on d 2 of lactation. A control high Lys diet (1.10% SID Lys) or a blend of a low (0.25% SID Lys) and high Lys diet (1.10% SID Lys) to target specific Lys requirement estimates based on NRC or INRA models.

[3]Calculated by N content in feed × feed intake.

[4]Calculated from mean litter gain and litter size according to equations in NRC (2012).

[5]Calculated from empty sow body weight and backfat according to equations in NRC (2012).

[6]Calculated from: (N intake + N from body reserves - N in milk).

[7]Calculated from: (N intake + N from body reserves - N in milk)/ N intake.

Table 1.3. The effect of precision feeding SID lysine to lactating sows on litter performance, Exp. 1[1]

Item	Control[2]	NRC	INRA	SEM	$P =$
Litter characteristics					
Litter size, n					
d 0	13.9	15.3	14.5	0.69	0.330
d 2	14.3	14.2	14.3	0.65	0.985
d 9	14.1	13.7	13.6	0.59	0.692
Wean	13.8	13.5	13.5	0.65	0.892
Litter weight, kg					
d 2	23.7	23.4	23.3	0.59	0.841
d 9	46.4[a]	41.8[b]	41.9[b]	1.17	0.004
Wean	80.1[a]	74.8[b]	72.6[b]	1.77	0.003
Mean pig BW, kg					
d 2	1.7	1.7	1.6	0.05	0.912
d 9	3.3	3.1	3.1	0.11	0.085
Wean	5.9[a]	5.6[ab]	5.4[b]	0.15	0.005
Litter ADG d 2 to wean, kg	3.0[a]	2.8[ab]	2.6[b]	0.08	0.003
Pig ADG d 2 to wean, g	216.4[a]	206.1[ab]	196.1[b]	6.39	0.004
Lys intake, g/kg of litter gain	23.5[a]	17.7[b]	15.4[c]	0.77	< 0.001
Preweaning mortality, %					
d 2 to wean	3.8	5.0	5.7	1.2	0.395

[a,b,c] Means in the same row that do not have a common superscript differ ($P < 0.05$).

[1]A total of 95 mixed-parity sows (Line 241, DNA, Columbus NE) and litters were used from day 2 of lactation until weaning.

[2]Sows were allotted to 1 of 3 treatments on d 2 of lactation. A control high Lys diet (1.10% SID Lys) or a blend of a low (0.25% SID Lys) and high Lys diet (1.10% SID Lys) to target specific Lys requirement estimates based on NRC or INRA models.

Table 1.4. The effect of precision feeding SID lysine to lactating on serum urea nitrogen and urine creatinine concentration, Exp. 1[1]

					P =		
Item	Control[2]	NRC	INRA	SEM	Treatment × day	Treatment	Day
Serum urea N concentration, mg/dL							
Day 9[3]	19.8[a]	14.0[b]	14.4[b]				
Weaning	19.7[a]	14.4[b]	14.0[b]	0.90	0.786	< 0.001	0.855
Urine creatinine concentration, mg/dL							
Day 9	117.9	112.4	136.9				
Weaning	117.2	112.6	139.5	18.35	0.982	0.263	0.953

[a,b] Means in the same row that do not have a common superscript differ ($P < 0.05$).

[1]A total of 95 mixed-parity sows (Line 241, DNA, Columbus NE) and litters were used from day 2 of lactation until weaning.

[2]Sows were allotted to 1 of 3 treatments on d 2 of lactation. A control high Lys diet (1.10% SID Lys) or a blend of a low (0.25% SID Lys) and high Lys diet (1.10% SID Lys) to target specific Lys requirement estimate based on NRC or INRA models.

[3]Blood and urine samples were taken on d 9 of lactation and at weaning to measure serum urea nitrogen and urine creatinine concentration.

Table 1.5. The effect of precision feeding SID lysine to meet the lactating sows requirement on sow performance, Exp. 2[1]

	Control[2]	Static blend	Dynamic blend	SEM	P =
Count, n	19	18	19		
Parity	2.0	2.0	2.1	0.49	0.982
Lactation length, d	18.3	18.5	18.4	0.27	0.864
Sow BW, kg					
Entry	254.4	255.9	257.1	12.29	0.912
Farrow	232.4	237.0	237.1	11.87	0.696
Wean	225.9	231.0	234.9	10.69	0.492
Sow BW change, kg					
Entry to farrow	-22.4	-18.7	-20.3	2.87	0.307
Farrow to wean	-7.2	-8.0	-2.6	3.41	0.232
Entry to wean	-29.7	-25.7	-22.9	3.72	0.263
Sow back fat, mm					
Entry	14.3	14.4	14.8	0.74	0.729
Wean	13.2	13.9	14.3	0.69	0.286
Change (entry to wean)	-1.2	-0.6	-0.5	0.36	0.295
Sow caliper score					
Entry	16.8	17.0	17.0	0.50	0.826
Wean	15.5	15.9	16.0	0.54	0.675
Change (entry to wean)	-1.4	-1.1	-1.0	0.33	0.654
Sow loin depth, mm					
Entry	45.9	45.9	46.8	1.23	0.552
Wean	45.7	46.6	46.8	0.85	0.449
Change (entry to wean)	-0.3	0.7	0.0	1.96	0.622
Sow ADFI, kg					
d 2 to d 9	5.5	5.8	5.5	0.40	0.526
d 9 to wean	7.7	8.1	8.1	0.30	0.579
d 2 to wean	6.8	7.1	7.0	0.26	0.661
Lys intake, g/d	77.7[a]	60.1[b]	59.7[b]	2.6	< 0.001
Wean-to-service interval, d	4.2	4.4	4.1	0.14	0.092
N balance, g/d					
Intake[3]	247.0[a]	149.4[b]	147.7[c]	9.41	< 0.001
In milk[4]	96.1	88.6	91.6	5.29	0.370
From body reserves[5]	7.6	10.0	2.5	5.15	0.260
Excreted[6]	159.5[a]	66.2[b]	58.6[b]	4.02	< 0.001
Excreted, %[7]	63.9[a]	43.9[b]	39.7[c]	1.59	< 0.001

[a,b,c] Means in the same row that do not have a common superscript differ ($P < 0.05$).

[1]A total of 56 mixed-parity sows (Line 241, DNA, Columbus NE) and litters were used from day 2 of lactation (the day after farrowing) until weaning.

[2]Sows were allotted to 1 of 3 treatments on d 2 of lactation. A control high Lys diet (1.10% SID Lys) or 1 of 2 blends, the static blend curve or dynamic blend curve, of a low (0.40% SID Lys) and high Lys diet (1.10% SID Lys) to target a specific Lys requirement based on the NRC recommendations +20%. The only difference between the static blend curve treatment and a dynamic blend curve was that the blend of the low and high Lys was adjusted every 2 days based on a rolling average of Lys intake for sows on the dynamic blend curve.

[3]Calculated by N content in feed × feed intake.

[4]Calculated from mean litter gain and litter size according to equations in NRC (2012).

[5]Calculated from empty sow body weight and backfat according to equations in NRC (2012).

[6]Calculated from: (N intake + N from body reserves - N in milk).

[7]Calculated from: (N intake + N from body reserves - N in milk)/ N intake.

Table 1.6. The effect of precision feeding SID lysine to meet the lactating sows requirement on litter performance, Exp. 2[1]

	Control[2]	Static blend	Dynamic blend	SEM	*P* =
Litter characteristics					
Litter size, n					
d 0	14.5	14.4	14.1	0.90	0.946
d 2	13.9	14.2	14.1	0.89	0.984
d 9	13.8	13.8	13.6	0.87	0.981
Wean	13.6	13.6	13.5	0.87	0.996
Litter weight, kg					
d 2	25.4	24.7	25.3	0.94	0.776
d 9	45.7	44.0	43.2	1.72	0.379
Wean	79.4	78.3	77.1	2.87	0.669
Mean pig BW, kg					
d 2	1.8	1.8	1.8	0.07	0.654
d 9	3.3	3.2	3.2	0.17	0.394
Wean	5.8	5.7	5.7	0.28	0.816
Litter ADG d 2 to wean, kg	2.9	2.9	2.8	0.14	0.525
Pig ADG d 2 to wean, g	215.0	211.6	208.1	13.99	0.638
Lys intake, g/kg of litter gain	23.5[a]	18.7[b]	19.2[b]	0.88	< 0.001
d 2 to wean mortality, %	2.6	4.7	3.4	0.01	0.444

[a,b,c] Means in the same row that do not have a common superscript differ ($P < 0.05$).

[1]A total of 56 mixed-parity sows (Line 241, DNA, Columbus NE) and litters were used from day 2 of lactation until weaning.

[2]Sows were allotted to 1 of 3 treatments on d 2 of lactation. A control high Lys diet (1.10% SID Lys) or 1 of 2 blends, the static blend curve or dynamic blend curve, of a low (0.40% SID Lys) and high Lys diet (1.10% SID Lys) to target a specific Lys requirement based on the NRC recommendations +20%. The only difference between the static blend curve treatment and a dynamic blend curve was that the blend of the low and high Lys was adjusted every 2 days based on a rolling average of Lys intake for sows on the dynamic blend curve.

Table 1.7. The effect of precision feeding SID lysine to meet the lactating sows requirement on serum urea nitrogen, Exp. 2[1]

					P =		
Treatment:	Control[2]	Static blend	Dynamic blend	SEM	Treatment × day	Treatment	Day
Serum urea N, mg/dL							
d 9[3]	19.2[a]	13.1[b]	12.3[b]				
Weaning	19.0[a]	13.5[b]	13.7[b]	0.63	0.286	< 0.001	0.710

[1]A total of 56 mixed-parity sows (Line 241, DNA, Columbus NE) and litters were used from day 2 of lactation (the day after farrowing) until weaning.

[2]Sows were allotted to 1 of 3 treatments on d 2 of lactation. A control high Lys diet (1.10% SID Lys) or 1 of 2 blends, the static blend curve or dynamic blend curve, of a low (0.40% SID Lys) and high Lys diet (1.10% SID Lys) to target a specific Lys requirement based on the NRC recommendations +20%. The only difference between the static blend curve treatment and a dynamic blend curve was that the blend of the low and high Lys was adjusted every 2 days based on a rolling average of Lys intake for sows on the dynamic blend curve.

[3]Blood samples were taken on d 9 of lactation and at weaning to measure serum urea N.

Chapter 2 - Effect of precision feeding standardized ileal digestible lysine and other amino acids to lactating sows compared to conventional feeding strategies in a commercial farm

ABSTRACT

A total of 728 sows (Camborough, PIC) and litters (Camborough × PIC 800) were used in a lactation study to evaluate the effect of precision feeding Lys compared to providing a single lactation diet on sow and litter performance. Sows were blocked by parity and allotted to 1 of 2 treatments at entry into farrowing. Treatments consisted of a control treatment or blend treatment fed a low and high Lys diet to reach target standardized ileal digestible (SID) Lys intake for each day of lactation. Sows fed the blend treatment were fed a blend of a low (0.60%) and high (1.07%) Lys diet to reach target daily Lys intake via a computerized feeding system (Gestal Quattro Opti Feeder, Jyga Technologies, St-Lambert-de-Lauzon, Quebec, CA). Sows fed the control treatment received only the high Lys diet. The Lys level in the high Lys diet was increased by both soybean meal and feed-grade amino acids (AA). Daily target Lys intake was based on NRC (2012) model estimates for litter size of 17 pigs, but levels were increased by 20% to reach an average target Lys intake of 61 g SID Lys/d for gilts and 65 g/d for parity 1 sows. Average Lys intake was 87% of target because sow average daily feed intake (ADFI) during lactation was lower than predicted. Sows fed the control treatment had greater ($P < 0.001$; 72.0 vs. 54.8 g/d) SID Lys intake than those fed the blend treatment. No differences ($P > 0.10$) in entry to wean (d 19) change in sow body weight (BW), backfat (BF), loin depth (LD), caliper score, or ADFI were observed between treatments. There were no differences ($P > 0.10$) in litter size at d 2 or wean; however, litters and pigs from sows fed the control treatment tended ($P <$

0.10) to have greater weight at wean and average daily gain (ADG) compared to litters from sows fed the blend treatment. Control-fed sows had greater (*P* = 0.002) serum urea N concentration at wean compared to d 10 and to sows fed the blend treatment. Milk crude protein (CP) content was greater (*P* = 0.05) for control fed sows at d 10 and wean compared to sows fed the blend treatment. The decreased litter growth rate from blend-fed sows was likely due to insufficient Lys intake to maximize litter growth performance because when only considering the sows fed the blend treatment that achieved their target Lys intake, there were no differences in pig or litter weight at wean.

List of Abbreviations

AA = amino acids

ADG = average daily gain

ADFI = average daily feed intake

BF = backfat

BW = bodyweight

CP = crude protein

LD = loin depth

Lys = lysine

NE = net energy

SID = standardized ileal digestible

WSI = wean to service interval

INTRODUCTION

Strathe et al. (2015) described the distinction between nutrient recommendations and requirement estimates. Recommendations are at the population level and determined using the requirements of the average sow in the herd. Requirements are based on an individual sow's needs. When feeding based on population recommendations, the requirements of some sows are not met, while in excess for others. Precision feeding can be used to prevent this issue. Precision feeding is used to give the right nutrients to meet an individual animal's dietary requirement at the right time depending on their stage of production (Pomar et al., 2009). Despite the potential benefits of precision feeding, its application in lactating sows remains limited, with most still receiving a single diet regardless of individual animal requirements.

While precision feeding offers a more tailored approach to meeting individual sow nutrient requirements, research on its effectiveness in lactating sows is limited. Craig et al. (2016) used a phase feeding approach looking at precision feeding energy, Lys, and Val and found no differences in sow or litter performance as the Val:Lys ratio increased. Gauthier et al. (2022) took a broader approach and used technology to determine the blend of a low and high AA and mineral diet to meet a specific sow's requirement and observed that precision fed sows had lower N and P excretion, but litter growth performance was 3% lower compared to conventional feeding strategies. A challenge of implementing precision feeding is the ability to accurately predict the nutrient requirements and feed intake of individual sows in real time.

In order for precision feeding to be effective, it is important to be able to predict nutrient requirements accurately. However, it is difficult to determine the exact needs of individual lactating sows because many factors affect nutrient requirements. Litter size and growth rate can be used to determine nutritional requirements during lactation (Tokach et al., 2019). Gaillard et al. (2021) suggested that using on-farm sensors to track feed and water intake, environmental conditions, and growth performance would provide real-time data on animal performance and health, leading to accurate predictions of nutrient requirements. Gauthier et al., (2021) took another approach to precision feeding by utilizing a database of feed intake records for over 78,000 sows to create a model to predict feed intake of a sow for the upcoming days based on past feed intake. This allows the ability to precision feed based on individual sow feed intake records. While predictive models can be used to estimate nutrient requirements for precision feeding, the accuracy of the model in estimating nutrient requirements is a concern. Refining these models is needed to ensure they effectively predict sow nutrient requirements and support sow and litter performance during lactation.

The NRC (2012) has a model that can be used to estimate sow Lys intake requirements for each day of lactation using model inputs such as sow parity, feed intake, body weight, litter size, and litter growth. Spinler et al. (2024) observed that the NRC (2012) model underestimates Lys intake needed to maximize litter growth performance. In the current study, the NRC model Lys curve was used as a base, but targets were increased by 20% for each parity for sows with a litter size of 17 pigs based on the results of Spinler et al. (2024), as this was determined to meet the sow's requirements and achieve similar litter growth performance compared to conventional feeding strategies. We hypothesized that precision feeding Lys to sows during lactation could be used to achieve similar sow and litter performance in a commercial production system. Therefore, the objective of this study was to evaluate the practical application of precision feeding Lys and other AA fed during lactation on sow and litter performance compared to a conventional feeding strategy to validate the application of diet blending based on expected feed intake from historical farm records in a commercial facility.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. The study was conducted at a commercial sow farm in eastern

Iowa (Brenneman Pork, Washington, IA, USA). Sows were housed in individual farrowing stalls equipped with a nipple waterer and a computerized feeding system (Gestal Quattro Opti Feeder, Jyga Technologies, St-Lambert-de-Lauzon, Quebec, CA) capable of blending two different diets and recording feed deliveries. Creep feed was not offered throughout the trial.

Animals and Diets

A total of 728 gilts and parity 1 sows, with an average parity of 1.5, (Camborough, PIC, Hendersonville, TN, USA) and litters (Camborough × PIC 800) were used in the lactation study. Sows were moved from gestation to farrowing at approximately d 114 of gestation. Upon entry into farrowing, sow weight, caliper, backfat depth (BF), and loin depth (LD) measurements were taken. Sow caliper score was taken at the last rib (Knauer and Baitinger, 2015). Backfat and LD measurements were taken at the 10th rib approximately 6 cm from the midline using real time ultrasound (ExaGo, BioTronics Inc., Pittsburgh, PA, USA).

Sows were allotted to 1 of 2 treatments at entry to the farrowing house, a control 1.07% standardized ileal digestible (SID) Lys diet or a blend treatment. The blend treatment was formed by mixing two diets: a low Lys (0.60% SID Lys) and a high Lys (1.07% SID Lys) diet (Table 1). Diets were manufactured at the Brenneman Pork Feed Mill (Washington, IA, USA). Pre-farrow, all sows were allowed 2.3 kg per day of the high Lys diet. Sows were given *ad libitum* access to feed and placed on their respective diets the day of farrowing. Sows fed the control diet were fed only the high Lys diet. Sows fed the blend treatment were fed a mixture of the low and high Lys diet with a separate curve created for gilts and parity 1 sows. Blends of the low and high Lys diets were created to target a specific Lys intake per day of 61 g SID Lys/d for gilts and 65 g/d for parity 1 sows. The crude protein (CP) content of the high Lys diet was 19.8% and the low Lys diet 14.5%. The Lys concentration of the high Lys diet was increased by both soybean meal and feed-grade AA to ensure Lys was first limiting. Other AA also increased with SID Lys as they were formulated on a ratio relative to Lys. The SID Lys intake target was calculated based on expected feed intake on the farm derived from historical feed intake records collected the previous 6 months. Lysine targets were based on the shape of the NRC (2012) model estimate recommendations for each parity with a litter size of 17 pigs (Figure 2-1). However, based on the results of Spinler et al. (2024), Lys targets were increased by 20% to achieve an average intake of 61 and 65 g/d for gilts and parity 1 sows. Spinler et al. (2024) observed that feeding sows according to the NRC (2012) model-predicted Lys requirements by blending a low (0.25% SID Lys) and high (1.10% SID Lys) Lys diet resulted in reduced litter growth performance compared to feeding a high-Lys diet. In a follow-up study, increasing Lys intake targets by 20% above the NRC (2012) model predictions by blending a low (0.40% SID Lys) and high (1.10% SID Lys) Lys diet led to litter growth performance similar to feeding only the high Lys diet. As a result, the study herein adopted a 20% increase in Lys targets from the NRC (2012) model predictions.

The feeding system allowed sows to be fed in 4 different feeding periods throughout the day and feed allowance within each period was allotted based on sow feeding behavior. Within each feeding period, sows could receive feed every 15 minutes. Feed intake curves were set based on average sow feed intake for each parity. Sows were allowed to eat 120% of expected feed intake to account for variation in intake and avoid limiting sow feed. Sow feed intake was analyzed on d 7 and 14 of lactation to identify sows that were eating below, or above targeted feed intake based on the previous 2 days feed intake to adjust for differences in expected vs actual feed intake. If a sow was eating 25% below targeted feed intake at either time point, they were fed a curve with a 10% increase in the proportion of the high Lys diet for the remainder of the study. If a sow was eating above target feed intake by 10% or greater at either time point, they were fed a diet with a 10% decrease in the proportion of the high Lys diet for the remainder of the study. This was done to more closely reach targeted Lys intake for low and high feed intake sows. Sow feed and Lys intake were analyzed assuming 5% feed wastage. Feeders were calibrated once a week for each diet by taking the average calibration value (weight of feed dropped in 5 turns of the feeder auger) from 5 random feeders. Complete feed samples were analyzed for DM, CP, and AA (AOAC, 2006; Ajinomoto Health & Nutrition North America, Inc., Eddyville, IA, USA).

On a subset of sows, blood and milk samples were taken on d 10 of lactation and the day before weaning. Blood samples were collected from 39 control-fed sows and 38 blend-fed sows equalized by parity. Seven mL of blood was collected from the jugular vein using a Monojets blood collection tube (Covidien, Minneapolis, MN, USA) containing no anticoagulant. Sow blood was collected after a 6 h fasting period and then centrifuged and serum was collected and stored at -20°C. Stored serum samples were then analyzed for urea N concentration (Urea Nitrogen Colorimetric Detection Kit, Arbor Assays, Ann Arbor, MI, USA). Milk samples were collected from 20 control-fed sows and 18 blend-fed sows. Approximately 30 mL of milk was collected from the 3rd, 4th, or 5th teat on either side and then stored at -20°C. To stimulate milk letdown, the ear was cleaned with isopropyl alcohol, and 0.3 mL of oxytocin (10 IU per mL) was administered in the ear vein. Milk samples were analyzed for CP concentration (LECO TruMac N, LECO Corporation, St. Joseph, MI, USA).

Litters were equalized to approximately 16 to 17 pigs within 24 h of the end of farrowing. On d 2 of lactation, after equalization, litter weight and size were recorded. Litter weight and size were also collected the day before weaning (d 19 of lactation). Pre-wean mortality for each sow was calculated by taking the litter size at wean divided by the litter size at d 2 after equalization. The wean-to-service interval was analyzed for each sow remaining in the herd after weaning.

Based on the results of the study, a subset of sows was used to determine the litter growth performance of blend-fed sows who met an average target Lys intake of 61 g/d during lactation compared to control fed sows. For blend fed sows to reach this target Lys intake, they had to have an ADFI of at least 7.25 kg over the lactation period. This subset of blend-fed sows was compared to control fed sows who had a similar ADFI of at least 7.25 kg, so differences due to Lys intake could be compared, not differences in energy intake. This analysis included 114 sows fed the control treatment and 100 sows fed the blend treatment.

Statistical Analysis

Performance data were analyzed using the lmer function of R software, version 1.4.171, as a randomized complete block design. Sow and litter were considered the experimental unit and the number of observations per treatment is provided in Table 2. Treatment was a fixed effect. Block (sow parity) and farrowing room were considered random effects. Litter weight at d 2 was used as a covariate for the evaluation of litter weight at wean, pig BW at d 2 and wean, pig ADG, and litter ADG. Pre-wean mortality was analyzed using a binomial distribution. Serum urea N and milk CP were analyzed as a repeated measure using the lmer function of R software with treatment, sample timepoint, and their interaction included as fixed effects. Plate, farrowing room, and sow were included as random effects in the statistical model for serum urea N, and farrowing room and sow were included as a random effect for CP analysis. Results are considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

RESULTS AND DISCUSSION

There is variability in nutrient requirements of lactating sows due to differences in parity and litter size. Both NRC (2012) and INRA (InraPorc, 2009) have models to estimate Lys requirements (g/d) for lactating sows. Sows have greater variability in nutrient requirements among individual animals compared to finishing pigs (Gauthier et al., 2019). Precision feeding could be an effective strategy to meet an individual lactating sow’s requirement. Spinler et al. (2024) compared NRC and INRA Lys requirement models for lactating sows, finding that a high Lys diet without feed blending resulted in increased litter performance. Litters from sows fed to meet NRC recommended Lys requirements had higher gain compared to the INRA curve litters. A follow-up study increased NRC Lys targets by 20%, averaging 60 g/d of SID Lys intake, and found no difference in litter growth compared to feeding a high Lys diet (Spinler et al., 2024). Therefore, our objective of this experiment was to implement precision feeding on a large-scale commercial farm following Lys requirements based on the NRC (2012) model plus 20%.

