Dietary calcium and phosphorous requirements and feed management for nursery pigs

by

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B.S., Kansas State University, 2013
M.S., University of Minnesota, 2015

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Animal Sciences and Industry
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Abstract

The dissertation consisted of 6 chapters involving studies in heavy weight market pig production, dietary Ca and P requirements for nursery pigs, antimicrobial resistance development in finishing pig microbiota, seasonal growth variability in commercial pig production, and leftover feed management in wean-to-finish pig productions. The first chapter presents a thorough review of published studies involving genetic selection, nutritional requirements, health, welfare, and pork quality of finishing pigs with marketing weight greater than 130 kg and assessed future research needs. Chapter 2 describes 2 experiments that evaluated the growth performance and percentage bone ash of early nursery pigs fed various combinations of Ca and P provided by inorganic sources or phytase. Feeding more than 0.90% dietary Ca decreased average daily gain (ADG), average daily feed intake (ADFI), gain:feed ratio (G:F), and percentage bone ash when diets were at or below NRC (2012) requirement for standardized total tract digestible (STTD) P. However, adding inorganic P or phytase to P deficient diets improved pig performance and alleviated the negative impacts of high dietary Ca concentration on growth performance. The experiment presented in chapter 3 characterized the dose-response to increasing digestible P in diets without or with 2,000 units of phytase for 6- to 13-kg pigs. Increasing STTD P from 80 to 140% of NRC (2012) requirement estimates in diets without phytase, and from 100 to 170% of NRC (2012) in diets with phytase, improved ADG, G:F, and percentage of bone ash. Estimated STTD P requirements varied depending on the response criteria and statistical models and ranged from 91 to >140% of NRC (2012) in diets without phytase, and from 116 to >170% of NRC (2012) for diets containing phytase. In addition, phytase exerted an extra-phosphoric effect on promoting pig growth and improved the P dose responses for ADG and G:F. In chapter 4, a study was conducted to determine the effects of tylosin administration route (through feed, drinking water, or intramuscular injection) on the growth performance and the development of antimicrobial resistance in fecal enterococci of finishing pigs. Pigs that received tylosin injection had decreased ADG and G:F compared with control pigs that did not receive any antibiotic treatment, which may be due to a stress response to the handling during injection administration. Moreover, tylosin administration via injection and feed resulted in a higher probability of enterococcal resistance to erythromycin and tylosin compared with drinking water treatment. Chapter 5 presents a retrospective analysis on the seasonal growth patterns of nursery and finishing pigs in 3 commercial production systems located in the Midwest US. Nursery ADG and ADFI expressed prominent seasonal variations and were similar among systems, whereas nursery G:F was not affected by season. Finisher ADG, ADFI, and G:F varied over seasons, but the magnitudes and patterns of change were system dependent. This chapter also presents the concepts underlying the implementation of a multi-level linear mixed model of production records to analyze seasonality and potentially other decision factors in commercial systems. Finally, in chapter 6, 2 experiments were conducted regarding the strategy of managing leftover finisher feed in a wean-to-finish production system. Experiment 1 evaluated the timing (phase) of feeding 2.5 kg/pig of finisher feed in a 5-phase nursery program. All growth responses decreased immediately when the finisher feed was blended into nursery diets; however, pigs greater than 11 kg (phase 3) had improved ability to compensate for the negative effects of finisher feed on overall growth performance. Experiment 2 was then carried out to investigate the maximum amount of finisher feed can be fed to 11-kg pigs. Increasing the finisher feed budget from 0 to 3.75 kg/pig resulted in a linear decrease in ADG and ADFI. However, the economic analysis indicated no change in income-over-feed-cost due to the timing and dose of blending finisher feed into nursery diets.

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My greatest thanks are to my mother, Yongping Wang, father, Bian Wu, and my wife, Jingwen Liao. The love, company, understanding, and support that you gave allowed me to complete my education abroad and have made me the person I am today.

Dedication

I want to dedicate this dissertation to my mother, Yongping Wang.

Preface

This dissertation is original work completed by the author, Fangzhou Wu. Chapters 1 and 6 were published in *Translational Animal Science*, chapter 2 was published in *Journal of Animal Science*, chapter 3 was published in *Animal*, chapter 4 was published in *Foodborne Pathogens and Disease*, and chapter 5 was published in *Journal of Swine Health and Production*. Each of the chapters was formatted according to the required standards of the corresponding journal.

Chapter 1 - A review of heavy weight market pigs: status of knowledge and future needs assessment[1]

ABSTRACT: Marketing weight is an important economic variable that impacts the productivity and profitability of finishing pig production. Marketing weight has been increasing worldwide over the past decades driven by the dilution of fixed production cost over more weight per pig and the improvement of genetic selection of lean-type pigs. This review was aimed to summarize current knowledge and assess the future research needs on producing finishing pigs with marketing weight greater than 130 kg. Based on a thorough literature review, increasing marketing weight affected overall pig growth; in particular, cumulative ADG decreased by 4.0 g, ADFI increased by 78.1 g, and G:F decreased by 0.011 for every 10 kg increase of marketing weight. Increasing marketing weight by 10 kg increased carcass yield by 0.41 percentage units, backfat by 1.8 mm, LM area by 1.9 cm^2, carcass length by 2.2 cm, and belly yield by 0.32 percentage units, but decreased percentage of fat-free-lean by 0.78 units and decreased loin, shoulder, and ham yields by 0.13, 0.16, and 0.17 percentage units, respectively. Studies that investigated the effects of marketing weight on pork quality observed decreased pH by 0.02 and 0.01 at 45 min and 24 h postmortem, respectively, and increased a* value by 0.28 per 10 kg marketing weight increase. Heavier market pigs had increased concentrations of saturated fatty acids and intramuscular fat. However, studies reported conflicting results for L* and b* values, drip loss, Warner-Bratzler shear force, and sensory properties of pigs in response to increasing marketing weight. A limited amount of research has been conducted to estimate nutrient

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[1] This work has been published in *Translational Animal Science*: F. Wu, K. R. Vierck, J. M. DeRouchey, T. G. O'Quinn, M. D. Tokach, R. D. Goodband, S. S. Dritz, and J. C. Woodworth. 2017. A review of heavy weight market pigs: status of knowledge and future needs assessment. Transl. Anim. Sci. 1:1–15.

requirements for pigs greater than 140 kg. Increased weight and size of heavy pigs can create challenges to farm and packer facilities and equipment. Discussions and recommendations are provided concerning the adjustments for floor and feeder space, barn design, ventilation, disease control, transportation, and carcass processing needed for increasing marketing weight. In conclusion, increasing marketing weight creates both opportunities and challenges to current finishing pig production, and future research is needed to provide nutritional and management guidelines and improve feed efficiency and meat quality of heavy weight market pigs.

Key words: carcass quality, growth, heavy pig, marketing weight, meat quality

INTRODUCTION

Marketing weight is an important variable that affects the profitability of finishing pig production due to its impact on pig growth, efficiency, and the quantity and quality of pork produced. Average marketing weight in the U.S. has been steadily increasing for over 80 yr and increased from 121.1 kg in 2004 to 125.6 kg in 2013 (NASS, 2014). A dilution of fixed production cost is a major force that drives the increase of marketing weight because the total number of pigs required to produce a given quantity of pork is reduced (Park and Lee, 2011). A drawback of the increased marketing weight is reduced G:F resulting from accelerated fat accretion and a declining rate of lean deposition during in the late finishing phase (Shields et al., 1983; Gu et al., 1991; Piao et al., 2004). In addition, increased weight and size of heavy pigs creates challenges to farm facilities and equipment, such as floor and feeder space, ventilation, and transportation systems, which in turn affects pig growth performance.

Some additional factors that require consideration when increasing marketing weight include genetic selection and nutritional requirements. Lean-genotype pigs are needed to prolong the period of efficient weight gain, while the selection for lean gain rate should also be balanced with the requirements of meat quality and animal health attributes. From a nutritional prospective, nutrient requirements are established for pigs less than 140 kg (NRC, 2012); however, pigs with further increased BW have greater maintenance needs than lighter BW and therefore, additional research is needed to provide nutritional guidelines. Finally, information regarding the impact of meat quality with increasing marketing weight, such as color, primal cut yields, and intramuscular fatness of heavy pigs and its subsequent impact on consumer preference are needed. This review evaluated published studies involving genetic selection, nutritional requirements, health, welfare, and pork quality of heavy weight market pigs and assessed future research needs.

MATERIALS AND METHODS

Examination of published studies was conducted via the Kansas State University Libraries, using databases including AGRICOLA, CAB International, MEDLINE, National Pork Board Research Database, and SCOPUS. No year of publication limits was set in any of the electronic database searches. Additional search of literature was performed within the following journals: *Journal of Animal Science*, *Animal*, *Animal Feed Science and Technology*, *Meat Science, Livestock Science*, and *Livestock Production Science*. Key words used for the above databases included: “heavy pig*”, “heavy hog*”, “heavy weight”, “finishing pig*”, “finishing hog*”, “late finishing pig*”, “late finishing hog*”, “slaughter weight”, “harvest weight”, “marketing weight”, along with the key words associated with the aspects of selection/genetics, nutrition, pork/meat quality, pork safety, and swine health and well-being. In addition, non-peer-reviewed publications (i.e., university extension and company reports) were also collected, closely scrutinized for accuracy and quality, and served as valuable resources of information for this review. Conference proceedings and abstracts that were not included in the peer-reviewed databases were searched using Searchable Proceedings of Animal Conferences (S-PAC) and Google Scholar search engine. Additionally, personal communication with genetic and production companies, university researchers, and packing plant personnel were performed for the collection of internally-generated information that had application for this review.

In this review, heavy weight market pigs refer to pigs with marketing weight greater than 130 kg. For the summary of marketing weight effects on pig growth performance, carcass characteristics, and pork quality, the data set excluded studies in which the greatest marketing weight used was less than 125 kg and pigs did not have *ad libitum* access to feed during the experiment. The screening threshold of 125 kg was adopted in order to obtain data from pigs marketed slightly lighter than the definition of heavy pig in order to improve the modeling quality. Sensitivities of growth, carcass, and pork quality traits in response to increasing marketing weight by 10 kg were generated using simple linear regression. These analyses were based on the assumption that traits had linear responses to the increase in marketing weight and there were no interactive effects between marketing weight and other factors (i.e., gender, inclusion of growth promoters). Such assumptions could be challenged; however, a simple linear regression approach was adopted because of the limited number of observations available for many of the response criteria. Average responses were reported as the mean among studies. In the calculation of average responses, studies by Latorre et al. (2004 and 2008) were excluded for ADG, ADFI, and G:F, because pigs were reported to be under heat stress, and a study by Serrano et al. (2008) was excluded for growth and carcass traits due to the use of Iberian obese pig breed that is typically not used in North America pig production. A study by Piao et al. (2004) was excluded in the calculation for drip loss due to the abnormally high value reported (greater than 3 standard deviations from the mean of all values).

RESULTS AND DISCUSSION

Impact of marketing weight on growth performance, carcass characteristics, and meat quality

Growth performance

Numerous studies have been conducted to investigate the effects of increasing marketing weight on growth performance (i.e., ADG, ADFI, and G:F) of growing-finishing or finishing pigs. A total of 14 experiments involving pigs harvested at weights greater than 125 kg were summarized in Table 1.1. Although instantaneous gain rate and feed intake of pigs follow allometric patterns as BW increases (sigmoid growth curve; Schinckel et al., 2006; Shull, 2013), we plotted the cumulative ADG and ADFI values against marketing weight reported by the reviewed studies and observed linear growth responses to increasing marketing weight. Eight out of the 14 reviewed studies reported a decrease in cumulative ADG of 3.6 to 54.9 g for every 10 kg increase in marketing weight, whereas the remaining studies showed increased ADG of 2.8 to 8.7 g when marketing weight increased by 10 kg. Cumulative ADFI was reported in 13 studies with ADFI increasing by 52.7 to 163.6 g in 11 studies. Conversely, ADFI decreased by 3.0 and 78.0 g in 2 studies (Latorre et al., 2004 and 2008, respectively) where heat stress of pigs under severe summer weather was reported. Reduction in cumulative G:F was observed in all the reviewed studies with the magnitude varying from 0.003 to 0.017 units per 10 kg marketing weight increase. On average (calculation excluded data from Latorre et al., 2004 and 2008 due to suppressed ADFI and data from Serrano et al., 2008 due to the use of an Italian obese pig breed), increasing marketing weight by 10 kg decreased cumulative ADG by 4.0 g, increased ADFI by 78.1 g, and decreased G:F by 0.011.

It is not surprising that pigs marketed at heavy weights have elevated ADFI, because the increased body size and physical capacity of the digestive tract improve the ability of pigs to consume more feed (Suarez-Belloch et al., 2013). Nevertheless, the efficiency of BW gain declines greatly during the late growth stages, which is attributed to accelerated fat accretion and declining rates of water and protein deposition (Shields et al., 1983; Gu et al., 1991; Piao et al., 2004). Increased maintenance requirements in heavy finishing pigs may also contribute to decreased G:F (Gu et al., 1991). For the ADG response, researchers (Schinckel et al., 2006; Jungst et al., 2012a, b; Shull, 2013) have demonstrated that the instantaneous growth rate of growing-finishing pigs (average between barrow and gilt) reaches a plateau at an average BW of 78 to 85 kg and decreases thereafter. However, evaluating data from the 14 experiments, it is difficult to accurately describe why cumulative ADG was improved in half of the experiments and diminished in the other half. Possible explanations of this discrepancy can be proposed. First, nutritional programs used and, particularly, the dietary energy and protein supply, varied among these studies, which would influence the growth responses of pigs at increasing marketing weight. Secondly, selection of the initial and terminal BW as well as number of marketing groups differed among studies and could also be a factor. Generally, the greater the initial BW (shorter overall feeding period) and wider range of marketing weight used, the more prominent responses were observed. However, use of wide marketing weight range tended to result in a quadratic response of cumulative ADG to increasing marketing weight (Shull, 2013), which also affected the precision of linear quantification for ADG. Thirdly, housing system and especially the floor and feeder spaces allowance could affect the ADFI and, subsequently, ADG of pigs. Furthermore, dissimilar genetic lines of pigs used in the studies had varied growth patterns at heavy weights. Lean-type pigs are desired for producing pigs marketed at heavy weights (Kim et al., 2005). However, some of the reviewed studies were carried out on pigs that were aimed for dry-cured ham production (Latorre et al., 2004 and 2008; Serrano et al., 2008), which were often selected for high fat thickness; discrepant growth responses of these pigs could be expected when compared with modern lean-type pigs. Finally, quantification of growth responses is also determined by the methodology used in the studies. Only studies reporting cumulative growth responses were compared herein because relatively few studies (Carr et al., 1978; Gu et al., 1991; Shull, 2013) in the literature reported instantaneous growth rate and the methodologies utilized to measure instantaneous growth rate differed among these studies.

Carcass characteristics

Increasing marketing weight greatly affects carcass characteristics of pigs. For this analysis, 25 studies were reviewed where carcass traits of pigs with increasing market weight were determined (Table 1.2). Twenty studies evaluated the percentage carcass yield of pigs harvested at heavy weights; increased yield was documented in 19 studies ranging from 0.05 to 1.05 percentage units per 10 kg increase in marketing weight. Across all studies, the mean increase in carcass yield was approximately 0.41 percentage units per 10 kg marketing weight increase. Increased carcass yield was due to a greater allometric growth coefficient of carcass than the whole body (Gu et al., 1992). Shields et al. (1983) suggested that the carcass only represented 70% of the live weight at 56 kg, but 79% by 146 kg; whereas, the relative proportion of the intestinal tract decreased from 5.6% to 4.3%, and that of internal organs also decreased from 4.5% to 3.2%. However, one study reported a reduced yield of 0.49 percentage units per 10 kg increase of marketing weight (Piao et al., 2004). This study was conducted in Korea where the definition and methodology of calculating carcass yield might have been different from that in North America.

All studies considered in this review observed an increase in backfat thickness with increased marketing weight. However, increases in backfat varied among studies, ranging from 0.5 to 3.0 mm per 10 kg marketing weight increase. Across the studies reviewed, there was an average increase in backfat of 1.8 mm per 10 kg increase in marketing weight. In terms of overall fat deposition, there is little published research evaluating specific areas of deposition, with the exception of the belly and back fat. Correa et al. (2008) reported significant increases in belly fat thickness as marketing weight increased from 107 to 125 kg, though no other studies have evaluated this trait.

Percentage fat-free lean, as provided in the cited studies, decreased with increased marketing weight in most studies. The observed reduction in percentage fat-free lean was most likely due to the increased backfat found in heavy pigs. In contrast, 3 studies found an increase in percentage fat-free lean ranging from 0.05 to 2.28 unit per 10 kg increase in marketing weight. Interestingly, the studies reported an increase in percentage fat-free lean were those that used greater initial BW and narrow ranges between initial and marketing weights than other studies.

As marketing weight increases, there is a general trend of increasing LM area and carcass length, which can be explained by the greater body size of heavy pigs. All the reviewed studies found an increase in LM area ranging from 0.1 to 2.7 cm^2, with an average of 1.9 cm^2 per 10 kg marketing weight increase. All the reviewed studies observed increasing carcass length with greater marketing weights. However, wide variation of the increase in carcass length was present ranging from 1.3 to 3.1 cm, with an average of 2.2 cm, per 10 kg of additional BW. Increased carcass length may cause issues in processing plants if pigs are too large to fit through typical equipment, such as rails, scalders, carcass splitters, and other mechanized fabrication equipment.

A total of 14 studies evaluated the effects of increasing marketing weight on subprimal cut yields. Belly yield increased with increasing marketing weight in all studies, ranging from only 0.09 to 0.61 percentage units per 10 kg marketing weight increase. In regards to lean primal cuts, yields were generally decreased. Ten studies observed decreased loin yield, ranging from 0.09 to 0.38 percentage units per 10 kg marketing weight increase. However, Cisneros et al. (1996) reported an increase in loin yield of 0.4 percentage yield per 10 kg increase in marketing weight. Of the 10 studies that evaluated shoulder yield, 7 studies reported a decrease ranging from 0.48 to 0.02 percentage units per 10 kg marketing weight increase. However, 3 studies found a slight increase in shoulder yield ranging from 0.08 to 0.09 percentage units per 10 kg marketing weight increase. Ham yield was affected similarly to shoulder and loin yields. As marketing weight increased, ham yield decreased in 10 out of the 13 studies. Decreases in ham yield ranged from 0.09 to 0.36 percentage units per 10 kg increase in marketing weight. However, 3 studies reported slight increases in ham yield; this might be related to how the loin was removed, as Latorre et al. (2004) and Serrano et al. (2008) were studies done with Italian heavy weight pigs. In addition, it is important to note that changes of primal cut yields were affected by whether the data reported trimmed or untrimmed cuts. More prominent responses could be expected for untrimmed cuts because a great amount of fat was deposited on the cuts during the last stages of growth. On average, increasing marketing weight by 10 kg increased belly yield by 0.32 percentage units, but reduced loin, shoulder, and ham yields by 0.13, 0.16, and 0.17 percentage units, respectively.

Pork quality

Pork quality is important for several reasons, including product functionality, consumer preference, and palatability. Several studies have evaluated pork quality traits as it relates to increased marketing weight (Table 1.3.). These include: pH, drip loss, cooking loss, Warner-Bratzler shear force, intramuscular fat or marbling scores, iodine value, as well as instrumental color scores and sensory panel data.

The majority of published literature has observed a decrease in pH as carcass weight increases. Decreased pH negatively affects drip loss, color, and several other pork quality traits. All the 6 studies reported initial pH measured at 45 min to 1 h postmortem, and 6 out of 8 studies evaluated ultimate pH at 24 h postmortem observed decreased pH values when increasing marketing weights. Beattie et al. (1999) and Martin et al. (1980) showed significant decreases in pH at 1 h postmortem, but no significant differences at 24 h or in ultimate pH when comparing pigs with increasing marketing weight from 92 to 131 kg and 73 to 137 kg, respectively. Additionally, Martin et al. (1980) also reported a negative, but weak, correlation ($r = -0.05$) between carcass weight and 1 h pH. When comparing pigs at 8 months of age (143.6 kg BW) versus those 10 months of age (181.8 kg BW), Virgili et al. (2003) observed a 0.05 unit reduction in pH of the semimembranosus at 1 h as well as at 24 h as marketing weight increased by 10 kg. Moreover, Cisneros et al. (1996) reported a reduction of pH at a rate of 0.01 unit at 45 min and a 0.02 unit reduction at 24 h postmortem per 10 kg of additional BW. Park and Lee (2011) observed a 0.02 unit reduction in 24 h pH per 10 kg increase in marketing weight from 116 to 133 kg. In a study involving pigs with increasing marketing weight from 120 to 170 kg, Durkin et al. (2012) observed a quadratic response of pH at 45 min postmortem. In that study, pH of semimembranosus increased by 0.01 unit per 10 kg increase in marketing weight from 120 to 140 kg and decreased at a similar rate when marketing weight increased from 140 to 170 kg. In contrast, Piao et al. (2004) and Bertol et al. (2015) observed increases in ultimate pH at 0.02 and 0.01 respectfully per 10 kg marketing weight increase.

With a reduction in pH, especially at 24 h, other pork quality factors, specifically instrumental color and drip loss are affected. Color is the number one factor affecting consumer decisions when purchasing meat, as it is used as an indicator of freshness (Mancini and Hunt, 2005). In regards to color, there are conflicting results related to increased marketing weight.

Overall, 9 studies have evaluated instrumental color in heavy weight carcasses. An example of the conflicting results can be found with L*, an instrumental color measurement used to evaluate the lightness or darkness of a product (greater L* value indicates a lighter color). Durkin et al. (2012) observed no significant differences in L* when comparing 120, 130, 140, 150, 160 kg pigs to those weighing greater than 170 kg. Park and Lee (2011) also observed no significant differences in L* values among pigs weighing 116, 124, and 135 kg. In contrast, Latorre et al. (2004) found a 2.48 unit reduction in L* value with a 10 kg increase in marketing weight when comparing pigs from 116 to 133 kg. In addition, when evaluating differences among pigs slaughtered at 144 and 182 kg, Virgili et al. (2003) determined a 0.01 unit reduction in L* value in the semimembranosus with every 10 kg increase in BW.

In the 8 studies evaluating a* value, an instrumental color measurement used to determine redness of a product (greater a* value indicates a more reddish color), most published literature found an increase or no significant differences as carcass weight increased. Increases in a* value were observed by Durkin et al. (2012) and Latorre et al. (2004). Durkin et al. (2012) found a 0.33 unit increase in CIE (Commission Internationale de l'Eclairage color system) a* values in the semimembranosus muscle when comparing pigs weighing 120, 130, 140, 150, 160 kg to those weighing greater than 170 kg. Latorre et al. (2004) observed a* value increased by 0.43 units per 10 kg marketing weight increase when evaluating the effects of gender on meat quality of pigs weighing 116, 124, and 133 kg. However, other studies found no significant differences in a* value with increasing carcass weights (Park and Lee, 2011; Virgili et al., 2003), thus providing no clear evidence as to the effect of increased carcass weights on a* instrumental color values.