Precision feeding gives the ability to meet an individual sows requirement, but it relies on accurate feed intake predictions. Standardized ileal digestible Lys intake was 87% of the targeted g/d for sows fed the blend treatment (Table 3). This is because sows ate less feed during the study than expected based on historical feed intake records from the farm. However, with this group of sows being the first group to be housed on the farm over the summer months, the high temperatures during resulted in lower sow ADFI than expected. The adjustments made to the feed curves on d 7 and 14 during lactation were not great enough to bring average Lys intake closer to target. This illustrates the need for a computerized feeding system to automatically adjust feed blends to achieve target nutrient intakes based on actual sow feed intake.

Sow Performance

There were no differences ($P > 0.10$) between treatments in sow BW at entry or wean or sow BW change from entry to wean (Table 3). No differences ($P > 0.05$) were observed for sow BF, LD, or caliper score at entry or wean, or changes from entry to wean. Average BF at farrowing was 17.5 mm which is consistent with the recommendations of Tarrés et al. (2006). Research has demonstrated that sows will mobilize body reserves during lactation due to deficiencies in nutrient intake compared to nutrient requirements (Theil, 2015; Gourley et al., 2017; Hojgaard et al., 2019). Gourley et al. (2017) observed that as average SID Lys intake over lactation increased from 39.9 to 62.1 g/d, sow BW and BF loss decreased. Hojgaard et al. (2019) also observed a reduction in sow BW loss as g/d of Lys intake increased from 39.4 to 63.9 g/d. As indicated by no differences observed in sow BW loss, sows fed the blend treatment did not mobilize more body reserves to meet the nutrient demands of lactation compared to sows fed the control treatment. Gauthier et al. (2022) also observed no differences in sow BW loss when control fed sows had an average Lys intake of 64.5 g/d compared to precision fed sows that achieved only 50.7 g/d. The discrepancy in the research is unknown but might suggest precision feeding can be used to minimize sow BW loss. Modern sows may be utilizing dietary nutrients and body reserves differently as indicated by the fact that even though precision fed sows had lower Lys intake they did not mobilize more body reserves to make up for this lower Lys intake, but it is unclear why.

Lactation ADFI did not differ ($P > 0.10$) between treatments but was below the pre-trial estimates that were based on historical intake on this farm (Table 3). Average feed intake was 6.4 kg/d which is in line with the feed intake during the precision feeding study of Gauthier et al. (2022). As expected, sows fed the control diet treatment had greater ($P < 0.001$) average daily

Lys intake during lactation compared to sows fed the blend treatment because they were fed only the high Lys diet. Sows fed the control treatment also had greater ($P < 0.001$) N intake compared to sows fed the blend treatment. These results are similar to the precision feeding study by Spinler et al. (2024). No differences ($P > 0.10$) in wean to estrus interval were observed between treatments which is likely a reflection of the lack of differences that were observed in body tissue mobilization. Minimizing sow body protein mobilization will have a positive impact on reproductive performance (Gourley et al., 2017).

Litter Performance

There were no differences ($P > 0.05$) in litter size at d 2 or at wean as well as litter weight and average pig weight at d 2 (Table 4). Litters from sows fed the control treatment tended to have greater ($P = 0.082$) litter weight at wean as well as average pig weight at wean ($P = 0.075$) compared to litters from sows fed the blend treatment. A tendency was observed for litters ($P = 0.090$) and pigs ($P = 0.062$) from sows fed the control treatment to have greater ADG than those fed the blend treatment. Adequate levels of Lys intake for sows during lactation leads to maximum litter growth performance (Hojgaard et al., 2019). In the study herein, sows fed the blend treatment likely did not consume enough Lys to maximize litter growth performance and yet did not mobilize more body reserves to meet the demands of lactation to make up for lower Lys intake compared to control-fed sows. A precision feeding study by Gauthier et al. (2022) found a reduction of 3% in litter ADG between precision fed and conventionally fed sows. A 3% reduction in litter ADG was also observed in the current study due to lower Lys intake.

No difference ($P > 0.10$) in pre-wean mortality from d 2 to wean was observed (Table 4). Control-fed sows had greater ($P < 0.001$) Lys intake per kg of litter gain compared to sows fed the blend treatment. Control fed sows consumed 33.2 g Lys per kg of litter gain compared to

27.4 g/kg for blend fed sows. A regression equation by Tokach et al. (2019) predicted a requirement of 27 g of Lys intake per kg of litter gain. Spinler et al. (2024) also observed lower Lys intake per kg of litter gain for precision fed sows compared to sows fed a traditional feeding strategy. Feeding a low CP diet has been found to increase N and AA retention and utilization efficiency (Huber et al., 2015). Sows fed the blend treatment were more efficient at utilizing dietary Lys for litter gain as indicated by the lower Lys intake per kg of litter gain.

Blood Criteria

Urea is a waste product from protein breakdown (Whang and Easter, 2000). Serum urea N is a measure of both muscle breakdown and dietary N intake. Over-feeding dietary protein results in increased energy expenditure and protein loss in urine because of the energetic cost to produce and excrete urea (Theil et al., 2020). There was an interaction ($P = 0.002$; Table 5) between treatment and sampling time for serum urea N content with control sows having the highest serum urea N concentration at wean. Serum urea N concentration was lower ($P < 0.05$) in sows fed the blend treatment at d 10 and at wean when compared to sows fed the control diet. Because there were no differences in LD change over lactation, the differences in serum urea N observed are likely due to differences in dietary protein intake and utilization. In finishing pigs, feed efficiency is negatively correlated with blood urea N (Whang and Easter, 2000). This was demonstrated in the current study by control fed sows having a greater serum urea N concentration and lower lysine efficiency compared with sows fed the blend treatment, as indicated by a higher g Lys intake per kg of litter gain. While control fed sows had greater litter growth, they likely had greater Lys intake than needed to maximize litter growth as shown by higher urea nitrogen levels.

Milk Parameters

Gauthier et al. (2019) observed that milk production explains more than 90% of the variation in a lactating sows' nutrient requirements. The Lys requirement of sows during lactation is determined almost completely by milk yield (Theil, 2015), leading to a direct correlation between Lys requirement and litter growth performance. Milk CP was greater (P = 0.050) for sows fed the control treatment at d 10 and wean compared to sows fed the blend treatment (Table 5). Utilization of AA by the mammary gland is affected by the concentration of AA in blood, how they are taken up by mammary cells, and metabolism of AA in the cell (Hurley et al., 2000). Noblet and Etienne (1987) observed that milk protein is not changed due to lactation diet because sows can mobilize body protein reserves to support lactation. However, Strathe et al. (2017) and Liu et al. (2020) observed that increasing dietary Lys intake increased milk protein concentration. Results of our study would indicate that sows on the blend treatment had lower milk protein because of lower Lys (protein) intake which was not compensated by increased mobilization of body reserves.

Additional Analysis and Considerations

Because ADFI was lower than anticipated, litter growth performance was also analyzed for only sows who reached an average lactation feed intake of 7.25 kg or greater on both the control and blend treatments (Table 6). This feed intake level allowed sows to consume an average Lys intake of 61 g/d or greater during lactation for both control and blend fed sows. One hundred and fourteen sows fed the control treatment and 100 sows fed the blend treatment reached an average feed intake of 7.25 kg or greater during lactation. As expected, Lys and N intake was still greater ($P < 0.001$; 85.9 vs 64.9 g/d and 252.2 vs 216.3 g/d) for sows fed the control diet compared to the blended diet, because control sows were fed only the high Lys diet.

However, when sows had an average feed intake of 7.25 kg or greater, there were no differences ($P > 0.05$) in litter growth performance between treatments. Gauthier et al. (2022) observed improved piglet growth performance when sows consumed 64.5 g/d of Lys vs 50.7 g/d, indicating that an average Lys intake of at least 60 g/d may be needed to maximize litter growth performance. Lysine intake per kg of liter weight gain was still greater ($P < 0.001$) for sows fed the control treatment compared to sows fed the blend treatment. This analysis would indicate that there was no difference in litter gain when blend fed sows had an average SID Lys intake of 61 g/d compared to sows fed a single high Lys diet during lactation with a litter size of approximately 14.8 weaned pigs. This is an important finding that illustrates that traditional feeding strategies of feeding a single diet during lactation can result in the over-feeding of Lys, resulting in increased diet cost and wasted nutrients as compared with precision feeding. Precision feeding can be used to achieve similar sow and litter growth performance compared to feeding a single diet during lactation.

Conventional feeding strategies are likely exceeding nutrient requirements (Gauthier et al., 2022), leading to wasted nutrients and increased diet costs. However, more research is needed to determine how precision feeding technology can be utilized to meet an individual sow requirement based on actual sow feed intake, not predicted sow feed intake. Future research should focus on the use of technology to automatically adjust dietary blends based on actual sow feed intake to prevent the under supplementation of nutrients that decrease sow milk production and litter growth performance.

Large databases can be created using ADFI to predict nutrient requirements of individual sows (Gauthier et al., 2019; 2021). Gauthier et al. (2022) conducted a study using technology that determined the blend of a low and high AA and mineral diet based on sow parity, litter size, and litter growth. The authors found that the technology used to predict the diet blend did not adequately account for variability in litter growth and milk production. In the current study, we overestimated feed intake, leading to lower Lys intake than targeted, which likely led to lower litter growth performance. Gauthier et al. (2022) experienced similar results and cited an underestimation of litter growth as a potential reason for differences in growth rate. Additional research is needed to understand the nutrient requirements of modern sows with larger litters and increased capacity for milk production to more accurately set the target nutrient intake.

In conclusion, there were no differences observed in sow BW, LD, or BF change over lactation during the study. Pigs and litters from sows fed the blend treatment tended to have decreased wean weights and ADG. Lower litter growth performance for litters from precision fed sows is likely due to lower SID Lys intake than required to maximize litter growth. However, when sows fed the blend treatment achieved target Lys intake, they had similar litter growth performance compared to litters from sows fed the control treatment. The next steps in this research would include using technology to automatically adjust diet blends to avoid the underfeeding of nutrients based on individual sow feed intake and litter growth.

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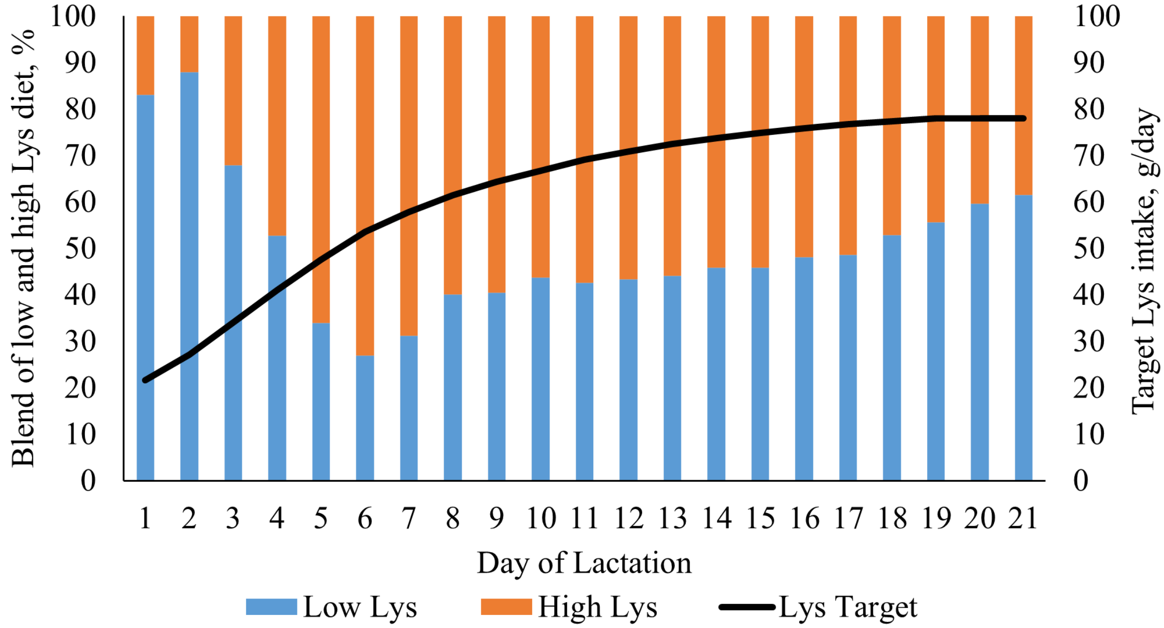

Figure 2-1. Target standardized ileal digestible Lys intake for parity 1 sows with a litter size of 17 pigs at equalization and the blend of the low and high Lys diets for the blend treatment.

Table 2.1.Composition of lactation diet (as-fed basis)[1]

Item	Low Lys	High Lys
Ingredient, %		
Corn	74.57	61.67
Soybean meal, 47% CP	11.21	23.93
Corn DDGS[2]	10.00	10.00
Calcium carbonate	1.43	1.36
Monocalcium P, 21% P	1.13	0.99
Sodium chloride	0.50	0.50
L-Lys-HCl	0.15	0.35
DL-Met	-	0.04
L-Thr	-	0.12
L-Trp	-	0.02
Vitamin and trace mineral premix	0.17	0.17
Choline chloride 60%	0.12	0.12
Feed additives[3]	0.74	0.74
Total	100	100
Calculated analysis		
SID amino acids, %		
Lys	0.60	1.07
Ile:Lys	77	63
Leu:Lys	209	145
Met:Lys	37	30
Met & Cys:Lys	74	56
Thr:Lys	68	65
Trp:Lys	20	19
Val:Lys	92	71
His:Lys	56	43
Total Lys, %	0.72	1.22
NE, kcal/kg	2,467	2,401
SID Lys:NE, g/Mcal	2.43	4.46
CP, %	14.5	19.8
Ca, %	0.82	0.81
P, %	0.59	0.62
STTD P, %	0.48	0.48
Analyzed values		
CP, %	13.2	18.8
Total Lys, %	0.72	1.18

[1]Feed was manufactured at the Brenneman Pork Feed Mill (Washington, IA).

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[2]Dried distiller grains with solubles

[3]Feed additives included Dynamate, Dual Defender, Provent, M-Mobilize, Chromax, 0.04%, and Optiphos Plus 2500 G.

Table 2.2. Number of sows included in each response criteria[1]

Response criteria	Control	Blend
Sow BW[2]	229	223
Sow caliper score[3]	355	360
Sow back fat[4]	330	344
Sow loin depth[4]	325	342
Weaun-to-service interval[5]	286	296
Litter weight[6]	328	340
Serum urea N[7]	39	38
Milk crude protein[7]	20	18

[1]A total of 728 gilt and parity 1 sows (Camborough, PIC, Hendersonville, TN) and litters (Camborough × PIC 800) were used.

[2]The sow scale malfunctioned during the last week of the study and thus 276 sow wean weights were not collected. If a wean weight for a sow was missed, sow entry weight was also removed from data analysis.

[3]Sow caliper scores were only analyzed for parity 1 sows as caliper was not designed to be used on gilts. If a caliper score was missing at entry or wean, both were removed from data analysis.

[4]Some sow backfat and/or loin depth measurements were missed throughout the study due to unsatisfactory ultrasound images which resulted in being unable to analyze backfat and loin depth or the wrong sow ID being recorded. If a backfat or loin depth measurement was missing at entry or wean, both were removed from data analysis.

[5]Wean-to-service interval was only recorded for sows that remained in the herd after farrowing.

[6]The pig scale malfunctioned during the trial resulting in some litter weights being missed. If a litter weight was missed at d 2 or wean, both were removed for the data set.

[7]Milk and blood samples were taken on a subset of sows from each treatment.

Table 2.3. Evaluation of precision feeding standardized ileal digestibility lysine on sow performance[1]

Item	Control[2]	Blend	SEM	$P =$
No. of sows, n	364	364		
Parity	1.6	1.5	0.07	0.859
Lactation length, d	19.3	19.3	0.26	0.656
Sow BW, kg				
Entry	216.6	217.3	16.75	0.611
Wean	188.4	190.1	16.26	0.252
Sow BW change, kg				
Entry to wean	-28.2	-27.2	1.67	0.395
Sow caliper score[3]				
Entry	12.0	12.0	0.20	0.826
Wean	10.4	10.3	0.21	0.319
Change (entry to wean)	-1.6	-1.7	0.24	0.442
Sow back fat, mm				
Entry	17.4	17.5	0.26	0.798
Wean	14.4	14.8	0.30	0.105
Change (entry to wean)	-2.9	-2.6	0.38	0.113
Sow loin depth, mm				
Entry	68.4	68.5	1.32	0.813
Wean	65.6	65.8	1.55	0.802
Change (entry to wean)	-2.6	-2.6	0.82	0.949
Lactation ADFI, kg	6.4	6.4	0.46	0.334
Lys intake, g/d	72.0	54.8	3.87	< 0.001
N intake, g/d	212.1	182.6	12.98	< 0.001
Wean-to-service interval, d	4.5	4.6	0.11	0.123

[1]A total of 728 gilt and parity 1 sows (Camborough, PIC, Hendersonville, TN) and litters (Camborough, × PIC 800) were used.

[2]Sows were allotted to 1 of 2 treatments upon entry to the farrowing house. A control high Lys diet (1.07% SID Lys) or a blended diet of low (0.60% SID Lys) and high Lys diets to target a specific Lys intake based on NRC (2012) requirement estimates with an additional 20% increase in SID Lys intake.

[3]Caliper scores only include measurements from parity 1 sows not gilts.

Table 2.4. Evaluation of precision feeding standardized ileal digestibility lysine on litter performance[1]

Item	Control[2]	Blend	SEM	*P* =
Litter characteristics				
Litter size, n				
d 2	16.7	16.7	0.21	0.913
Wean	14.6	14.5	0.20	0.593
Litter weight, kg				
d 2	24.2	23.9	1.57	0.307
Wean[3]	69.7	68.1	3.65	0.082
Mean pig BW, kg				
d 2[3]	1.46	1.46	0.01	0.781
Wean[3]	4.81	4.71	0.23	0.075
Litter ADG d 2 to wean, kg/d[3]	2.35	2.27	0.18	0.090
Pig ADG d 2 to wean, g/d[3]	160.5	155.5	11.98	0.062
Lys intake, g/kg of litter gain	33.2	27.4	1.59	< 0.001
d 2 to wean mortality, %	12.8	13.4	0.75	0.318

[1]A total of 728 gilt and parity 1 sows (Camborough, PIC, Hendersonville, TN) and litters (Camborough × PIC 800) were enrolled from farrowing to wean.

[2] Sows were allotted to 1 of 2 treatments upon entry to the farrowing house. A control high Lys diet (1.07% SID Lys) or a blended diet of low (0.60% SID Lys) and high Lys diets to target a specific Lys intake based on NRC (2012) requirement estimates with an additional 20% increase in SID Lys intake.

[3]Litter weight at d 2 was used as a covariate in the statistical analysis.

Table 2.5. Evaluation of precision feeding standardized ileal digestibility lysine and amino acids on blood urea nitrogen and milk crude protein[1]

				P =		
Item	Control[2]	Blend	SEM	Treatment × day	Treatment	Day
Serum urea N, mg/dL						
d 10[3]	14.9[b]	12.7[c]	0.63	0.002	< 0.001	0.002
Wean	17.5[a]	13.0[c]				
Milk crude protein, %						
d 10	5.5	5.0	0.13	0.455	0.050	0.580
Wean	5.6	5.2				

[a,b,c] Means in the same row that do not have a common superscript differ ($P < 0.05$).

[1]A total of 39 control and 38 blend fed sows were used for blood collection and 20 control and 18 blend fed sows were used for milk collection.

[2] Sows were allotted to 1 of 2 treatments upon entry to the farrowing house. A control high Lys diet (1.07% SID Lys) or a blended diet of low (0.60% SID Lys) and high Lys diets to target a specific Lys intake based on NRC (2012) requirement estimates with an additional 20% increase in SID Lys intake.

[3]Blood and milk samples were taken on d 10 of lactation and at wean to measure blood urea N and milk crude protein.

Table 2.6. Evaluation of precision feeding standardized ileal digestibility lysine and amino acids on litter performance in a commercial setting for sows with an average feed intake of 7.25 kg or greater[1]

Item	Control[2]	Blend	SEM	*P* =
Count, n	114	100		
Lactation ADFI, kg	7.5	7.6	0.22	0.214
Lys intake, g/d	85.9	64.9	1.26	< 0.001
N intake, g/d	252.2	216.3	5.13	< 0.001
Litter characteristics				
Litter size, n				
d 2	16.7	16.8	0.41	0.854
Wean	14.7	14.9	0.39	0.750
Litter weight, kg				
d 2	24.6	24.6	1.45	0.906
Wean	72.6	73.1	6.04	0.775
Mean pig BW, kg				
d 2	1.49	1.48	0.08	0.623
Wean	4.97	4.92	0.39	0.598
Litter ADG d 2 to wean, kg/d	2.49	2.52	0.22	0.703
Pig ADG d 2 to wean, g/d	169.9	168.6	14.23	0.801
Lys intake, g/kg of litter gain	35.4	27.4	2.06	< 0.001
d 2 to wean mortality, %	11.4	10.9	0.76	0.665

[1]A total of 214 gilts and parity 1 sows with an average lactation feed intake of 7.25 kg or greater (Camborough, PIC, Hendersonville, TN) and their litters (Camborough × PIC 800) were used to compare litter growth performance between litters from control and blend fed sows.

[2]Sows were allotted to 1 of 2 treatments upon entry to the farrowing house. A control high Lys diet (1.07% SID Lys) or a blended diet of low (0.60% SID Lys) and high Lys diets to target a specific Lys intake based on NRC (2012) requirement estimates with an additional 20% increase in SID Lys intake.

[3]Litter weight at d 2 was used as a covariate in the statistical analysis.

Chapter 3 - Does split-suckling influence pre- and postweaning pig growth performance and mortality?

ABSTRACT

A total of 1,513 sows and litters, approximately 505 litters per treatment, were used to determine the effects of two split-suckling protocols on litter growth performance and mortality pre- and postweaning compared to no split-suckling. Sows were blocked by parity and allotted to one of three treatments: no split-suckling (control), or one of two split-suckle protocols. The first split-suckle protocol was based on birth order, where the first 8 pigs born were marked at birth, and at the completion of farrowing, were removed from the sow for 45 min. After 45 min, the first 8 born pigs were returned to the sow and the unmarked pigs born later in the birth order were removed from the sow for 45 min. Then, all pigs were returned to the sow. The second split-suckling protocol was based on body weight (BW.) After farrowing was completed, the 8 heaviest pigs in the litter were removed from the sow for 90 min and then returned to the sow, completing the split-suckle treatment. Litters on either split-suckle treatment were split-suckled within 18 h of birth, after the completion of farrowing if litters were born during the day or the following morning for litters born overnight. Cross-fostering occurred after split-suckling within treatment by 24 h after the completion of farrowing. No differences were observed in litter size or pig weights at the time of split-suckling (d 1) or at weaning as well as preweaning mortality. Preweaning mortality from split-suckle to weaning was also analyzed by birth weight category within treatment, light (≤ 1.2 kg), medium (1.2 < x ≤ 1.5 kg), and heavy (≥ 1.5 kg) pigs, and was not affected by treatment. When litters were grouped by sow parity, timing of split-suckling (day of birth vs. the following morning), or functional teat count, no differences in preweaning mortality were observed among treatments. A subset of pigs was monitored through the nursery

and finishing phases. No treatment differences were observed in average daily gain, average daily feed intake, gain-to-feed ratio, or mortality in either phase. Overall, the split-suckling protocols evaluated in this study did not influence pig growth performance or mortality during the pre- or postweaning periods compared to no split-suckling.

List of abbreviations

ADFI, average daily feed intake

ADG, average daily gain

BW, body weight

G:F, gain to feed ratio

INTRODUCTION

As a result of genetic selection for high producing sows, litter size in the swine industry has increased (Knap et al., 2023). Average born alive in the U.S. has increased from 13.6 in 2019 to 14.0 in 2024 (MetaFarms, 2025). However, sow colostrum production is not related to litter size and does not increase as litter size increases (Devillers et al., 2007). This leads to reduced and unequal colostrum intake in large litters due to greater nursing competition (Jenkins et al., 2025) and the sow's limited colostrum production capacity (Farmer and Quesnel, 2009). When pigs consume less than 200 g of colostrum, preweaning mortality was 43.4% compared to just 7.1% when colostrum intake was greater than 200 g (Devillers et al., 2011; Quesnel et al., 2012). Due to the importance of consuming adequate colostrum and its impact on pig survival, it is necessary to explore management practices that can increase colostrum intake.

Split-suckling is a management strategy that attempts to ensure that all pigs within a litter consume adequate colostrum to reduce preweaning mortality. During split-suckling, a portion of piglets in the litter are temporarily removed from the sow to reduce competition at the sow's underline, giving the remaining pigs less competition to consume colostrum. Typically, the first born (Morton et al., 2019; Vallet, 2019) or heaviest pigs (Vandaele et al., 2020; Arnaud et al., 2023a; Romero et al., 2023) are temporarily removed from the sow to prioritize colostrum intake for later born or light weight pigs. Split-suckling protocols vary, and published research does not suggest one best strategy to increase colostrum intake and reduce preweaning mortality. Vallet (2019) observed that split-suckling by removing the first five pigs born for up to 4 h after the birth of the 9th pig in the litter resulted in a tendency for a reduction in preweaning mortality. Preweaning mortality was reduced from 15.1 to 11.7% in litters that were split-suckled compared to litters not split-suckled. However, Arnaud et al. (2023a) evaluated split-suckling based on body weight (BW) by removing the 6 heaviest pigs in the litter for 60 min and then removing the same 6 pigs again for 60 min, 90 min later. Split-suckling did not reduce preweaning mortality compared to no split-suckling.

With differences in split-sucking protocols utilized and varying effects on preweaning mortality, further research is needed using a large sample size to understand the potential impact of this practice on pig performance. Therefore, the objective of this experiment was to evaluate the effects of two different split-suckling strategies on pre- and postweaning growth performance and mortality of pigs compared to no split-suckling. We hypothesized that split-suckled litters would have increased colostrum intake and, therefore, better preweaning survival than litters not split-suckled.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment, protocol number 4577.2. The study was conducted at a commercial sow farm in eastern Nebraska (Saint Edward, NE, USA). Sows and their litter were housed in individual farrowing stalls measuring 2.1 × 1.5 m. Pigs were provided 2.1 × 0.5 m on one side of the sow and 2.1 × 0.3 m on the other side with a heat lamp above the larger area. Sows were induced to farrow in the morning on d 115 of gestation using prostaglandin F2alpha (lutalyse; Zoetis, Parsippany, NJ, USA). Needle teeth were clipped, and antibiotic (10 mg; Excede, Zoetis, Parsippany, NJ, USA) intramuscular injections were given within 24 h of birth. Tails were docked, pigs were given an intramuscular injection of Fe (200 mg GleptoForte; Ceva Animal Health, LLC, Lenexa, KS, USA), and male pigs were surgically castrated 3 to 4 d after birth. Creep feed was offered to all litters from d 10 post-farrowing until weaning.

Animals

A total of 1,513 sows (average parity 3.6; Line 241: DNA, Columbus, NE) and litters (Line 241 × 600, DNA) were used. Sows were moved from the gestation facility to the farrowing facility at approximately d 110 of gestation. On d 110 of gestation, sows and their litter were allotted to one of three treatments, a control and two different split-suckling protocols. In the control treatment, litters were not split-suckled. The split-suckling protocols were based on pig birth order or body weight. Split-suckle treatments were applied within 3 h of the end of farrowing if a sow farrowed during the day and within 18 h of the start of farrowing if a sow farrowed overnight. The end of farrowing was defined as when placenta was passed. For litters split-suckled based on birth order, as the sow was farrowing, the first 8 pigs born were marked with livestock marking paint. Farm staff were present to attend sow farrowing from 0500 to 2400 h. Upon the completion of farrowing, the first 8 pigs were then removed from the sow and placed under a heat lamp in the area adjacent to the sow for 45 min. Pigs were separated from the sow using a plastic board that reached from the front to the end of the farrowing stall (2.1 m), providing an area of approximately 0.58 m^2. After 45 min, the first 8 pigs born were returned to the sow and the remaining unmarked, later born pigs were removed from the sow and placed behind the board for 45 min. Then, these pigs were placed back on the sow and the split-suckle protocol was complete. If farrowing was not attended to determine pig birth order, the heaviest 8 pigs were removed first, followed by the lighter pigs. For litters that were split-suckled based on body weight, after the completion of farrowing, the 8 heaviest pigs in the litter were removed from the sow and placed under a heat lamp in the stall behind the split-suckle board for 90 min. After 90 min, the 8 heaviest pigs were returned to the sow and the split-suckle protocol was complete.

Functional teat count was recorded at split-suckling (d 1) of the study. Functional teats were defined as an elongated, pointed teat with no visual defects that can produce milk and can be suckled by a pig (Arend et al., 2023). Individual pig weights were taken before split-suckle treatments were applied. Day 1 of the study was the day split-suckling occurred: for sows that farrowed during the day, this was the day of birth, and for sows that farrowed in the late evening or overnight, it was the following morning. Pigs were given an ear tag for individual identification when weights were recorded before split-suckling. After the split-suckle treatment was applied, litters were cross fostered within treatment by 24 h after the completion of farrowing. Fallback pigs were identified between d 2 to 12 post-farrowing as small and gaunt pigs too light to compete with their littermates. These pigs were removed from their sow and placed with a nurse sow not included in the study. When fallback pigs were removed from the sow's litter and placed onto a nurse sow, the weight of the pig and the date were recorded.

Individual pig weights were recorded again the day before weaning (average d 20) on all pigs. All preweaning mortalities were recorded, including the date and reason for death. At the time of split-suckling, after litter equalization, and at weaning, litter size was recorded. Pig count at split-suckling included only pigs that were alive at the time of ear tagging and weighing. Preweaning mortality only included pigs that were weighed and tagged and does not include pigs that died before initial weights were taken or fallback pigs that were removed from the litter. The 1,513 litters included in the study all contained 10 pigs or greater.

On a subset of approximately 45 litters per treatment, blood samples were taken from every pig in the litter. Blood samples were collected approximately 24 h after the birth of the first pig in the litter. Three mL of blood were collected from the jugular vein using a non-heparinized blood collection tube (Monoject, Covidien, Minneapolis, MN, USA) and a 20 G × 13 mm needle (Neogen, Lansing, MI, USA). At the time of blood collection, the pig's weight was also recorded. Serum was separated from whole blood through centrifugation at 1,800 × g for 30 min and stored at -80°C until analysis for immunocrit ratio. Briefly, 50 µL of serum was mixed with a 40% ammonium sulfate solution and centrifuged (12,000 × g) in a hematocrit centrifuge tube (Fisher Scientific, Waltham, MA, USA) for 10 min. Immunocrit ratio was calculated by taking the ratio of the precipitate to the length of the serum tube (Vallet et al., 2013)

Additional analysis was conducted to identify if there was a subset of the population where split-suckling positively affected growth performance or reduced preweaning mortality. Additional analyses included determining if there were differences in split-suckle treatment based on litter size, teat count, timing of split-suckle application, or sow parity. Preweaning growth performance and mortality were analyzed on a subset of sows where litter size at split-suckling was greater than functional teat count (n =729). Functional teat count categories were: 14 or less (n = 729) or 15 or more (n = 676). Timing of split-suckling was divided into two categories: split-suckling immediately after farrowing (n = 784) or the following morning for litters that farrowed overnight (n= 223). Sows were divided into four parity groups: parity 1 (n = 339), parity 2 (n = 293), parity 3 to 4 (n = 426), and parity 5 and greater (n= 455).

A subset of pigs, 2,208 pigs split equally across the three treatments (32 pens per treatment) were followed into the nursery to measure postweaning growth performance and mortality. Pigs that were followed into the nursery were selected because they were born the week of intensive blood collection to measure immunocrit ratio. Nursery pens were 1.8 × 3.0 m with feeder space taking up 0.31 m^2, allowing for 0.23 m^2 per pig. Pigs were penned by treatment and fed the same diets in 3 phases. Feed intake was measured on a pen basis using a computerized feeding system (Gestal Evo feeding system, Jyga Technologies, St-Lambert-de-Lauzon, QC, CA). Individual pig weights were taken at the end of the nursery period (48 to 52 d postweaning) before pigs were moved to a finishing facility.

Of the 2,208 pigs that were followed into the nursery, a subset of 882 pigs were followed into the finishing facility (14 pens per treatment). Pigs that had blood samples collected preweaning were selected to be followed into the finisher. During the finisher period, all pigs were fed the same 6 dietary phases. Individual pig feed intake was measured during the finishing period (Nedap Feeders, Nedap, Groenlo, NL). Finisher pens were 2.9 × 5.7 m with 2 computerized feeders (Nedap Feeders, Nedap, Groenlo, NL) in each pen, accounting for 1.2 m^2 each, allowing for 0.67 m^2 per pig of floor space. Before the first marketing event, individual pig weights were taken (81 d after transfer from the nursery). Growth performance, including average daily gain (**ADG**), average daily feed intake (**ADFI**), gain:feed ratio (**G:F**), and mortality were determined for the nursery and finishing periods.

Statistical Analysis

Performance data were analyzed using the lmer function of R software, version 1.4.171 as a randomized complete block design. Sow and litter were considered the experimental unit depending on the response variable. Treatment was a fixed effect. Block (sow parity) and farrowing room were considered random effects. Preweaning mortality and percentage of fallback pigs fostered to nurse sows were analyzed using a binomial distribution. Preweaning mortality was also analyzed by BW category within litter (light, medium, or heavy) using a binomial distribution. To create the light, medium, and heavy BW categories, the distribution of pig BW at split-suckling was divided into three categories. Litter growth performance and mortality were also analyzed on a subset of the population, where litter size at split-suckling was greater than sow functional teat count. Treatment comparisons were determined considering the interaction of the split-suckle treatment and parity as well as the interaction between split-suckle treatment and timing of split-suckling and sow functional teat count. For the analysis of immunocrit ratio, treatment was a fixed effect, and sow was considered a random effect. The nursery and finisher data were analyzed using treatment as a fixed effect with nursery or finisher room included in the model as a random effect. Pen was considered the experimental unit. Results are considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

RESULTS

Overall population

As expected, no differences were observed among split-suckle treatments for sow parity, functional teat count, or weaning age (Table 1). There were no differences in litter size at split-suckling, after litters were equalized, or at weaning (d 20). Litter and pig weight at split-suckling and at weaning and preweaning ADG were not different among treatments. Preweaning mortality from split-suckling to d 2, d 2 to weaning, and split-suckling to weaning was not affected by treatment. There was no difference in the percentage of fallback pigs that were removed and placed with a nurse sow. Preweaning mortality within BW category, light: ≤ 1.2 kg, medium: 1.2 to 1.5 kg, or heavy: ≥ 1.5 kg, was not different among the three split-suckle treatments.

For pigs sampled for immunocrit ratio, there were no differences in pig BW or weight gain at any time point in the study (Table 2). No differences were observed among the three treatments for immunocrit ratio, indicating similar colostrum intake among pigs.

Litter size at d 1 greater than functional teat count

A subset of the population was analyzed to determine the effect of split-suckling when litter size was greater than functional teat count (237 to 250 sows per treatment; Table 3). Within this subset, there were no differences in parity or functional teat count, litter size at split-suckling, after litter equalization, or weaning. No differences were observed for litter weight or pig BW at split-suckling or weaning or pig ADG. Preweaning mortality from split-suckling to d 2 was greater ($P < 0.05$) in litters not split-suckled compared to litters split-suckled based on birth order, with litters split-suckled based on body weight intermediate. However, preweaning mortality from split-suckling to weaning, as well as the percentage of fallback pigs placed with nurse sows were not different among treatments.

Interactions between treatment and functional teat count

Sows were divided into two functional teat count categories, sows that had 14 or less functional teats and sows that had 15 or more functional teats (Table 4). No treatment differences nor interactions between split-suckle treatment and functional teat count were observed. Pigs weaned from sows with 15 or more functional teats had a lower ($P < 0.05$) BW at weaning and preweaning ADG compared to pigs weaned from sows with 14 or less functional teats. However, no differences in litter weight at weaning were observed.

Interactions between treatment and timing of split-suckling

The timing of split-suckling was analyzed by comparing litters that were split-suckled the same day they were born to those that were split-suckled the day after farrowing (Table 5). This analysis does not include litters on the control treatment that were not split-suckled. There were no interactions observed between treatment and split-suckle timing. A main effect of split-suckle time was observed for pig ADG, where litters split-suckled directly after the completion of farrowing had greater ($P < 0.05$) ADG compared to litters that were split-suckled the morning after birth (litters born in the evening or overnight).

Interactions between treatment and parity

Sow parity was divided into four groups: parity 1, 2, 3 to 4, and parity 5+ sows. There were no interactions between treatment and parity for any response criteria except for the percentage of fallback pigs removed and placed with nurse sows ($P < 0.05$). In parity 1 sows, litters not split-suckled had a lower ($P < 0.05$) percentage of fallback pigs compared to litters split-suckling by birth order or body weight. However, in parity 2, 3 to 4, and 5+ sows, the percentage of fallback pigs was not different among treatments.

Parity group differences

Parity 1 sows had a smaller litter size and lighter pig and litter weights at split-suckling and weaning ($P < 0.05$) compared to all other parity groups (Table 6). Parity 5+ litters at split-suckling and weaning were lighter than parity 2 and 3 to 4 litters. Pigs from parity 2 sows were heaviest at split-suckling ($P < 0.05$), with pigs from parity 3 to 4 sows being heavier than parity 5+ pigs. Pigs from parity 3 to 4 sows were heavier at weaning compared to pigs from parity 1 and 5+ sows ($P < 0.05$). Pig ADG was greater in pigs from parity 3 to 4 and 5+ sows than parity 1 and 2, and greater in parity 2 than parity 1 ($P < 0.05$).

Interaction between treatment and BW on immunocrit ratio

The interaction between treatment and piglet BW at split-suckling was evaluated to determine whether immunocrit ratio differed by treatment across BW categories (Table 7). Immunocrit ratio was not affected by treatment split-suckling BW, or their interaction, indicating that immunocrit ratio was consistent across all weight groups. Pigs weighing ≥1.5 kg at split-suckling were heavier at all time points and gained more preweaning than pigs weighing < 1.5 kg ($P < 0.05$). Pigs weighing 1.2 to 1.5 kg at split-suckling were also heavier and gained more at all time points than pigs weighing < 1.2 kg at split-suckling.

Postweaning pig performance

A subset of 2,208 pigs, represented equally across the three treatments, were followed into the nursery (Table 8). Starting BW in the nursery was greater for pigs split-suckled by BW compared to pigs not split-suckled, with pigs split-suckled by birth order intermediate. However, because there was no difference in BW at weaning for the overall data when including all pig weights at weaning, this difference was likely due to chance. Final BW at the end of the nursery (d 48 to 52 postweaning) was not different among treatments. No differences in ADG, ADFI, G:F, or mortality were observed during the nursery period. A subset of 882 pigs that were followed into the nursery were also followed into the finisher phase. No differences in starting or final BW before the first marketing event (d 81 post nursery) were found. No differences were observed in growth or mortality.

DISCUSSION

One of the primary components of colostrum is immunoglobulins (Verstegen et al., 1998). Immunoglobulins are proteins that provide passive immunity from the sow to the new born pig, but are not able to pass through the sow's placenta (Dividich et al., 2005). Immunoglobulin concentrations in colostrum rapidly decrease after farrowing, with immunoglobulin G levels being approximately 52 mg/mL in colostrum and 10 mg/mL in milk at 24 h post farrowing (Loisel et al., 2013).

Split-suckling is a strategy that attempts to ensure that all pigs within a litter, especially in large litters, consume adequate colostrum (Arnaud et al., 2023b). Split-suckling strategies reported in the literature aim to ensure adequate colostrum intake, particularly for light birth weight pigs or those born later in the birth order. (Arnaud et al., 2023b). Colostrum quality declines rapidly as time from the start of parturition increases (Farmer, 2015). Thus, pigs born later in the birth order receive lower quality colostrum as well as reduced time to consume colostrum compared to pigs born earlier in the birth order. The split-suckle treatment based on birth order was designed to attempt to ensure adequate colostrum intake for pigs born later in the litter by reducing competition.

Multiple split-suckle protocols are used in commercial swine production, and data does not indicate one best protocol that leads to reduced preweaning mortality. This variability is reflected when comparing the results of the current study to previous studies. Vallet (2019) observed a tendency for a reduction in preweaning mortality, 15.1 vs 11.7%, when litters were split-suckled by removing the first five pigs born for up to 4 h after the birth of the 9th pig in the litter, whereas the present study found no differences. Vallet (2019) visually assessed pigs via stomach palpation to confirm nursing before removal from the sow. Results suggest that ensuring pigs have nursed before split-suckling may be important, though standardizing on-farm visual assessments for colostrum intake is challenging. In agreement with our results, Morton et al. (2019) observed that split-suckling by birth order resulted in no differences in preweaning mortality or growth performance when split-suckling by removing pigs born in the first half of the birth order for 90 min. Because birth weight influences colostrum intake, split-suckling can also be performed based on pig weight.

Devillers et al. (2007) observed that colostrum intake of newborn pigs is correlated with birth weight, with heavier pigs having increased colostrum consumption. Therefore, the split-suckle treatment based on BW was designed to ensure adequate colostrum intake for light weight pigs by reducing nursing competition. For the split-suckle treatment based on BW, the heaviest 8 pigs were removed from the sow for 90 min because this allowed the lighter pigs remaining on the sow to nurse for at least two nursing cycles. Colostrum flow is continuous until 10 to 11 h after the first pig is born, after that, sows let down colostrum every 40 to 50 min (Lewis and Hurnik, 1985). Huser et al. (2015) observed that removing the largest pigs in the litter for 2 h increased survival of small pigs weighing less than 850 g by 13% compared to no split-suckling or a rotational protocol where the litter was divided into two groups and alternately removed for 1 h over a 4 h period. However, no differences in pig survivability were observed for pigs weighing greater than 850 g. The study herein did not find any differences among treatments for preweaning mortality among light pigs ≤ 1.2 kg. Studies by Huser et al. (2015) and Vallet (2019) observed improvements in preweaning mortality when pigs were removed for 2 h or longer, which contrasts with the current results, where pigs were removed for either 45 min or 90 min based on split-suckle treatment. In agreement with Donovan and Dritz (2000), Morton et al.

(2019), Vandaele et al. (2020), Arnaud et al. (2023a), and Romero et al. (2023), no differences in preweaning mortality were observed when split sucking based on BW.

Vandaele et al. (2020) and Romero et al. (2023) observed that split-suckling by BW reduced pig preweaning growth rate. Romero et al. (2023) observed a reduction in ADG of 20 g/d when pigs were split-suckled based on BW. The split-suckling protocol used by Romero et al. (2023) involved removing pigs with a birth weight greater than 950 g from the sow for 60 min. These pigs were removed in two groups, with each group being removed for 60 min, two times. Vandaele et al. (2020) split-suckled by removing the heaviest pigs from the first half of the birth order for 3 h, followed by the heaviest from the second half of the birth order for 3 h, once daily for the first 3 d after birth. This resulted in decreased preweaning growth rate during the first 3 d after farrowing compared to no split-suckling or a single split-suckling event performed only on the day of birth. The Vandaele et al. (2020) study indicates that split-suckling for multiple days may hurt growth performance of pigs removed from the sow. Arnaud et al. (2023a) and Morton et al. (2019) observed that split-suckling based on BW did not improve pig growth performance or preweaning mortality. Arnaud et al. (2023a) evaluated the effects of split sucking by removing the six heaviest pigs in the litter for 60 min and then removing the same six pigs for 60 min again 90 min later, while Morton et al. (2019) removed the six heaviest pigs in the litter for 90 min one time. The literature indicates that split-suckling based on birth order or BW results in variable responses, with the majority of studies finding no differences compared to no split-suckling.

Devillers et al. (2004) observed a linear relationship between colostrum intake and pig BW gain during the first 24 h after farrowing. Romero et al. (2023) observed that split-suckling increased gain within the first 24 h after birth. However, Vandaele et al. (2020) observed that split-suckling resulted in lower pig gain during the first 24 h after birth. In contrast, the current study observed no differences in gain within the first 24 h after birth, which is in agreement with the results of Morton et al. (2019).