The evaluation of b* is an instrumental determination of yellowness in meat (greater b* value indicates more yellowish color). Much like L* value, the 7 studies that evaluated meat color found contradictory findings, with 4 studies finding increased values and 3 studies finding reduced values. Durkin et al. (2012) reported an increase of 0.1 unit in b* value per 10 kg marketing weight increase. When evaluating the differences in meat quality and carcass characteristics among 8 and 10 month old Italian pigs weighing 144 and 182 kg, respectively, Virgili et al. (2003) determined there was a 0.17 unit reduction in b* values in the semimembranosus per 10 kg marketing weight increase. Overall as marketing weights increased, there are conflicting results on instrumental color, especially in L* and b* values in published literature. However, such changes in instrumental color values may be of little biological significance, but may result in a minimal impact on consumer preference.

Drip loss, a measurement of water holding capacity, is readily affected by both pH and chilling method. Of the studies evaluating the effects of increasing carcass weight on pork quality, 10 studies evaluated drip loss with conflicting results reported. With increasing BW, drip loss was increased in 6 studies, decreased in 3 studies, and inconsistent response of drip loss to increasing marketing weight was observed in 1 study. Cisneros et al. (1996) and Park and Lee (2011) found a 0.29 percentage unit increase in drip loss per additional 10 kg of BW. In addition, Martin et al. (1980) determined that carcass weight was negatively related (r = -0.31) to percentage expressible juice. As age and carcass weight increased, Virgili et al. (2003) observed a 0.34 percentage unit increase in drip loss for every 10 kg increase in marketing weight from 144 to 182 kg. Durkin et al. (2012) reported that drip loss of pigs marketed at 140 kg was approximately 3% less than pigs marketed at 130, 150, and 160 kg, but was not different from those marketed at 120, 140, and 170 kg. Methodology reported by these studies did not indicate any differences in chilling methods that may have affected drip loss results.

Pork fat quality is important for product functionality and use. Three studies have evaluated the effects of increasing carcass weight on the fatty acid profiles (expressed as the percentage of fatty acid over total fat content) of pork carcasses. All of the studies observed non-significant differences in MUFA among pigs of different BW (Lo Fiego et al., 2005; Correa et al., 2008; Raj et al., 2010). In a study by Raj et al. (2010), where pigs weighing 90, 110, and 130 kg were evaluated for subcutaneous fatty acid profiles, concentrations of PUFA were reduced by 0.37 percentage units per 10 kg marketing weight increase from 90 to 130 kg. Conversely, SFA contents were increased by 0.46 percentage units per 10 kg marketing weight increase when comparing pigs weighing 90 and 130 kg (Raj et al. 2010). When examining the fatty acid profiles of fat coverings of hams in Italian heavy pigs weighing 151, 164, and 176 kg, Lo Fiego et al. (2005) observed similar results to Raj et al. (2010); as BW increased, there was a 0.36 percentage unit increase in SFA content for every 10 kg increase in marketing weight. In addition, these authors reported significant reductions in PUFA concentration as marketing weight increased; Lo Fiego et al. (2005) reported a 0.52 percentage unit reduction and Raj et al. (2010) observed a 0.37 percentage unit reduction in PUFA concentration per 10 kg increase in marketing weight. Conversely, in a study comparing bellies from heavy weight market pigs intended for cured ham production, Correa et al. (2008) observed a tendency (*P* = 0.06) for increased PUFA content when comparing pigs weighing 107, 115, and 125 kg. However, Lo Fiego et al. (2005) observed a 0.72 unit decrease in iodine value per 10 kg increase of marketing weight. Iodine value does not affect bellies' functionality when ranging from 70 to 75 g/100g (Benz et al., 2011). Iodine values reported by Correa et al. (2008) and Lo Fiego et al. (2005) did not exceed this acceptance range, suggesting that an increase in marketing weight resulted in minimal reductions in pork product functionality.

Warner-Bratzler shear force (WBSF) results are conflicting in studies evaluating increasing marketing weight. Of the 8 studies that evaluated WBSF, Beattie et al. (1999) and Latorre et al. (2004) observed no significant differences when comparing pigs weighing 70, 80, 90, and 100 kg, as well as 116, 124, and 133 kg, respectfully. On the contrary, Cisneros et al. (1996) observed a slight reduction of 0.08 kg per 10 kg marketing weight increase in WBSF, which may be due to the increased intramuscular fat content associated with increased carcass weights. Martin et al. (1980) also observed a slightly positive, significant relationship between increasing carcass weights and shear force (r = 0.08), which indicated a tougher product with increasing marketing weight. In addition, Durkin et al. (2012) reported a quadratic effect of BW on tenderness; pigs weighing 140 and 160 kg had greater WBSF values and, therefore, were more tender than those weighing 120, 150, and 170 kg.

Marbling or intramuscular fat is a primary driver for both juiciness and tenderness in pork products (Cannata et al., 2010). Multiple studies (Cisneros et al., 1996; Huff-Lonergan et al., 2002; Park and Lee, 2011) demonstrated a concurrent increase in intramuscular fat in the longissimus dorsi muscle as carcass weight increases, with an exception that Martin et al. (1980)

observed a weak, negative response (r = -0.02) of marbling to increasing carcass weight from 73 to 137 kg.

There were only 3 studies evaluated the sensory properties of heavy weight market pigs and have produced mixed results. Huff-Lonergan et al. (2002) observed significant, positive responses of juiciness (r = 0.09) and off-flavor presence (r = 0.14) to increasing carcass weight. Increase in off-flavors is likely a result of increased PUFA concentration along with enhanced fat deposition in heavy pigs (Correa et al., 2008). Contrary to those findings, Cisneros et al. (1996) observed decreased tenderness and juiciness by 0.1 and 0.04%, respectively, for every 10 kg increase in marketing weight from 100 to 160 kg. Park and Lee (2011) observed increased presence of off-flavor in raw pork as marketing weight increased from 116 to 133 kg; however, after cooking, there were no significant differences in flavor profiles. Further research is needed to determine the true effects of increasing carcass weight on sensory panel ratings.

After a thorough literature review, it was determined that there has been no research evaluating the impact of chilling rate on meat quality traits with heavy weight market pigs. Research is needed to evaluate if increased wind speeds and decreased cooler temperatures are needed to appropriately chill heavier carcasses to prevent undesirable meat quality traits. Additionally, future study is also in need to determine the effects of heavy marketing weight on pork safety, such as microbiological populations, antimicrobial treatments, or the potential associated dilution of sprayed-on antimicrobials (i.e., organic acids) due to increased cut and carcass size.

Factors to consider when increasing marketing weight

Genetics

Genetic selection of pigs with high lean-gain potential is essential for the production of heavy pigs. Neely et al. (1979) observed that pigs selected from lean litters (sorted based on backfat) had slower weight gain during the early stages of growth (15 to 86 kg), but gained at a faster rate thereafter compared with pigs from fat litters. During the last finishing period, lean-type pigs have less deposition of fat, thus exhibit better feed efficiency compared with non-lean genotypes (Kim et al., 2005; Park and Lee, 2011). Growth performance and carcass traits of heavy pigs varied considerably when different genetic lines are assessed. In a study where pig growth of 5 genotypes were compared at 3 BW (100, 114, and 127 kg), Gu et al. (1991) observed that there was no genotype × BW interaction and the difference among genotypes could be as large as 11.0, 7.3, and 14.0% for ADG, ADFI, and G:F, respectively. Similarly, Latorre et al. (2003) compared pigs bred from 3 sire lines at 2 marketing weights (122 vs. 136 kg). There were no genotype by marketing weight interactions and differences of 3.3, 1.6, and 4.9% for ADG, ADFI, and G:F, respectively, were observed. More recently, a breeding stock company (PIC, Hendersonville, TN) evaluated 2 different genotypes (PIC280 vs. PIC359) fed to 145 kg; a 2.7 kg difference was observed between lines on final BW, driven by significant differences in ADG (18 g), ADFI (90 g), and G:F (0.006 g/g; personal communication, 2016).

Effects of genetic line on carcass characteristics should also be considered when increasing marketing weight. Using 5 genotypes and 2 marketing weights (130 and 160 kg), Peloso et al. (2010) demonstrated that genetic background was responsible for dissimilar deposition rates of fat and lean during the transition of increasing marketing weight and led to significantly varied HCW, backfat thickness, and LM depth of pigs at harvest. Pigs from different genetic lines also exhibit varied patterns in partitioning fat towards intramuscular, subcutaneous (backfat), or internal (kidney) sites at heavy weights, which contributes to a difference in meat quality among genotypes (Franci et al., 2001).

Nutrition

In general, heavy pigs have decreased requirements for dietary protein concentration (Crovetto et al., 1999, Galassi et al., 2010), likely due to decreased lean gain compared with lighter finishing pigs. Limited information is available regarding the nutritional requirements of heavy pigs over 140 kg. The NRC (2012) growth model estimates a SID Lys requirement of 0.53% (assuming corn-soybean meal diet which would contain 2,350 kcal NE/kg) for finishing pigs with 130 kg BW, which is decreased to 0.49% at 140 kg BW. However, it is important to note that these estimates have not been validated by empirical studies. Using factorial approaches, Manini et al. (1997) predicted that the SID Lys requirement of a 120 kg pig was 0.48%, and the value was reduced to 0.44 and 0.41% of the diet for pigs with 140 and 160 kg BW, respectively. Although the change of SID Lys requirement appears to be marginal, adjustment of diet formulation or an additional feeding phase should be considered as marketing weight increases. This is because a slight decrease in feed cost during late finishing phase can be economically significant due to the increased ADFI of heavy pigs. In addition, tissue turnover rates and maintenance requirements change as the pig grows, the ideal AA to Lys ratios may change with pig weight (Mahan and Shields, 1998a). For example, Thr, Met, and Trp are needed in greater concentrations relative to Lys in older than in younger pigs (Hahn and Baker, 1995), possibly due to a greater requirement for maintenance than for growth purposes. Furthermore, dietary P requirement estimates may decrease during the last feeding phase of heavy pigs. Mahan and Shields (1998b) observed that body Ca:P ratio greatly increased from 75 to 145 kg. This is because body Ca is mainly present in bone tissue, whereas P is present in soft and hard tissues; in heavy pigs, Ca and P deposition largely occurs in skeletal tissue with a declining deposition of P in muscle.

The dietary energy concentration may vary for heavy finishing pigs because of their increased capacity to adjust feed intake to meet energy requirements (Suarez-Belloch et al. 2013). More importantly, increased gut capacity allows heavy pigs to digest and utilize energy from fibrous feedstuffs more efficiently through hindgut fermentation (Just et al., 1983; Noblet and Shi, 1994; Zanfi and Spanghero, 2012). This provides swine producers with an opportunity to lower feed cost by feeding fibrous feed ingredients. Galassi et al. (2007) compared growth performance of pigs fed 0, 12 and 24% wheat bran diets (11.8, 14.4, and 17.2% NDF, respectively) over different BW ranges; ADG and feed efficiency were worsened from 44 to 70 kg, numerically impaired from 70 to 98 kg, but were unaffected from 98 to 176 kg when wheat bran was included in the diets. In another study where pigs were fed 0, 15, and 30% sugar beet pulp in diets (14.2, 15.8, and 20.9% NDF, respectively), Galassi et al. (2005) observed that increasing dietary fiber worsened ADG and feed efficiency of pigs from 106 to 120 kg BW, but had no effect on pigs from 120 to 170 kg BW. This observation was supported by the observation that pigs fed the 3 different diets had similar energy digestibility measured at 154 kg. However, pigs fed in the 2 studies above were restrictively fed at approximately 2.25 kg DM/d. Future studies are needed to examine the effects of dietary fiber on growth performance of heavy pigs with *ad libitum* feeding. In addition, it is important to realize that pigs fed in a university environment may respond differently to the increased dietary fiber compared with pigs raised in a commercial environment because the feed intake of commercial pigs is subject to other restrictive factors, such as stocking density and hygiene (De la Llata et al., 2001). Meanwhile, the negative impact of dietary fiber on carcass yield should also be considered. The magnitude of this effect may be enlarged in heavy pigs due to their increased gut volume.

Feed additives and feeding strategies have been developed to help mitigate the increased fat deposition in heavy finishing pigs. Feeding ractopamine HCl before marketing allows pigs to produce heavier and leaner carcasses with improved gain rate and efficiency compared with untreated pigs (Apple et al., 2007). The efficacy of ractopamine HCl has been confirmed in pigs raised up to 136 kg (Carr et al., 2009; Peterson et al., 2015). Porcine somatotropin is also effective in promoting pig growth performance and carcass leanness (Johnston et al., 1993), and such effects appear to be more prominent in heavy pigs (Kanis et al., 1990). However, somatotropin is not approved to be used in swine in the U.S.

Limiting fat deposition in heavy pigs may also be achieved via feed restriction. Slightly decreased feed intake increases nutrient digestibility, improves the efficiency of energy utilization, and decreases the amount of dietary energy partitioned to fat deposition. Nieto et al. (2012) suggested that pigs allowed to consume 70 and 95% of *ad libitum* feed intake were able to retain similar amounts of body protein when raised to 150 kg. This finding indicates that heavy pigs may not require *ad libitum* feeding to attain the maximum protein deposition. Once pigs reach their genetic potential for maximum protein deposition, feed restriction becomes more effective in decreasing excessive fat gain. Although restricted feeding leads to decreased backfat thickness and slightly improved or unchanged G:F in heavy pigs, reduced ADG is often observed as a consequence of decreased feed intake (Hansson, 1974; Kim et al., 2005; García-Valverde et al., 2008). Moreover, feasibility of restricted feeding is questionable, at least in current U.S. production systems, with regards to the current feeder design and additional labor cost. As an alternative, feeding low-energy diets has been proposed to achieve the goal of restricting energy intake. However, the usefulness of this strategy is challenged by the fact that heavy finishing pigs increase feed intake to compensate for the reduced dietary energy density (Kim et al., 2005). It appeared that early finishing pigs fed low-energy diets had limited ability to adjust feed intake to maintain the same energy intake compared with pigs fed high-energy diets (Smith et al., 1999; Apple et al., 2004; Zhang et al., 2011); whereas heavy finishing pigs were able to maintain high feed and energy intake regardless of energy density of the diets (Suarez-Belloch et al., 2013). Although feeding low-energy diets effectively reduced backfat thickness, impaired ADG was still commonly observed. More importantly, inconsistent responses of caloric efficiency were often obtained when pigs were fed diets with decreased energy densities (Apple et al., 2004; Zhang et al., 2011; Suarez-Belloch et al., 2013), indicating a limited advantage of feeding low-energy diets to heavy finishing pigs.

Another challenge of raising heavy pigs is derived from the interactive effects between increasing marketing weight and gender on pig growth performance (Carr et al., 1978; Sather et al., 1980; Conte et al., 2011). Generally, barrows grow faster than gilts during late finishing phase, because gilts reach puberty at approximately 110 kg BW when declining feed intake and growth rate are commonly observed (Hansson, 1974; Sather et al., 1980). Additionally, barrows have greater reductions of lean gain rate than gilts as BW increase, indicating a different nutritional requirement for barrows and gilts. For instance, the Lys requirement suggested by the NRC (2012) growth model is approximately 0.05% lower for barrows than for gilts at both 130 and 140 kg BW. As a result, different feeding and marketing strategies are potentially needed for barrows and gilts. Through an economic model, Jolly et al. (1980) however argued that marketing both genders at equal weights resulted in negligible income penalty. Immunocastration has been used as an alternative of physical castration to eliminate boar taint while maintaining a pig growth performance similar to intact males. The efficacy of immunocastration has been verified for pigs with heavy marketing weight up to 176 kg (Zamaratskaia et al., 2008). However, as the length of mixed-housing period increases with marketing weight, it is possible that immunocastrated boars may stimulate the onset of puberty in gilts; whereas, no research has been identified to address this question.

Animal housing

One major challenge of housing heavy pigs is the reduced floor space per pig. With a constant stocking density, space allowance becomes a limiting factor for ADFI and, subsequently, ADG of heavy pigs (Edmonds and Baker, 2003; Brumm, 2004; DeDecker et al., 2005). Weatherup et al. (1998) compared the growth performance of pigs housed individually and in groups (6 pigs/pen) and suggested that, with greater space allowance, individually housed pigs had a greater magnitude of increase in ADFI and less degree of reduction in ADG than group-housed pigs when marketing weight was raised. An allometric expression of the floor space required by pigs over a range of weights was proposed by Petherick (1983) and Baxter (1984) using the equation: $A, \mathrm{m}^2 = k \times (\mathrm{BW, kg})^{0.667}$, where A represents floor space allowance and k represents a space allowance coefficient. When k is below 0.0336, decreased ADFI and ADG are often observed in pigs housed on fully slated floors (Gonyou et al., 2006). Calculations using the above equation with $k = 0.0336$, suggest that an average increment of 0.02 m^2/pig is required for every 5 kg increase of pig BW from 125 to 150 kg in order not to negatively affect growth performance (Table 1.4). When adequate floor space cannot be provided, the impact of restricted pen space on pig performance is dependent on the magnitude of the restriction. A meta-analysis conducted by Flohr (2015) established a set of equations to predict ADG, ADFI, and G:F based on pig BW. From this meta-analysis, for every 0.001 below the critical k value (0.0336), ADG, ADFI, and G:F are expected to decrease by 0.88, 0.58, and 0.31%, respectively, for pigs over 125 kg BW.

A pig removal strategy seems to be a good alternative to provide adequate floor space for heavy pigs in which the heaviest pigs within a pen are harvested first when they reach the target marketing weight, then the remainder pigs in the pen are provided increased floor space for improved growth. DeDecker et al. (2005) removed 25 and 50% of the heaviest pigs (13 or 26 out of 52 pigs/pen) when average pen weight reached 113 kg, which resulted in increased ADG (20.6 and 21.0%), ADFI (10.8 and 7.9%), and G:F (7.7 and 14.3%). Similarly, Jacela et al. (2009) observed that when 8 or 16% of the heaviest pigs (2 or 4 pigs out of a pen of 25) were removed when average pen weight reached 109 kg, pigs remaining in the pen had increased ADG (11.5 and 14.2%), ADFI (7.5 and 4.0%), and G:F (5.2 and 11.5%).

Appropriate feeder space is also essential for heavy pigs to maximize feed intake and gain. Excessive feeder space may increase feed wastage and decrease G:F when ample floor space is provided (Myers et al., 2012); whereas, limiting feeder space negatively affects growth performance especially when pigs have restricted floor space (Jungst et al., 2013). Size of a feeder hole should be 1.1 times the shoulder width (Brumm, 2012; Table 1.4), which can be estimated using: shoulder width (mm) = $64.0 \times (\text{BW, kg})^{0.33}$ (Petherick, 1983).

Height of waterers also should be adjustable based on the increased height of heavy pigs and the design of waterers. A general guideline for adjusting waterer height has been provided by Gonyou (1996). Nipple waterers pointed straight out from the wall should be placed at shoulder height, which can be predicted using: nipple waterer height, cm = $15 \times (\text{BW, kg})^{0.33}$. Nipple waterers mounted at a downwards angle should be placed 5 cm above the back of the pig, which can be estimated using: nipple waterer height, cm = $18 \times (\text{BW, kg})^{0.33}$. Finally, when water bowls are used, pigs should drink water with their head slightly lowered. Capacity of water pipes leading into the barn should also be sized accordingly to accommodate the increased total water consumption of heavier pigs. Nevertheless, excessive supply of water should be avoided in order to minimize water wastage and manure production. In addition, the height of pen partitions should be considered to accommodate the greater height of heavy pigs.

As BW increases, pigs generate more body heat but have decreased ability to dissipate this heat; thus, heavy pigs need lower critical ambient temperature and are more vulnerable to heat stress than light pigs (Renaudeau et al., 2011). According to a prediction equation from Brown-Brandt et al. (2004), heat production of pigs increases by 2% for every 5 kg increase in BW, indicating that barn ventilation rates need to be adjusted accordingly (Table 1.4). A production manual published by PIC (2014) recommends that barn temperature should be maintained at 16 °C for pigs from 96 to 138 kg and the minimal air exchange rates for pigs with 127 and 138 kg BW are 13.0 and 14.3 CFM/pig, respectively. In addition, ammonia emission is augmented as feed intake and manure production increase in heavy pigs (Ni et al., 2000), which can create a further challenge for proper barn ventilation.

Animal health

The duration of immunity following vaccinations for common swine pathogens when pigs are kept in barns to heavier weights is a complex subject. In theory, the need for vaccine protection is decreased in heavier pigs because of their more developed immune system compared with young and naïve pigs. The necessity of providing heavy pigs an additional vaccination should be evaluated based on the immune status of the herd, because pigs with originally low antibody titers have greater response to vaccination, while pigs with originally high antibody titers have marginal benefits from the additional vaccination. It is also important to realize that the duration of immunity given by vaccination varies among vaccine products, types of vaccine (live vs. killed virus), and pathogens that vaccines are developed to against. Typically, vaccines designed to be given as 2 separate doses have longer protection than those given as single dose (Dick Hesse, personal communication). However, given the high economic cost of mortality in heavy pigs and the fact that risks of late-finishing disease, such as porcine reproductive and respiratory syndrome, influenza, and mycoplasma pneumonia, are still high, an additional dose of vaccine for heavy pigs has been occasionally used by producers (Dick Hesse, personal communication). However, for many vaccines, the effectiveness of an additional booster has not been critically evaluated and caution needs to be taken in regard to the legal withdraw period required following the vaccination.

Transportation

Transportation can induce a high amount of stress in heavy weight market pigs. dalla Costa et al. (2009) observed elevated salivary cortisol concentrations and heart rate during loading and transport and Fitzgerald et al. (2009) reported higher mortality rate when pigs were transported at heavier weights compared with those marketed at lighter weights. As pigs grow heavier, they need more space provided in the trailer and better ventilation as they can become exhausted faster during transportation than light weight pigs. Meanwhile, the number of animals that can be transported per truck decreases with greater marketing weight (Table 1.4). Based on recommendations by Grandin (2012), truck space required by pigs transported during cool weather increases from 0.43 to 0.50 m^2/pig as marketing weight increases from 125 to 150 kg. Requirements for truck space may further increase when distance of transport and ambient temperature increase because pigs tend to spend more time laying (Guise et al., 1998; Torrey et al. 2013). The efficiency of loading and transporting heavy pigs also depends on the trailer design. Heavier pigs are reluctant to walk up a steep ramp and should be provided no more than a 15° ramp slope (Grandin, 2012).

Packing plant

With an increase in marketing weight, there are several practical packing plant considerations needed, including: processing equipment, transportation, and worker safety concerns. Through personal communication with meat scientists associated with large packing plants, increased body size, carcass length, and limb length of heavy pigs have been a main area of consideration. First, with an increase in final BW, line speed may decrease due to fewer numbers of pigs that can be stunned through carbon dioxide chambers used at nearly all major pork packing plants. Line speed can also be limited by USDA inspection, because a greater amount of time is needed to inspect a larger carcass. Second, as carcass length increases, pigs may not be able to be properly exsanguinated due to large variations in hind limb length and rail height. Rail height in older packing plants may also be a risk factor for de-hairing and scalding equipment as carcasses may drag on their backs at the bottom of scalding tanks. Furthermore, as pigs exit the de-hairing process, workers splitting carcasses will have to spin or roll a greater than 130 kg carcass into position. As the carcass continues through the harvesting process, longer limbs may also contribute to issues at the gambrel table, on conveyor belts, and on the main break table. Increased carcass weight may result in ergonomic concerns as workers need to handle and manipulate heavier hams, shoulders, and loins. Automated loin pullers and belly cutters may help mediate some of these issues. In addition, wind speeds and cooling times required to properly chill heavy carcasses will need to be evaluated. Increased carcass size creates challenges on cooling capacity of packing plants, as greater airflow around and under the carcasses is needed. Coolers in older packing plants may already be running at the maximum wind speeds and cooling capacity and these packing plants may not have the capability to build additional cooling system. Finally, more storage space is also needed in coolers for the increased carcass weight and length.

Another consideration for increased carcass weights are consumer preferences. As carcass weight increases, there is a large weight increase in all of the primal cuts. Longer loins would be more desirable from a processing standpoint compared with increased loin diameter. This is because larger LM area would result in changes in portion controlled cutting. Chops cut to a standardized thickness would be heavier and resultantly more expensive during retail marketing, impacting the number of chops sold per package. Conversely, chops cut to a standardized weight would be thinner, requiring modifications to cooking methods currently used by both foodservice and consumers. It is unclear what impact these changes in chop thickness and weight would have on consumer preference. Furthermore, increasing marketing weight also affects the processing capacity of cull plants that specialize in handling lightweight cull pigs. When marketing weight range increases, cull pig weights would also have to increase. Some of these plants would have to drastically alter their plant design and space to process larger carcasses.

Conclusion

Many production variables are affected with increasing marketing weight. Generally, heavy weight market pigs eat more, but gain more slowly and less efficiently than pigs marketed at lighter weights. Heavier carcasses are associated with greater carcass yield, length, and LM area, but they also have greater backfat thickness and decreased percentage fat-free lean. Genetic selection of lean-type pigs and research on nutritional requirements for pigs greater than 140 kg are needed to mitigate the reduction in feed efficiency and carcass leanness (summary for future research needs are provided in Table 1.5). Increasing marketing weight may result in minimal impacts on pork quality, but future studies are in need to evaluate consumer preferences on pork from heavy pigs with a focus on color, portion sizes, and sensory characteristics. In conclusion, as marketing weight increases approximately 0.5 kg per year (NASS, 2014), adjustments for nutritional and management guidelines, facility design, and packing plant equipment are necessary to accommodate increased biological and physical requirements of heavy weight market pigs.

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TABLES

Table 1.1. Summary of studies investigating the effects of market weight on overall growth performance (changes per 10 kg marketing weight increase)[1]

Reference	Initial weight, kg	Marketing weight, kg	Pigs/pen	Space/pig, m^2	Total pigs	ADG, g	ADFI, g	G:F
Neely et al. (1979)	15	100,113,127	6	-	200	8.7	52.7	-0.004
Sather et al. (1980)	2	73,84,98,109,123,134	4	1.44	288	-16.0	102.0	-0.015
Kanis et al. (1990)	60	100,140	1	-	96	-19.5	56.3	-0.012
Johnston et al. (1993)	59	105,127	3	2.30	120	8.0	54.0	-0.003
Cisneros et al. (1996)	60	100,115,130,145,160	4	1.17	160	4.0	100.0	-0.006
Leach et al. (1996)	40	110,125,140	4	1.20	144	-18.6	-	-0.010
Weatherup et al. (1998)[2]	50	92,103,113,125	1	6.00	96	-9.2	111.3	-0.017
Weatherup et al. (1998)[3]	50	92,103,113,125	6	1.00	288	2.8	91.9	-0.014
Latorre et al. (2003)	25	122,136	5	1.10	240	7.1	78.6	-0.009
Latorre et al. (2004)	75	116,124,133	8	1.00	192	-38.0	-3.0	-0.010
Piao et al. (2004)	27	100,110,120,130	4	1.01	224	-7.3	76.4	-0.014
Latorre et al. (2008)	107	120,125,130,135,140	10	1.05	200	-54.9	-78.0	-0.010
Serrano et al. (2008)	25	145,156	15	1.50	360	8.2	163.6	-0.013
Shull (2013) Exp.2	6	113,125,136,147,159,170,181	20	1.06	2240	-3.6	58.1	-0.012
Average[4]	-	-	-	-	-	-4.0	78.1	-0.011

[1] Generated by simple linear regression analyses by EXCEL.

[2] Individual housing was evaluated.

[3] Group housing was evaluated.

[4] Studies by Latorre et al. (2004 and 2008) were excluded from the calculation because pigs were reported to be under heat stress; study by Serrano et al. (2008) was excluded from calculation due to the use of Iberian obese pig breed that was uncommonly used in north America pig production.

Table 1.2. Summary of studies investigating the effects of marketing weight on carcass characteristics (changes per 10 kg marketing weight increase)[1]

							Subprimal yield, %			
Reference	Marketing weight, kg	Yield, %	Backfat, mm	Fat-free lean, %	LM area, cm2	Length, cm	Belly	Loin	Shoulder	Ham
Hansson (1975)	68,88,108,128	0.84	2.1	-1.03	1.7	3.1	-	-	-	-
Carr et al. (1978)	45,68,91,114,136	-	2.0	-1.00	2.2	2.4	-	-	-	-0.09
Neely et al. (1979)	100,113,127	-	1.0	0.07	2.0	1.9	-	-	-	-
Sather et al. (1980) and Martin et al. (1980)	73,84,98,109,123,134	-	-	-0.47	2.3	2.3	0.53	-	-0.48	-0.20
Shields et al. (1983)	56,76,90,107,127,146	1.05	2.8	-	1.7	2.3	0.12	-0.19	-0.15	-0.28
Kanis et al. (1990)	100,140	-	1.1	-0.55	-	-	-	-	-	-
Gu et al. (1991 and 1992)	100,114,127	0.34	3.0	-1.09	1.1	2.3	-	-	-	-
Johnston et al. (1993)	105,127	0.05	0.9	-0.18	2.7	-	-	-	-	-
Crome et al. (1996)	107,125	0.33	2.1	-	1.2	2.1	0.61	-0.18	-	0.14
Cisneros et al. (1996)	100,115,130,145,160	0.32	1.6	-	1.8	1.9	0.09	0.40	-0.18	-0.16
Leach et al. (1996)	110,125,140	0.16	1.4	-1.59	0.1	1.7	0.45	-0.38	0.08	-0.19
Weatherup et al. (1998)[2]	92,103,113,125	0.68	1.6	-1.28	-	-	-	-	-	-
Weatherup et al. (1998)[3]	92,103,113,125	0.35	1.5	0.09	-	-	-	-	-	-
Beattie et al. (1999)	96,108,121,133	0.29	-	-	2.2	-	-	-	-	-
Wagner et al. (1999)	25,45,64,84,100,129,152	0.67	2.3	-0.77	2.3	2.7	-	-0.09	-	-0.19
Latorre et al. (2003)	122,136	0.29	0.5	-	-	2.1	-	-0.21	-0.21	-0.36
Virgili et al. (2003)	144,182	0.34	-	-	1.5	-	-	-0.29	-0.32	-0.19
Latorre et al. (2004)	116,124,133	0.77	2.9	-	-	2.4	-	-	-0.29	0.04
Piao et al. (2004)	100,110,120,130	-0.49	0.9	0.05	2.3	3.1	-	-	-	-
Correa et al. (2008)	107,115,125	0.41	-	-	-	2.0	0.13	-0.12	0.12	-0.28
Corino et al. (2008)	111,160	0.38	2.0	-1.85	-	-	-	-0.06	-	-
Latorre et al. (2008)	120,125,130,135,140	0.48	2.5	-	-	1.3	-	-0.18	-0.02	-0.34
Serrano et al. (2008)	145,156	0.91	1.2	-	-	-	-	-0.18	0.09	0.36
Shull (2013) Exp.1	75,91,106,121,134,147,168	-	1.7	-	2.6	-	-	-	-	-
Shull (2013) Exp.2	115,124,134, 145,157,166,176	0.43	1.8	-1.36	1.9	-	-	-	-	-
Average[4]	-	0.41	1.8	-0.78	1.9	2.2	0.32	-0.13	-0.16	-0.17

[1] Generated by simple linear regression analyses by EXCEL.

[2] Individual housing was evaluated.

[3] Group housing was evaluated.

[4] Study by Serrano et al. (2008) was excluded from calculation due to the use of Iberian obese pig breed which was uncommonly used in north America pig production.

Table 1.3. Summary of studies investigating the effects of marketing weight on pork quality (changes per 10 kg marketing weight increase)[1]

Reference	Marketing weight, kg	L*	a*	b*	Initial pH	Ultimate pH	Drip loss, %	WBSF[2], kg
Beattie et al. (1999)	92, 105, 118, 131	0.52	-0.02	0.18	-	-0.01	0.22	-0.05
Bertol et al. (2015)[3]	100, 115, 130, 145	-0.23	0.23	-	-0.05	0.01	0.34	-
Bertol et al. (2015)[4]	100, 115, 130, 146	0.04	0.16	-	-0.04	-	0.08	0.14
Cisneros et al. (1996)	100, 115, 130, 145, 160	-	-	-	-0.01	-0.02	0.29	-0.08
Durkin et al. (2012)	120, 130, 140, 150, 160, 170	-0.14	0.34	0.10	-0.02	-0.01	0.27	0.01
Leach et al. (1996)	110,125,140	-1.23	0.30	-0.14	-0.01	-	-0.35	0.24
Latorre et al. (2004)	116, 124, 133	-2.48	-	-0.24	-	-	-	0.11
Moon et al. (2003)	95, 105, 115, 125	-	-	-	-	-0.04	0.21	-
Piao et al. (2004)	100, 110, 120, 130	1.15	1.18	0.42	-	0.02	-4.75	-0.04
Virgili et al. (2003)[5]	144,182	-0.01	0.10	-0.17	-0.01	-0.05	-	0.16
Virgili et al. (2003)[6]	144,182	-	-	-	-	-	-0.34	-
Weatherup et al. (1998)	92,103,113,125	0.17	0.12	0.20	-	-0.01	0.30	-
Average		-0.25	0.30	0.05	-0.02	-0.01	-0.11	0.06

[1] Generated by simple linear regression analyses by EXCEL.

[2] Warner-Bratzler Shear Force.

[3] Ham was evaluated.

[4] Longissimus dorsi was evaluated.

[5] Semimembranosus was evaluated.

[6] Resulted due to 20.7% drip loss in 100 kg pigs; no differences in methodology present.

[7] Study by Piao et al. (2004) was excluded from calculation for drip loss effect due to the abnormally high value reported (greater than 3 standard deviations from the mean of all values).

Table 1.4. Changes in facility recommendations for pigs based on final marketing weight

	Marketing weight, kg					
Items	125	130	135	140	145	150
Floor space/pig[1], m^2	0.84	0.86	0.89	0.91	0.93	0.95
Feeder space[2], cm	34.6	35.1	35.5	36.0	36.4	36.8
Drinker height, cm						
Right-angled waterer[3]	73.8	74.8	75.7	76.6	77.5	78.4
Downward waterer[4]	88.6	89.7	90.8	91.9	93.0	94.1
Heat production[5], kcal/h	242.1	248.1	254.0	259.7	265.5	271.1
Pigs/truck[6]	163	156	151	145	140	136
Truck space/pig[7], m^2	0.43	0.44	0.45	0.47	0.48	0.50

[1] Estimated using: floor space, $m^2 = k \times (\text{BW, kg})^{0.667}$, where $k = 0.0336$ (Gonyou et al., 2006).

[2] Estimated using: feeder space = 1.1 × shoulder width (Brumm, 2012), and shoulder width, mm = $64.0 \times (\text{BW, kg})^{0.33}$ (Petherick, 1983).

[3] Estimated using: right-angled waterer height, cm = $15 \times (\text{BW, kg})^{0.33}$ (Gonyou, 1996).

[4] Estimated using: downward waterer height, cm = $18 \times (\text{BW, kg})^{0.33}$ (Gonyou, 1996).

[5] Estimated using: heat production (W/kg) = $14.11 \times (\text{BW, kg})^{-0.38}$ (Brown-Brandt et al., 2004)

[6] Assuming maximum truck load of 20,321.1 kg.

[7] Adapted from recommendation from Grandin (2012).

Table 1.5. Recommendations for future research needs in production of heavy weight market pigs

Item	Future research needed
Nutrition	
Protein and AA	Lysine and other AA requirements for pigs greater than 140 kg
Protein and AA	Minimum CP (CP:Lys ratio) requirement for pigs greater than 140 kg
Energy	Effect of decreasing and increasing dietary energy on growth performance
Energy	Effects of restricted feeding (feed intake and energy intake restrictions) on energy and nutrient utilization
Fiber	Assess the ability of heavy pig to maintain feed intake and utilize dietary energy when fed high-fiber diets
Gender effect	Applicability and necessity of split-sex feeding and housing
Meat quality	
Color	Effects of increasing carcass weight on meat color and customer preference
Sensory property	Effects of increasing carcass weight on sensory property
Food safety	Antibiotic treatment timing and duration on resistance in heavy pigs
Food safety	Pathogen (e.g. Salmonella) shedding during transportation of heavy pigs
Animal health	
Immunity	Validation of duration of protection by major swine disease vaccines
Immunity	Effects of an additional vaccine booster on disease control of late finishing pigs
Bone structure	Macro and micro mineral requirements for pigs greater than 140 kg
Facilities	
Floor space	Effects of serial marketing on the space requirement as marketing weight increases
Ventilation	Effects of increasing BW on barn ventilation requirement
Transportation	Effects of increasing marketing weight on transportation efficiency and loss
Packing plant	Industry survey for the maximum carcass weight that packers and cull plants can currently process
Economics	Effects of increasing marketing weight on profitability of finishing pig production
Meta-analysis	Effects of marketing weight on cumulative growth performance and carcass characteristics

Chapter 2 - Effects of dietary calcium to phosphorus ratio and addition of phytase on growth performance of nursery pigs[1]

ABSTRACT: Two studies were conducted to evaluate the growth performance and percentage bone ash of nursery pigs fed various combinations of Ca and P provided by inorganic sources or phytase. In Exp. 1, pens of pigs (n = 720, initially 6.1 ± 0.98 kg) were blocked by initial BW. Within blocks, pens were randomly assigned to 1 of 6 treatments (12 pens per treatment) in a 3-phase diet regimen. Treatments were arranged in a 2 × 3 factorial with main effects of Ca (0.58 vs. 1.03%) and standardized total tract digestible (STTD) P (0.33 and 0.45% without phytase, and 0.45% with 0.12% of the P released by phytase). During treatment period, Ca × P interactions were observed for all growth criteria ($P < 0.05$). When diets had low Ca, pigs fed 0.45% STTD P with phytase had greater ($P < 0.01$) ADG and ADFI than those fed 0.33 or 0.45% STTD P without phytase. When high Ca was fed, ADG and ADFI were similar among pigs fed 0.45% STTD P with or without phytase and were greater than those fed 0.33% STTD P. Gain:feed was reduced ($P < 0.01$) when high Ca and low STTD P were fed relative to other treatments. On d 21, radiuses were collected from 1 pig per pen for bone ash analysis. Pigs fed 0.33% STTD P had decreased ($P < 0.05$) percentage bone ash than those fed 0.45% STTD P with or without phytase when high Ca was fed, but this P effect was not observed for low Ca diets (Ca × P interaction, $P = 0.007$). In Exp. 2, 36 pens (10 pigs per pen, initially 6.0 ± 1.08 kg) were used in a completely randomized design. Treatments were arranged in a 2 × 3 factorial with the main effects of STTD P [at or above NRC (2012) requirement estimates] and total Ca (0.65, 0.90, and 1.20%). Experimental diets were fed during phases 1 and 2, followed by a common phase 3 diet.

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Diets at NRC (2012) P level contained 0.45 and 0.40% STTD P, compared with 0.56 and 0.52% for diets greater than the NRC (2012) estimates, in phase 1 and 2, respectively. During treatment period, increasing Ca decreased (linear, $P = 0.006$) ADG, but increasing STTD P marginally increased ($P = 0.084$) ADG, with no Ca × P interaction. When diets contained NRC (2012) P levels, pigs fed 1.20% Ca had decreased ($P < 0.05$) G:F than those fed 0.65 or 0.90% Ca; however, when high STTD P were fed, G:F was not affected by Ca (Ca × P interaction, $P = 0.018$). In conclusion, excess Ca decreased pig growth and percentage bone ash when diets were at or below NRC (2012) requirement for STTD P, but these negative effects were alleviated by adding monocalcium P or phytase to the diet.

Key words: bone ash, calcium, growth performance, nursery pig, phosphorus, phytase

INTRODUCTION

Appropriate dietary Ca and P concentrations are essential for nursery pig performance. Accurate formulation for Ca and P is even more important in recent years with the routine use of phytase in swine diets. Research has demonstrated that feeding excess dietary Ca impairs P absorption, resulting in reduced growth performance and bone calcification of pigs (Reinhart and Mahan, 1986; Stein et al., 2011; Gonzalez-Vega et al., 2016). This effect is especially prominent when diets are marginal in P (Letourneau-Montminy et al., 2012; NRC, 2012). Moreover, excess Ca can bind to phytate in the small intestine, decrease the solubility of phytate, and therefore impair the ability of phytase to release P (Dersjant-Li et al., 2014).

Diets can have excess Ca for multiple reasons, including formulation errors, variability in laboratory analysis of ingredients, neglecting the Ca content of carriers in premixes or other additives, and not accounting for Ca released by phytase. Meanwhile, diets can also be deficient in P due to formulation errors or by overestimating the amount of P released for the given amount of phytase in the diet. In addition, recent research (Vier et al., 2017) has suggested that NRC (2012) may underestimate the standardized total tract digestible (**STTD**) P requirement for nursery pigs. Thus, in commercial production there is an increased risk of overfeeding Ca. The effects of dietary Ca and P concentration as well as their ratio on growth performance and P retention have been extensively studied in growing-finishing pigs. However, to our knowledge, such information is limited for pigs less than 15 kg BW. Therefore, the objective of this study was to evaluate the growth performance and percentage bone ash of early nursery pigs in response to different combinations of dietary STTD P and Ca concentrations provided by monocalcium P or phytase.

MATERIALS AND METHODS

All experimental procedures in this study were approved by the Kansas State University Institutional Animal Care and Use Committee (Manhattan, KS).

Animals and housing

Two studies were conducted at the Cooperative Research Farm's Swine Research Nursery (Kalmbach Feeds, Inc., Sycamore, OH). Each pen (1.52 × 1.83 m^2) had slated metal floors and was equipped with a 4-hole stainless-steel feeder and a nipple-cup waterer. Five barrows and 5 gilts (PIC 280 × Camborough, Genus PIC, Hendersonville, TN) were housed in each pen and were allowed ad libitum access to feed and water throughout the experiments. In Exp. 1, 720 weaned pigs were used from 2 rooms with 36 pens per room. Upon arrival, pigs were individually weighed and assigned to pens in order to achieve balanced pen weights within room. After 4 d of adaptation, pens of pigs were blocked by BW (initial pig BW = 6.1 ± 0.98 kg) and allotted randomly to 1 of 6 dietary treatments (Tables 2.2 and 2.3). In Exp. 2, 360 weaned pigs with initial

BW of 6.0 ± 1.08 kg were housed in a single room with 36 pens. Pens of pigs were allotted to 1 of 6 dietary treatments (Tables 2.4 and 2.5) in a completely randomized manner.

Diets and experimental design

All ingredients containing Ca and P were sampled and sent to 2 labs (Ward Laboratories, Inc. Kearney, NE and Cumberland Valley Analytical Services Inc., Maugansville, MD) for analysis of Ca and P in duplicate in each lab (Table 2.1). The average of the 4 lab results for each ingredient was used in diet formulation in both experiments. In Exp. 1, the 6 dietary treatments were arranged in a 2 × 3 factorial, with 2 levels of Ca (0.58 and 1.03%) and 3 levels of STTD P (0.33% with no phytase, 0.45 with no phytase, and 0.45% with 0.12% of the P assumed to be released by phytase). Diets with phytase contained 1,000 phytase units (**FYT**) of Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ) with an assumed releasing value of 0.12% for Ca and STTD P. Pigs were fed in 3 phases, with the experimental diets provided in phases 1 (d 0 to 14) and 2 (d 14 to 28). A common phase 3 diet was then fed to all pigs from d 28 to 42. Nutrient and standardized ileal digestible AA digestibility coefficients used for diet formulation were obtained from NRC (2012). All diets were provided in meal form.

In Exp. 2, the 6 dietary treatments were arranged in a 2 × 3 factorial with 2 levels of STTD P (at or above NRC (2012) requirement estimates) and 3 levels of total Ca (0.65, 0.90, and 1.20%). Pigs were fed in 3 phases with the experimental diets provided in phases 1 (d 0 to 10) and 2 (d 10 to 24), followed by a common phase 3 diet from d 24 to 45. Diets formulated to meet NRC (2012) P requirement (**NRC**) contained 0.45 and 0.40% STTD P in phases 1 and 2, respectively. Diets formulated to exceed NRC (2012) P requirement (>**NRC**) contained 0.56 and 0.52% STTD P in phases 1 and 2, respectively. Diets did not contain phytase with the dietary Ca and P mainly provided by monocalcium phosphate and limestone. Phase 1 diets were prepared in pellet form and phases 2 and 3 diets were provided in meal form. Pigs and feeders were weighed at the end of each feeding phase to determine ADG, ADFI, and G:F ratio in both of the experiments.

Bone ash analysis

On d 21 of Exp. 1, 1 median-weight gilt from each pen was euthanized using a CO_2 chamber and radiuses were collected. Bones were then transferred on dry ice to the Kansas State University Swine Laboratory and stored at -20°C until analysis. After thawing at room temperature (24°C) in plastic bags for 24 h, bones were autoclaved for 60 min, adhering tissue and cartilage caps were removed, then dried at 105°C for 7 d. Dried radiuses were ashed in a muffle furnace at 600°C for 24 h to determine total ash weight and percentage bone ash.