In addition to growth performance, several studies also assessed colostrum intake using immunocrit ratio as an indicator. Immunocrit ratio is a measure of pig serum immunoglobulin level and is used as an indicator of colostrum intake of the pig (Vallet et al., 2013). A higher immunocrit ratio indicates a higher colostrum intake. Similar to the current study, Morton et al. (2019) and Huser et al. (2015) found no differences in immunocrit ratio between pigs split-suckled and not split-suckled. Vandaele et al. (2020) and Arnaud et al. (2023a) estimated colostrum intake using equations developed by Theil et al. (2014) and found no differences between split-suckling and no spilt-suckling. Vallet (2019) found that split-suckling by removing the first 5 pigs born for 4 h increased immunocrit ratio in pigs weighing less than 1.0 kg but not in pigs weighing more than 1.0 kg. In the current study, split-suckling did not increase immunocrit ratio in light birth weight pigs weighing less than 1.2 kg. There was no interaction between treatment and BW category for immunocrit ratio, indicating that split-suckling by BW did not affect colostrum intake of lighter weight pigs that remained on the sow during split-suckling based on BW. Similar to the present study, Morton et al. (2019) also evaluated pig birth weights in three categories, light, < 1.11 kg, medium, $1.11 < \times \leq 1.45$ kg, and heavy, ≥ 1.5 kg, and found no interaction between treatment and BW category for immunocrit ratio. The lack of difference in immunocrit ratio and pig gain within the first 24 h after birth in the current study indicates that the split-suckle protocols applied in this study did not have an effect on colostrum intake of pigs.

Because of potential confounding variables in split-suckling protocols in the literature (parity, teat count relative to litter size, timing of split-suckling), additional analysis was conducted to determine if split-suckling had a positive effect on subsets of the population. For litters where pig count at split-suckling was greater than functional teat count, split-suckling by birth order resulted in reduced preweaning mortality from split-suckling to d 2 compared to no split-suckling. The average litter size in this subset of the population was 16.9 vs 15.0 in the whole study population, which indicates that split-suckling may be more effective in large litters. However, no significant differences in mortality were observed from split-suckling to weaning, but litters not split-suckled had numerically higher mortality. When looking at the reason for mortality in this population from split-suckling to d 2, litters not split-suckled had a higher percentage of pigs laid on by the sow compared to litters split-suckled by birth order. Donovan and Dritz (2000) evaluated two split-suckling strategies, removing the heaviest 50% of the litter for two h or removing the heaviest 50% of the litter for 2 h, followed by removing the lightest 50% for an additional 2 h. The split-suckling strategies evaluated were effective in reducing variation in pig ADG, but only in litters with more than nine pigs. This reduction in variation contributed to more uniform pigs at weaning. Collectively, these findings suggest that the greatest potential to gain a benefit from split-suckling is in larger litters. However, in our study, split-suckling did not significantly influence mortality between split-suckling and weaning.

The interaction between split-suckle treatment and parity was assessed because primiparous sows produce less colostrum than multiparous sows (Devillers et al., 2007; Ferrari et al., 2014). Thus, split-suckling may be more effective in gilt litters compared to litters from multiparous sows due to the lower gilt colostrum production. Romero et al. (2023) observed that split-suckling was more effective in gilt versus multiparous sow litters, with pigs from gilts that were split-suckled having greater gain within the first 24 h after birth compared to litters from multiparous sows that were split-suckled. However, no other treatment by parity interactions were observed in the study (Romero et al., 2023). In agreement with the results of the study herein, Romero et al. (2023) observed that split-suckling was not more effective in litters born from primiparous vs multiparous sows for overall preweaning ADG or mortality.

Because colostrum quality changes once farrowing begins, an analysis between split-suckling performed immediately after farrowing versus the following morning for litters that farrowed overnight was conducted. No differences in pre-wean mortality were observed between litters split-suckled directly after the completion of farrowing versus those split-suckled the following morning for litters that farrowed overnight. Pigs split-suckled directly after the completion of farrowing had a greater preweaning ADG compared to litters from sows that farrowed in the evening or overnight that were split-suckled the following morning after birth. The reason for this is that pigs that were split-suckled the next morning had more time to consume colostrum, making them heavier at the time of split-suckling compared to those weighed and split-suckled immediately after birth, which led to a lower ADG. It is important to note that all pigs were split-suckled within 18 h of the birth of the first pig, within the typical time of colostrum production (Quesnel et al., 2012). Due to the induction protocol used on farm, the majority of litters were split-suckled the day of birth (784 litters the same day of birth vs 223 litters the following morning).

Wiegert and Knauer (2019) observed that sow colostrum production and pig colostrum consumption increased as functional teat count increased. Due to the potential effect of functional teat count on colostrum production, the effect of functional teat count was analyzed, and there was no interaction between teat count and treatment. This suggests that split-suckling does not result in a positive effect when functional teat count is below 14 teats vs above 15 teats. Pigs weaned from sows with 14 or less functional teats had greater preweaning ADG and weaning weight compared to pigs weaned from sows with 15 or more functional teats. This is likely because sows with 15 or more teats had numerically greater litter size at weaning. Overall, treatment responses were not affected by the interaction between treatment and parity, spilt-suckle timing, or teat count, indicating that the effectiveness of split-suckling is not dependent on these factors.

Colostrum intake has shown long-term effects on pig growth performance, with pigs consuming greater than 290 g of colostrum gaining 2 kg more by 6 weeks of age compared to pigs consuming less than 290 g of colostrum (Devillers et al., 2011). Declerck et al. (2016) observed that as total colostrum intake increased from 0 to 899 g, preweaning and nursery mortality decreased, illustrating the long-term effects of colostrum intake. The greatest improvement occurred when total intake rose from 0 to 228 g, with more modest reductions observed as colostrum intake increased above 228 g. In their study, there also was a positive correlation between colostrum intake and pig weight at weaning and the end of the nursery and finishing period. Due to the long-term impact of colostrum intake, postweaning growth performance and mortality were evaluated.

Only Arnaud et al. (2023a) and Romero et al. (2023) have evaluated the effects of split-suckling on postweaning growth performance. Consistent with the present findings, Romero et al. (2023) observed no effect of split-suckling on postweaning growth compared to no split-suckling. In contrast, Arnaud et al. (2023a) observed a 1.8 kg reduction in market weight in pigs that were split-suckled, attributed to lower weaning weights. Arnaud et al. (2023a) split-suckled by removing the six heaviest pigs for 60 min twice, suggesting that removing pigs multiple times during split-suckling can hurt pig growth performance, which was also observed in the results of the study by Vandaele et al. (2020). However, the current study found that the split-suckling strategies implemented did not affect lifetime growth performance or mortality, likely due to the lack of treatment differences in colostrum intake.

In conclusion, the split-suckling protocols evaluated in this study, split-suckling by birth order or body weight, did not affect preweaning or postweaning growth performance or mortality compared to no split-suckling. The lack of significant differences is likely due to similar colostrum intake across groups, as suggested by pig immunocrit ratios. Findings from this study, along with previous literature, suggest that the effectiveness of split-suckling protocols is variable and split-suckling does not consistently reduce preweaning mortality. Future studies should focus on evaluating other ways to invest time during the early postnatal period to improve pig livability.

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Table 3.1. The effect of split-suckle protocol on litter and pig growth performance and preweaning mortality1

	Control	Split-suckle protocol[2]		SEM	$P =$
		Birth order	Birth weight		
No. of sows and litters, n	506	504	503		
Parity	3.6	3.6	3.6	0.88	0.995
Teat count, n[3]	14.7	14.5	14.6	0.06	0.121
Wean age, d	20.0	20.0	20.0	0.13	0.983
Litter size, n					
d 1	14.9	15.0	15.0	0.46	0.889
Equalization	14.5	14.6	14.6	0.17	0.638
Weaning	12.3	12.2	12.4	0.25	0.733
Litter weight, kg					
d 1	20.2	20.3	20.4	0.99	0.704
Weaning	67.9	67.6	68.4	2.78	0.536
Mean pig BW[4], kg					
d 1	1.36	1.36	1.37	0.039	0.849
Weaning	5.51	5.53	5.52	0.161	0.843
Pig ADG, g/d	219	220	219	7.0	0.837
Preweaning mortality, %					
Split-suckle to d 2	2.5	2.0	2.2	0.37	0.178
Split-suckle to weaning	10.6	10.6	10.4	0.75	0.922
Fallback pigs %[5]	6.1	7.1	6.5	1.02	0.111
Preweaning mortality by BW[4] category, %					
d 1 to weaning					
Light, ≤ 1.2 kg	15.7	17.3	16.3	1.30	0.411
Medium, 1.2 < × ≤ 1.5 kg	8.8	8.4	8.7	0.68	0.871
Heavy, ≥ 1.5 kg	7.2	6.4	6.6	0.56	0.550

[1]A total of 1,513 mixed-parity sows (Line 241, DNA, Columbus NE) and litters were used from birth until weaning.

[2]Sows and their litter were allotted to one of three treatments. Control litters were not split-suckled. In the split-suckling treatment based on birth order, the first eight pigs born were removed from the sow for 45 min then placed back with the sow and the remaining pigs were removed for 45 min. In the split-suckling treatment based on birth weight, the eight heaviest piglets were removed from the sow for 90 min before being returned.

[3]Teat count includes only functional teats.

[4]BW- body weight.

[5]Fallback pigs unable to compete with littermates for milk consumption were removed from the litter and placed on nurse sows.

Table 3.2. The effect of split-suckle protocol on pig weight gain and immunocrit ratio[1]

		Split-suckle protocol[2]			
	Control	Birth order	Control	SEM	$P =$
No. of sows and litters, n	45	45	44		
Parity	3.6	3.8	3.6	0.33	0.862
Mean pig BW[3], g					
d 1	1.32	1.38	1.37	0.027	0.330
d 2	1.38	1.42	1.41	0.031	0.636
Weaning	5.28	5.17	5.34	0.086	0.358
Pig gain, g					
d 1 to 2	56	40	43	9.4	0.440
d 1 to weaning	3,928	3,769	3,947	79.1	0.212
Immunocrit ratio[4]	0.076	0.079	0.078	0.0028	0.784

[1]Blood samples were collected on 134 whole litters to determine immunocrit ratio 24 h after the birth of the first pig in the litter. At the time of blood collection, pig weight was also recorded.

[2]Sows and their litter were allotted to one of three treatments. Control litters were not split-suckled. In the split-suckling treatment based on birth order, the first eight pigs born were removed from the sow for 45 min then placed back with the sow and the remaining pigs were removed for 45 min. In the split-suckling treatment based on birth weight, the eight heaviest piglets were removed from the sow for 90 min before being returned.

[3]BW- body weight.

[4]A 3 mL blood sample was taken from each pig on approximately 45 litters per treatment. Serum was pulled from whole blood and used to determine immunocrit ratio.

Table 3.3. The effect of split-suckle protocol on litter and pig growth performance and preweaning mortality for sows that had greater pig count than functional teat count at d 1[1]

		Split-suckle protocol[2]			
	Control	Birth order	Birth weight	SEM	*P* =
No. of sows and litters, n	237	252	240		
Parity	4.0	3.8	3.9	0.87	0.999
Teat count, n[3]	14.4	14.2	14.2	0.07	0.092
Litter size, n					
d 1	16.8	16.8	17.0	0.32	0.829
Equalization	15.0	15.1	15.3	0.26	0.716
Weaning	12.3	12.3	12.4	0.28	0.902
Litter weight, kg					
d 1	22.2	22.0	22.5	0.76	0.219
Weaning	67.8	68.0	68.9	2.81	0.553
Mean pig BW[4], kg					
d 1	1.32	1.32	1.33	0.029	0.490
Weaning	5.47	5.47	5.49	0.159	0.853
Pig ADG[5], g/d	206	208	208	6.80	0.745
Preweaning mortality, %					
Split-suckle to d 2	3.3[a]	2.4[b]	2.5[ab]	0.47	0.025
Split-suckle to weaning	12.4	11.7	11.6	0.93	0.659
Fallback pigs, %[6]	7.9	9.0	8.4	1.17	0.371

[a,b,c]Means in the same row that do not have a common superscript differ ($P < 0.05$).

[1]A total of 729 mixed-parity sows (Line 241, DNA, Columbus NE) and litters were used from birth until weaning.

[2]Sows and their litter were allotted to one of three treatments. Control litters were not split-suckled. In the split-suckling treatment based on birth order, the first eight pigs born were removed from the sow for 45 min then placed back with the sow and the remaining pigs were removed for 45 min. In the split-suckling treatment based on birth weight, the eight heaviest piglets were removed from the sow for 90 min before being returned.

[3]Teat count includes only functional teats.

[4]BW- body weight.

[5]ADG- average daily gain.

[6]Fallback pigs unable to compete with littermates for milk consumption were removed from the litter and placed on nurse sows.

Table 3.4. Interactive means between teat count and split-suckle protocol on litter and pig growth performance and preweaning mortality[1]

	Control		Split-suckle protocol[2]: Birth order		Split-suckle protocol[2]: Birth weight			*P* =		
Teat Count[3]:	≤ 14	≥ 15	≤ 14	≥ 15	≤ 14	≥ 15	SEM	Treatment × teat count	Treatment	Teat count
No. of sows and litters, n	250	236	283	196	267	217				
Parity	3.6	3.3	3.6	3.3	3.5	3.4	0.17	0.563	0.912	0.108
Teat count, n[3]	13.8	15.6	13.8	15.6	13.7	15.6	0.04	0.855	0.837	0.000
Litter size, n										
d 1	14.9	15.1	15.1	15.1	15.2	14.9	0.26	0.663	0.673	0.718
Equalization	14.5	14.4	14.6	14.6	14.7	14.7	0.27	0.991	0.827	0.844
Wean	12.1	12.3	12.1	12.2	12.2	12.5	0.25	0.922	0.943	0.467
Litter weight, kg										
d 1	20.2	20.3	20.2	20.6	20.6	20.1	1.02	0.143	0.324	0.662
Weaning	68.1	67.2	67.6	67.5	68.4	68.1	2.88	0.864	0.686	0.396
Mean pig BW[4], kg										
d 1	1.37	1.36	1.35	1.37	1.37	1.36	0.042	0.343	0.311	0.625
Weaning	5.58	5.42	5.55	5.47	5.54	5.45	0.169	0.567	0.733	0.003
Pig ADG[5], g/d	222	214	221	217	219	216	7.2	0.425	0.645	0.003
Preweaning mortality, %										
Split-suckle to d 2	2.7	2.3	2.1	1.9	2.2	2.1	0.42	0.709	0.219	0.327
Split-suckle to weaning	10.8	10.5	11.4	9.5	10.7	9.7	0.90	0.455	0.647	0.658
Fallback pigs, %[6]	6.8	5.5	7.1	7.0	6.8	6.3	0.86	0.313	0.928	0.044

[1]A total of 1,513 mixed-parity sows (Line 241, DNA, Columbus NE) and litters were used from birth until weaning.

[2]Sows and their litter were allotted to one of three treatments. Control litters were not split-suckled. In the split-suckling treatment based on birth order, the first eight pigs born were removed from the sow for 45 min then placed back with the sow and the remaining pigs were removed for 45 min. In the split-suckling treatment based on birth weight, the eight heaviest piglets were removed from the sow for 90 min before being returned.

[3]Teat count includes only functional teats.

[4]BW- body weight.
[5]ADG- average daily gain.
[6]Fallback pigs unable to compete with littermates for milk consumption, were removed from the litter and placed on nurse sows.

Table 3.5. Interactive means between split-suckle time and split-suckle protocol on litter and pig growth performance and preweaning mortality[1]

	Split-suckle protocol[2]					*P* =		
	Birth order		Birth weight					
Split-suckle time[3]:	Same day	Next day	Same day	Next day	SEM	Treatment × split-suckle time	Treatment	Split-suckle time
No. of sows and litters, n	404	100	380	123	---	---	---	---
Parity	3.6	3.6	3.6	3.6	0.88	0.854	0.921	0.933
Teat count, n[4]	14.6	14.5	14.6	14.5	0.38	0.801	0.836	0.924
Litter size, n								
d 1	15.0	15.0	15.2	14.9	0.55	0.652	0.769	0.999
Equalization	14.5	14.8	14.6	14.9	0.35	0.971	0.728	0.532
Weaning	12.3	12.2	12.4	12.4	0.37	0.864	0.452	0.765
Litter weight, kg								
d 1	20.2	20.5	20.2	21.1	1.06	0.217	0.770	0.433
Weaning	67.9	67.1	68.4	68.8	3.02	0.461	0.533	0.478
Mean pig BW[5], kg								
d 1	1.36	1.38	1.36	1.39	0.043	0.479	0.840	0.284
Weaning	5.53	5.49	5.51	5.54	0.167	0.237	0.327	0.325
Pig ADG[6], g/d	222	212	220	215	7.0	0.290	0.264	0.002
Preweaning mortality, %								
Split-suckle to weaning	10.8	9.4	10.6	9.2	1.00	0.965	0.725	0.141
Fallback pigs, %[7]	7.2	7.5	6.8	6.8	1.04	0.725	0.439	0.624

[1]A total of 1,007 mixed-parity sows (Line 241, DNA, Columbus NE) and litters were used from birth until weaning.

[2]Sows and their litter were allotted to one of three treatments. In the split-suckling treatment based on birth order, the first eight pigs born were removed from the sow for 45 min then placed back with the sow and the remaining pigs were removed for 45 min. In the split-suckling treatment based on birth weight, the eight heaviest piglets were removed from the sow for 90 min before being returned.

[3]Split-suckle time refers to if a litter was split-suckled the same day they were born or the following morning (litters born overnight).

[4]Teat count includes only functional teats.

[5]BW- body weight.

[6]ADG- average daily gain.

[7]Fallback pigs unable to compete with littermates for milk consumption, were removed from the litter and placed on nurse sows.

Table 3.6. Main effect of sow parity[1]

	Parity					
	1	2	3 to 4	5 +	SEM	*P* =
No. of sows and litters, n	339	293	426	455		
Parity						
Teat count, n[2]	14.6	14.6	14.6	14.5	0.05	0.085
Wean age, d	19.9[bc]	20.1[ab]	20.2[a]	19.9[c]	0.12	0.002
Litter size, n						
d 1	13.6[b]	15.0[a]	15.7[a]	15.6[a]	0.23	0.001
Equalization	14.3	14.8	14.8	14.7	0.22	0.505
Weaning	12.1	12.9	12.5	11.8	0.21	0.123
Litter weight, kg						
d 1	17.5[c]	21.6[a]	21.8[a]	20.2[b]	0.20	0.001
Weaning	61.2[c]	71.6[a]	72.1[a]	66.0[b]	0.80	0.001
Mean pig BW[3], kg						
d 1	1.30[c]	1.46[a]	1.40[b]	1.30[c]	0.011	0.001
Weaning	5.07[c]	5.64[ab]	5.76[a]	5.62[b]	0.060	0.001
Pig ADG[4], g/d	200[c]	219[b]	228[a]	228[a]	2.3	0.001
Preweaning mortality, %						
d 1 to d 2	1.9	1.6	2.8	2.8	0.23	0.071
d 1 to weaning	11.9	9.1	10.6	12.5	0.53	0.084
Fallback pigs %[5]	5.2[c]	5.4[bc]	6.7[b]	9.3[a]	0.92	0.001

[1]A total of 1,513 mixed-parity sows (Line 241, DNA, Columbus NE) and litters were used from birth until weaning.

[2]Teat count includes only functional teats.

[3]BW- body weight.

[4]ADG- average daily gain.

[5]Fallback pigs unable to compete with littermates for milk consumption, were removed from the litter and placed on nurse sows.

Table 3.7. Interactive means between d 1 pig weight and split-suckle protocol on immunocrit ratio and pig gain[1]

	Split-suckle protocol												
	Control[2]			Birth order			Body weight				*P* =		
BW:	< 1.2 kg	1.2 < × ≤ 1.5 kg	≥ 1.5 kg	< 1.2 kg	1.2 < × ≤ 1.5 kg	≥ 1.5 kg	< 1.2 kg	1.2 < ×≤ 1.5 kg	≥ 1.5 kg	SEM	Treat-ment × BW	Treat-ment	BW
Piglets, n	228	249	176	198	210	217	210	203	229				
Parity	3.6	3.6	3.7	3.9	3.8	3.8	3.6	3.6	3.6	0.34	0.999	0.860	0.985
Immunocrit ratio[3]	0.073	0.078	0.078	0.076	0.082	0.078	0.077	0.079	0.078	0.0035	0.863	0.636	0.163
Mean pig BW[4], kg													
d 1	1.05	1.34	1.65	1.05	1.34	1.68	1.04	1.35	1.67	0.011	0.293	0.829	<0.001
d 2	1.10	1.40	1.69	1.09	1.40	1.70	1.10	1.40	1.70	0.017	0.959	0.922	<0.000
Wean	4.66	5.21	6.00	4.49	5.09	5.72	4.63	5.36	5.87	0.100	0.207	0.437	<0.001
Pig gain, g													
d 1 to 2	53	63	49	42	57	24	53	48	30	11.7	0.739	0.354	0.522
d 1 to weaning	3,591	3,870	4,351	3,416	3,743	4,041	3,550	4,004	4204	98.4	0.166	0.410	<0.001

[1]Blood samples were collected on 134 whole litters, approximately 45 litter per treatment to determine immunocrit ratio 24 h after the birth of the first pig in the litter.

[2]Sows and their litter were allotted to one of three treatments. Control litters were not split-suckled. In the split-suckling treatment based on birth order, the first eight pigs born were removed from the sow for 45 min then placed back with the sow and the remaining pigs were removed for 45 min. In the split-suckling treatment based on birth weight, the eight heaviest piglets were removed from the sow for 90 min before being returned.

[3]A 3 mL blood sample was taken from each pig on approximately 45 litter per treatment. Serum was seperated from whole blood and used to determine immunocrit ratio.

[4]BW- body weight.

Table 3.8. The effect of split-suckle protocol on nursery and finisher pig performance[1]

	Control[1]	Split-suckle protocol Birth order	Body weight	SEM	P =
Nursery[2]					
Pens, n	32	32	32	---	---
Starting BW[3], kg	5.1[b]	5.1[ab]	5.3[a]	0.05	0.020
Final BW[3] (49 d postweaning), kg	25.2	25.0	25.1	0.29	0.839
ADG[4], g	400	400	394	6.1	0.700
ADFI[5], g	513	517	516	9.1	0.940
G:F[6]	0.78	0.78	0.77	0.010	0.549
Mortality, %	4.5	3.1	4.1	0.008	0.400
Finisher[7]					
Pens, n	14	14	14	---	---
Starting BW[3], kg	25.5	24.8	27.8	0.54	0.137
Final BW[3] (77 d post-nursery), kg	102.5	102.9	104.3	1.09	0.332
ADG[4], kg	0.97	0.97	1.00	0.021	0.148
ADFI[5], kg	2.41	2.39	2.44	0.030	0.316
G:F[6]	0.40	0.41	0.41	0.008	0.576
Mortality, %	3.7	4.1	1.7	0.012	0.200
Removals, %	2.7	3.4	2.7	1.057	0.800
Mortality + removals, %	6.4	7.7	4.5	1.824	0.300

[1]Sows and their litter were allotted to one of three treatments. Control litters were not split-suckled. In the split-suckling treatment based on birth order, the first eight pigs born were removed from the sow for 45 min then placed back with the sow and the remaining pigs were removed for 45 min. In the split-suckling treatment based on birth weight, the eight heaviest piglets were removed from the sow for 90 min before being returned.