Chemical analysis

Complete diet samples were obtained and delivered to the Kansas State University Swine Laboratory, Manhattan, KS, and stored at -20°C until analysis. Feed samples were analyzed for DM, CP, ether extract, Ca, and P at Ward Laboratories, Inc. (Kearney, NE). Concentrations of Ca and P in complete feed samples were also analyzed at Cumberland Valley Analytical Services Inc. (Maugansville, MD) and Midwest Laboratories (Omaha, NE) in duplicate. Standard procedures from AOAC (2006) were followed for analysis of moisture (Method 934.01), CP (Method 990.03), ether extract (Method 920.39), Ca and P (Method 985.01). At Cumberland Valley Analytical Services Inc. (Maugansville, MD), AOAC (2000) method (985.01) was used for Ca and P analyses with modifications of ashing a 0.35 g sample for 1 h at 535°C, digestion in an open crucible for 20 min in 15% nitric acid on a hot plate, and sample dilution to 50 mL and analysis on an inductively coupled plasma spectrometer (PerkinElmer 3300 XL and 5300 DV ICP; PerkinElmer Inc., Shelton, CT).

Statistical analysis

Experiment 1 was analyzed in a randomized completely block design with a 2 × 3 factorial treatment structure. The statistical model contained the main effects of Ca and STTD P and their interactions as well as random effects of room and weight block within room. The initial statistical model included treatment and the effect of treatment within room as fixed effects. Because there was no evidence that the treatment effect was different across rooms, the treatment within room term was removed from the model and data from the 2 rooms were pooled in the analyses of growth performance and percentage bone ash. One pen from 0.58% Ca + 0.45% STTD P treatment encountered issues with feeder adjustment and had restricted feed intake as noted in the daily observation records; therefore, data from this pen were excluded from all the analyses. In Exp. 2, data were analyzed in a completely randomized design with a 2 × 3 factorial treatment structure. The statistical model contained the main effects of STTD P and Ca and their interaction. Single degree-of-freedom contrasts were performed to test the linear and quadratic effects of increasing Ca and their interactions with P concentration. All statistical analyses were conducted using the GLIMMIX procedure of SAS version 9.4 (SAS Institute, Inc., Cary, NC) with pen as the experimental unit. Means were reported as least-squares means. For response criteria with significant Ca × P interaction, means were separated by the PDIFF option with a Tukey–Kramer adjustment. Results were considered significant at $P < 0.05$ and marginally significant at $0.05 < P < 0.10$.

RESULTS

Chemical analysis

Analyzed Ca concentrations in feed ingredients were similar between the 2 laboratories (Table 2.1). However, a 15% inter-laboratory discrepancy was observed for monocalcium phosphate, the primary source of P in the experimental diets; therefore, the average values were used in the diet formulation. It is worthy to note that significant amounts of Ca were included in minor ingredients, such as vitamin and trace mineral premixes, phytase, and selenium premix. However, given the small inclusion rates, these ingredients only contributed 0.03% total Ca in the experimental diets. The analyzed dietary Ca and P concentrations were slightly greater than the formulated values but followed similar patterns as the designed treatment structure (Tables 2.2 to 2.5).

Experiment 1

During phase 1 (d 0 to 14; Table 2.6), Ca × P interactions were observed for ADG and G:F ($P < 0.05$) but not for ADFI. Pigs fed diets containing 0.45% STTD P with phytase had greater ($P < 0.01$) ADG than pigs fed 0.45% STTD P without phytase or pigs fed 0.33% STTD P regardless of dietary Ca concentration. The ADG of pigs fed diets containing 0.45% STTD P without phytase was greater ($P < 0.001$) than that of pigs fed 0.33% STTD P when diet contained high (1.03%) Ca concentration but not for diets with low (0.58%) Ca concentration. Regardless of Ca level, feeding 0.45% STTD P with phytase improved ($P < 0.05$) ADFI compared with diets with 0.33 or 0.45% STTD P with no phytase. Pigs fed 0.45% STTD P with or without phytase exhibited greater ($P < 0.10$) G:F than pigs fed 0.33% STTD P, and the magnitude of these differences was more prominent when diets contained high Ca concentrations (Ca × P interaction, $P < 0.001$).

During phase 2 (d 14 to 28), Ca × P interactions were observed for all growth criteria ($P < 0.05$). Pigs fed diets containing 0.45% STTD P with or without phytase had greater ($P < 0.05$) ADG than those fed 0.33% STTD P when high Ca was added to diets but not for diets containing low Ca concentrations. When diets contained low Ca, feeding 0.45% STTD P with phytase resulted in greater ($P < 0.001$) ADFI than feeding the 0.33% STTD P diet, with ADFI of pigs fed 0.45% STTD P without phytase intermediate. When fed high Ca, ADFI of pigs fed 0.45% STTD P with or without phytase was greater ($P < 0.01$) than those fed 0.33% STTD P. Pigs fed 0.33%

STTD P had lower ($P < 0.001$) G:F than those fed 0.45% STTD P without phytase when diets contained high Ca concentration; however, no differences were observed among low Ca diets.

When combining the treatment periods (d 0 to 28), Ca × P interactions were observed for all growth responses ($P < 0.05$). When low Ca was added to diets, feeding 0.45% STTD P with phytase increased ($P < 0.01$) ADG and ADFI compared with pigs fed 0.45% STTD P without phytase and pigs fed 0.33% STTD P. However, with high Ca, ADG and ADFI were similar among pigs fed 0.45% STTD P with or without phytase but were greater than those fed 0.33% STTD P diet. Gain to feed was decreased ($P < 0.01$) when low STTD P and high Ca were added to the diet compared with other dietary treatments. On d 28, when diets contained low Ca concentrations, pigs fed 0.45% STTD P with phytase had greater ($P < 0.01$) BW than pigs fed 0.45% STTD P without phytase and those fed 0.33% STTD P. When diets contained high Ca, BW was similar among pigs fed 0.45% STTD P with or without phytase, but was greater ($P < 0.01$) than those fed 0.33% STTD P diet.

During the post-treatment period from d 28 to 42, all pigs received a common phase 3 diet. No evidence for significant Ca × P interaction was observed for ADG. Pigs previously fed 1.03% Ca had greater ($P < 0.001$) ADG than those previously fed 0.58% Ca. Pigs previously fed 0.33% STTD P tended to have greater ($P = 0.054$) ADG than those previously fed 0.45% STTD P with phytase, but similar ADG to pigs previously fed 0.45% STTD P without phytase. Pigs previously fed 0.45% STTD P with or without phytase had greater ($P < 0.05$) ADFI than those previously fed 0.33% STTD P, but the magnitude of these differences was greater in high Ca than in low Ca diets (Ca × P interaction, $P = 0.063$). For G:F, a Ca × P interaction ($P < 0.001$) was observed. When diets contained low Ca concentration, pigs previously fed 0.45% STTD P with phytase had decreased ($P = 0.027$) G:F compared with those previously fed 0.33% STTD P, with G:F of pigs previously fed 0.45% STTD P without phytase intermediate. When high Ca was added to diets, G:F was similar among pigs previously fed 0.45% STTD P with or without phytase, but was poorer ($P < 0.01$) than those previously fed 0.33% STTD P.

Overall (d 0 to 42), Ca × P interaction was observed for all growth criteria ($P < 0.10$). Feeding 0.33% STTD P decreased ($P < 0.01$) ADG compared with feeding 0.45% STTD P with or without phytase, but this effect was only observed when high Ca was fed. For ADFI, when diets contained low Ca concentration, feeding 0.45% STTD P with phytase resulted in greater ($P = 0.018$) ADFI than feeding 0.33% STTD P diet, with that of pigs fed 0.45% STTD P without phytase intermediate. When high Ca was fed, ADFI of pigs fed 0.45% STTD P with or without phytase was greater ($P < 0.01$) than those fed 0.33% STTD P. Dietary STTD P level did not affect overall G:F regardless of Ca concentration; however, G:F was decreased ($P = 0.005$) by feeding 1.03% Ca compared with feeding 0.58% Ca when diets contained 0.33% STTD P. This Ca effect was not observed when diets contained 0.45% STTD P with or without phytase. Similarly, final BW of pigs fed 0.33% STTD P was decreased ($P < 0.01$) relative to pigs fed 0.45% STTD P with or without phytase when high Ca was fed with no P response with low dietary Ca concentration.

Pigs fed 0.33% STTD P had decreased ($P < 0.05$) percentage bone ash compared with those fed 0.45% STTD P with or without phytase when high Ca was added to diets, but this P effect was not observed among treatments with low Ca concentration (Ca × P interaction, $P = 0.007$).

Experiment 2

During phase 1 (d 0 to 10), no evidence of Ca × P interactions were observed for any growth criteria ($P > 0.38$; Table 2.7). Calcium and STTD P concentrations did not affect ADG or d 10 BW. However, increasing Ca increased (linear, $P = 0.014$) ADFI but decreased (linear, $P = 0.009$) G:F.

During phase 2 (d 10 to 24), a marginal Ca × P interaction was observed for ADG (*P* = 0.088) and a significant interaction for G:F (*P* = 0.001), but not for ADFI or BW. Pigs fed 1.20% Ca had decreased (*P* < 0.05) ADG and G:F compared with those fed 0.65 and 0.90% Ca when diets contained NRC STTD P; however, this detrimental effect of high Ca was not observed in pigs fed >NRC STTD P. Average daily feed intake was not affected by dietary Ca or STTD P. Day 24 BW was decreased (linear, *P* = 0.006) by increasing Ca regardless of the STTD P concentration in diets. Feeding >NRC STTD P resulted in a marginally greater (*P* = 0.096) d 24 BW than those fed NRC STTD P.

When combining the treatment periods (d 0 to 24), no Ca × P interactions were observed for ADG and ADFI. Increasing Ca decreased (linear, *P* = 0.006) ADG, but had no evidence for an effect on ADFI. Similarly, feeding >NRC STTD P marginally increased (*P* = 0.084) ADG, but had no evidence for an effect on ADFI, compared with pigs fed NRC STTD P. Concentrations of Ca and STTD P had an interactive effect on G:F (*P* = 0.015). When diets contained NRC STTD P, pigs fed 1.20% Ca had poorer (*P* < 0.05) G:F than those fed 0.65 and 0.90% Ca; however, when >NRC STTD P was fed, G:F was not affected by dietary Ca concentration.

During the post-treatment period from d 24 to 45, all pigs received a common phase 3 diet. No interactive or main effects of Ca and STTD P concentrations were observed for ADG, ADFI, or final BW. However, pigs previously fed increasing dietary Ca had improved (linear, *P* = 0.003) G:F regardless of the STTD P content previously fed in phase 1 and 2 diets. As a result of this compensatory gain, overall (d 0 to 45) growth responses were not affected by the Ca and P concentrations fed during phases 1 and 2.

DISCUSSION

In high Ca diets, free Ca binds with P in the chyme to form insoluble salts, resulting in decreased digestion and absorption of dietary P (Heaney and Nordin, 2002). As an example, Stein et al. (2011) reported a linear reduction of apparent total tract digestibility of P from 56.9 to 46.2% when dietary Ca increased from 0.33 to 1.04% in growing pig. Therefore, it has been widely established that excess Ca may negatively affect pig growth performance depending on the level of P in diets (Reinhart and Mahan, 1986; Liu et al., 1998; Gonzalez-Vega et al., 2016). The total Ca and STTD P requirements estimated by NRC (2012) are 0.85 and 0.45%, respectively, for 5 to 7 kg (phase 1) pigs and 0.80 and 0.40%, respectively, for 7 to 11 kg (phase 2) pigs. In Exp. 1, we observed that feeding 1.03% total Ca decreased ADG, ADFI, and G:F when diets were deficient in STTD P (0.33%), but these detrimental effects of excess Ca were not observed when adequate P diets (0.45%) were fed. This observation is in agreement with a recent study in 100- to 130-kg finishing pigs where excess Ca (total Ca:STTD P ratio greater than 2.2:1) in diets decreased ADG only when STTD P was at or below the NRC (2012) estimated requirements (Merriman et al., 2017). Results from Exp. 2 suggest that increasing dietary Ca decreased G:F independent of STTD P in phase 1. However, during phase 2, the detrimental effects of high Ca on ADG and G:F were only observed in pigs fed NRC STTD P (0.40%) but not for pigs fed 0.52% STTD P. It is possible that 0.40% STTD P just met, or was marginally below, the requirement of pigs during phase 2, which resulted in a P deficiency when high Ca was added to the diets. This marginal deficiency in STTD P is also supported by the observation that feeding high levels of STTD P (>NRC) tended to improve ADG from d 0 to 24. Vier et al. (2017) also reported that NRC (2012) may underestimate STTD P requirements for optimal performance and economic return in 11 to 25 kg nursery pigs.

Reinhart and Mahan (1986) observed that when diets contained low P (0.05% below NRC), total Ca:total P ratios above 1.3:1 decreased growth performance of pigs in any production phase, whereas when high dietary P (0.10% above NRC) was provided, wide total Ca:total P ratio up to 2.0:1 could be fed without detrimental effects. In another study, Qian et al. (1996), observed improved growth performance of 9 to 23 kg pigs when total Ca:total P ratio was narrowed from 2.0:1 to 1.2:1 regardless of dietary P concentration (0.36 or 0.45% total P). In the present study, total Ca:total P ratios ranging from 0.8:1 to 1.6:1 were fed without reduction in growth performance, but decreased performance was observed when total Ca:total P ratio exceeded 1.9:1. Interestingly, during the common phases of both the experiments, pigs previously fed low STTD P and high Ca diets grew faster and were more efficient than pigs from other treatments, suggesting a compensatory gain effect in response to the increased P and reduced Ca concentrations in the phase 3 diet. However, in Exp.1, these pigs were not able to fully compensate for the negative effects of P deficiency when diets contained excess Ca. In contrast to the compensatory gain observed in our study, Gonzalo et al. (2017) studied the effects of P depletion and repletion on growing-finishing pig performance and observed that previous P deficiency decreased ADG and ADFI during the subsequent repletion period.

Supplementing phytase to low P diets alleviated the impact of P deficiency on growth performance, and the magnitude of improvement was greater in diets containing high Ca. This observation is expected because increasing STTD P above the requirement of pigs by adding phytase improves their tolerance to wide Ca:P ratio. Moreover, the diets that included phytase to achieve 0.45% STTD P also improved ADG and ADFI of pigs over the diets containing 0.45% STTD P from only inorganic source, and this phytase response was more evident during phase 1 of the experiment, when dietary P would have been more limiting than during phase 2. It is possible that the 0.12% release value suggested by the manufacturer for 1,000 FYT of phytase underestimated the true digestible P and Ca release, resulting in more Ca, P, or possibly other nutrients becoming available to the pig.

Dietary Ca concentration has also been reported to alter the releasing ability of phytase. Proposed mechanisms for a Ca-phytase interaction include: 1) formation of a Ca-phytate complex that reduces the solubility of phytate and its accessibility by phytase; 2) competition of Ca for active sites of the enzyme resulting in indirect repression of phytase activity; and 3) a high acid binding capacity of inorganic Ca sources may influence phytase activity depending on their pH activity spectrum (Selle et al., 2009). Qian et al. (1996) suggested that increasing total Ca:total P ratio between 1.2:1 and 2.0:1 in diets resulted in approximately 1.95% reduction in the efficacy of supplemental phytase for each 0.1 unit change in Ca:P ratio. However, the negative effects of high Ca on phytase activity was not observed in the present study. Feeding 1.03% total Ca to phytase-supplemented diets resulted in similar growth performance and percentage bone ash as those fed 0.58% Ca.

According to the Ca × P interaction observed for bone ash concentration, increasing dietary Ca exacerbated the deficiency of P (feeding 0.33% STTD P) for bone mineralization, compared with an improvement when diets contained adequate P (0.45% STTD P). This can be explained by the fact that a wider Ca:P ratio (about 2.2:1) is required to form hydroxyapatite-like compounds for bone development (Crenshaw, 2001). Similar observations were reported by Letourneau-Montminy et al. (2012) where increasing dietary Ca from 0.5 to 0.8% decreased P retention by 0.016% in pigs fed a diet containing 0.1% non-phytate P, while it increased P retention of pigs by 0.026% when diet contained 0.3% non-phytate P. Furthermore, the growth promoting effects of phytase were not observed for percentage bone ash. This observation is in contrast with the growth performance data, where it appeared that the P release by adding phytase was underestimated. Therefore, it is possible that the beneficial effect of phytase on growth performance was a result of liberating other nutrients in the diet.

In summary, our data suggests that feeding excess dietary Ca negatively affected growth performance and percentage bone ash of nursery pigs when diets are deficient in STTD P. The STTD P estimates by NRC (2012) met the requirement of nursery pigs when diets contain low Ca concentrations, but resulted in decreased growth performance when diets contained more than 0.90% Ca. Future research is in need to determine the optimal Ca:P ratio in early nursery diets. Moreover, adding inorganic P or phytase to P deficient diets improved pig performance and alleviated the negative impacts of high dietary Ca concentration on growth performance.

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TABLES

Table 2.1. Analyzed Ca and P concentrations in feed ingredients (as-fed basis)

	Ca, %			P, %		
	Lab 1[1]	Lab 2[2]	Average	Lab 1	Lab 2	Average
Corn	0.06	0.02	0.04	0.28	0.23	0.26
Soybean meal	0.35	0.31	0.33	0.63	0.62	0.62
HP 300[3]	0.39	0.37	0.38	0.72	0.72	0.72
Spray-dried whey	0.84	0.86	0.85	0.86	0.87	0.86
Monocalcium P (21% P)	15.80	15.85	15.83	22.00	19.01	20.50
Limestone	36.48	39.55	38.02	0.01	0.01	0.01
Trace mineral premix	7.44	8.03	7.74	0.01	ND[4]	0.01
Vitamin premix	12.58	13.69	13.13	0.07	0.04	0.05
Phytase[5]	11.77	12.87	12.32	0.11	0.05	0.08
Selenium premix	35.66	40.41	38.04	0.02	0.02	0.02

[1] Lab 1 (Ward Laboratories, Inc., Kearney, NE); samples were analyzed in duplicates and average values were reported.

[2] Lab 2 (Cumberland Valley Analytical Services Inc., Maugansville, MD); samples were analyzed in duplicate and average values were reported.

[3] Hamlet Protein, Inc., Findlay, OH.

[4] Not detectable.

[5] Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ).

Table 2.2. Diet formulation, phase 1 (Exp. 1; as-fed basis)

	Phase 1 (d 0 to 14)					
Ca, %:	0.58	0.58	0.58[1]	1.03	1.03	1.03[1]
STTD P, no phytase, %:	0.33	0.45	0.33	0.33	0.45	0.33
STTD P, with phytase, %:	-	-	0.45	-	-	0.45
Ingredients, %						
Corn	44.02	43.32	44.49	41.86	41.16	42.40
Soybean meal	25.18	25.23	25.15	25.33	25.38	25.29
HP 300[2]	6.00	6.00	6.00	6.00	6.00	6.00
Spray-dried whey	20.00	20.00	20.00	20.00	20.00	20.00
Beef tallow	2.20	2.45	2.05	3.00	3.25	2.80
Monocalcium P (21% P)	0.19	0.87	0.19	0.20	0.88	0.20
Limestone	0.62	0.34	0.29	1.80	1.52	1.47
Salt	0.45	0.45	0.45	0.45	0.45	0.45
L-Lys HCl	0.38	0.38	0.38	0.38	0.38	0.38
DL-Met	0.23	0.23	0.23	0.23	0.23	0.23
L-Thr	0.18	0.18	0.18	0.18	0.18	0.18
L-Trp	0.03	0.03	0.03	0.03	0.03	0.03
L-Val	0.08	0.08	0.08	0.09	0.09	0.09
Trace mineral premix[3]	0.09	0.09	0.09	0.09	0.09	0.09
Vitamin premix[4]	0.05	0.05	0.05	0.05	0.05	0.05
Choline chloride	0.04	0.04	0.04	0.04	0.04	0.04
Phytase[5]	-	-	0.04	-	-	0.04
Zinc oxide	0.27	0.27	0.27	0.27	0.27	0.27
Selenium	0.02	0.02	0.02	0.02	0.02	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition						
Standardized ileal digestible AA, %						
Lys	1.40	1.40	1.40	1.40	1.40	1.40
Ile:Lys	61	61	61	61	61	61
Leu:Lys	116	116	116	115	115	115
Met:Lys	37	37	37	37	37	37
Met & Cys:Lys	58	58	58	58	58	58
Thr:Lys	65	65	65	65	65	65
Trp:Lys	20	20	20	20	20	20
Val:Lys	70	70	70	70	70	70
Total Lys, %	1.53	1.53	1.53	1.53	1.53	1.53
CP, %	21.01	20.98	21.02	20.95	20.92	20.96
NE, kcal/kg	2,568	2,568	2,569	2,569	2,568	2,568

Ca, no phytase, %	0.58	0.58	0.46	1.03	1.03	0.91
Ca, with phytase, %	0.58	0.58	0.58	1.03	1.03	1.03
STTD P, no phytase, %	0.33	0.45	0.33	0.33	0.45	0.33
STTD P, with phytase, %	0.33	0.45	0.45	0.33	0.45	0.45
Total P, %	0.52	0.66	0.52	0.52	0.66	0.52
Analyzed composition, %						
DM	91.31	92.17	91.76	91.52	91.61	91.22
CP	21.90	20.45	22.15	21.10	21.55	21.40
Fat	4.35	4.40	3.75	4.95	5.05	4.65
Ca[6]	0.56	0.65	0.60	0.93	1.00	0.87
P[6]	0.61	0.74	0.62	0.62	0.81	0.61

[1] Phytase was added to diets at the level of 1,000 phytase units with assumed release value of 0.12% for Ca and standardized total tract digestible (STTD) P.

[2] Hamlet Protein, Inc., Findlay, OH.

[3] Provided per kg of premix: 29.6 g Mn from manganese oxide, 104 g Fe from iron sulfate, 112 g Zn from zinc sulfate, 16 g Cu from copper sulfate, 1600 mg I from calcium iodate.

[4] Provided per kg of premix: 28,659,800 IU vitamin A, 4,409,200 IU vitamin D_3, 105,821 IU vitamin E, 801,665 mg vitamin K, 15,423 mg riboflavin, 66,138 mg pantothenic acid, 110,230 mg niacin, 79 mg vitamin B_{12}, 4,409 mg folic acid, 44 mg thiamin, 44 mg pyridoxine, and 4.4 mg biotin.

[5] Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ).

[6] Averaged across analyzed values from Ward Laboratories, Inc. (Kearney, NE), Cumberland Valley Analytical Services Inc. (Maugansville, MD), and Midwest Laboratories (Omaha, NE).