[2]A subset of pigs, 2,208, were used to evaluate nursery growth performance and mortality.

[3]BW- body weight.

[4]ADG- average daily gain.

[5]ADFI- average daily feed intake.

[6]G:F- gain to feed ratio.

[7]A subset of pigs, 882, were used to evaluate finishing growth performance and mortality.

Chapter 4 - Effect of feed intake on litter growth and sow body weight from farrowing to weaning

ABSTRACT

A retrospective analysis was conducted to determine the relationship between lactation average daily feed intake (ADFI) and litter average daily gain (ADG) and sow body weight (BW) change over lactation. Data from 991 gilts and 3,393 multiparous sows across eight studies were used. Gilts and multiparous sow ADFI were categorized into quintiles, and linear and quadratic orthogonal polynomial contrasts were tested to determine the relationship between lactation ADFI and sow and litter performance. Gilts lost less weight (quadratic, $P < 0.05$) from farrow to weaning as lactation feed intake increased with the largest change in BW loss occurring between gilts with an ADFI of ≤ 5.30 and between 5.30-5.90 kg/d. In multiparous sows, BW change from farrow to weaning shifted from weight loss to gain (linear, $P < 0.05$) with increasing ADFI. Gilts had greater body weight loss during lactation compared to multiparous sows, with over half of the multiparous sows in the analysis gaining body weight. In both gilts and multiparous sows, increasing ADFI increased (linear; $P < 0.05$) litter ADG as well as litter size at weaning. Regression equations were developed to predict litter ADG and sow BW change for gilts and multiparous sows over lactation using backward stepwise regression. Lactation ADFI and litter ADG accounted for the majority of variation in maternal BW change over lactation, and litter size at weaning accounted for the majority of variation in litter ADG. Regression equations indicate that a one kg increase in ADFI increased litter ADG by 107 and 60 g and decreased BW loss by 4.74 and 5.19 kg for gilts and multiparous sows, respectively, when all other variables are held constant. At similar ADFI levels, multiparous sows may lose, maintain, or gain body weight during lactation. Sows that have both high feed intake and lose

BW during lactation have greater litter ADG compared to sows with similar feed intake that gain BW during lactation. The analysis indicates that while increased feed intake during lactation improves both litter growth and reduces sow BW change, ADFI does not fully explain the variation in performance. The analysis indicates that over half of the multiparous sows gain BW from farrow to weaning, while the majority of gilts lose BW. For both gilts and multiparous sows, gilts and sows with similar ADFI that lose BW over lactation have greater litter ADG compared to those that gain BW during lactation.

List of abbreviations

AA, amino acid

ADFI, average daily feed intake

ADG, average daily gain

BW, body weight

NE, net energy

WSI, wean to service interval

INTRODUCTION

Because lactation feed intake affects litter growth, sow body condition, and subsequent reproductive performance (Eissen et al., 2003), the goal of feeding sows during lactation is to maximize feed intake for milk production and reduce mobilization of body reserves (Tokach et al., 2019). When feed intake during lactation does not meet a sow's nutrient requirement, sows will mobilize body reserves to compensate for deficient nutrient intake (Clowes et al., 2003). Gourley et al. (2017) observed that at deficient Lys intake levels, sows mobilized body reserves to support litter growth, resulting in no differences in litter growth rate. However, high body weight (BW) loss can have negative consequences on subsequent reproduction. Multiple studies have observed that an increase in sow BW loss during lactation leads to an increase in wean to service interval (WSI; Eissen et al., 2003; Thaker and Bilkei, 2005; Strathe et al., 2017). However, recent research indicates that sows are not mobilizing body reserves even when they are deficient in Lys or other nutrients, resulting in lower litter growth performance (Liu et al., 2020; Spinler et al., 2024; 2025). Muller et al. (2022) noted that, contrary to previous findings indicating that sows mobilize body reserves when nutrient intake is insufficient (Revell et al., 1998; Eissen et al., 2003; Costermans et al., 2020), modern sows are not mobilizing body reserves in response to inadequate nutrient intake. Potential reasons include higher lactation feed intake, resulting in decreased needs to mobilize body reserves, and improvements in genetics leading to leaner, more efficient sows with a lower basal metabolic requirement.

There is a relationship between feed intake, milk production, and litter growth performance, as increased energy intake drives milk yield and, consequently, improves litter growth (Strathe et al., 2017; Hawe et al., 2020; Estrada et al., 2024). Strathe et al. (2017) developed a regression equation and determined that a one kg increase in average daily feed intake (ADFI) can increase litter average daily gain (ADG) by 220 to 440 g/d, depending on sow parity. Individual amino acids (AA) and energy intake, not just total feed intake, can affect milk yield and milk composition (Theil et al., 2014). Therefore, ensuring sows consume adequate feed during lactation is critical for meeting both energy and AA requirements and supporting optimal litter growth.

Sow lactation feed intake has increased by roughly 30% over the last 30 years (Rodríguez et al., 2023), leading to increased sow productivity. Sows classified as having a rapid increase in ADFI over lactation, characterized by an early peak before day 10 of lactation with no subsequent decline, averaged 5.87 kg of feed intake (Koketsu et al. 1996b). In contrast, sows classified as having a rapid increase in ADFI using the same characterization by Estrada et al. (2024) had an ADFI of 7.90 kg, a 25% increase compared to Koketsu et al. (1996b). Given the high feed intake levels now observed in commercial herds, it remains uncertain whether the relationship between ADFI, litter ADG, and sow BW change during lactation is linear or if a breakpoint exists beyond which additional intake no longer benefits sow or litter performance. High lactation feed intake may exceed nutrient requirements for maintenance and maximizing litter ADG for some sows, leading to sow weight gain and increased nutrient excretion. Due to recent increases in sow feed intake, higher litter growth, and variations in how sows mobilize body reserves in response to low nutrient intake, the objective of this retrospective analysis was to quantify the relationship between lactation ADFI, litter ADG, and sow BW change over lactation. We hypothesized that there would be a quadratic relationship between ADFI and sow BW change and litter ADG, where increases in feed intake beyond a certain point would no longer improve sow or litter performance.

MATERIALS AND METHODS

The initial dataset included data from eight different trials totaling 4,516 gilts and sows. Data from individual research trials were included in the analysis that recorded individual sow lactation feed intake, sow body weight at entry into farrowing and at weaning, litter weight at d 2, after litter equalization, and at weaning, as well as provided complete formulated diets. Individual sow and litter data were recorded for each trial. For the following reasons, 132 gilts and multiparous sows were removed: missing feed intake data, ADFI below 2.7 kg, ADFI above 11.3 kg, litter size at weaning was greater than litter size at d 2, mortality greater than 7 pigs, and maternal weight gain over lactation greater than 90 kg. The final dataset included in the analysis totaled 4,384 females, of which there were 991 gilts and 3,393 multiparous sows (Supplemental table 1). In the current analysis, gilts are defined as animals that are nursing their first litter. Tables 1 and 2 describe the range in performance for gilts and multiparous sows across the eight trials, as well as the range in formulated dietary net energy (NE) levels and Lys:AA ratios.

For all trials, sows were weighed at entry into farrowing and before weaning. Two trials recorded sow BW after farrowing. For trials that did not record sow BW after farrowing, the equation developed by Mallmann et al. (2018) was used to estimate sow BW after farrowing. Litter size was recorded at d 2 and at weaning. Day 2 litter size refers to the number of pigs in each litter after pigs were cross-fostered to equalize litter size. Litter weight was recorded after litters were equalized and at weaning. Sow lactation feed intake was recorded using electronic feeders (Jyga Technologies, St-Lambert-de-Lauzon, Quebec, CA). Sows were provided ad libitum access to feed in all studies. Diets for each experimental treatment within a trial were reformulated using NRC (2012) nutrient values for ingredients to standardize nutrient concentrations. These values were then used to determine average NE, kcal/d, and AA, g/d, intake over lactation based on lactation ADFI and dietary energy and AA levels.

Sow lactation ADFI was divided into quintiles to analyze the relationship between lactation ADFI and sow and litter performance. Because multiparous sows had greater lactation ADFI and a wider feed intake range compared to gilts, they were analyzed separately using different intake groups. Separating into the quintile groups resulted in the following ADFI groups for gilts: < 5.30, 5.30 to 5.90, 5.90 to 6.40, 6.40 to 6.95, and ≥ 6.95 kg/d. For multiparous sows, the ADFI groups were: < 6.00, 6.00 to 6.85, 6.85 to 7.45, 7.45 to 8.30, and $\geq$ 8.30 kg/d.

Equations were developed to predict litter ADG and sow BW change from farrow to weaning. Body weight at farrow is the empty sow BW after farrowing. The predictor variables evaluated in the model to estimate litter ADG and sow BW change included ADFI, weaning age, litter size at d 2, litter size at weaning, NE intake (kcal/kg), dietary SID Lys, %, Met:Lys, Trp:Lys, Thr:Lys, Val:Lys, and Lys:CP. Histidine:Lys, Ile:Lys, and Leu:Lys ratio were not included as predictor variables in the model due to high correlation ($r > 0.65$) with SID Lys. For the estimate of litter ADG, sow BW change from farrow to weaning was used as a predictor variable, and for the estimate of sow BW change from farrow to weaning, litter ADG was used as a predictor variable.

As an additional analysis, sow BW change over lactation was divided into three separate categories for gilts and sows with an equal number of animals in each category to compare changes in litter ADG at different levels of feed intake and sow lactation BW change. Gilt BW change categories were: ≤ -11.0, -11.0 to 1.4, and ≥ 1.4 kg/d. Multiparous sow BW change categories were: ≤ -3.3 kg, -3.33 to 13.3 kg, and ≥ 13.3 kg. The relationship between lactation ADFI, litter ADG, and sow BW change was graphed, with separate linear regression lines for each sow BW change category.

NRC comparison

Predicted sow BW change and litter ADG from the regression equations were compared with values predicted from the NRC (2012) models. Inputs for both the regression equations and the NRC (2012) model were derived from average sow and litter performance in the dataset at increasing ADFI. The NRC (2012) lactating sow Excel model was used to predict BW change over lactation. To predict litter ADG, the NRC (2012) eq. 8-70 was used. The equation was algebraically rearranged to solve for litter ADG:

Litter ADG (g/d) = mean milk energy output (kcal/d) + 90 × litter size ÷ 4.92

Mean milk energy output was estimated for each sow in the dataset using NRC (2012) eq. 8-70. Then, the linear relationship between mean milk energy output and ADFI was determined:

Mean milk energy output, kcal/kg = 548.19 × ADFI, kg + 9187.4

This relationship was used to predict mean milk energy output at increasing levels of lactation ADFI for the prediction of litter ADG.

Statistical Analysis

Performance data were analyzed by gilt and sow ADFI group using the lmer function of R software. Lactation ADFI group was included in the model as a fixed effect. Trial was included in the model as a random effect, and weaning age was included as a covariate. Linear and quadratic orthogonal polynomial contrasts were used to evaluate the effect of increasing feed intake group. Discrete data were analyzed using a negative binomial distribution. Results are considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

The prediction equations were developed in R (Version 4.4.3) using the lmer function. To reduce multicollinearity among predictor variables, a correlation analysis was conducted using the corr function in R studio. When two variables had a correlation coefficient of greater than 0.65, one was excluded from the analysis based on model performance. The Kennard-Stone algorithm (Kennard and Stone, 1969) was used to divide the database into a calibration (80%) and validation (20%) dataset. Backward stepwise regression was used to develop prediction equations for litter ADG and sow BW change over lactation. Trial was used as a random effect in the model. Model development began with linear terms, followed by the addition of linear and quadratic terms, and then expanded to include linear, quadratic, and all possible interaction terms. Terms were included in the model if they were statistically significant ($P < 0.05$). The model with the lowest Bayesian Information Criterion (BIC) was selected as the best fitting model. The coefficient of determination (R^2) was calculated to determine the proportion of variation explained by the model, while mean bias and standard error of prediction (SEP) were used to assess model accuracy and repeatability, respectively, using the validation dataset

RESULTS AND DISCUSSION

Lactation ADFI effect on litter ADG and sow BW change

In gilts, entry and post-farrow BW varied by ADFI group, where BW initially decreased and then increased with greater ADFI, (quadratic; $P < 0.05$; Table 3) with gilts in the lowest and highest ADFI categories having similar BW. For gilts, entry and post-farrow BW were not closely associated with lactation ADFI. Body weight at weaning increased (quadratic; $P < 0.05$; Table 3) with increasing ADFI. Gilt BW at weaning increased steadily with greater ADFI, increasing by about 1% with each ADFI group until the highest feed intake group, where there was a 4% increase in BW between gilts consuming 6.40 to 6.95 kg and gilts consuming more than 6.95 kg/d. Body weight loss from entry to weaning and farrow to weaning decreased (quadratic; $P < 0.05$) as ADFI increased. Body weight loss decreased from -12.5 kg in the lowest feed intake group to 0 kg in the highest feed intake group from farrow to weaning. No differences in WSI due to ADFI were observed in gilts.

In multiparous sows, BW at entry and farrowing varied among ADFI groups, where BW decreased through the intermediate ADFI group and then plateaued thereafter (quadratic; $P < 0.05$; Table 3). Multiparous sow BW at weaning decreased (quadratic; $P < 0.05$; Table 4) as lactation ADFI increased from less than 6.0 to 7.45 kg, then increased as ADFI increased from 7.45 to greater than 8.30 kg, with the highest ADFI group having the greatest BW at weaning. Body weight loss from entry to weaning decreased (quadratic; $P < 0.05$) as ADFI increased in multiparous sows, with the greatest reduction in BW loss occurring between sows consuming less than 6.0 kg and 6.00-6.85 kg. However, BW loss from farrow to weaning decreased (linear, $P < 0.05$) with increasing ADFI group, with sows gaining BW when ADFI was greater than 6.85 kg. For multiparous sows, no differences in WSI were observed between sow ADFI group. When comparing BW change for gilts and multiparous sows, the majority of gilts lost BW from farrow to weaning, while over half of the multiparous sows gained BW during lactation. Multiparous sows with an ADFI of greater than 6.85 kg gained BW during lactation. In contrast, gilts with the highest ADFI, greater than 6.95 kg, maintained BW over lactation.

Several other studies have observed a positive relationship between lactation ADFI and maternal BW change over lactation (Eissen et al., 2003; Strathe et al., 2017; Estrada et al., 2024). Increasing lactation feed intake in gilts is important to reduce BW loss, increase litter weight gain, and improve subsequent reproductive performance. Decreasing BW loss during the first lactation also increases litter size during the next reproductive cycle (Eissen et al., 2003). Farmer et al. (2016) also noted that proper gilt body condition is important for mammogenesis because gilts that are too thin or obese have impaired mammary development compared to gilts in proper body condition, impacting lifetime milk production.

As expected, for both gilts and multiparous sows, Lys and NE intake and Lys intake per kg of litter gain increased (linear; $P < 0.05$) as ADFI increased. The lower Lys intake per kg of litter gain at low ADFI suggests that gilts and sows with lower feed and Lys intake are more efficient at utilizing dietary Lys for litter gain. Feeding sows a low crude protein diet in lactation has been shown to increase N and AA retention and AA utilization efficiency (Huber et al., 2015). Similarly, restricted fed sows given 4 kg per day had greater lactation efficiency, producing more milk per kg of feed intake, than sows given 8 kg per day (De Bettio et al., 2016). Bergsma et al. (2009) observed that sows with lower feed intake were more efficient at utilizing energy toward milk production and litter gain compared to sows with higher feed intake, similar to the results of the current analysis. However, even though gilts and sows with lower lactation feed intake appeared more efficient, they had lower litter growth performance and mobilized more body reserves than gilts and sows with higher feed intake. The Lys intake per kg of litter gain value only accounts for dietary Lys, it does not account for Lys that is mobilized from maternal muscle tissue and used for milk production, making it difficult to determine whether sows were more efficient at lower lactation feed intakes.

In gilts and multiparous sows, no differences in litter size or litter weight at d 2 were observed among lactation ADFI groups. However, in gilts on d 2, pig BW was slightly lower for sows in the middle ADFI categories than sows with the highest ADFI (quadratic; $P < 0.05$). This difference was due to chance, because d 2 pig weights were recorded prior to lactation feed intake. In contrast, no differences in pig weight at d 2 were observed between ADFI groups for multiparous sows. For both gilts and multiparous sows, weaning litter size, weaning litter and pig weight, as well as litter and pig ADG increased (linear; $P < 0.05$) with increasing ADFI. The greatest increase in litter ADG occurred as ADFI increased from the lowest to the second-lowest intake group in both gilts and multiparous sows. Similar to the results of the current analysis, Koketsu et al. (1996b) observed an increase in litter size at weaning as lactation ADFI increased. Increased litter size and gain are associated with increased feed intake during lactation (Eissen et al., 2000).

Body condition at farrowing can also affect lactation feed intake. This analysis indicates that multiparous sows that enter farrowing with the highest BW consume less feed, have greater BW loss over lactation, and lower litter growth performance, which has been observed in previous trials (Revell et al., 1998; Cools et al., 2014). When comparing litter growth performance in the present analysis, multiparous sows had greater pig and litter ADG at similar ADFI, and overall higher litter growth performance compared to gilts.

The analysis of lactation ADFI for gilts and multiparous sows indicates that as ADFI, and therefore NE and Lys intake, increases, sow BW loss over lactation decreases and litter ADG increases. Similar results have been observed in the literature (De Bettio et al., 2016; Choi et al., 2017; Estrada et al., 2024), with increased feed intake improving litter growth performance and minimizing sow BW loss. De Bettio et al. (2016) observed that restricted fed sows consuming 4.14 kg/d had greater BW loss (28.2 vs 7.8 kg) and lower litter ADG (2.43 vs 2.70 kg) compared to ad libitum fed sows consuming 6.43 kg/d; however, no differences in WSI were observed, which was also observed in the current analysis. Similar to the results of the current analysis, Estrada et al. (2024) observed an increase in weaning weight and a decrease in sow BW loss during lactation when classifying sows by low (5.48 kg/d), average (6.85 kg/d), and high (8.17 kg/d) ADFI. Choi et al. (2017) reported that when sows were fed diets formulated with higher energy and amino acid concentrations compared to NRC requirement estimates, sow BW loss decreased (19.6 vs. 23.9 kg) and pig ADG increased (229 vs. 203 g/d). These improvements occurred despite similar ADFI, indicating that nutrient density, rather than feed intake alone, influences sow and litter performance. Sow lactation diets are formulated to meet the requirements of the average sow in the herd. Sows that have lower feed intake than the herd average will have deficient amino acid and energy intake, while sows with high feed intake may be wasting nutrients. This is especially important in gilts because they have approximately 15% lower ADFI compared to multiparous sows (Strathe et al., 2017).

In response to inadequate nutrient intake, sows mobilize body reserves to support lactation demands. However, the ability of sows to compensate for insufficient nutrient intake by mobilizing body reserves has limits, as excessively low feed intake reduces milk production and litter growth rate even when body reserves are mobilized (Theil et al., 2023) compared to sows with higher feed intake. Theil et al. (2023) observed that when sows lose more than 10% of BW during lactation and energy is deficient by more than 3.6 Mcal/d, milk production is reduced. Based on the results of the current study, NE required for maintenance and milk production were estimated using equations from Noblet and Etienne (1989) and Li et al. (2024). Estimated NE required for maintenance and milk production per d were compared with average NE intake per d. In gilts with the lowest ADFI, NE intake averaged 5.7 Mcal/d below the estimated requirement for maintenance and milk production, leading to BW loss during lactation. In contrast, sows with the highest ADFI consumed 0.8 Mcal/d more than their estimated requirement for maintenance and lactation, resulting in BW gain during lactation.

Regression analysis

Sow BW change over lactation

The results of the multivariable regression analysis to predict litter ADG and gilt and sow BW change over lactation are shown in Table 5. For equations to predict both litter ADG and maternal BW change, the simple linear model had the best fit, resulting in the lowest BIC. The stepwise models to predict maternal BW change and litter ADG were validated using 135 datapoints for gilts and 484 datapoints for sows, and results indicated a positive relationship between observed and predicted values, with points following the line of best fit (figures 4-1 and 4-2). The variables included in the regression model to predict sow BW change over lactation explain 40% and 36% of the variation for gilts and multiparous sows, respectively.

The first variable selected through backward selection to predict both gilt and sow BW change over lactation was ADFI. If all other variables are held constant, when ADFI increases by

1 kg, BW loss over lactation decreases by 4.74 and 5.19 kg for gilts and multiparous sows, respectively. Litter ADG was included in the model as a significant predictor for both the gilt and multiparous sow equations. For both equations, as litter ADG increases, sow BW loss increases over lactation. For every 100 g increase in litter ADG, BW loss over lactation increases by 0.973 and 0.832 kg for gilts and multiparous sows, respectively, when all other variables are held constant. Average daily feed intake and litter ADG have the greatest impact on sow BW change over lactation. Together, lactation ADFI and litter ADG accounted for the majority of the variation in sow BW change, explaining 21.8% in gilts and 18.1% in multiparous sows, respectively. For both gilts and multiparous sows, increased ADFI reduces sow BW loss, indicating that increased nutrient intake decreases maternal body reserve mobilization during lactation. Generally, sows lose BW during lactation because of high milk yield and inadequate nutrient intake. The slope for ADFI was greater in older parity sows compared to gilts, suggesting that multiparous sows exhibit greater sensitivity to increases in feed intake, allocating a larger proportion toward maternal body gain or reduced BW loss. The regression equation indicates that for both gilts and multiparous sows, an increase in litter ADG increases sow BW loss over lactation due to partitioning of nutrients toward milk production and mobilization of body reserves.

Weaning age was a significant predictor for gilt BW change, with increased weaning age increasing gilt BW loss. Pig count at d 2 was a significant predictor for multiparous sows, with increased pig count at d 2, decreasing sow BW loss over lactation. Weaning age alone explains only 1.0% of the variation in BW change for gilts, and pig count at d 2 explains only 1.2% of the variation for multiparous sows.

Similar to equations developed by Strathe et al. (2017) and Holen et al. (2022), ADFI was included as a significant predictor of gilt and multiparous sow BW. Litter size after equalization was included in the equation developed herein for multiparous sows, and equations developed by Strathe et al. (2017) and Holen et al. (2022) but not for the prediction of gilt BW change. Backfat loss over lactation was included as a significant predictor in equations developed by Strathe et al.(2017), but was not recorded in all studies used to develop the equations in the current analysis. The addition of gilt and sow lactation backfat loss could potentially improve the R^2 of the current regression equation.