Table 2.3. Diet formulation, phases 2 and 3 (Exp. 1; as-fed basis)[1]

	Phase 2						Phase 3
Ca, %:	0.58	0.58	0.58[2]	1.03	1.03	1.03[2]	0.86
STTD P, no phytase, %:	0.33	0.45	0.33	0.33	0.45	0.33	0.37
STTD P, with phytase, %:	-	-	0.45	-	-	0.45	0.47
Ingredients, %							
Corn	52.18	51.48	52.70	50.04	49.34	50.56	59.47
Soybean meal	29.54	29.59	29.50	29.69	29.74	29.65	35.15
HP 300[3]	3.00	3.00	3.00	3.00	3.00	3.00	-
Spray-dried whey	10.00	10.00	10.00	10.00	10.00	10.00	-
Beef tallow	2.20	2.45	2.00	3.00	3.25	2.80	2.00
Monocalcium P (21% P)	0.59	1.27	0.59	0.60	1.28	0.60	1.22
Limestone	0.66	0.38	0.33	1.84	1.56	1.51	1.06
Salt	0.50	0.50	0.50	0.50	0.50	0.50	0.35
L-Lys HCl	0.38	0.38	0.38	0.38	0.38	0.38	0.29
DL-Met	0.20	0.20	0.20	0.20	0.20	0.20	0.15
L-Thr	0.18	0.18	0.18	0.18	0.18	0.18	0.13
L-Trp	0.03	0.03	0.03	0.03	0.03	0.03	0.01
L-Val	0.09	0.09	0.09	0.09	0.09	0.09	-
Trace mineral premix[4]	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Vitamin premix[5]	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Choline chloride	0.04	0.04	0.04	0.04	0.04	0.04	-
Phytase[6]	-	-	0.04	-	-	0.04	0.02
Zinc oxide	0.27	0.27	0.27	0.27	0.27	0.27	-
Selenium	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition							
Standardized ileal digestible AA, %							
Lys	1.35	1.35	1.35	1.35	1.35	1.35	1.27
Ile:Lys	61	61	61	61	60	61	64
Leu:Lys	119	118	119	118	117	118	127
Met:Lys	36	36	36	36	36	36	35
Met & Cys:Lys	58	58	58	58	58	58	59
Thr:Lys	65	65	65	65	65	65	64
Trp:Lys	20	20	20	20	20	20	20
Val:Lys	71	71	71	71	71	71	68
Total Lys, %	1.49	1.49	1.49	1.49	1.49	1.49	1.42
CP, %	20.68	20.66	20.70	20.61	20.59	20.63	20.65
NE, kcal/kg	2,535	2,535	2,535	2,536	2,535	2,535	2,480

Ca, no phytase, %	0.58	0.58	0.46	1.03	1.03	0.91	0.76
Ca, with phytase, %	0.58	0.58	0.58	1.03	1.03	1.03	0.86
STTD P, no phytase, %	0.33	0.45	0.33	0.33	0.45	0.33	0.37
STTD P, with phytase, %	0.33	0.45	0.45	0.33	0.45	0.45	0.47
Total P, %	0.54	0.68	0.55	0.54	0.68	0.54	0.62
Analyzed composition, %							
DM	89.94	90.30	90.73	90.92	90.60	90.33	88.76
CP	23.05	21.35	22.35	22.10	21.45	21.10	21.80
Fat	4.75	4.50	4.25	4.80	4.95	4.45	4.45
Ca[7]	0.63	0.65	0.54	1.32	1.37	1.13	0.75
P[7]	0.69	0.78	0.64	0.65	0.76	0.62	0.69

[1] Phase 2 diets were fed from d 14 to 28 and phase 3 diet were fed from d 28 to 42.

[2] Phytase was added to diets at the level of 1,000 phytase units with assumed release value of 0.12% for Ca and standardized total tract digestible (STTD) P.

[3] Hamlet Protein, Inc., Findlay, OH.

[4] Provided per kg of premix: 29.6 g Mn from manganese oxide, 104 g Fe from iron sulfate, 112 g Zn from zinc sulfate, 16 g Cu from copper sulfate, 1600 mg I from calcium iodate.

[5] Provided per kg of premix: 28,659,800 IU vitamin A, 4,409,200 IU vitamin D_3, 105,821 IU vitamin E, 801,665 mg vitamin K, 15,423 mg riboflavin, 66,138 mg pantothenic acid, 110,230 mg niacin, 79 mg vitamin B_{12}, 4,409 mg folic acid, 44 mg thiamin, 44 mg pyridoxine, and 4.4 mg biotin.

[6] Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ).

[7] Averaged across analyzed values from Ward Laboratories, Inc. (Kearney, NE), Cumberland Valley Analytical Services Inc. (Maugansville, MD), and Midwest Laboratories (Omaha, NE).

Table 2.4. Diet formulation, phase 1 (Exp. 2; as-fed basis)

	Phase 1 (d 0 to 10)					
STTD[1] P:	NRC (0.45%)			>NRC (0.56%)		
Ca, %:	0.65	0.90	1.20	0.65	0.90	1.20
Ingredients, %						
Corn	46.66	45.54	44.14	46.04	44.92	43.53
Soybean meal	21.33	21.40	21.50	21.38	21.45	21.55
HP 300[2]	3.75	3.75	3.75	3.75	3.75	3.75
Fish meal	2.50	2.50	2.50	2.50	2.50	2.50
Spray-dried whey	20.00	20.00	20.00	20.00	20.00	20.00
Beef tallow	2.60	3.00	3.50	2.80	3.20	3.70
Monocalcium P (21% P)	0.63	0.63	0.63	1.25	1.25	1.25
Limestone	0.30	0.95	1.75	0.04	0.70	1.49
Salt	0.50	0.50	0.50	0.50	0.50	0.50
L-Lys HCl	0.48	0.48	0.48	0.48	0.48	0.48
DL-Met	0.24	0.24	0.24	0.24	0.24	0.24
L-Thr	0.21	0.21	0.21	0.21	0.21	0.21
L-Trp	0.03	0.03	0.03	0.03	0.03	0.03
L-Val	0.15	0.15	0.15	0.15	0.15	0.15
Trace mineral premix[3]	0.09	0.09	0.09	0.09	0.09	0.09
Vitamin premix[4]	0.05	0.05	0.05	0.05	0.05	0.05
Vitamin E (20,000 IU)	0.05	0.05	0.05	0.05	0.05	0.05
Choline chloride	0.04	0.04	0.04	0.04	0.04	0.04
Zinc oxide	0.39	0.39	0.39	0.39	0.39	0.39
Selenium premix	0.02	0.02	0.02	0.02	0.02	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition						
Standardized ileal digestible AA, %						
Lys	1.40	1.40	1.40	1.40	1.40	1.40
Ile:Lys	55	55	55	55	55	55
Leu:Lys	109	108	108	109	108	107
Met:Lys	38	38	38	38	38	38
Met & Cys:Lys	58	58	57	58	57	57
Thr:Lys	64	63	63	64	63	63
Trp:Lys	18	18	18	18	18	18
Val:Lys	70	70	70	70	70	70
Total Lys, %	1.53	1.53	1.53	1.53	1.53	1.53
CP, %	20.89	20.83	20.76	20.86	20.80	20.73
NE, kcal/kg	2,606	2,606	2,606	2,606	2,606	2,606

Ca, %	0.65	0.90	1.20	0.65	0.90	1.20
STTD Ca[5], %	0.51	0.67	0.87	0.53	0.69	0.88
P, %	0.66	0.65	0.65	0.78	0.78	0.77
STTD P, %	0.45	0.45	0.45	0.56	0.56	0.56
Available P[6], %	0.42	0.42	0.42	0.55	0.55	0.55
Analyzed composition, %						
DM	90.42	90.09	90.91	89.84	90.15	89.82
CP	21.30	21.00	20.90	21.10	20.90	21.10
Fat	5.10	5.30	6.00	5.10	5.90	6.00
Ca[7]	0.66	0.80	1.23	0.66	0.82	1.27
P[7]	0.64	0.66	0.66	0.78	0.80	0.73

[1] STTD = standardized total tract digestible.

[2] Hamlet Protein, Inc., Findlay, OH.

[3] Provided per kg of premix: 29.6 g Mn from manganese oxide, 104 g Fe from iron sulfate, 112 g Zn from zinc sulfate, 16 g Cu from copper sulfate, 1600 mg I from calcium iodate.

[4] Provided per kg of premix: 28,659,800 IU vitamin A, 4,409,200 IU vitamin D_3, 105,821 IU vitamin E, 801,665 mg vitamin K, 15,423 mg riboflavin, 66,138 mg pantothenic acid, 110,230 mg niacin, 79 mg vitamin B_{12}, 4,409 mg folic acid, 44 mg thiamin, 44 mg pyridoxine, and 4.4 mg biotin.

[5] Standardized total tract digestibility coefficients for Ca content of feed ingredients were from Stein (2016).

[6] Determined using availability coefficients from NRC (1998).

[7] Averaged across analyzed values from Ward Laboratories, Inc. (Kearney, NE), Cumberland Valley Analytical Services Inc. (Maugansville, MD), and Midwest Laboratories (Omaha, NE).

Table 2.5. Diet formulation, phases 2 and 3 (Exp. 2; as-fed basis)[1]

	Phase 2						Phase 3
STTD[2] P:	NRC (0.40%)			>NRC (0.52%)			0.37%
Ca, %:	0.65	0.90	1.20	0.65	0.90	1.20	0.77
Ingredients, %							
Corn	57.76	56.63	55.23	57.01	55.87	54.50	62.60
Soybean meal	24.88	24.96	25.05	24.93	25.01	25.10	32.23
Fish meal	3.50	3.50	3.50	3.50	3.50	3.50	-
Spray-dried whey	10.00	10.00	10.00	10.00	10.00	10.00	-
Beef tallow	1.00	1.40	1.90	1.25	1.65	2.15	1.00
Monocalcium P (21% P)	0.61	0.61	0.61	1.29	1.29	1.29	1.25
Limestone	0.38	1.03	1.83	0.09	0.75	1.53	1.10
Salt	0.60	0.60	0.60	0.60	0.60	0.60	0.60
L-Lys HCl	0.40	0.40	0.40	0.40	0.40	0.40	0.40
DL-Met	0.18	0.18	0.18	0.18	0.18	0.18	0.18
L-Thr	0.17	0.17	0.17	0.17	0.17	0.17	0.17
L-Trp	0.03	0.03	0.03	0.03	0.03	0.03	-
L-Val	0.10	0.10	0.10	0.10	0.10	0.10	0.07
Trace mineral premix[3]	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Vitamin premix[4]	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Zinc oxide	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Selenium premix	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition							
Standardized ileal digestible AA, %							
Lys	1.30	1.30	1.30	1.30	1.30	1.30	1.28
Ile:Lys	57	57	57	57	57	57	59
Leu:Lys	116	116	115	116	116	115	121
Met:Lys	37	37	36	37	37	36	36
Met & Cys:Lys	58	57	57	57	57	57	58
Thr:Lys	63	63	63	63	63	63	63
Trp:Lys	19	19	19	19	19	19	17
Val:Lys	70	69	69	69	69	69	69
Total Lys, %	1.44	1.44	1.44	1.44	1.44	1.44	1.43
CP, %	20.70	20.64	20.58	20.66	20.61	20.54	21.19
NE, kcal/kg	2,518	2,518	2,518	2,518	2,518	2,518	2,445
Ca, %	0.65	0.90	1.20	0.65	0.90	1.20	0.77
STTD Ca[5], %	0.49	0.65	0.85	0.51	0.67	0.86	0.54

P, %	0.62	0.62	0.62	0.76	0.75	0.75	0.61
STTD P, %	0.40	0.40	0.40	0.52	0.52	0.52	0.37
Available P[6], %	0.36	0.36	0.36	0.50	0.50	0.50	0.32
Analyzed composition, %							
DM	89.96	89.24	89.83	89.61	90.05	89.35	88.60
CP	21.20	21.10	21.30	21.10	21.70	21.20	21.30
Fat	4.00	4.20	4.50	4.20	4.50	4.90	4.00
Ca[7]	0.73	0.97	1.33	0.72	0.93	1.24	0.76
P[7]	0.64	0.63	0.66	0.79	0.81	0.76	0.65

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[1] Phase 2 diets were fed from d 10 to 24 and phase 3 diet were fed from d 24 to 45.

[2] STTD = standardized total tract digestible.

[3] Provided per kg of premix: 29.6 g Mn from manganese oxide, 104 g Fe from iron sulfate, 112 g Zn from zinc sulfate, 16 g Cu from copper sulfate, 1600 mg I from calcium iodate.

[4] Provided per kg of premix: 28,659,800 IU vitamin A, 4,409,200 IU vitamin D_3, 105,821 IU vitamin E, 801,665 mg vitamin K, 15,423 mg riboflavin, 66,138 mg pantothenic acid, 110,230 mg niacin, 79 mg vitamin B_{12}, 4,409 mg folic acid, 44 mg thiamin, 44 mg pyridoxine, and 4.4 mg biotin.

[5] Standardized total tract digestibility coefficients for Ca content of feed ingredients were from Stein (2016).

[6] Determined using availability coefficients from NRC (1998).

[7] Averaged across analyzed values from Ward Laboratories, Inc. (Kearney, NE), Cumberland Valley Analytical Services Inc. (Maugansville, MD), and Midwest Laboratories (Omaha, NE).

Table 2.6. Effects of Ca and P concentrations on growth performance of nursery pigs (Exp. 1)[1]

	Treatment							Probability, $P <$		
Ca, %:	0.58	0.58	0.58[2]	1.03	1.03	1.03[2]				
STTD P, no phytase, %:	0.33	0.45	0.33	0.33	0.45	0.33	SEM	Ca × P	Ca	P
STTD P, with phytase, %:	-	-	0.45	-	-	0.45				
BW, kg										
d 0	6.1	6.1	6.1	6.1	6.1	6.1	0.06	0.773	0.609	0.208
d 14	8.9^{bc}	9.1^{b}	10.0^{a}	8.6^{c}	9.3^{b}	10.0^{a}	0.13	0.023	0.439	0.001
d 28	16.4^{c}	16.4^{c}	17.8^{a}	14.9^{d}	16.8^{bc}	17.3^{ab}	0.21	0.001	0.003	0.001
d 42	27.6^{ab}	27.6^{ab}	28.6^{a}	26.7^{b}	28.2^{a}	28.7^{a}	0.32	0.034	0.853	0.001
Phase 1 (d 0 to 14)										
ADG, g	204^{bc}	216^{b}	283^{a}	179^{c}	231^{b}	279^{a}	7.2	0.019	0.393	0.001
ADFI, g	272^{b}	272^{b}	338^{a}	269^{b}	288^{b}	334^{a}	7.2	0.241	0.594	0.001
G:F, g/kg	749^{b}	794^{ab}	835^{a}	665^{c}	802^{a}	836^{a}	12.7	0.001	0.015	0.001
Phase 2 (d 14 to 28)										
ADG, g	534^{a}	522^{a}	545^{a}	451^{b}	535^{a}	522^{a}	10.5	0.001	0.001	0.001
ADFI, g	725^{c}	741^{bc}	780^{ab}	712^{c}	780^{ab}	789^{a}	10.9	0.050	0.173	0.001
G:F, g/kg	737^{a}	704^{ab}	699^{ab}	633^{d}	686^{bc}	661^{cd}	8.0	0.001	0.001	0.165
Treatment (d 0 to 28)										
ADG, g	365^{c}	365^{c}	411^{a}	312^{d}	379^{bc}	398^{ab}	6.6	0.001	0.002	0.001
ADFI, g	493^{c}	501^{bc}	554^{a}	485^{c}	528^{ab}	556^{a}	7.1	0.042	0.217	0.001
G:F, g/kg	740^{a}	729^{a}	742^{a}	642^{b}	718^{a}	715^{a}	6.2	0.001	0.001	0.001
Post-treatment (d 28 to 42)										
ADG, g	800^{ab}	798^{ab}	774^{b}	842^{a}	815^{ab}	816^{ab}	11.8	0.428	0.001	0.068
ADFI, g	1056^{c}	1066^{ab}	1073^{ab}	1042^{c}	1121^{a}	1093^{ab}	14.7	0.063	0.093	0.007
G:F, g/kg	757^{b}	749^{bc}	722^{c}	809^{a}	727^{bc}	747^{bc}	9.4	0.001	0.010	0.001
d 0 to 42										
ADG, g	502^{ab}	502^{ab}	526^{a}	479^{b}	517^{a}	530^{a}	6.9	0.020	0.805	0.001

ADFI, g	701^{c}	706^{bc}	742^{ab}	692^{c}	742^{ab}	750^{a}	9.0	0.044	0.130	0.001
G:F, g/kg	715^{a}	710^{ab}	708^{ab}	692^{b}	697^{b}	707^{ab}	4.5	0.055	0.001	0.616
Bone ash[3], %	44.11^{bc}	45.62^{ab}	45.75^{ab}	42.63^{c}	47.95^{a}	45.50^{ab}	0.611	0.007	0.692	0.001

[1] A total of 720 mixed gender pigs (PIC 280 × Camborough, Genus PIC, Hendersonville, TN) with initial BW of 6.1 ± 0.98 kg were used in a 42-d growth trial with 10 pigs per pen and 12 replications (pen) per treatment. One pen from 0.58% Ca + 0.45% standardized total tract digestible (STTD) P treatment encountered issues with feeder allowance and had restricted feed intake; therefore, data from this pen were excluded from all the analyses.

[2] Phytase (Ronozyme HiPhos 2500, DSM Nutritional Products, Inc., Parsippany, NJ) was added to diets at the level of 1,000 phytase units with assumed release value of 0.12% for Ca and STTD P.

[3] Radius samples collected from 1 median-weight gilt from each pen on d 21.

[abcd] Means with different superscripts within a row differ ($P < 0.05$).

Table 2.7. Effects of Ca and P concentrations on growth performance of nursery pigs (Exp. 2)[1]

	Treatment							Probability, *P* <				
STTD[2] P:	NRC[3]			>NRC[4]			SEM	Ca × P	Main effect		Ca	
Ca, %:	0.65	0.90	1.20	0.65	0.90	1.20			Ca	P	Linear	Quadratic
BW, kg												
d 0	6.0	6.0	6.0	6.0	6.0	6.0	0.01	0.968	0.989	0.758	0.897	0.947
d 10	6.8	6.8	6.8	6.8	6.7	6.7	0.06	0.833	0.502	0.129	0.410	0.406
d 24	11.5	11.5	10.7	11.7	11.5	11.4	0.19	0.181	0.018	0.096	0.006	0.560
d 45	25.2	25.5	24.8	25.3	25.3	25.2	0.36	0.644	0.467	0.756	0.381	0.388
Phase 1 (d 0 to 10)												
ADG, g	77	73	75	73	64	65	5.9	0.879	0.507	0.138	0.418	0.405
ADFI, g	108	107	115	101	102	117	4.4	0.551	0.022	0.433	0.014	0.188
G:F, g/kg	709	680	651	724	624	555	40.3	0.386	0.029	0.173	0.009	0.709
Phase 2 (d 10 to 24)												
ADG, g	339^{a}	335^{a}	281^{b}	353^{a}	341^{a}	337^{a}	11.6	0.088[5]	0.008	0.011	0.003	0.371
ADFI, g	441	457	444	459	441	435	13.5	0.406	0.699	0.860	0.434	0.760
G:F, g/kg	769^{a}	732^{a}	637^{b}	767^{a}	774^{a}	773^{a}	16.3	0.001[6]	0.002	0.001	0.001	0.336
Treatment (d 0 to 24)												
ADG, g	230	226	195	236	226	224	8.1	0.203	0.020	0.084	0.006	0.622
ADFI, g	302	311	307	310	300	303	9.0	0.559	0.988	0.753	0.876	0.994
G:F, g/kg	760^{a}	725^{a}	639^{b}	761^{a}	753^{a}	738^{a}	16.3	0.015[6]	0.001	0.003	0.001	0.439
Post-treatment (d 24 to 45)												
ADG, g	650	669	660	644	658	656	10.4	0.944	0.294	0.395	0.337	0.216
ADFI, g	978	977	944	976	962	961	17.9	0.684	0.383	0.990	0.175	0.816
G:F, g/kg	665	685	699	660	684	685	9.0	0.747	0.008	0.354	0.003	0.269
d 0 to 45												
ADG, g	426	431	411	425	427	425	8.3	0.532	0.424	0.622	0.360	0.349
ADFI, g	618	619	603	618	609	610	11.4	0.758	0.588	0.939	0.310	0.908

G:F, g/kg	690	696	682	687	702	699	8.2	0.510	0.399	0.322	0.906	0.180

[1] A total of 360 barrows and gilts (PIC 280 × Camborough, Genus PIC, Hendersonville, TN) with initial BW of 6.0 ± 1.08 kg were used in a 45-d trial with 10 pigs per pen and 6 replications (pen) per treatment.

[2] STTD = standardized total tract digestible.

[3] NRC = STTD P levels formulated to meet NRC (2012) requirement estimates (0.45% for phase 1 and 0.40% for phase 2).

[4] >NRC = STTD P levels formulated to exceed NRC (2012) requirement estimates (0.56% for phase 1 and 0.52% for phase 2).

[5] Linear Ca × P interaction: $P = 0.070$; quadratic Ca × P interaction: $P = 0.196$.

[6] Linear Ca × P interaction: $P < 0.01$; quadratic Ca × P interaction: $P > 0.10$.

[ab] Means with different superscripts within a row differ ($P < 0.05$).

Chapter 3 - Standardized total tract digestible phosphorus requirement of 6 to 13-kg pigs fed diets without or with phytase[1]

Abstract

Dietary P concentration greatly affects pig growth performance, environmental impact, and diet cost. A total of 1080 pigs (initially 5.9 ± 1.08 kg) from 3 commercial research rooms were used to determine the effects of increasing standardized total tract digestible (STTD) P concentrations in diets without and with phytase on growth performance and percentage bone ash. Pens (10 pigs/pen, 9 pens/treatment) were balanced for equal weights and randomly allotted to 12 treatments. Treatments were arranged in 2 dose titrations (without or with 2000 units of phytase) with 6 levels of STTD P each. The STTD P levels were expressed as percentage of the NRC (2012) requirement estimates (% of NRC; 0.45 and 0.40% for phases 1 and 2, respectively) and were: 80, 90, 100, 110, 125, and 140% of NRC in diets without phytase and 100, 110, 125, 140, 155, and 170% of NRC in diets with phytase. Diets were provided in 3 phases, with experimental diets fed during phases 1 (day 0 to 11) and 2 (day 11 to 25), followed by a common diet from day 25 to 46. On day 25, radius samples from 1 median-weight gilt per pen were collected for analysis of bone ash. During the treatment period, increasing STTD P from 80 to 140% of NRC in diets without phytase improved average daily gain (ADG; quadratic, $P < 0.01$), average daily feed intake (ADFI; quadratic, $P < 0.05$), and gain:feed (G:F; linear, $P < 0.01$). Estimated STTD P requirement in diets without phytase was 117 and 91% of NRC for maximum ADG according to quadratic polynomial (QP) and broken-line linear (BLL) models, respectively, and was 102, 119, and >140% of NRC for maximum G:F using BLL, broken-line quadratic, and linear

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[1] This work has been published in the *Animal* Journal: F. Wu, J. C. Woodworth, M. D. Tokach, S. S. Dritz, J. M. DeRouchey, R. D. Goodband, and J. R. Bergstrom. 2019. Standardized total tract digestible phosphorus requirement of 6 to 13-kg pigs fed diets without or with phytase. Anim. (In press)

models, respectively. When diets contained phytase, increasing STTD P from 100 to 170% of NRC improved ADG (quadratic, $P < 0.05$) and G:F (linear, $P < 0.01$). Estimated STTD P requirement in diets containing phytase was 138% for maximum ADG (QP) and was 147 (QP) and 116% (BLL) of NRC for maximum G:F. Increasing STTD P increased (linear, $P < 0.01$) percentage bone ash regardless of phytase addition. When comparing diets containing the same STTD P levels, phytase increased ($P < 0.01$) ADG, ADFI, and G:F. In summary, estimated STTD P requirements varied depending on the response criteria and statistical models and ranged from 91 to >140% of NRC (0.41 to >0.63% of phase 1 diet and 0.36 to >0.56% of phase 2 diet) in diets without phytase, and from 116 to >170% of NRC (0.52 to >0.77% of phase 1 diet and 0.46 to >0.68% of phase 2 diet) for diets containing phytase. Phytase exerted an extra-phosphoric effect on promoting pig growth and improved the P dose responses for ADG and G:F.

Keywords: bone ash, growth performance, nursery pigs, phosphorus, phytase

Implications

Dietary P concentration can greatly affect pig growth performance and diet cost. Current NRC (2012) recommendations for digestible P need to be updated for nursery pigs with modern genetics and fed commercial diets. This study characterized the dose-response to increasing digestible P in diets without or with high dose of phytase for 6- to 13-kg pigs. Results suggested that the P requirement varied depending on the response criteria (e.g. growth rate, feed efficiency, or bone ash concentration), statistical models, and the addition of phytase. The requirement estimates and response equations developed from this study can be used to determine the optimum P feeding concentrations based on local production considerations.

Introduction

Phosphorus is the second most abundant mineral in the animal body after Ca, and its dietary concentration greatly affects pig growth performance, environmental impact, and diet cost. The NRC (2012) estimates the standardized total tract digestible (STTD) P requirement of nursery pigs using a simple regression method based on a limited amount of published studies; thus, empirical data are needed to validate these STTD P requirement estimates. In a recent dose titration study, Vier *et al.* (2017a) reported that feeding STTD P concentrations above the NRC (2012) requirement estimate improved growth performance and percentage bone ash in 11 to 25 kg nursery pigs. However, to our knowledge, limited research has been published that investigates the STTD P requirement of early nursery pigs from weaning to 13 kg BW.

Phytase is commonly added to diets for pigs to increase availability of phytate-bound P. Feeding high doses of phytase also promotes growth performance of nursery pigs (Walk *et al.*, 2013; Zeng *et al.*, 2015; Patience *et al.*, 2015) by reducing the anti-nutritional effects of phytate and increasing availability of amino acids, trace minerals, and energy (Cowieson *et al.*, 2011). It is possible that the faster growth rate of pigs and additional dietary energy released by phytase may, in turn, alter pigs' nutrient requirements. Therefore, there is an increasing interest in determining the dietary STTD P requirement of pigs fed diets containing phytase. The objective of this study was to determine the effects of increasing STTD P concentration in diets without or with high levels (2000 phytase units; FYT/kg) of phytase on growth performance and percentage bone ash of nursery pigs from 6 to 13 kg BW.

Material and methods

All experimental procedures in this study were approved by the Kansas State University Institutional Animal Care and Use Committee (Manhattan, KS).

Diets and Experimental Design

All ingredients that were used to manufacture the experimental diets and contained Ca and P were sampled 4 times at the feed mill before the start of the study. Ingredient samples were sent to 2 labs (Ward Laboratories, Inc. Kearney, NE and Cumberland Valley Analytical Services Inc., Maugansville, MD) for analysis of Ca and P in duplicate in each lab (Table 3.1). The average of the 16 lab results for each sampled ingredient was used in the diet formulation. All diets were manufactured at a commercial feed mill (Kalmbach Feeds, Inc., Upper Sandusky, OH) following the same standard procedure for each treatment. The dietary treatments were arranged in 2 dose titrations with 6 levels of STTD P in diets that contained either 0 or 2000 FYT/kg of a novel microbial phytase from *Citrobacter braakii* expressed in *Aspergillus oryzae* (Ronozyme HiPhos 2500, DSM Nutritional Products, Inc., Parsippany, NJ). The STTD P levels were expressed as the percentage of the NRC (2012) requirement estimates (% of NRC) because 2 feeding phases were involved during the designated weight range, with different STTD P levels (0.45 and 0.40%, respectively) were recommended for 5 to 7 and 7 to 11 kg BW pigs [Table 16-1A; NRC (2012)]. For diets without phytase, the experimental STTD P levels were: 80, 90, 100, 110, 125, and 140% of NRC, corresponding to 0.36, 0.40, 0.45, 0.50, 0.56, and 0.63% STTD P in phase 1 diets and 0.32, 0.36, 0.40, 0.44, 0.50, and 0.56% of STTD P in phase 2 diets (Table 3.2). For diets containing phytase, the experimental STTD P levels were: 100, 110, 125, 140, 155, and 170% of NRC; these STTD P levels included the manufacturer suggested release value of 0.158% STTD P and 0.105% STTD Ca for 2000 FYT/kg phytase in corn-soybean meal-based swine diets. Thus, STTD P levels corresponded to 0.45, 0.50, 0.56, 0.63, 0.70, and 0.76% STTD

P in phase 1 diets and 0.40, 0.44, 0.50, 0.56, 0.62, and 0.68% STTD P in phase 2 diets. The phytase-containing diets with the lowest STTD P dose (100% of NRC) were formulated with negligible (0.02%) amounts of inorganic P source. Phase 1 diets (Table 3.3) were offered from day 0 to 11 and phase 2 diets (Table 3.4) were offered from day 11 to 25. A common phase 3 diet containing 0.45% STTD P was then fed to all pigs from day 25 to 46. Ingredient loading values, standardized ileal digestible AA digestibility coefficients, and STTD coefficients for P were obtained from NRC (2012) for each ingredient. Diets were formulated to contain similar net energy and AA concentrations within phase. All diets were balanced for an total Ca:total P ratio of 1.20:1. Phase 1 diets were pelleted, and phases 2 and 3 diets were provided in meal form.

Animals and Housing

The study was conducted at the Cooperative Research Farm's Swine Research Nursery (Kalmbach Feeds, Inc., Sycamore, OH). Each pen (1.52 × 1.83 m) had completely slatted metal floors and was equipped with a 4-hole stainless-steel feeder and a nipple-cup waterer. Five barrows and 5 gilts (PIC 280 × Camborough, Genus PIC, Hendersonville, TN) were housed in each pen and were allowed ad libitum access to feed and water throughout the experiment. Experimental diets were delivered in bags, weighed, and added manually to the feeders.

A total of 1080 weaned pigs with initial BW of 5.9 ± 1.08 kg were used in 3 rooms with 36 pens per room. Upon arrival, pigs were individually weighed and assigned to pens to achieve balanced pen weights within room. In each room, pens of pigs were allotted to 1 of 12 dietary treatments (9 replications per treatment) in a completely randomized manner. Pigs and feeders were weighed on day 0, 11, 25, and 46 to determine average daily gain (ADG), average daily feed intake (ADFI), and gain:feed ratio (G:F).

Bone Ash Analysis

At the end of treatment period (day 25), 1 median-weight gilt from each pen was euthanized using CO_2 chamber, and the radius was collected. Bones were then transferred with dry ice to the Kansas State University Swine Laboratory and stored at -20°C until analysis. After thawing at room temperature (24°C) in plastic bags for 24 h, bones were autoclaved for 60 min, adhering tissue and cartilage caps were removed (without defatting), then dried at 105°C for 7 d. Dried radiuses were then ashed in a muffle furnace at 600°C for 24 h. Percentage bone ash was calculated as: Bone ash, % = ashed bone weight, g ÷ dried bone weight, g × 100.

Chemical Analysis

For each complete diet, subsamples were obtained from a minimum of 6 feeders during each week to form a composite sample. Diet samples were delivered to the Kansas State University Swine Laboratory, Manhattan, KS, and stored at -20°C until analysis. Ingredient and complete diet samples were analyzed for DM, CP, Ca, and P at Ward Laboratories, Inc. (Kearney, NE). Concentrations of Ca and P in complete diet samples were also analyzed at Cumberland Valley Analytical Services Inc. (Maugansville, MD) and Midwest Laboratories (Omaha, NE) in duplicate. Diets containing phytase were submitted to DSM Technical Marketing Analytical Services Laboratory (Belvidere, NJ) for phytase analysis. The means of analyzed nutrient values for complete diets are presented in Tables 3.3 and 3.4. Standard procedures from AOAC (2006) were followed for analysis of moisture (Method 934.01), CP (Method 990.03), and Ca and P (Method 985.01). At Cumberland Valley Analytical Services Inc. (Maugansville, MD), AOAC (2000) method (985.01) was used for Ca and P analyses with modifications of ashing a 0.35g sample for 1 h at 535°C, digestion in an open crucible for 20 min in 15% nitric acid on a hot plate, and sample dilution to 50 mL and analysis on an inductively coupled plasma spectrometer (PerkinElmer 3300 XL and 5300 DV ICP; PerkinElmer Inc., Shelton, CT).

Statistical Analysis

Growth performance and bone ash data were analyzed in a randomized complete block design using pen as the experimental unit and room as a random effect in all statistical models. Phytase and phytase × STTD P interaction effects were analyzed in a 2 × 4 factorial treatment structure, with main effects of phytase (0 or 2000 FYT/kg) and STTD P levels (100, 110, 125, and 140% of NRC) that represented the dose treatments duplicated between the 2 titration sets. This analysis was conducted to determine the extra-phosphoric effect of feeding phytase on pig growth performance. Within each (without or with phytase) dose titrations, the 6 STTD P doses were evaluated using single df linear and quadratic contrasts. Unequally spaced linear and quadratic contrast coefficients were derived using the IML procedure in SAS (Version 9.4, SAS Institute Inc., Cary, NC). Statistical models accounting for heterogeneous residual variances were used when they improved model fit. All models were fit using the GLIMMIX procedure of SAS. Means were reported as least-squares means and results were considered significant at $P < 0.05$ and marginally significant at $0.05 < P < 0.10$.

Using procedures outlined by Goncalves *et al.* (2016), dose response models were fit separately for each (without or with phytase) STTD P titration. Response criteria modeled were ADG, ADFI, and G:F during the treatment period (day 0 to 25), as well as percentage bone ash. Competing statistical models included linear (LM), quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ). Dose response models were compared based on the Bayesian information criterion (BIC), where the smaller the value, the better (Milliken and Johnson, 2009). A decrease in BIC greater than 3 was considered a significant improvement in fit. The 95% confidence interval of the estimated requirement to reach maximum performance or to reach plateau performance was computed. Results reported correspond to inferences yielded by the best fitting models. Codes for statistical analysis are given in Supplementary Materials S1.

Results

Diet Analysis

Analyzed total P concentrations of dietary treatments were reasonably consistent with calculated levels and followed similar patterns as the designed treatment structure (Tables 3.3 and 3.4). Analysis of total Ca was more variable than P, with analyzed Ca:analyzed P ratios in diets within an acceptable range from 1.1:1 to 1.6:1. This was expected because higher analytical variations within and among laboratories were often observed for Ca than P (Jones *et al.*, 2018).

Growth Performance

Phytase × STTD P interactions were assessed using the 8 treatments with overlapping STTD P levels between the 2 dose titrations. No phytase × STTD P interactions were observed for any growth response or percentage bone ash except a tendency for ADG ($P = 0.08$) during the treatment period (day 0 to 25). This was the result of a linear increase ($P < 0.05$) in ADG for pigs fed increasing STTD P from 100 to 140% of NRC in diets containing phytase, but no evidence of difference for pigs fed diets without phytase (Table 3.5). Feeding phytase increased ($P < 0.01$) ADG from day 0 to 25 compared with diets without phytase, and the magnitude of this improvement enlarged as STTD P level increased from 100 to 140% of NRC. Due to this tendency for a phytase × STTD P interaction on ADG, STTD P requirements were modeled separately for diets without and with phytase.

During the treatment period (day 0 to 25), increasing STTD P from 80 to 140% of NRC in diets without phytase increased ADG (quadratic, $P < 0.01$; Figure 3.1A) and day 25 BW (quadratic, $P < 0.05$). The best fitting models for ADG were QP and BLL. The QP model estimated that the maximum ADG was reached at 117% (95% CI: [86, >140%]) of NRC and then decreased with greater STTD P, with 99% of maximum ADG achieved at 106% of NRC. The BLL model suggested that the ADG response plateaued at 91% (95% CI: [76, 107%]) of NRC. When diets contained 2000 FYT/kg phytase, increasing STTD P from 100 to 170% of NRC increased ADG (quadratic, $P < 0.05$; Figure 3.1B) and tended to increase day 25 BW (quadratic, $P = 0.08$). The QP model estimated that ADG reached maximum at 138% (95% CI: [110, >170%]) of NRC and then decreased with greater STTD P, with 99% of maximum ADG achieved at 122% of NRC.

For ADFI during the treatment period, pigs fed diets containing phytase had greater ($P < 0.01$) ADFI than those fed diets without phytase regardless of STTD P levels (380 vs. 352 g, respectively). Increasing STTD P from 80 to 140% of NRC increased (quadratic, $P < 0.05$) ADFI when phytase was not included in the diets (Figure 3.2). The QP model suggested that the maximum ADFI was achieved when diet contained STTD P of 109% (95% CI: [80, 140%]) of NRC, with 99% of maximum ADFI achieved at 97% of NRC. When diets contained phytase, there was no evidence ($P > 0.26$) for any STTD P dose effect on ADFI.

Gain:feed during the treatment period was increased ($P < 0.01$) by adding phytase to diets regardless of STTD P levels (781 vs. 758 g/kg, respectively; Table 3.5). Increasing STTD P from 80 to 140% of NRC in diets without phytase increased (linear, $P < 0.01$; quadratic, $P = 0.06$) G:F (Figure 3.3A), with LM (BIC = 505.2), BLL (BIC = 503.3), and BLQ (BIC = 504.5) as competing models. The LM model estimated the maximum G:F at greater than 140% of NRC; the estimated LM regression equation was: G:F, g/kg = 644.57 + 0.90 × (STTD P, % of NRC). The BLL and BLQ suggested that the plateau G:F was achieved at STTD P of 102% (95% CI: [85, 118]%) and 119% (95% CI: [24, 213%]) of NRC, respectively. Similarly, increasing STTD

P from 100 to 170% of NRC in diets containing phytase also increased (linear, $P < 0.01$; quadratic, $P = 0.07$) G:F (Figure 3.3B). The best fit models were QP (BIC = 489.8) and BLL (BIC = 489.2). The QP model estimated the maximum G:F achieved at STTD P of 147% (95% CI: [120, >170%]) of NRC, with 99% of maximum G:F achieved at 122% of NRC. The BLL plateau was estimated at 116.4% (95% CI: [85.2, 147.7%]) of NRC.

Intake of STTD P per kg of gain during the treatment period was increased (linear, $P < 0.01$) by increasing STTD P in both sets of formulations but was decreased ($P < 0.01$) by adding phytase to the diets (STTD P intake included the assumed P release by phytase; Figure 3.4).

During the post-treatment period (day 25 to 46), all pigs were fed the same common diet without phytase containing 0.45% STTD P (136% of NRC requirement estimate). Pigs previously fed diets containing phytase had decreased ($P < 0.05$) ADG (680 vs. 717 g, respectively), ADFI (1054 vs. 1091 g, respectively), and G:F (645 vs. 657 g/kg, respectively) compared with that of pigs previously fed diets not containing phytase. The STTD P content of diets fed previously did not affect growth performance except for ADFI of pigs previously fed phytase diets, whereby ADFI tended to increase (linear, $P = 0.08$) as more STTD P was fed previously.

Percentage Bone Ash

Pigs fed diets containing phytase had decreased ($P < 0.05$) bone ash weight, but similar percentage bone ash, compared with those fed diets without phytase. Both bone ash weight (quadratic, $P < 0.05$) and percentage bone ash (linear, $P < 0.01$) increased with increasing STTD P. When diets contained no phytase, the LM model (BIC = 264.3) estimated the maximum percentage bone ash achieved at greater than 140% of NRC (Figure 3.5A. When diets contained phytase, the LM model (BIC = 257.6) estimated the maximum percentage bone ash achieved at greater than 170% of NRC (Figure 3.5B).

Discussion

The present study characterized the dose-response to increasing STTD P in diets without or with high dose of phytase. The dose levels were structured to capture the potential response plateau suggested by literature (NRC, 2012). The phytase-containing diets with the lowest STTD P dose (100% of NRC) only contained negligible (0.02%) amounts of inorganic P source, which prevented us from testing the 80 or 90% of NRC doses in diets containing phytase.

The STTD P requirements estimated in the present study varied depending on the response criteria and statistical models. In diets without phytase, QP and BLL models resulted in numerically different STTD P requirement estimates for ADG. Based on our experience with modeling nutrient requirements using the method described by Goncalves *et al.* (2016), QP model tends to be more sensitive to detecting the maximum response and, therefore, results in a numerically higher STTD P requirement estimate of 117% (95% CI: [86, >140%]) of NRC in contrast to 91% (95% CI: [76, 107%]) of NRC suggested by the BLL model. However, given the wide CI these requirement estimates are not statistically different. Smaller increment of titration doses and more advanced modeling techniques are needed in future research to verify our observation. In a QP model, the STTD P level that maximizes growth performance may not be economically optimal and a large proportion of the maximum performance can be achieved at a considerably lower STTD P level for the majority of the pigs. In this case, 95 and 99% of the maximum ADG can be achieved at STTD P level of 92 and 106% of NRC, respectively. These results suggest that the NRC (2012) recommendations are reasonably accurate for ADG response when diets do not contain phytase. Likewise when using ADFI and G:F as the response criteria, the estimated STTD P requirements in diets not containing phytase ranged from 102 to greater than 140% of NRC depending on statistical models.

When 2000 FYT/kg phytase was added in the diets, the estimated plateau doses of STTD P for ADG (138% of NRC) and G:F (147 and 116% of NRC using QP and BLL models, respectively) numerically increased compared with that for diets without phytase. Caution is needed when comparing the requirement estimates between diets without and with phytase given the wide CI of the estimates and because different dose ranges were tested for the 2 titrations. It is possible that the STTD P requirements might have been increased to support the improved ADG and G:F and potentially higher dietary energy when phytase was added to diets. However, it is worth noting that the dietary STTD P concentrations tested herein were derived from assumed digestibility coefficients that are determined mostly using growing pigs, but in fact, P digestibility increases with greater piglet BW (Kemme *et al.*, 1997). Therefore, adjustments in STTD P requirement estimates may be needed for young pigs.

Comparing diets that contained the same STTD P contents, positive effects of feeding 2000 FYT/kg phytase were observed for ADG, ADFI, and G:F. Additionally, STTD P intake per kg of gain was reduced ($P < 0.01$) by adding phytase to diets, indicating a better efficiency of utilizing P for growth. This extra-phosphoric effect of phytase on growth performance has also been observed in other studies (Walk *et al.*, 2013; Zeng *et al.*, 2015; Patience *et al.*, 2015). Walk *et al.* (2013) observed 9, 11, and 3% improvements in ADG, ADFI, and G:F, respectively, when 2500 FYT/kg phytase was fed to nursery pigs from 7 to 12 kg BW. The magnitude of the phytase effects observed by Walk *et al.* (2013) was in close agreement with the present study where averagely 11, 8, and 3% improvements in ADG, ADFI, and G:F, respectively, were observed.

Using pigs of greater BW range from 6 to 22 kg, Patience *et al.* (2015) reported 2 and 3% increase in ADG and G:F, respectively, by feeding 2500 FTU/kg phytase. Proposed mechanisms for the growth-promoting effects of high-dose phytase include the near-complete destruction of anti-nutritional effects of phytate and generation of other nutrients such as inositol, as well as increased availability of other nutrients like AA, minerals, or energy (Adeola and Cowieson, 2011).

Dietary Ca concentration is an important factor when investigating the effect of P and phytase on pig performance because excess dietary Ca impairs P absorption and the efficacy of phytase (Reinhart and Mahan, 1986; Dersjant-Li *et al.*, 2015; Wu *et al.*, 2018). A constant total Ca:total P ratio of 1.2:1 was maintained when formulating the experimental diets, resulting in analyzed Ca:analyzed P ratios ranging from 1.1:1 to 1.6:1. However, an arguably low release value (0.105%) for STTD Ca was recommended by the phytase manufacturer and used in diet formulation. Cowieson *et al.* (2011) suggested that more Ca than P release should be expected at a given dose of phytase. Therefore, it is possible that more digestible Ca was available for pigs fed diets containing phytase. However, a previous study conducted in the same facility involving pigs of similar BW range and the same phytase source as the present study suggested that total Ca:total P ratios ranging from 0.8:1 to 1.6:1 can be fed without change in growth performance (Wu *et al.*, 2018).

Interestingly, we observed a detrimental effect of withdrawing phytase during the post-treatment period on growth performance of pigs previously fed phytase diets compared with those fed diets without phytase. In addition, the magnitude of such effect diminished over time; specifically, 17, 9, and 10% decrease in ADG, ADFI, and G:F respectively, were observed during the 1st week post-treatment, in contrast to 6, 3, and 2%, respectively, for the 2nd week post-treatment and no performance difference during the 3rd week post-treatment among pigs previously fed diets without or with phytase (data not shown). To our knowledge, this observation has not been reported in other studies for nursery pigs. Because the common diet fed did not contain phytase, we hypothesize that pigs previously fed high phytase diets had not been exposed to phytate as an anti-nutritional factor; thus, when switched to a diet without phytase the digestive function of these pigs may have been compromised and required a period of adaptation to the high-phytate diets. In commercial pig production, phytase inclusion is often reduced from nursery to grower and finisher diets. Therefore, further research is needed to investigate the effects of complete or step-down removal of dietary phytase on pig growth performance.

Percentage bone ash values reported in the present study agreed with other studies (Brana *et al.*, 2006; Gourley *et al.*, 2018) where bones were not defatted during the analysis and pigs of similar BW range were utilized. Regardless of phytase addition, increasing STTD P concentration linearly increased percentage bone ash, suggesting a STTD P requirement greater than 140% of NRC in diets without phytase and 170% of NRC in phytase-containing diets is needed for maximizing bone mineralization. This observation is consistent with other studies (Ekpe et al., 2002; Saraiva et al., 2012; Vier et al., 2017b) where the Ca and P required to maximize bone ash content is greater than that required to maximize growth. The NRC (2012) requirement estimates for P and Ca are based on maximizing growth and optimizing mineral retention. Greater P requirement for bone development is particularly important for gilts that are intended for future sows. It is surprising that when diets contained the same STTD P levels (100, 110, 125, and 140% of NRC diets), pigs fed phytase had decreased bone ash weight, even though percentage bone ash was similar, compared with those fed diets without phytase. A possible explanation is that the releasing ability of 2000 FYT/kg phytase used in the present study was overestimated, which, however, contradicted the growth performance results. Overestimation of phytase release ability could contribute to the increase of STTD P requirement estimates for diets containing phytase. Most frequently, digestibility of P and growth responses have been used to establish the release values for phytases. It is possible that the release values of 2000 FYT/kg phytase used in the present study was adequate for maximum growth but was suboptimal for maximum bone development. The increased rate and efficiency of whole-body growth when fed high dose of phytase may require additional dietary STTD P for maximum bone ash weight.