Litter ADG

The variables included in the regression model to predict litter ADG explained 58% and 59% of the variation in litter ADG for gilts and multiparous sows, respectively (Table 5). For equations developed to predict litter ADG, the first variable included through backward selection was ADFI. The regression equation indicates that a 1 kg increase in ADFI leads to a greater increase in litter ADG in gilts vs multiparous sows (107 vs 60 g). Lactation ADFI was a poor single predictor of litter ADG, explaining only 6.0% of the variation in litter ADG for gilts and 3.9% in multiparous sows. The regression equations indicate that as sow BW loss over lactation increases by 1 kg, litter ADG increases by 9 and 4 g, respectively, when all other variables are held constant. Sow BW change over lactation alone explains only 8.8% and 3.3% of the variation in litter ADG for gilts and multiparous sows, respectively. Pig count at d 2 and pig count at weaning were included in the model as significant predictors of litter ADG, with an increase in pig count at d 2 reducing litter ADG in both prediction equations and an increase in pig count at weaning increasing litter ADG. Across both parity groups, pig count at weaning was the strongest single predictor of litter ADG, explaining 36.2% of the variation in gilts and 39.5% in multiparous sows, while pig count at day 2 explained 13.0% and 12.3%, respectively. Formulated SID Lys percent was included as a significant predictor for litter ADG for gilts only. This is likely because gilts have a higher SID Lys requirement estimate for maternal body protein compared to multiparous sows to support maternal growth (Trottier et al., 2014). As dietary SID Lys level increases by 0.1%, litter ADG increases by 55 g in gilts. However, dietary SID Lys level only accounted for 1.1% of the variation in litter ADG in this dataset. Through backward selection, weaning age was selected as the last significant factor to predict litter ADG of multiparous sows, with an increase in weaning age increasing litter ADG. As weaning age increases by 1 d, litter ADG increases by 13 g, but accounted for only 0.5% of the variation in litter ADG.

Other regression equations developed to predict litter ADG also have found that litter ADG increases as ADFI and litter size at weaning increase (Strathe et al., 2017; Holen et al., 2022). In contrast to the regression equations developed herein, equations developed to predict litter ADG by Holen et al. (2022) included dietary net energy as a predictor of litter ADG; however, net energy was not a significant predictor in the current model. Equations developed by Strathe et al. (2017) included backfat loss and ADFI over specific days of lactation. Both of these variables were included in the current analysis, however, the R^2 for equations developed to predict litter ADG of gilts was similar between the two equations, 55% vs 58%.

The regression equation developed herein indicates that a one kg increase in ADFI increases litter ADG at a greater rate in gilts compared to multiparous sows (107 vs 60 g); although the difference is relatively small. This is a surprising observation because gilts are still growing and partitioning nutrient intake between milk production and maternal growth. Pluske et al., (1998) observed that gilts will use nutrients from increased feed intake to improve body condition rather than increase milk production. Cozannet et al. (2018) determined that gilts prioritize increased energy intake during lactation for their own body growth, whereas multiparous sows use it to support higher milk production and litter growth, likely because gilts are still maturing during their first lactation. A study evaluating the effects of energy intake of gilts in lactation found that as energy intake increased, no differences in litter weight at weaning were observed, suggesting similar milk production, but maternal BW gain over lactation increased as energy intake increased, again highlighting that gilts prioritize maternal BW gain over milk production (Pluske et al., 1998). Equations developed by Strathe et al. (2017) indicate that increases in ADFI result in greater improvements in litter ADG for multiparous sows compared to gilts. Gilt feed intake is limited by physical capacity to consume feed (Lewis and Bunter, 2011), and they are less efficient at converting nutrients into milk compared to older parity sows (Pluske et al., 1998). Gilts have a smaller udder compared to sows and are still undergoing mammary gland development during the first lactation (Balzani et al., 2016), leading to lower milk yield (Rempel et al., 2023).

A potential explanation for the differing ADFI coefficients between gilts and multiparous sows in predicting litter ADG in the analysis herein is that gilts typically consume less feed during lactation. Their lower nutrient intake constrains litter growth, causing increases in ADFI to yield greater marginal improvements in litter ADG compared with older sows. Another potential explanation is that modern gilts are more efficient at utilizing nutrients and can support larger litters. When comparing the results of Pluske et al. (1998) to the current analysis, the average gilt BW at farrowing was 177 kg, compared to 203 kg in the current analysis. Heavier gilts at farrowing have greater body reserves that can be mobilized to support lactation. Likewise, litter size at weaning increased from 8.6 (Pluske et al., 1998) and 10.2 (Cozannet et al.,

2018) pigs in previous studies to 13.1 pigs in the current analysis. These differences in gilt and litter characteristics could play a role in the differences in responses observed in the current analysis for nutrient portioning of gilts.

Figures 4-3 and 4-4 compare predicted maternal BW change and litter ADG between the equations developed for gilts and multiparous sows developed in the analysis herein and NRC (2012) prediction models. Inputs for the equations were derived from the analyzed data and their observed relationships as ADFI increased (Tables 6 and 7). The NRC (2012) sow lactation BW change model predicted substantially greater BW loss for both gilts and multiparous sows at low lactation ADFI compared with the equations developed in the current analysis, -17.7 vs -4.0 and -27.5 vs -3.1 at an ADFI of 5.5 kg for gilts and multiparous sows, respectively. The developed prediction equation indicates that modern sows are more efficient and lose less BW over lactation at low feed intake. When comparing the regression results for gilts and multiparous sows, gilt and multiparous sow BW change is similar, with multiparous sows losing slightly less BW at low feed intake levels below 6.0 kg. As ADFI increased, multiparous sows lost less BW and began to gain BW at approximately 6.5 kg ADFI, whereas gilts began gaining BW at around 7.5 kg ADFI. As litter ADG increases, there is a greater change in maternal BW for gilts compared to sows.

Equation 8-70 from the 2012 NRC was used to predict litter ADG and compared to the equation developed in the current analysis. The NRC equation predicted a higher litter ADG compared to the equation developed in this analysis for gilts. Predicted values were much closer for multiparous sows, only a 0.02 kg difference for multiparous sows compared to 0.21 kg for gilts with an ADFI of 6.0 kg. The higher predicted litter ADG for gilts using the NRC (2012) equation compared to the equation developed in the current analysis was a surprising result because modern gilts have higher milk production and higher litter gain. The NRC prediction equation was developed using an average litter size smaller than that observed in the current analysis. When looking at the data used to develop the NRC equation, litters were equalized to 9 or 10 pigs. In contrast, the average litter size at equalization in the current analysis was 14.5. This likely contributes to the equation overestimating litter ADG for gilts, as the litter sizes in this study fall outside the range used to develop the NRC model. Koketsu et al., (1996a) observed that sows with an ADFI of 5.4 kg during lactation weaned litters averaging 53.3 kg and 8.7 pigs. In comparison, sows in the lowest ADFI group, 5.3 kg ADFI, weaned heavier litters averaging 76.8 kg and 12.5 pigs. This comparison highlights the substantial improvement in sow production over time, as modern sows are capable of producing more milk and raising larger litters at similar feed intake.

The comparison of predicted litter ADG of gilts and sows for the developed regression equation in this analysis indicates that sows had a greater litter ADG compared to gilts. However, the slope of the line for multiparous sows is flatter than that for gilts as ADFI increases due to multiple factors. In the regression equation, litter ADG is primarily influenced by the number of pigs weaned, and gilts in this dataset had larger litter sizes at weaning compared to sows. Lactation ADFI is also a key factor, with the equation indicating that litter ADG increases more rapidly with rising ADFI in gilts than in sows. Additionally, sows exhibit greater BW gain at high ADFI levels, which in turn is associated with lower litter ADG due to increased nutrient partitioning toward maternal gain rather than milk production.

Relationship between BW gain and BW loss on litter ADG

The analysis indicates that ADFI affects both litter ADG and sow BW change over lactation. However, the analysis also indicates a complex interaction among the three variables, such that the effect of ADFI on litter ADG cannot be interpreted without also considering sow BW change, and vice versa. Figures 4-5 and 4-6 illustrate the relationship between lactation ADFI, litter ADG, and sow BW change over lactation for gilts and multiparous sows, respectively. Maternal BW change over lactation was divided into 3 categories, with an equal number of animals in each category, for gilts and multiparous sows and the relationship between ADFI and litter ADG was compared within BW category. The figures illustrate that even at similar ADFI, sows can lose, maintain, or gain BW during lactation. Gilts and sows that lose BW over lactation and have high feed intake have the highest litter ADG. Strathe et al. (2017) observed that sows with high milk production had both high feed intake and high body reserve mobilization, suggesting that their physical capacity to consume feed may limit overall performance. Hooyberghs et al. (2025) observed that sows that lose BW over lactation have a higher piglet survival rate, likely due to increased milk production. The difference between nutrient intake and nutrients required for maintenance and milk production determines the sows demand to mobilize body reserves for milk production (Theil et al., 2023). Closer examination of the data in the present analysis showed that gilts and sows with similar feed intake that lost BW during lactation had greater litter ADG and weaned larger litters compared with those that gained BW. When sows lose body weight during lactation, it indicates that body reserves are being mobilized to use toward milk synthesis or for maintenance requirements. When sows have both high nutrient intake and mobilize body reserves, they have more nutrients available for milk synthesis, likely increasing milk yield.

In the current analysis, gilts and sows that lost BW over lactation were heavier at entry and had a greater litter weight at d 2 and weaning compared to sows that had moderate BW change or gained BW over lactation. However, litter size at d 2 was similar between sows that lost and gained BW over lactation. A potential explanation for why sows lose BW over lactation compared to sows that gain BW with similar ADFI is that sows that lose BW had a heavier litter and average pig weight at d 2, increasing nursing pressure. Sows raising average birth weight pigs had greater BW loss over lactation compared to sows raising light birth weight pigs, even when feed intake was similar (Hawe et al., 2020). Larger piglets are more effective at stimulating milk production and emptying milk from teats (Grahofer and Plush, 2023), leading to increased total milk yield.

Another possible explanation is that sows that lost BW during lactation were heavier at entry and farrow compared to sows that gained BW at similar ADFI levels. A study comparing performance of restricted vs *ad libitum* fed sows, observed that milk production and body reserve mobilization was not dependent solely on lactation feed intake (Costermans et al., 2020). The results of Costermans et al. (2020) and the current analysis indicate that feed intake is important, but body reserves at farrowing are an independent driver of milk production. A sow that is heavier at farrowing has more body reserves to mobilize to increase milk production compared to leaner sows with similar feed intake. Thongkhuy et al. (2020) observed that sows that had greater than 15 mm of backfat at entry to farrowing had greater backfat loss during lactation and higher milk yield from d 3 to 10 of lactation than sows with less backfat at entry.

While increased body reserves at farrowing can support greater milk production, excessive body fat can have negative consequences for sow health and reproductive outcomes. Sows that are overweight have an increased incidence of stillborns (Gourley et al., 2020) and lameness (Knage-Rasmussen et al., 2014). A quadratic increase in litter gain was observed as backfat increased from less than 10 mm to 22 mm, but decreased when backfat exceeded 22 mm for gilts and sows due to decreased feed intake (Kim et al., 2015). Clowes et al. (2003 observed that sows that lost greater than 10% of their BW during lactation had lower milk production and litter gain compared to sows that lost less than 10% of their BW during lactation. In the study herein, gilts and sows in the highest BW loss categories lost 9.6% and 5.6% of their BW, respectively, which likely contributes to the lack of a negative response in litter performance in the highest BW loss category. In the current analysis, only 17% of gilts and 5% of sows lost greater than 10% of their BW during lactation.

CONCLUSION

In conclusion, these findings highlight that lactation ADFI, litter ADG, and sow BW change are intricately connected, emphasizing the importance of considering them together to fully understand sow and litter performance. For both gilts and multiparous sows, greater ADFI was associated with reduced body weight loss and improved litter performance. However, over half of the multiparous sows included in the analysis gained BW from farrow to weaning and the majority of gilts lost BW. The regression equation shows that high feed intake reduces BW loss; however, gilts experience greater BW loss when supporting litters with high ADG compared to older parity sows. Litter ADG increases as ADFI and litter size increase, with gilt litters having a greater improvement in growth compared to multiparous litters as ADFI increases. Sow BW change during lactation also plays an important role in the litter ADG, as sows at similar feed intake levels that lose weight have higher litter ADG and wean heavier litters, compared to sows that gain weight.

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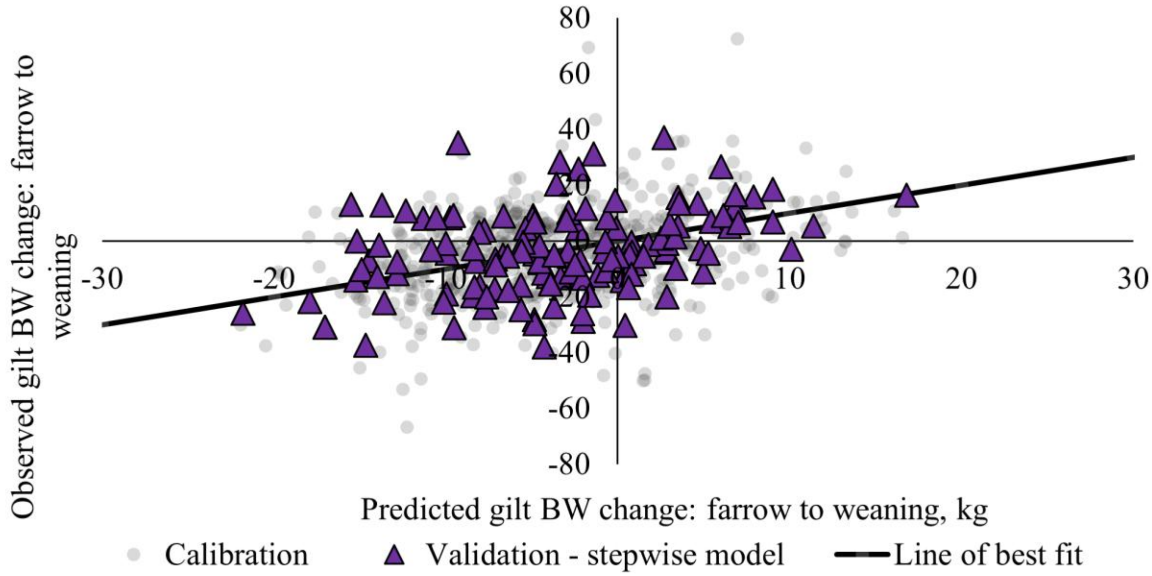

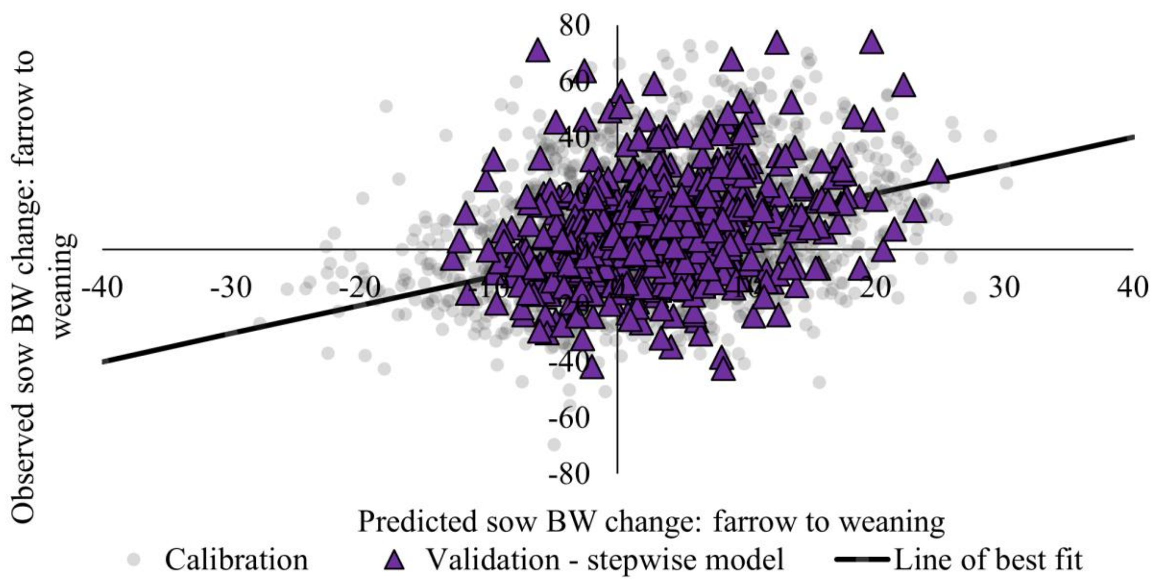

Figure 4-1. Regression analysis of the relationship between predicted and observed gilt and sow BW weight change, based on the prediction model selected through stepwise selection. Gray circles represent data points used for model calibration (gilts; n= 531, sows; n = 1935) and purple triangles represent points used for model validation (gilts; n= 135, sows; n = 484). The solid line represents the line of best fit (predicted = observed).

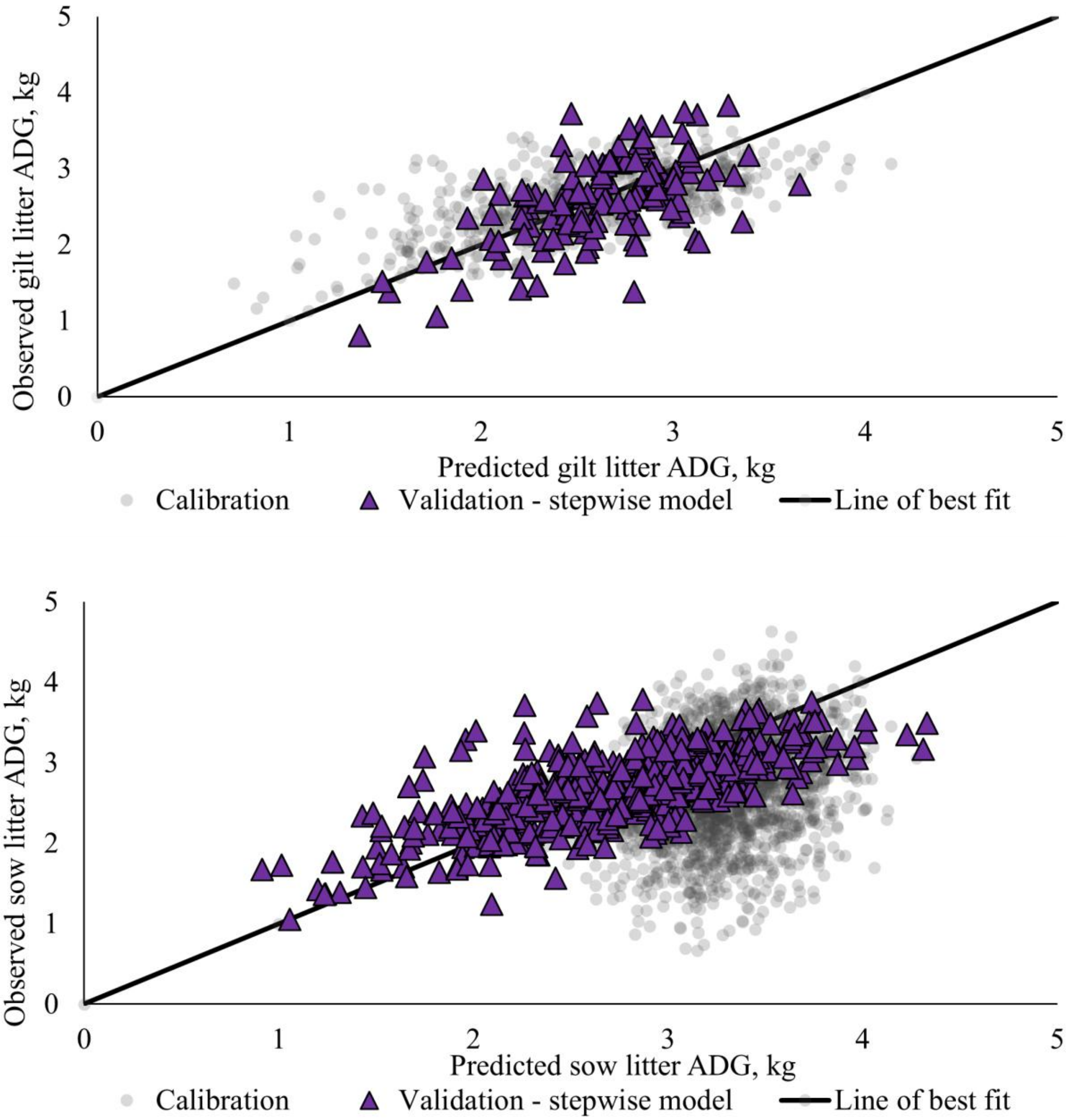

Figure 4-2. Regression analysis of the relationship between predicted and observed gilt and sow litter ADG, based on the prediction model selected through stepwise selection. Gray circles represent data points used for model calibration (gilts; n= 531, sows; n = 1935) and purple triangles represent points used for model validation (gilts; n= 135, sows; n = 484). The solid line represents the line of best fit (predicted = observed).

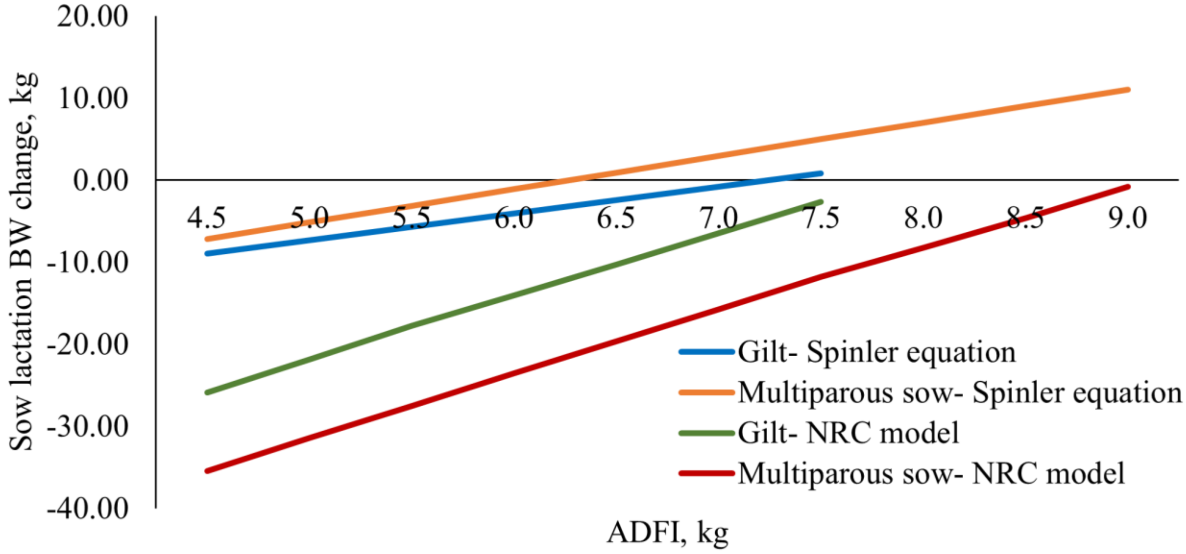

Figure 4-3. Comparison of predicted sow body weight (BW) change during lactation using equations developed in the present analysis (Gilts = 3.580 + (4.738 × ADFI, kg) – (9.734 × Litter ADG, kg) – (0.569 × Wean Age); Multiparous sows = −30.936 + (5.188 × ADFI, kg) – (8.316 × Litter ADG, kg) + (1.404 × Pig Count d 2)) vs NRC (2012) excel based model predictions for gilts and multiparous sows. Table 5 outlines the inputs to the regression equations.