In conclusion, increasing dietary STTD P improved ADG, ADFI, G:F, and percentage bone ash. The estimated STTD P requirements varied based on the growth response criteria and statistical models and ranged from 91 to greater than 140% of the NRC (2012) requirement estimates (corresponding to 0.41 to >0.63% of phase 1 diet and 0.36 to >0.56% of phase 2 diet) in diets containing no phytase, and from 116 to 147% of NRC (corresponding to 0.52 to >0.77% of phase 1 diet and 0.46 to 0.59% of phase 2 diet) for diets containing 2000 FYT/kg phytase. Higher dietary concentration of STTD P (>140 and >170% of NRC for diets without and with phytase, respectively) is needed for maximizing bone mineralization than for growth performance. In addition, the high dose of phytase appeared to exert an extra-phosphoric effect on promoting growth performance and improved the dose responses of ADG and G:F to dietary STTD P in 6- to 13-kg nursery pigs.

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Table 3.1. Analyzed Ca and P concentrations in feed ingredients (as-fed basis)

	Ca, %			P, %		
Ingredient	Midwest[1]	CVAS[2]	Average	Midwest	CVAS	Average
Corn	<0.01	0.01	0.01	0.26	0.23	0.24
Soybean meal	0.39	0.44	0.42	0.65	0.61	0.63
HP 300[3]	0.41	0.41	0.41	0.79	0.73	0.76
Dried whey	0.91	0.85	0.88	0.88	0.80	0.84
Monocalcium P (21% P)	15.91	16.36	16.13	22.08	17.58	19.83
Limestone	38.20	38.59	38.39	<0.01	0.02	0.01
Trace mineral premix	7.22	7.58	7.40	0.10	0.01	0.06
Vitamin premix	9.41	10.49	9.95	0.02	0.01	0.02
Selenium premix	37.11	41.76	39.44	<0.01	0.01	0.01

[1] Midwest Laboratories (Omaha, NE); 4 samples per ingredient were analyzed in duplicates and average values were reported.

[2] Cumberland Valley Analytical Services (CVAS) Inc. (Maugansville, MD); 4 samples per ingredient were analyzed in duplicates and average values were reported.

[3] Enzymatically treated soy product (Hamlet Protein, Inc., Findlay, OH).

Table 3.2. Dietary treatment structure (as-fed basis)[1]

Phytase[2]	0 FYT/kg diet						2000 FYT/kg diet					
STTD P, % of NRC[3]	80	90	100	110	125	140	100	110	125	140	155	170
Phase 1 (day 0 to 11)												
STTD P, no phytase, %	0.36	0.40	0.45	0.50	0.56	0.63	0.29	0.34	0.40	0.47	0.54	0.61
STTD P, with phytase, %	-	-	-	-	-	-	0.45	0.50	0.56	0.63	0.70	0.76
Total P, %	0.56	0.61	0.66	0.71	0.78	0.86	0.48	0.53	0.61	0.68	0.76	0.83
Available P,[4] no phytase, %	0.31	0.36	0.42	0.47	0.54	0.62	0.24	0.29	0.36	0.44	0.52	0.59
Available P, with phytase, %	-	-	-	-	-	-	0.42	0.47	0.54	0.62	0.70	0.77
Total Ca, %	0.67	0.73	0.79	0.85	0.94	1.03	0.58	0.64	0.73	0.82	0.91	1.00
STTD Ca,[5] no phytase, %	0.49	0.54	0.58	0.62	0.69	0.75	0.43	0.47	0.54	0.60	0.67	0.73
STTD Ca, with phytase, %	-	-	-	-	-	-	0.53	0.58	0.64	0.71	0.77	0.84
Total Ca:total P	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Phase 2 (day 11 to 25)												
STTD P, no phytase, %	0.32	0.36	0.40	0.44	0.50	0.56	0.24	0.28	0.34	0.40	0.46	0.52
STTD P, with phytase, %	-	-	-	-	-	-	0.40	0.44	0.50	0.56	0.62	0.68
Total P, %	0.53	0.58	0.62	0.67	0.74	0.80	0.45	0.49	0.56	0.63	0.69	0.76
Available P, no phytase, %	0.26	0.31	0.35	0.40	0.47	0.53	0.17	0.22	0.29	0.36	0.42	0.49
Available P, with phytase, %	-	-	-	-	-	-	0.35	0.40	0.47	0.54	0.60	0.67
Total Ca, %	0.64	0.69	0.75	0.80	0.88	0.96	0.54	0.59	0.67	0.75	0.83	0.91
STTD Ca, no phytase, %	0.46	0.50	0.53	0.57	0.63	0.69	0.38	0.42	0.48	0.54	0.59	0.65
STTD Ca, with phytase, %	-	-	-	-	-	-	0.49	0.53	0.58	0.64	0.70	0.76
Total Ca:total P	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20	1.20
Phase 3 (day 25 to 46)												
STTD P, no phytase, %	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45

STTD = standardized total tract digestible.

[1] A total of 1080 barrows and gilts (PIC 280 × 1050, Hendersonville, TN) with initial body weight of 5.9 ± 1.08 kg were used in a 46-d trial with 10 pigs per pen and 9 replications (pen) per treatment to determine the effects of increasing STTD P concentrations in diets without and with phytase on growth performance and percentage bone ash.

[2] Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ); FYT/kg = phytase unit.

[3] Dietary STTD P levels expressed as percentage of NRC (2012) requirement estimates. The NRC (2012) requirement estimates for nursery pigs from 5 to 7 kg and 7 to 11 kg, expressed as percentage of the diets, are 0.45 and 0.40% STTD P, respectively. Therefore, treatment concentrations represented 80, 90, 100, 110, 125, 140, 155, and 170% of the NRC (2012) requirement.

[4] Availability coefficients for P content of feed ingredients were from NRC (1998).

[5] Digestibility coefficients for Ca content were from Stein (2016).

Table 3.3. Diet formulation, phase 1 (day 0 to 11; as-fed basis)

Phytase[1]	0 FYT/kg diet						2000 FYT/kg diet					
STTD[2] P, % of NRC[3]	80	90	100	110	125	140	100	110	125	140	155	170
Ingredients, %												
Corn	45.77	45.23	44.69	44.13	43.40	42.59	46.48	45.93	45.12	44.35	43.55	42.80
Soybean meal	22.72	22.76	22.80	22.85	22.89	22.94	22.67	22.71	22.77	22.84	22.88	22.93
HP 300[4]	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
Dried whey	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Beef tallow	2.10	2.30	2.50	2.70	2.95	3.25	1.85	2.05	2.35	2.60	2.90	3.15
Monocalcium P (21% P)	0.40	0.65	0.90	1.15	1.52	1.90	0.02	0.27	0.65	1.02	1.40	1.77
Limestone	0.74	0.79	0.84	0.90	0.97	1.05	0.63	0.69	0.76	0.84	0.92	1.00
Salt	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
L-Lysine HCl	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48	0.48
DL-Methionine	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
L-Threonine	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21
L-Tryptophan	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
L-Valine	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Trace mineral premix[5]	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Vitamin premix[6]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Vitamin E (20000 IU)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Choline chloride	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Phytase	-	-	-	-	-	-	0.08	0.08	0.08	0.08	0.08	0.08
Zinc oxide	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Selenium premix	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Calculated composition												
Standardized ileal digestible AA, %												
Lysine	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Isoleucine:Lysine	57	57	57	57	57	57	57	57	57	57	57	57

Leucine:Lysine	111	111	110	110	110	110	111	111	111	110	110	110
Methionine:Lysine	38	38	38	38	38	38	38	38	38	38	38	38
Methionine & Cystine:Lysine	58	58	58	58	58	58	58	58	58	58	58	58
Threonine:Lysine	64	64	64	64	64	64	64	64	64	64	64	64
Tryptophan:Lysine	19	19	19	19	19	19	19	19	19	19	19	19
Valine:Lysine	71	71	71	71	71	71	71	71	71	71	71	71
Total Lysine, %	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53	1.53
CP, %	21.17	21.14	21.12	21.10	21.05	21.01	21.20	21.18	21.14	21.11	21.06	21.02
Net energy, MJ/kg	10.76	10.76	10.76	10.76	10.76	10.76	10.76	10.76	10.76	10.76	10.76	10.76
Analyzed composition												
DM, %	92.00	91.71	92.13	91.85	91.58	92.02	91.37	91.56	91.82	91.63	91.93	91.94
CP, %	21.30	22.20	21.40	21.70	21.10	21.80	22.40	22.40	20.40	20.90	21.10	21.00
Ca[7], %	0.70	0.78	0.83	0.84	0.95	1.02	0.61	0.69	0.75	0.88	0.88	0.98
P[7], %	0.58	0.64	0.69	0.73	0.81	0.90	0.48	0.54	0.61	0.73	0.75	0.86
Phytase, FYT/kg	-	-	-	-	-	-	1796	1782	1574	1488	1364	2002

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[1] Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ); FYT/kg = phytase unit.

[2] STTD = standardized total tract digestible.

[3] The NRC (2012) requirement estimate for nursery pigs from 5 to 7 kg, expressed as a percentage of the diet, is 0.45% STTD P. Therefore, treatment concentrations represented 80, 90, 100, 110, 125, 140, 155, and 170% of the NRC (2012) requirement.

[4] Enzymatically treated soy product (Hamlet Protein, Inc., Findlay, OH).

[5] Provided per kg of diet: 26.6 mg Mn from manganese oxide, 93.6 mg Fe from iron sulfate, 100.8 mg Zn from zinc sulfate, 14.4 mg Cu from copper sulfate, 1.44 mg I from calcium iodate.

[6] Provided per kg of diet: 14330 IU vitamin A, 2205 IU vitamin D_3, 53 IU vitamin E, 400.8 mg vitamin K, 7.7 mg riboflavin, 33.1 mg pantothenic acid, 55.1 mg niacin, 0.04 mg vitamin B_{12}, 2.2 mg folic acid, 0.022 mg thiamin, 0.022 mg pyridoxine, and 0.002 mg biotin.

[7] Averaged across analyzed values from Ward Laboratories, Inc. (Kearney, NE), Cumberland Valley Analytical Services Inc. (Maugansville, MD), and Midwest Laboratories (Omaha, NE).

Table 3.4. Diet formulation, phases 2 and 3 (day 11 to 25 and day 25 to 46, respectively; as-fed basis)

	Phase 2												Phase 3
Phytase[1]	0 FYT/kg diet						2000 FYT/kg diet						
STTD[2] P, % of NRC[3]	80	90	100	110	125	140	100	110	125	140	155	170	
Ingredients, %													
Corn	53.71	53.26	52.75	52.31	51.60	50.90	54.53	54.03	53.34	52.63	51.92	51.22	61.32
Soybean meal	28.29	28.32	28.36	28.39	28.44	28.49	28.23	28.27	28.31	28.37	28.42	28.47	33.07
HP 300[4]	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	3.75	-
Dried whey	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	-
Beef tallow	1.00	1.15	1.35	1.50	1.75	2.00	0.70	0.90	1.15	1.40	1.65	1.90	1.00
Monocalcium P (21% P)	0.53	0.75	0.97	1.19	1.53	1.86	0.10	0.32	0.65	0.98	1.32	1.65	1.65
Limestone	0.81	0.86	0.91	0.95	1.02	1.09	0.70	0.74	0.81	0.88	0.95	1.02	1.08
Salt	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
L-Lysine HCl	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
DL-Methionine	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.18
L-Threonine	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.18
L-Tryptophan	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
L-Valine	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09
Trace mineral premix[5]	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Vitamin premix[6]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Phytase	-	-	-	-	-	-	0.08	0.08	0.08	0.08	0.08	0.08	-
Zinc oxide	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Selenium premix	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Calculated composition													
Standardized ileal digestible AA, %													
Lysine	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.35	1.30
Isoleucine:Lysine	60	60	60	60	60	60	60	60	60	60	60	60	59
Leucine:Lysine	118	118	118	118	117	117	119	119	118	118	118	117	120

Methionine:Lysine	37	36	36	36	36	36	37	37	36	36	36	36	35
Methionine & Cystine:Lysine	58	58	58	58	58	58	58	58	58	58	58	58	58
Threonine:Lysine	64	64	64	64	64	64	64	64	64	64	64	64	64
Tryptophan:Lysine	19	19	19	19	19	19	19	19	19	19	19	19	19
Valine:Lysine	71	71	71	71	71	71	71	71	71	71	71	71	71
Total Lysine, %	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.45
CP, %	21.89	21.86	21.84	21.82	21.78	21.75	21.93	21.90	21.87	21.83	21.80	21.76	21.52
Net energy, MJ/kg	10.41	10.41	10.41	10.41	10.41	10.41	10.41	10.41	10.41	10.41	10.41	10.41	10.41
Analyzed composition													
DM, %	90.12	90.73	91.15	91.35	91.49	90.64	91.38	91.15	90.86	90.99	91.30	90.76	90.27
CP, %	21.60	22.10	21.70	21.90	22.10	21.30	22.90	21.90	22.50	22.10	22.30	23.00	22.00
Ca[7], %	0.83	0.93	0.90	0.83	1.00	0.95	0.63	0.65	0.73	0.87	0.82	1.03	0.91
P[7], %	0.54	0.59	0.65	0.70	0.76	0.80	0.46	0.53	0.58	0.66	0.70	0.90	0.74
Phytase, FYT/kg	-	-	-	-	-	-	2394	2081	1785	2026	2000	2342	-

[1] Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ); FYT/kg = phytase unit.

[2] STTD = standardized total tract digestible.

[3] The NRC (2012) requirement estimate for nursery pigs from 7 to 11 kg, expressed as a percentage of the diet, is 0.40% STTD P. Therefore, treatment concentrations represented 80, 90, 100, 110, 125, 140, 155, and 170% of the NRC (2012) requirement.

[4] Enzymatically treated soy product (Hamlet Protein, Inc., Findlay, OH).

[5] Provided per kg of diet: 26.6 mg Mn from manganese oxide, 93.6 mg Fe from iron sulfate, 100.8 mg Zn from zinc sulfate, 14.4 mg Cu from copper sulfate, 1.44 mg I from calcium iodate.

[6] Provided per kg of diet: 14330 IU vitamin A, 2205 IU vitamin D_3, 53 IU vitamin E, 400.8 mg vitamin K, 7.7 mg riboflavin, 33.1 mg pantothenic acid, 55.1 mg niacin, 0.04 mg vitamin B_{12}, 2.2 mg folic acid, 0.022 mg thiamin, 0.022 mg pyridoxine, and 0.002 mg biotin.

[7] Averaged across analyzed values from Ward Laboratories, Inc. (Kearney, NE), Cumberland Valley Analytical Services Inc. (Maugansville, MD), and Midwest Laboratories (Omaha, NE).

Table 3.5. Effects of standardized total tract digestible (STTD) P and phytase on growth performance and percentage bone ash[1]

	BW, kg			Treatment (day 0 to 25)			Post-treatment (day 25 to 46)			Bone ash, g	Bone ash, %
	day 0	day 25	day 46	ADG, g	ADFI, g	G:F, g/kg	ADG, g	ADFI, g	G:F, g/kg		
P level with 0 FYT/kg phytase[2]											
80%	5.9	11.9	26.5	239	339	704	700	1066	657	1.66	42.9
90%	5.9	12.5	27.3	263	361	727	709	1073	662	1.78	44.4
100%	5.9	12.6	27.7	267	354	752	726	1096	662	2.05	45.4
110%	5.9	12.6	27.6	270	362	746	714	1099	650	2.02	46.9
125%	5.9	12.5	27.3	263	348	755	707	1075	658	2.40	49.0
140%	5.9	12.6	27.6	265	345	769	720	1093	659	2.44	48.8
P level with 2000 FYT/kg phytase[2]											
100%	5.9	13.2	27.6	286	376	762	691	1065	649	1.80	45.6
110%	5.9	13.3	27.2	297	383	777	662	1033	640	1.94	46.1
125%	5.9	13.3	27.7	296	376	785	681	1061	642	2.31	48.6
140%	5.9	13.5	27.9	305	384	796	686	1058	648	2.25	49.7
155%	5.9	13.4	27.9	301	384	786	689	1077	640	2.58	50.5
170%	5.9	13.2	28.0	291	370	786	705	1090	647	2.39	50.4
SEM	0.17	0.49	0.83	14.0	14.3	11.6	18.6	34.8	7.7	0.141	0.95
Source of variation,[3] $P <$											
Phytase	0.16	0.01	0.81	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.99
0 FYT/kg phytase											
P, linear	0.12	0.02	0.10	0.02	0.82	0.01	0.49	0.37	0.83	0.01	0.01
P, quadratic	0.44	0.02	0.15	0.01	0.04	0.06	0.58	0.42	0.77	0.49	0.20
2000 FYT/kg phytase											
P, linear	0.21	0.69	0.21	0.45	0.72	0.01	0.16	0.08	1.00	0.01	0.01
P, quadratic	0.43	0.08	0.96	0.03	0.26	0.07	0.30	0.35	0.65	0.02	0.11

ADG = average daily gain; ADFI = average daily feed intake; G:F = gain:feed ratio; FYT/kg = phytase unit.

[1] A total of 1080 barrows and gilts (PIC 280 × 1050, Hendersonville, TN) with initial body weight of 5.9 ± 1.08 kg were used in a 46-d trial with 10 pigs per pen and 9 replications (pen) per treatment to determine the effects of increasing STTD P concentrations in diets without and with phytase on growth performance and percentage bone ash.

[2] Dietary STTD P levels expressed as percentage of NRC (2012) requirement estimates.

[3] Phytase effect and P × phytase interaction were analyzed in a 2 × 4 factorial with the main effects of P (100, 110, 125, or 140%) and phytase (0 or 2000 FYT/kg). No P × phytase interaction was observed for any response criteria ($P > 0.22$) except for ADG of treatment period ($P = 0.08$), whereby ADG was increased (linear, $P < 0.05$) by increasing STTD P in diets containing phytase, but not in diets without phytase.

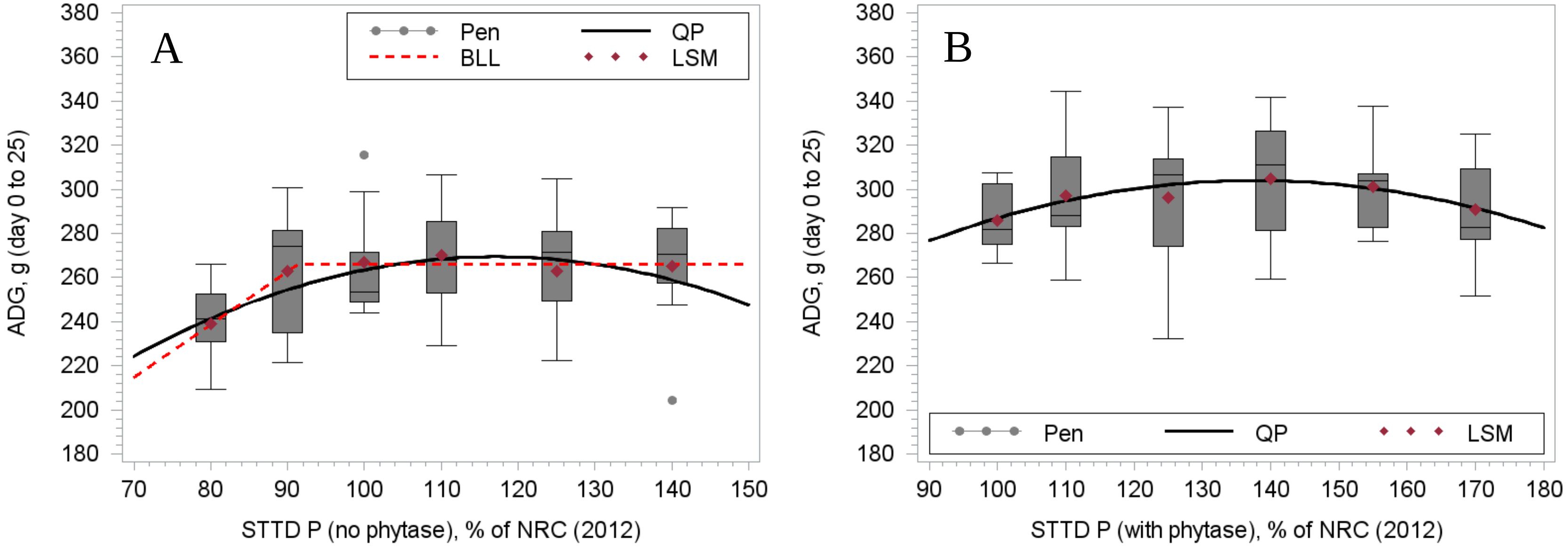

Figure 3.1. A total of 1080 barrows and gilts with initial body weight of 5.9 ± 1.08 kg were used in a 46-d trial to determine the effects of increasing standardized total tract digestible (STTD) P concentrations in diets without and with phytase on growth performance. Fitted regression models on day 0 to 25 average daily gain (ADG) as a function of increasing STTD P as percentage of NRC (2012) requirement estimate (% of NRC) in 6- to 13-kg pigs fed diets containing 0 (A) or 2000 (B) units of phytase. A. The quadratic polynomial model (QP; BIC = 481.7) estimated the maximum mean ADG at 117% (95% CI: [86, >140%]) of NRC, with 99% of maximum ADG achieved at 106% of NRC; the estimated QP regression equation was: ADG, g = -8.45 + 4.74 × (STTD P, % of NRC) - 0.02 × (STTD P, % of NRC)^2. The broken-line linear (BLL; BIC = 479.0) plateau was estimated at 91% (95% CI: [76, 107%]) of NRC. B. The QP model (BIC = 470.1) estimated the maximum mean ADG at 138% (95% CI: [110, >170%]) of NRC, with 99% of maximum ADG achieved at 122% of NRC; the estimated QP regression equation was: ADG, g = 76.18 + 3.31 × (STTD P, % of NRC) - 0.012 × (STTD P, % of NRC)^2. The LSM represents least square means.