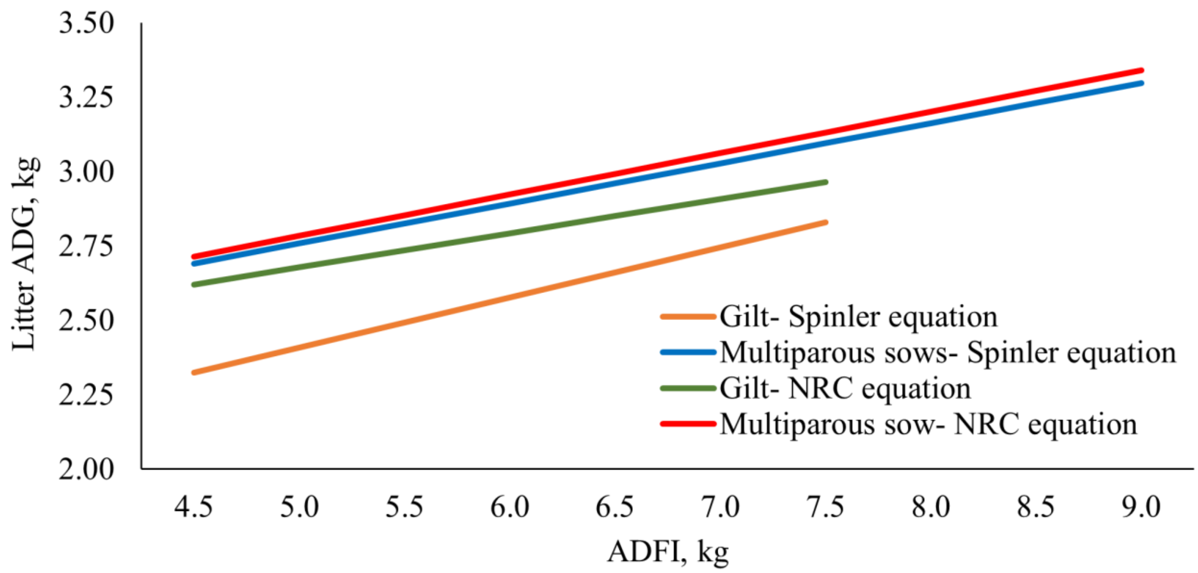

Figure 4-4. Comparison of liter average daily gain (ADG) using equations developed in the present analysis (Gilts= 0.042 + (0.107 × ADFI, kg) + (0.550 × SID Lys) − (0.009 × Gilt BW change farrow to weaning, kg) − (0.122 × Pig Count d 2) + (0.236 × Pig Count Wean); Multiparous sows = 0.288 + (0.060 × ADFI, kg) − (0.004 × Sow BW change farrow to weaning, kg) − (0.118 × Pig Count d 2) + (0.280 × Pig Count Wean) + (0.013 × Wean Age)) vs NRC (2012) prediction equation 8-70 for gilts and multiparous sows. Table 6 outlines the inputs to the regression equations.

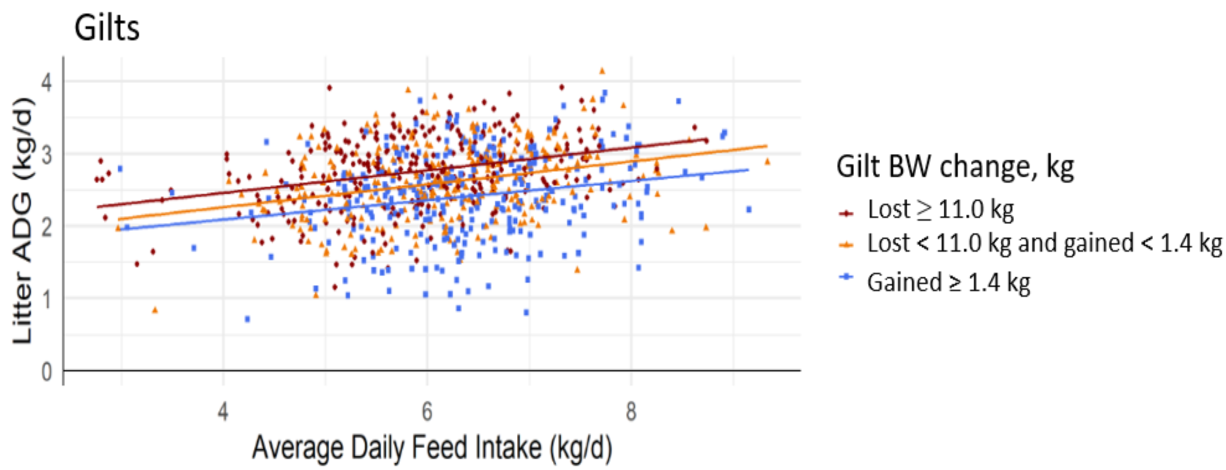

Figure 4-5. Relationship between average daily feed intake (ADFI; kg/d), litter average daily gain (ADG; kg/d), and body weight (BW) change in gilts. Sows were divided into three categories based on body weight change from farrow to weaning (BW change, kg): ≤ −11.0 kg (dark red), −11.0 to 1.4 kg (orange), and ≥ 1.4 kg (blue). Points represent individual sows, and the lines show linear regression trends for each BW change group..

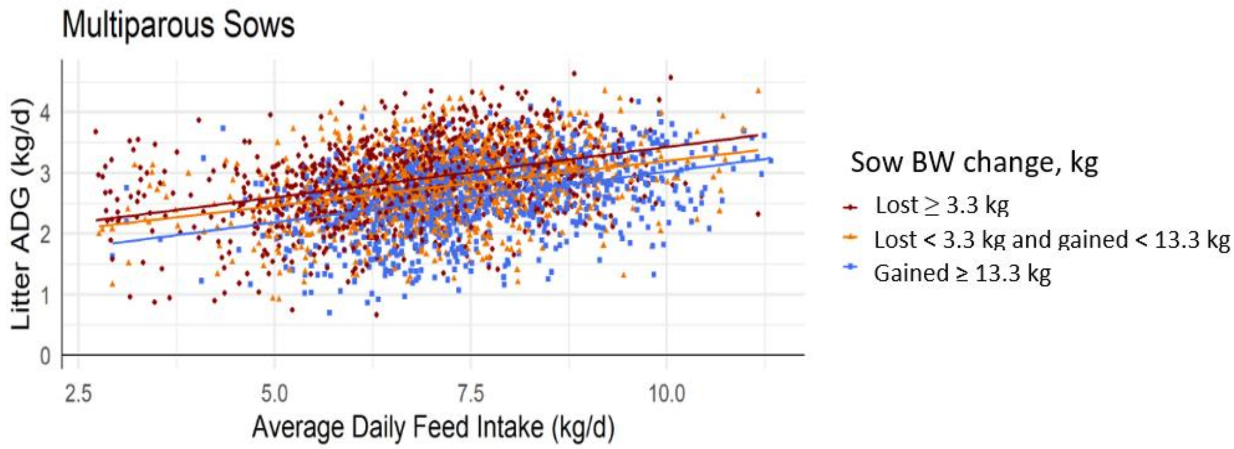

Figure 4-6. Relationship between average daily feed intake (ADFI; kg/d), litter average daily gain (ADG; kg/d), and body weight (BW) change in multiparous sows. Sows were divided into three categories based on body weight change from farrow to weaning (BW change, kg): ≤ −3.3 kg (dark red), −3.3 to 13.3 kg (orange), and ≥ 13.3 kg (blue). Points represent individual sows, and the lines show linear regression trends for each BW change group.

Table 4.1. Descriptive statistics of data used in the analysis- gilts

	Minimum	Average	Maximum
NE, kcal/kg	2,401	2,441	2,507
SID Lys	0.59	1.02	1.28
Met:Lys	0.26	0.30	0.50
Trp:Lys	0.18	0.19	0.28
Thr:Lys	0.62	0.64	0.95
Val:Lys	0.70	0.74	1.27
ADFI, kg	2.8	6.2	9.5
Gilt BW			
Entry, kg	147.0	219.5	333.5
Farrow, kg	131.0	198.6	304.8
Weaning, kg	125.6	193.4	307.5
Pig count d 2	10.0	15.0	19.0
Pig count weaning	7.0	13.4	18.0
Litter weight d 2, kg	10.0	21.4	38.4
Litter weight weaning, kg	30.3	70.8	114.0
Pig weight d 2, kg	0.7	1.4	2.7
Pig weight weaning, kg	2.6	5.3	9.5

Table 4.2. Descriptive statistics of data used in the analysis- multiparous sows

	Minimum	Average	Maximum
NE, kcal/kg	2,408	2,401	2,507
SID Lys	0.58	1.03	1.28
Met:Lys	0.30	0.26	0.45
Trp:Lys	0.16	0.19	0.26
Thr:Lys	0.52	0.64	0.87
Val:Lys	0.69	0.69	1.15
ADFI, kg	2.7	7.2	11.3
Sow BW			
Entry, kg	155.6	276.9	404.0
Farrow, kg	140.5	276.9	381.4
Weaning, kg	141.5	257.4	386.0
Pig count d 2	7.0	14.5	20.0
Pig count weaning	6.0	12.5	20.0
Litter weight d 2, kg	9.8	22.2	38.5
Litter weight weaning, kg	30.6	76.6	129.5
Pig weight d 2, kg	0.7	1.5	2.7
Pig weight weaning, kg	3.2	6.1	10.9

Table 4.3. Lactation sow feed intake effect on litter ADG and lactation gilt BW change[1]

	Lactation ADFI[2], kg						P =	
	≤ 5.30	5.30-5.90	5.90-6.40	6.40-6.95	≥ 6.95	SEM	Linear	Quadratic
No. of gilts	195	206	194	197	199			
Parity	1.0	1.0	1.0	1.0	1.0			
ADFI[2], kg	4.8	5.7	6.2	6.7	7.5	0.03	< 0.001	0.991
Gilt BW[3], kg								
Entry	225.9	223.2	220.7	222.3	226.8	6.76	0.856	0.003
Farrow	205.1	202.3	200.0	201.6	206.4	6.47	0.676	0.001
Weaning	193.0	195.6	197.1	198.5	206.5	7.49	< 0.001	0.033
Gilt BW[3] change, kg								
Entry to weaning	-33.4	-27.7	-23.6	-23.8	-20.5	2.87	< 0.001	< 0.001
Farrow to weaning	-12.5	-6.8	-2.9	-3.1	0.0	2.78	< 0.001	0.032
Lys intake, g/d	46.5	57.0	61.9	66.4	74.0	2.18	< 0.001	0.004
Lys intake, g/kg of litter gain	22.4	24.6	27.7	27.2	28.7	1.26	< 0.001	0.110
NE intake, Mcal/d	12.0	14.1	15.4	16.6	18.7	1.79	< 0.001	0.866
WSI[4], d	4.3	4.8	4.3	4.4	4.4	0.35	0.674	0.668
Litter size, n								
d 2	14.0	14.5	14.5	14.6	14.4	0.43	0.311	0.150
Weaning	12.5	13.1	12.9	13.5	13.3	0.39	0.023	0.412
Litter weight, kg								
d 2	20.8	21.1	21.2	21.5	21.7	0.72	0.194	0.919
Weaning	69.7	70.9	70.1	74.1	75.8	3.62	< 0.001	0.801
Mean pig BW[3], kg								
d 2	1.49	1.47	1.47	1.48	1.52	0.044	0.181	0.026
Weaning	5.35	5.43	5.47	5.51	5.70	0.144	< 0.001	0.236
Litter ADG[5], kg	2.39	2.59	2.55	2.73	2.80	0.073	< 0.001	0.675
Pig ADG[5], g	196	203	203	208	215	8.64	< 0.001	0.741

[1]A total of 991 gilts from eight studies were divided into quintiles of lactation ADFI, with each quintile representing 20% of the population, to evaluate the effects of feed intake on sow BW change during lactation and litter growth performance.

[2]ADFI- average daily feed intake.

[3]BW- body weight.

[4]WSI- wean to service interval.

[5]ADG- average daily gain.

Table 4.4. Lactation sow feed intake effect on litter ADG and lactation multiparous sow BW change[1]

	Lactation ADFI[2], kg						*P* =	
	≤ 6.00	6.00-6.85	6.85-7.45	7.45-8.30	≥ 8.30	SEM	Linear	Quadratic
No. of sows	678	683	674	676	682			
Parity	3.6	3.5	3.5	3.5	3.8			
ADFI[2], kg	5.3	6.5	7.1	7.8	9.1	0.04	< 0.001	0.947
Sow BW[3], kg								
Entry	288.9	279.8	271.0	273.0	272.2	8.93	< 0.001	< 0.001
Farrow	261.6	253.8	245.3	247.1	245.6	8.43	< 0.001	< 0.001
Weaning	252.6	251.2	248.4	252.4	257.9	10.17	0.006	< 0.001
Sow BW[3] change, kg								
Entry to weaning	-36.2	-28.5	-22.7	-20.7	-14.3	3.97	< 0.001	0.038
Farrow to weaning	-8.9	-2.5	2.9	5.1	12.1	4.00	< 0.001	0.601
Lys intake, g/d	52.1	65.3	71.4	78.2	90.7	2.17	< 0.001	0.450
Lys intake, g/kg of litter gain	22.0	26.5	27.7	29.9	33.1	1.50	< 0.001	0.149
NE intake, Mcal/d	13.3	16.3	17.8	19.6	22.5	2.22	< 0.001	0.440
WSI[4], d	5.2	6.8	6.2	5.0	5.7	1.64	0.843	0.531
Litter size, n								
d 2	14.5	14.5	14.4	14.5	14.5	0.28	0.905	0.818
Weaning	12.5	12.7	12.8	12.8	12.9	0.35	0.030	0.491
Litter weight, kg								
d 2	22.7	22.8	22.7	23.0	22.9	0.83	0.162	0.821
Weaning	74.8	76.9	78.6	79.9	81.5	2.11	< 0.001	0.461
Mean pig BW[3], kg								
d 2	1.57	1.58	1.58	1.59	1.59	0.051	0.162	0.930
Weaning	5.97	6.06	6.16	6.22	6.33	0.127	< 0.001	0.902
Litter ADG[5], kg	2.66	2.76	2.85	2.90	2.99	0.082	< 0.001	0.488
Pig ADG[5], g	220	224	230	232	238	7.5	< 0.001	0.732

[1]A total of 3,393 sows from eight studies were divided into quintiles of lactation ADFI, with each quintile representing 20% of the population, to evaluate the effects of feed intake on sow BW change during lactation and litter growth performance.

[2]ADFI- average daily feed intake.

[3]BW- body weight.

[4]WSI- wean to service interval.

[5]ADG- average daily gain.

2

Table 4.5. Regression models to predict litter ADG and sow BW change from farrow to weaning in gilts and multiparous sows

Variable[1]	Equation	R^2
Sow BW change farrow to weaning, kg- gilts	3.580 + (4.738 × ADFI, kg) – (9.734 × Litter ADG, kg) – (0.569 × Wean age)	0.40
Sow BW change farrow to weaning, kg- multiparous sows	−30.936 + (5.188 × ADFI, kg) – (8.316 × Litter ADG, kg) + (1.404 × Pig count d 2)	0.36
Litter ADG, kg- gilts[2,3]	0.042 + (0.107 × ADFI, kg) + (0.550 × SID Lys) − (0.009 × Gilt BW Change farrow to weaning, kg) − (0.122 × Pig count d 2) + (0.236 × Pig count wean)	0.58
Litter ADG, kg- multiparous sows	0.288 + (0.060 × ADFI, kg) − (0.004 × Sow BW change farrow to weaning, kg) − (0.118 × Pig count d 2) + (0.280 × Pig count weaning) + (0.013 × Weaning age)	0.59

[1]ADG, average daily gain; ADFI, average daily feed intake; SID, standardized ileal digestibility
[2]Dietary SID Lys should be expressed as a percent.
[3]Pig count d 2 = count of pigs in a litter at 24 h postpartum, after cross fostering

Table 4.6. Inputs used to predict lactation sow body weight change across increasing sow lactation average daily feed intake using equations developed in the current analysis (Spinler) and NRC (2012) model outputs[1]

	ADFI, kg			
Item	4.5	6.0	7.5	9.0
Spinler equation- Gilts[2]				
Litter ADG, kg	2.34	2.52	2.70	-
Weaning age, d	19.4	20.2	21.1	-
Spinler equation- Multiparous sows[3]				
Litter ADG, kg	-	2.60	2.81	3.01
Pig Count d 2	-	14.51	14.51	14.51
NRC model- Gilts[4]				
Sow BW[5] farrow, kg	200.5	199.8	199.1	-
Pig ADG, g/d	206	211	216	-
Average litter size[6]	13.34	13.56	13.79	-
NRC model- Multiparous sows[4]				
Sow BW[5] farrow, kg	-	258.2	250.8	243.4
Pig ADG, g/d	-	229	235	241
Average litter size[6]	-	13.74	13.97	14.20

[1]Comparison of prediction equation found in figure 4-3.

[2] = 3.580 + (4.738 × ADFI, kg) – (9.734 × Litter ADG, kg) – (0.569 × Wean age).

[3] = −30.936 + (5.188 × ADFI, kg) – (8.316 × Litter ADG, kg) + (1.404 × Pig count d 2).

[4]ME of Diet, kg/kcal = 3292.

[5]BW- body weight

[6]Average litter size from litter d 2, after litter equalization, to weaning.

Table 4.7. Inputs used to predict litter average daily gain (ADG) across increasing sow lactation average daily feed intake (ADFI) using equations developed in the current analysis (Spinler) and NRC (2012) model outputs[1]

	ADFI, kg			
Item	4.5	6.0	7.5	9.0
Spinler equation- Gilts[2]				
SID Lys, %	1.02	1.02	1.02	-
Gilt BW[3] change, kg[4]	-10.2	-5.6	-0.9	-
Pig count d 2	14.95	14.95	14.95	-
Pig count weaning	12.59	13.16	13.54	-
Spinler equation- Multiparous sows[5]				
Sow BW[3] change, kg[4]	-	-2.6	5.5	11.2
Pig count d 2	-	14.51	14.51	14.51
Pig count weaning	-	12.98	13.43	13.88
Weaning age, d	-	20	20	20
NRC Eq. 8-70- Gilts				
Milk energy output, kcal/d	11,654	12,477	13,299	-
Average litter size[6]	13.77	14.06	14.34	-
NRC Eq. 8-70- Multiparous sows				
Milk energy output, kcal/d	-	12,803	13,809	14,816
Average litter size	-	13.74	13.97	14.20

[1]Comparison of prediction equations found in figure 4-4.

[2] = 0.042 + (0.107 × ADFI, kg) + (0.550 × SID Lys) − (0.009 × Gilt BW change farrow to weaning, kg) − (0.122 × Pig count d 2) + (0.236 × Pig count wean).

[3]BW = body weight

[4]Maternal BW change from farrow to weaning.

[5] = 0.288 + (0.060 × ADFI, kg) − (0.004 × Sow BW change farrow to weaning, kg) − (0.118 × Pig count d 2) + (0.280 × Pig count wean) + (0.013 × Wean age).

[6]Average litter size from litter d 2, after litter equalization, to weaning.

Chapter 5 - Chapter 5- Determining optimal corn DDGS levels in finishing pig diets

SUMMARY

Corn dried distillers grains with solubles (DDGS) are a byproduct of ethanol production. As ethanol plants continue to extract more oil from DDGS, the amount of energy available in the diets containing DDGS may decrease. Recent studies evaluating low-oil DDGS in finishing pig diets have observed decreased growth performance compared with past studies with high-oil DDGS. To support the decision-making process, the Kansas State Applied Swine Nutrition Team has developed a tool to assist practitioners, nutritionists, and producers in determining the most economical addition of DDGS based on predicted changes in growth performance.

Keywords: swine, dried distillers grains with solubles, grow finish pigs, economics

INTRODUCTION

Corn dried distillers grains with solubles (DDGS) are a byproduct of ethanol production and are a commonly used feed ingredient in swine diets. In a review paper, Stein and Shurson(Stein and Shurson, 2009) reported that DDGS can be included in nursery and grow-finish diets at levels of up to 30% without negatively affecting growth performance. However, research findings summarized in their review were collected before 2009, when oil content of DDGS was greater than 10%. In recent years, ethanol plants have been extracting more oil during the production of ethanol(Kerr et al., 2013), resulting in DDGS with oil contents of 6% or less. Extracted corn oil produced per bushel of corn has increased by 52% from 2015 to 2024, while DDGS produced per bushel of corn has decreased by 11%. The amount of ethanol produced per bushel of grain has increased by 7% from 2015 to 2024(Scott), reflecting improved efficiency in starch extraction and conversion during ethanol production. Changes in oil and starch content alter the net energy (NE) value and nutrient composition of DDGS.

Using indirect calorimetry (respiration chambers), Li et al.(Li et al., 2017a) determined the NE value of multiple DDGS sources with low, medium, or high levels of oil. The NE value of DDGS with 5.3% and 4.0% oil was 86.4% and 84.5% respectively, compared to the NE value of high oil DDGS containing 11.7% oil. Variation in NE values between high- and low-oil DDGS has contributed to changes in the growth performance of pigs fed diets containing low-oil DDGS. Recent research with low oil DDGS(Faccin et al., 2024; Lazaga et al., 2024b; Lazaga et al., 2024a; Lee et al., 2024) (less than 6.5% oil) has shown reductions in growth performance compared to previous studies using high oil DDGS(Salyer et al., 2012a; Graham et al., 2014) (greater than 10% oil). These findings highlight the need for producers to carefully reconsider the addition of low oil DDGS in diets to account for changes in growth performance. To support the decision-making process, the Kansas State Applied Swine Nutrition Team has developed a tool to help producers determine the most economical levels of DDGS in finishing pig diets, factoring in feed cost savings and income over feed cost on both live and carcass weight basis with varying DDGS oil content.

NUTRIENT COMPOSITION OF LOW OIL DDGS

During the production of DDGS, starch is fermented to produce ethanol and the concentrations of crude protein, fat, and fiber are increased to approximately three times the level found in corn(Salyer et al., 2012a). When the oil is further extracted, crude protein and fiber fractions increase, making up a larger portion of the total nutrients in DDGS. Fat and oil are the most energy-dense component of swine diets, and its inclusion is the most effective strategy to increase dietary energy concentration(Noblet and van Milgen, 2004). Consequently, as the oil and starch content of DDGS decreases, the NE value of DDGS decreases.

Over 2,900 DDGS samples from 65 ethanol plants across eight Midwestern states were collected from 2013 to 2024 by Pillen Family Farms (Columbus, NE, USA). The oil, neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein, and starch concentrations were analyzed using NIR (equations developed by Ajinomoto, Itasca, IL, USA; Figure 5-1). The average oil content decreased from approximately 10% in 2013 to 6% in 2020, staying consistent around 6% from 2020 to 2024. Crude protein, neutral detergent fiber (NDF), and acid detergent fiber (ADF) have increased as oil content has decreased, while starch content has decreased. In comparison, samples collected from 10 Midwest ethanol plants from 1997 to 1999 contained an average of 10.9% oil(Spiehs et al., 2002).

CONSIDERATIONS FOR FEEDING LOW OIL DDGS

Traditionally, research has indicated that DDGS can be included in finishing diets at concentrations of up to 30% without significantly affecting growth performance(Stein and Shurson, 2009; Buenavista et al., 2021). Recent studies using low oil DDGS show greater reductions in growth performance as DDGS inclusion increases compared to data with high oil DDGS. Graham et al.(Graham et al., 2014) observed a 1.0% decrease in ADG and 2.2% poorer feed efficiency when pigs were fed a diet containing 20% DDGS with 12.1% oil, compared to pigs fed a diet without DDGS. In contrast, Lazaga et al.(Lazaga et al., 2024b) observed a 2.6% reduction in ADG and 3.3% poorer feed efficiency when pigs were fed 20% DDGS with 6.2% oil, suggesting a greater negative impact of low-oil DDGS on growth performance. Li et al(Li et al., 2017b) speculated that the residual oil remaining in DDGS may have a lower digestibility than the extracted oil.

In addition to changes in growth performance, a reduction in carcass yield is frequently observed when feeding DDGS due to its high NDF and ADF content. High dietary NDF concentrations leads to increased intestinal tract weight, resulting in decreased carcass yield(Agyekum et al., 2012; Soto et al., 2019). To avoid the losses associated with decreased carcass yield, a fiber withdrawal strategy can be implemented by removing high fiber ingredients from the diet and replacing them with lower fiber ingredients before marketing. Asmus et al.[17] compared pigs fed a diet containing 30% DDGS and 19% wheat midds up to market with a fiber withdrawal strategy, where high-fiber ingredients were removed 23 days before market and pigs were fed a corn soybean meal based diet. Carcass yield was 71.7% for pigs fed the high-fiber diet to market and 73.0% for pigs fed the fiber withdrawal diets. Therefore, producers should consider using a fiber (DDGS) withdrawal strategy when including DDGS in the grow-finish diet.

PREDICTING NE OF DDGS

Assigning correct energy values to ingredients is important to optimize diet cost and accurately predict pig performance. It has been shown that digestible energy (DE) and metabolizable energy (ME) underestimate the energy value of fats and starch and overestimate the energy value of protein and fiber(Noblet and van Milgen, 2004). Because corn DDGS contain three times the amount of fiber as corn(Salyer et al., 2012b), the NE system is the most accurate method for evaluating energy because it accounts for the losses that occur during digestion, absorption, and metabolism. This provides a more precise measure of energy that is available for maintenance and growth. Multiple equations are available to predict the NE value of feed ingredients or complete feeds. Net energy value of DDGS in the decision-making tool can be determined based on using NE as a percentage of corn NE or a regression equation using

DDGS oil and ADF content to predict NE. The regression equation was developed based on 35 different DDGS samples from 18 papers. The regression equation developed was: NE, kcal/kg = 1952.929 + 39.307 × oil, % – 1.429 × ADF, %. Based on the regression equation utilized in the calculator, as oil content decreases by 1%, NE decreases by 39.3 kcal/kg when ADF level is held constant. The NE value is used to predict changes in growth performance(Cordoba, 2024) and carcass yield(Soto et al., 2019) to increasing levels of DDGS ranging from 5 to 30%.

DECISION-MAKING TOOL TO DETERMINE OPTIMAL DDGS LEVEL IN FINISHING PIG DIETS

In 2013, the Kansas State University Applied Swine Nutrition Team developed a tool to help producers determine the optimal level of DDGS to include in finishing diets to maximize economic return based on predicted growth performance and feed cost. However, with changes in the nutrient composition of DDGS and the potential effect on pig growth performance, there was a need for an updated DDGS tool. The goal of the revised DDGS tool is to combine feed cost, growth performance, and carcass yield to help producers determine the most economical DDGS inclusion level by phase based on user-provided costs.

Diet formulation

The tool allows producers to determine optimal DDGS level based on multiple diet formulation scenarios:

1. Diets with or without added fat to equalize NE. Adding fat equalizes NE between DDGS diets and a corn-soybean meal-based diet (no DDGS). Using diets without added fat will result in DDGS diets having lower NE compared to corn-soybean meal diets, leading to reduced gain and poorer feed efficiency.

2. Diets utilizing a DDGS withdrawal strategy by removing DDGS from the last phase or including DDGS in the diet until marketing. Utilizing a withdrawal strategy removes DDGS in the last dietary phase (~22 days before market) to minimize reductions in carcass yield. If a fiber withdrawal strategy is not used, DDGS remains in the diet until marketing, and carcass yield is decreased(Soto et al., 2019).

3. Diets with and without added L-Val. Diets with L-Val have the maximum allowable L-Lys until Ile becomes the limiting amino acid, followed by the addition of feed-grade amino acids to meet requirements for Met, Thr, Trp, and Val. Diets without L-Val have a higher soybean meal level and a reduced amount of feed-grade amino acids. Diets without L-Val were formulated by first adding the maximum allowable L-Lys until Val or Ile become limiting. Feed-grade amino acids were then added to meet amino acid requirements for Met, Thr, and Trp.

Diets were formulated across six dietary phases, with phase 1 to 5 diets covering roughly equal weight ranges. Phase 6 begins around the estimated weight of the first marketing (topping) event. Based on the findings from Cemin et al.(Cemin et al., 2019), dietary Val:Lys and Ile:Lys ratios were increased as Leu:Lys ratios increase. If ratios are not adjusted in actual diet formulation, growth performance may be lower than calculator predicted performance.

Predicted growth performance

The decision-making tool uses equations to predict average daily gain (ADG), gain to feed (G:F), and yield based on diet nutrient composition. Equations to predict ADG and G:F were derived from Cordoba, 2024(Cordoba, 2024). Predicted ADG and G:F were determined based on formulated NE, SID Lys, crude protein, NDF, and pig weight. A fiber withdrawal period of 22 d and NDF content of the last two diets are used in the equation to predict carcass yield(Soto et al., 2019). Predicted growth performance and yield were used to determine income over feed cost (IOFC) on a live and carcass weight basis.

Comparison: observed vs predicted performance results

Recent studies using low oil DDGS (less than 6.5% oil(Faccin et al., 2024; Lazaga et al., 2024b; Lazaga et al., 2024a; Lee et al., 2024)) have shown greater reductions in growth performance as DDGS inclusion increases compared to past studies with high oil DDGS (greater than 10% oil)(Salyer et al., 2012a; Graham et al., 2014). The predicted changes in ADG and feed efficiency with additions of 10, 20, or 30% DDGS compared to a corn-soybean meal-based diet were compared with observed results from four(Faccin et al., 2024; Lazaga et al., 2024b; Lazaga et al., 2024a; Lee et al., 2024) studies to validate the calculator. Observed vs predicted carcass yield was evaluated using data from three studies[5,7-8]. Although there was variation in responses across studies, observed vs predicted values relative to the line of equality indicate that predicted values were reasonably accurate, giving users confidence in the use of the calculator to predict performance (Figure 5-2).

Economic considerations

The tool calculates the most economical inclusion level of DDGS by dietary phase for maximum return based on feed cost savings and IOFC on a live and carcass weight basis. The economic value of DDGS depends on its price relative to corn and soybean meal. Dried distillers grains with solubles may become more economical as the price of corn and soybean meal increases. The oil and starch content of DDGS affects the economic value of DDGS because of their impact on NE and, therefore, pig growth performance. When DDGS are included in the diet, the need for supplemental inorganic phosphorus is reduced. Therefore, the cost of inorganic phosphorus also directly affects the economic value of DDGS.

The tool can be found on the Kansas State University Applied Swine nutrition website; https://www.asi.k-state.edu/extension/swine/calculators.html. Embedded in the tool is a detailed user guide that provides more information on development and use of the tool.

CONCLUSION

Changes in ethanol manufacturing practices have reduced the oil and starch content of DDGS, resulting in lower NE values for DDGS than observed in the past. Recent studies using low oil DDGS consistently show reductions in ADG and poorer feed efficiency. Changes in pig growth performance when feeding low oil DDGS led to the development of a decision-making tool to determine the optimal level of DDGS. The calculator predicts the effects of added DDGS on feed cost, growth performance, and carcass yield to determine the most economical use in finishing pig diets based on IOFC.

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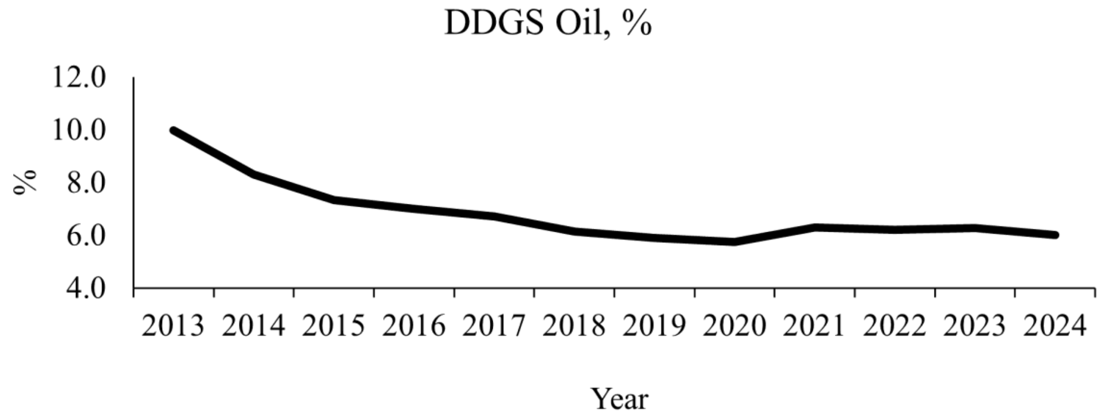
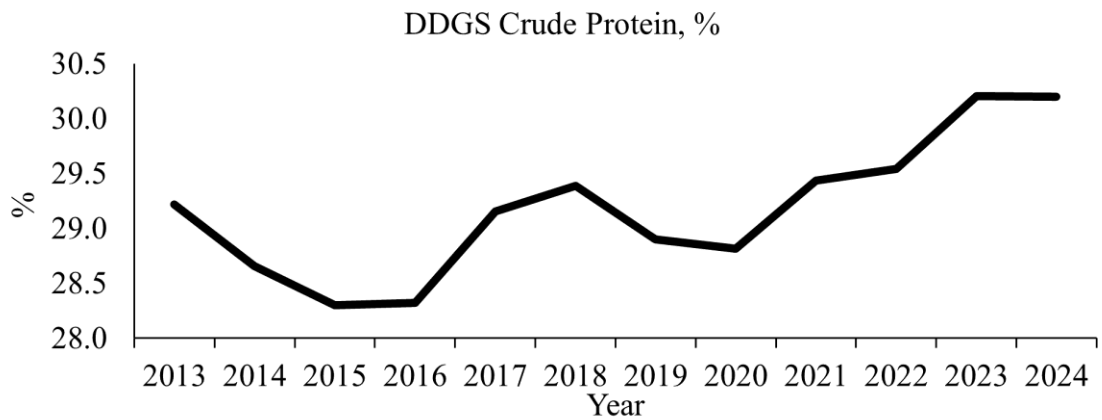
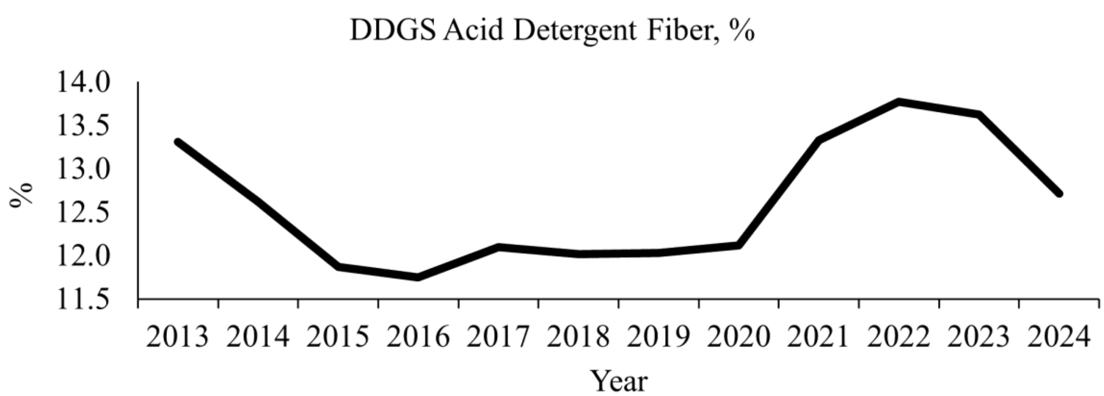
A


DDGS Oil, %
12.0
10.0
8.0
6.0
4.0
%
2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024
Year

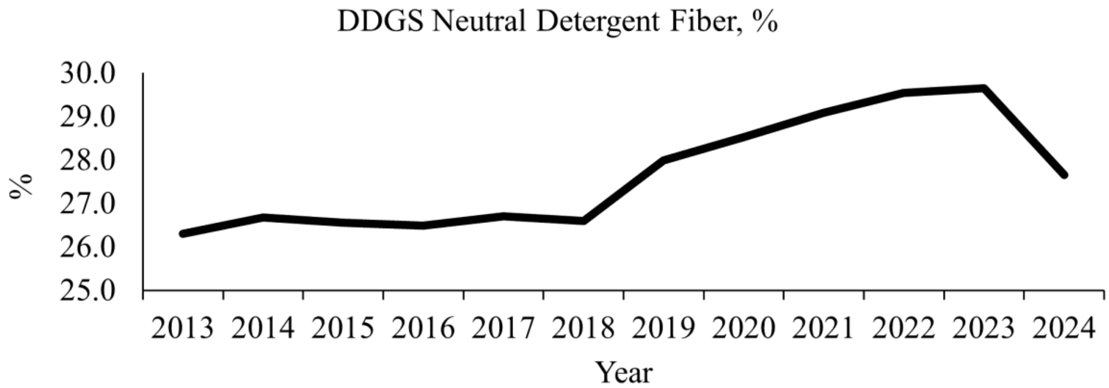
B


DDGS Crude Protein, %
30.5
30.0
29.5
29.0
28.5
28.0
%
2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024
Year

C


DDGS Acid Detergent Fiber, %
14.0
13.5
13.0
12.5
12.0
11.5
%
2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024
Year

D



E

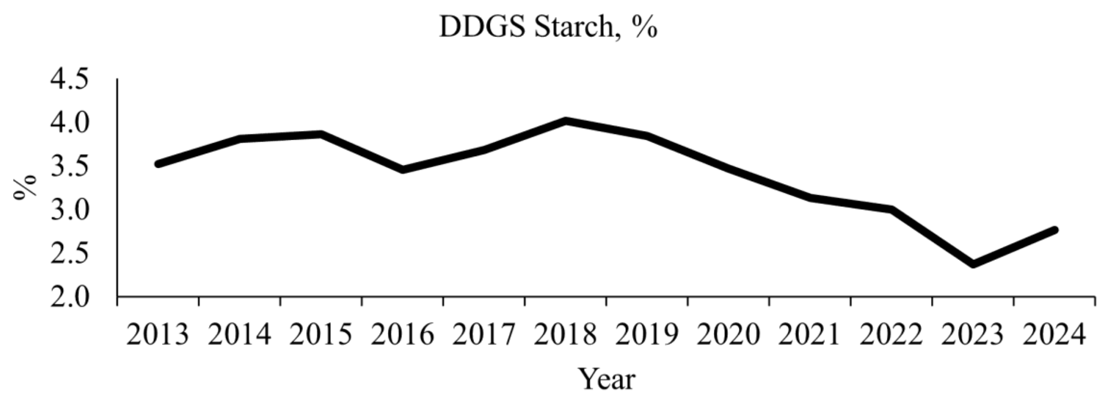
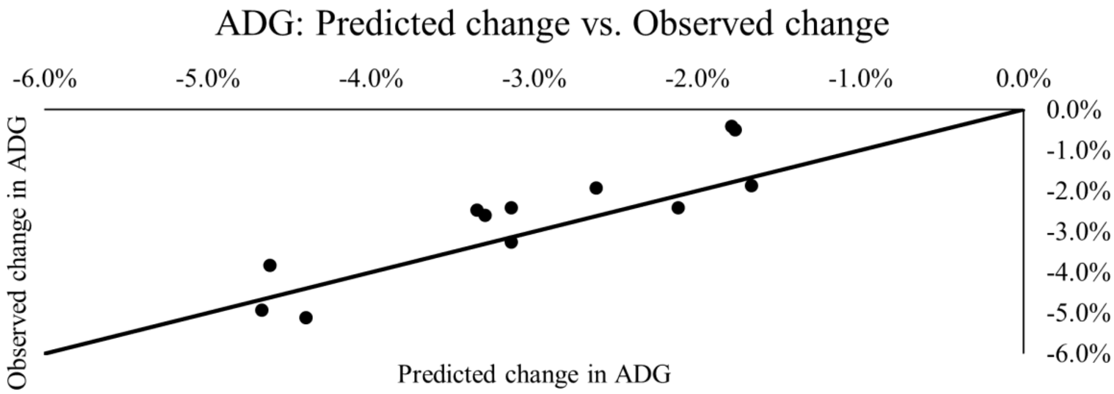
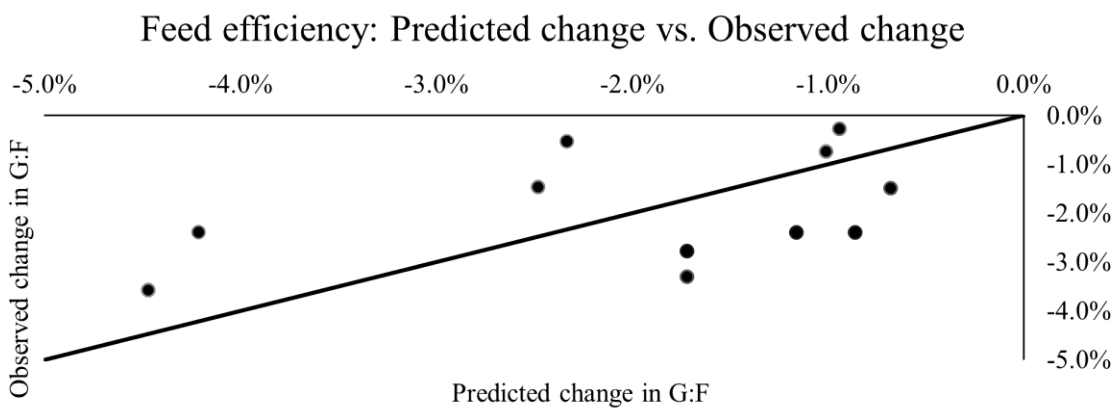


Figure 5-1. Changes in nutrient composition of DDGS from 2013 to 2024 for A. oil, B. crude protein, C. acid detergent fiber, D. neutral detergent fiber, and E. starch determined using NIR analysis of 2,935 DDGS samples.

A


ADG: Predicted change vs. Observed change
-6.0%
-5.0%
-4.0%
-3.0%
-2.0%
-1.0%
0.0%
0.0%
-1.0%
-2.0%
-3.0%
-4.0%
-5.0%
-6.0%
Observed change in ADG
Predicted change in ADG

B


Feed efficiency: Predicted change vs. Observed change
-5.0%
-4.0%
-3.0%
-2.0%
-1.0%
0.0%
0.0%
-1.0%
-2.0%
-3.0%
-4.0%
-5.0%
Observed change in G:F
Predicted change in G:F

C

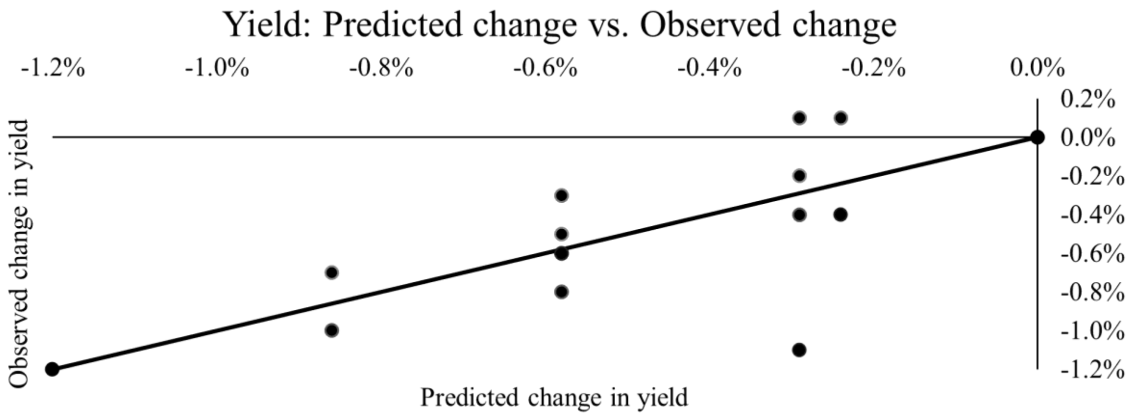


Figure 5-2. Plots of actual vs. predicted values relative to the line of equality of A. ADG, B. feed efficiency, and C. carcass yield.

Appendix A - Chapter 4 supplemental table

Supplemental Table 1. Descriptive statistics by study[1]

			Sow body weight, kg				Litter size, n		Litter weight, kg		Pig weight, kg	
Study	Gilts, n	Sows, n	Entry	Farrow	Weaning	ADFI, kg	d 2	Weaning	d 2	Weaning	d 2	Weaning
1	34	61	256	228	226	7.0	13.6	13.6	23.5	75.8	1.7	5.6
2	14	42	264	243	237	7.3	14.1	13.6	20.0	78.2	1.8	5.8
3	313	402	217	196	190	6.9	16.7	14.6	24.3	71.5	1.5	4.9
4	192	777	234	210	208	7.4	14.2	13.0	23.5	83.9	1.6	6.4
5	108	404	294	266	257	6.3	13.8	11.7	19.0	66.6	1.4	5.7
6	135	804	274	250	264	6.2	13.7	11.5	20.4	69.7	1.5	6.1
7	81	298	281	255	267	6.7	14.5	12.5	21.8	75.9	1.5	6.1
8	114	605	291	264	27	8.0	14.8	12.5	22.2	80.1	1.5	6.4

[1] Data was used from 8 trials, totaling 4.384 sows, 991 gilts and 3,393 multiparous sows.