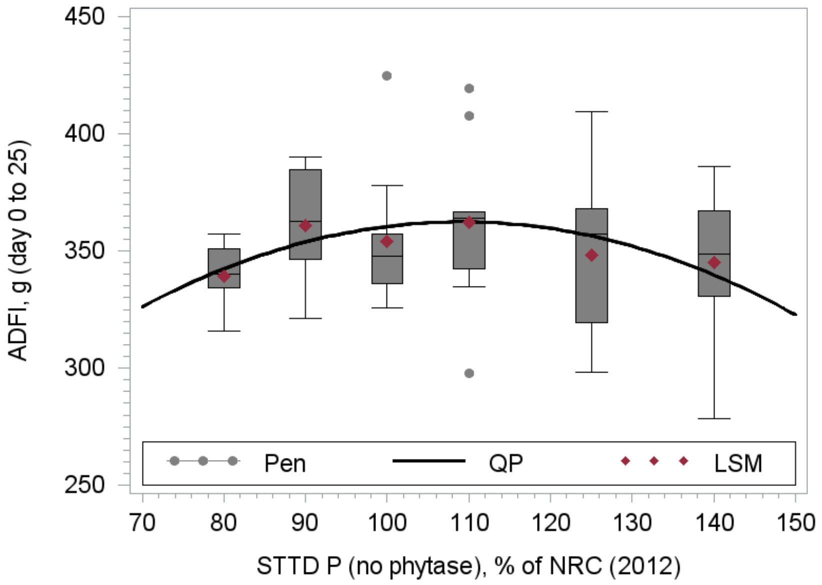

Figure 3.2. A total of 1080 barrows and gilts with initial body weight of 5.9 ± 1.08 kg were used in a 46-d trial to determine the effects of increasing standardized total tract digestible (STTD) P concentrations in diets without and with phytase on growth performance. Fitted quadratic polynomial (QP; BIC = 502.2) regression models on day 0 to 25 average daily feed intake (ADFI) as a function of increasing STTD P as percentage of NRC (2012) requirement estimate (% of NRC) in 6- to 13-kg pigs fed diets without phytase. The QP model estimated the maximum mean ADFI at 109% (95% CI: [80, 140%]) of NRC, with 99% of maximum ADFI achieved at 97% of NRC; the estimated QP regression equation was: ADFI, g = 80.91 + 5.16 × (STTD P, % of NRC) - 0.024 × (STTD P, % of NRC)^2. The LSM represents least square means.

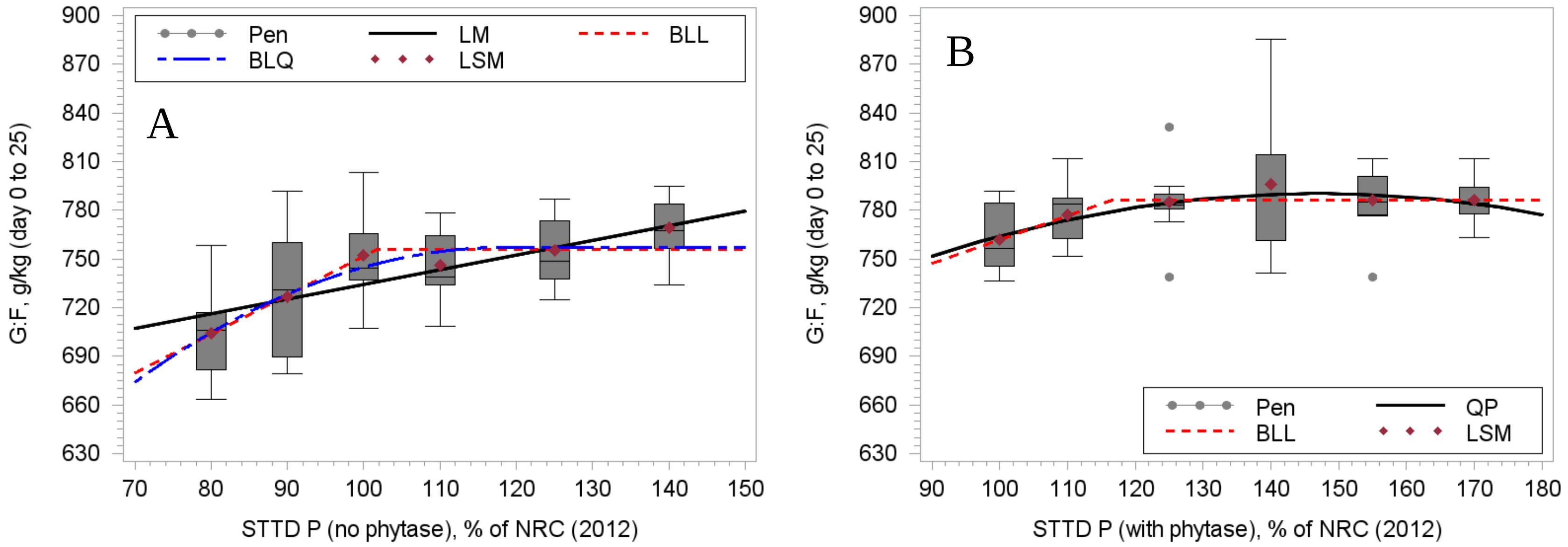

Figure 3.3. A total of 1080 barrows and gilts with initial body weight of 5.9 ± 1.08 kg were used in a 46-d trial to determine the effects of increasing standardized total tract digestible (STTD) P concentrations in diets without and with phytase on growth performance. Fitted regression models on day 0 to 25 gain:feed ratio (G:F) as a function of increasing STTD P as percentage of NRC (2012) requirement estimate (% of NRC) in 6- to 13-kg pigs fed diets containing 0 (A) or 2000 (B) units of phytase. A. The linear model (LM; BIC = 505.2) estimated the maximum mean G:F at greater than 140% of NRC; the estimated LM regression equation was: G:F, g/kg = 644.57 + 0.90 × (STTD P, % of NRC). The broken-line linear (BLL; BIC = 503.3) plateau was estimated at 102% (95% CI: [85, 118%]) of NRC. The broken-line quadratic (BLQ; BIC = 504.5) plateau was estimated at 119% (95% CI: [24, 213%]) of NRC. B. The QP model (BIC = 489.8) estimated the maximum mean G:F at 147% (95% CI: [120, >170%]) of NRC, with 99% of maximum G:F achieved at 122% of NRC; the estimated QP regression equation was: G:F, g/kg = 534.32 + 3.48 × (STTD P, % of NRC) - 0.012 × (STTD P, % of NRC)^2. The BLL (BIC = 489.2) plateau was estimated at 116% (95% CI: [85, 148%]) of NRC. The LSM represents least square means.

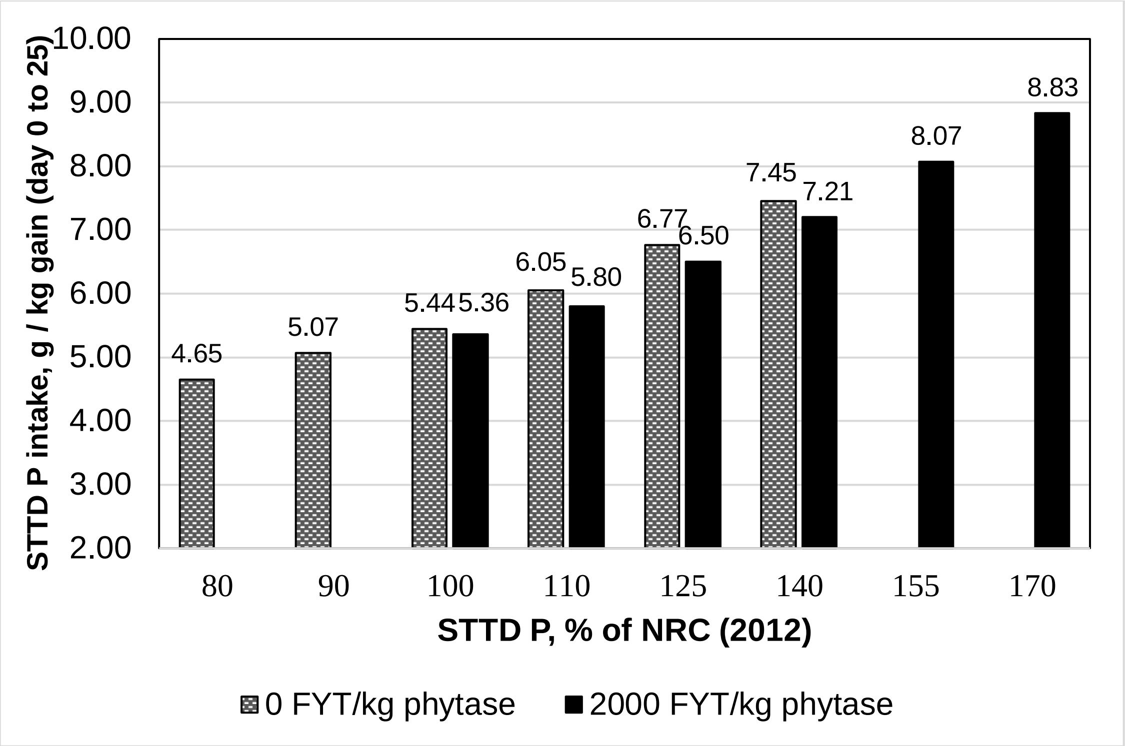

Figure 3.4. Effects of standardized total tract digestible (STTD) P and 2000 phytase unit (FYT/kg) of Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ) on STTD P intake (g) per kg gain during treatment period (day 0 to 25). Phytase main effect [analyzed in a 2 × 4 factorial with the main effects of P (100, 110, 125, or 140%) and phytase (0 or 2000 FYT/kg)], $P < 0.01$; STTD P effect (0 FYT/kg phytase): linear $P < 0.01$, quadratic $P = 0.38$; STTD P effect (2000 FYT/kg phytase): linear $P < 0.01$, quadratic $P = 0.16$.

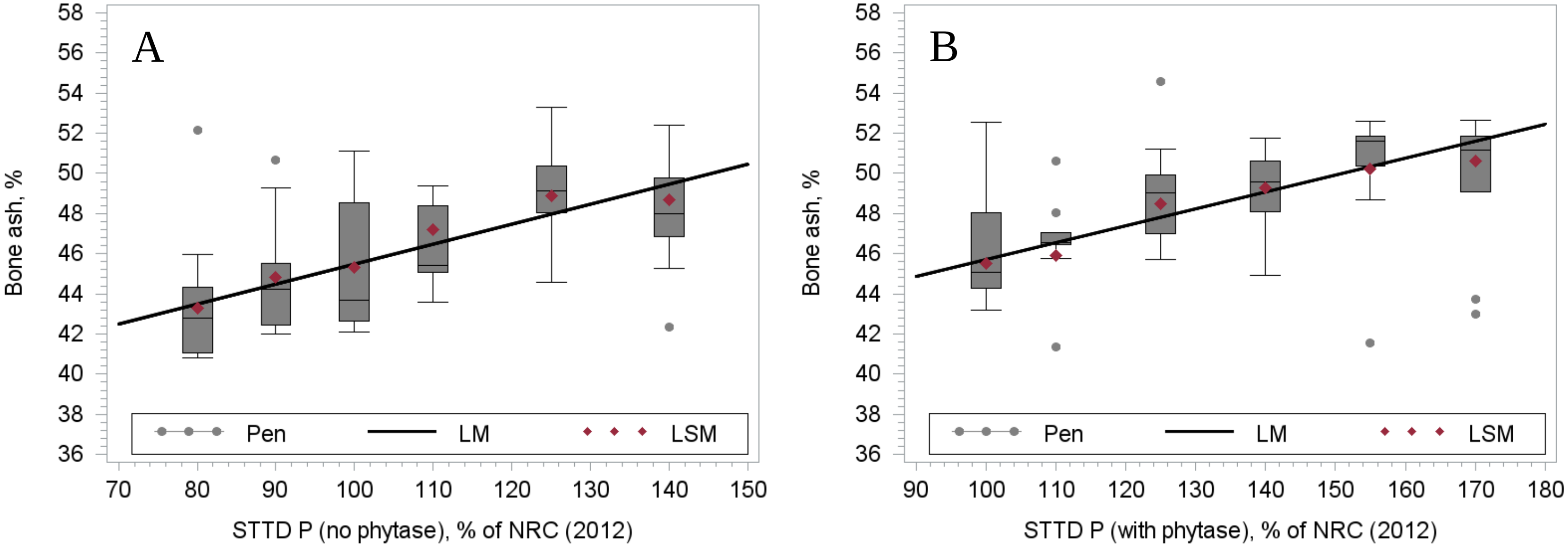

Figure 3.5. A total of 1080 barrows and gilts with initial body weight of 5.9 ± 1.08 kg were used in a 46-d trial to determine the effects of increasing standardized total tract digestible (STTD) P concentrations in diets without and with phytase on percentage bone ash. Fitted regression models on percentage bone ash as a function of increasing STTD P as percentage of NRC (2012) requirement estimate (% of NRC) in 6- to 13-kg pigs fed diets containing 0 (A) or 2000 (B) units of phytase. A. The linear model (LM; BIC = 264.3) estimated the maximum mean percentage bone ash at greater than 140% of NRC; the estimated LM regression equation was: bone ash, % = 28.79 + 0.095 × (STTD P, % of NRC) + 0.56 × (BW, kg). B. The LM model (BIC = 257.6) estimated the maximum mean percentage bone ash at greater than 170%; the estimated LM regression equation was: bone ash, % = 32.27 + 0.084 × (STTD P, % of NRC) + 0.37 × (BW, kg). The LSM represents least square means.

Chapter 4 - Effects of tylosin administration routes on the prevalence of antimicrobial resistance among fecal enterococci of finishing swine[1]

Abstract

Antibiotics can be administered orally or parenterally in swine production, which may influence antimicrobial resistance (AMR) development in gut bacteria. A total of 40 barrows and 40 gilts were used to determine the effects of tylosin administration route on growth performance and fecal enterococcal AMR. The antibiotic treatments followed FDA label directions and were: 1) no antibiotic (CON), 2) 110 mg tylosin per kg feed for 21 days (IN-FEED), 3) 8.82 mg tylosin per kg BW through intramuscular injection twice daily for the first 3 d of each week for 3 weeks (IM), and 4) 66 mg tylosin per liter of drinking water (IN-WATER). Antibiotics were administered during d 0 to 21 and all pigs were then fed the CON diet from d 21 to 35. Fecal samples were collected on d 0, 21, and 35. Antimicrobial susceptibility was determined by microbroth dilution method. No evidence of route × sex interaction ($P > 0.55$) was observed for growth performance. From d 0 to 21, pigs receiving CON and IN-FEED had greater ($P < 0.05$) average daily gain (ADG) than those receiving IM, with the IN-WATER group showing intermediate ADG. Pigs receiving CON had greater ($P < 0.05$) gain to feed ratio (G: F) than IM and IN-WATER, but were not different from pigs receiving IN-FEED. Overall, enterococcal isolates collected from pigs receiving IN-FEED or IM were more resistant ($P < 0.05$) to erythromycin and tylosin than CON and IN-WATER groups. Regardless of administration route,

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[1] This work has been accepted for publication in *Foodborne pathogens and disease*: F. Wu, M. D. Tokach, J. M. DeRouchey, S. S. Dritz, J. C. Woodworth, R. D. Goodband, K. Chitakasempornkul, N. M. Bello, K. Capps, S. Remfry, T. G. Nagaraja, and R. G. Amachawadi. 2019. Effects of Tylosin administration routes on the development of antimicrobial resistance in fecal enterococci of finishing swine. Foodborne Pathog. Dis. doi:10.1089/fpd.2018.2551.

the estimated probability of AMR to these 2 antibiotics was greater on d 21 and 35 than d 0. In summary, IM tylosin decreased ADG and G:F in finishing pigs, which may be due to a response to the handling during injection administration. Tylosin administration via injection and feed resulted in greater probability of enterococcal AMR to erythromycin and tylosin compared with in-water treatment.

Keywords: administration route, antimicrobial resistance, fecal enterococci, finishing pig, growth performance, tylosin.

Introduction

In the swine industry, antimicrobial feed additives have traditionally been used to prevent enteric infections, promote growth, and improve production efficiency (Muhl and Liebert, 2007). However, the continued expansion of antimicrobial resistance (**AMR**) among commensal and pathogenic bacteria constitutes a major public health concern. Therefore, in swine production systems, there is considerable interest and effort in identifying feeding and management practices that maintain and improve production efficiency without promoting AMR in bacteria.

Antibiotics are administered either in-feed, in-water, or parenterally. The oral route, through either feed or water, is by far the most common route of administration of antibiotics in pigs (Callens *et al.*, 2012; Merle *et al.*, 2012). Oral administration is more convenient when treating a large number of pigs compared with individual treatment through the injectable route. Nevertheless, oral administration exposes gut bacteria directly to high concentrations of antibiotics and thus has been hypothesized to have a greater potential in promoting the emergence and amplification of AMR in the gut. A study using a mouse model suggests that oral administration of antibiotics has a greater impact on promoting and amplifying AMR in gut microbiota compared with intravenous injection (Zhang *et al.*, 2013). However, to our knowledge, no study has been conducted to compare the impacts of oral administration of antibiotics through feed or water versus injectable administration on the development of AMR among gut bacteria in pigs.

Tylosin is used to treat or prevent swine dysentery, and other bacterial infections, including arthritis, ileitis, and erysipelas in swine (Dritz et al., 2002). Tylosin was selected as the antibiotic treatment because of its widespread use in the U.S. swine industry and its varying formulations that can be administered through different routes. The use of tylosin in swine production is ubiquitous. The understanding of how the oral route of administration affects resistance selection in the gut is fundamental to our use of this drug in swine production, and the way to evaluate the effect is to compare it to other routes. Therefore, the objective of this study was to determine the effects of tylosin administration route on the growth performance and the development of AMR in fecal enterococci of finishing pigs.

Materials and Methods

All experimental procedures in this study were approved by the Kansas State University Institutional Animal Care and Use Committee (IACUC # 3529.10; Manhattan, KS).

Animals and housing

The study was conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. Pigs were housed in an environmentally controlled barn with completely slatted concrete floor. Each pen (1.52 m × 1.52 m) was equipped with a single-hole stainless steel feeder and a cup waterer for *ad libitum* access to feed and water. Each drinker was equipped with an individual water reservoir allowing for independent water treatment. Each 2 pens (1 barrow pen and 1 gilt pen sharing the same treatment) were segregated by solid pen dividers to minimize nasal contact and manure cross-contamination among pigs from different treatment groups; the combination of these 2 pens served as the experimental unit. A total of 40 barrows and 40 gilts (Line 600 × 241; DNA, Columbus, NE) were individually housed and used in a 35-d trial. Pigs were individually weighed, blocked by initial body weight (93.9 ± 3.57 kg), sex, and barn location, and assigned to pens 17 d prior to the start of the experiment. Early allotment was done in order to avoid pig movement across pens on d 0 and minimize cross-contamination for fecal sample collection. Pigs were weighed and feed disappearance was recorded on d 0, 21, and 35 to determine average daily gain (**ADG**), average daily feed intake (**ADFI**), and gain: feed ratio (**G:F**). The water reservoir was weighed and refilled twice daily to determine daily water consumption for each pig.

Diets and experimental design

On d 0, immediately following fecal collection, experimental treatments were assigned to the animals. The antibiotic treatments followed Food and Drug Administration (FDA) label directions for swine dysentery control and were: 1) a corn-soybean meal-based diet (Table 4.1) with no antibiotic (**CON**), 2) a basal diet with 110 mg tylosin (Tylan®100; Elanco Animal Health, Indianapolis, IN) per kg feed for 21 d (**IN-FEED**), 3) an average target dose of 8.82 mg tylosin (Tylan®200; Elanco Animal Health, Indianapolis, IN) per kg body weight through intramuscular injection twice daily for the first 3 d of each week during the 3-week treatment period (**IM**), and 4) 66 mg tylosin (Tylan®Soluble; Elanco Animal Health, Indianapolis, IN) per liter of drinking water for the first 3 d of each week during the 3-week treatment period (**IN-WATER**). Antibiotic treatments were terminated on d 21 and all pigs were fed the CON diet from d 21 to 35.

Complete diet samples were obtained at manufacture and delivered to the Kansas State University Swine Laboratory, Manhattan, KS, and stored at -20°C until analysis. Feed samples were analyzed for dry matter, crude protein, ether extract, calcium, and phosphorous at Ward Laboratories, Inc. (Kearney, NE). Standard procedures from AOAC (2006) were followed for analysis of moisture (Method 934.01), crude protein (Method 990.03), ether extract (Method 920.39), calcium and phosphorous (Method 985.01).

Fecal sample collection

Fecal samples from each pig were collected into individual Whirl-Pak® bags (Nasco, Ft. Atkinson, WI) on d 0 (baseline), 21 (end of treatment period), and 35 (end of post-treatment period). Samples were transported on ice to the laboratory at Kansas State University (Manhattan, KS) and stored at 4°C prior to processing within 24 h.

Bacterial isolation, identification, and PCR detection of *erm*(B) gene

For bacterial isolation, approximately 1 g of feces from each sample was suspended in 9 mL of phosphate buffer saline. Fifty µl of the fecal suspension were then spread-plated onto M-*Enterococcus* agar plates for the selective isolation of *Enterococcus* spp. from each fecal sample. Unless otherwise specified, all the culture media were obtained from Difco (Becton-Dickinson and Company, Sparks, MD). M-*Enterococcus* plates were incubated at 42°C for 24 to 36 h. Two putative colonies (pin-point red, pink, or metallic red) were selected from each M-*Enterococcus* agar; next, each was individually streaked onto a blood agar plate (Remel, Lenexa, KS) and incubated at 37°C for 24 h. Preliminary genus confirmation of each of the enterococcal isolates was performed by esculin hydrolysis. Two confirmed *Enterococcus* isolates per original fecal sample were preserved using cryo-protect beads (Cryocare; Key Scientific Products, Round Rock, TX) and stored at -80°C for future use.

DNA was extracted from enterococcal isolates by suspending a single colony from the blood agar plate in nuclease-free water with Chelex® 100 Resin (Bio-Rad Laboratories, Hercules, CA) and boiling for 10 min. Species identification was carried out to identify *E. faecium* and *E. faecalis* using multiplex polymerase chain reaction (Jackson et al., 2004). *E. faecium* ATCC19434 and *E. faecalis* ATCC29212 (American Type Culture Collection, Manassas, VA) isolates served as reference strains for speciation. The primer and PCR condition for detection of *erm*(B) gene was as per Amachawadi et al. (2010). *Enterococcus faecium* BAA-2127 strain served as positive control for detection of *erm*(B) gene. The primers were supplied by Integrated DNA Technologies (IDT, Coralville, IA).

Antimicrobial susceptibility testing

Antimicrobial susceptibility testing, as outlined by the Clinical and Laboratory Standards Institute (2018), was performed on one of the two stored isolates per fecal sample to determine the minimal inhibitory concentrations to each of 16 antimicrobials using the Sensititre® (TREK Diagnostic Systems, Oakwood Village, OH) micro-broth dilution procedure. The enterococcal isolate preserved in cryo-protect beads was streaked onto a blood agar plate and incubated at 37°C for 24 h. Individual colonies were selected and suspended in demineralized water (TREK Diagnostic Systems) and turbidity was adjusted to 0.5 McFarland turbidity standards. Then, 10 μL of the bacterial inoculum was added to cation-adjusted Mueller–Hinton broth and vortexed.

The Sensititre® automated inoculation delivery system (TREK Diagnostic Systems) was used to dispense 100 μL of the broth into National Antimicrobial Resistance Monitoring System panel plates (CMV3AGPF; TREK Diagnostic Systems) designed for Gram-positive bacteria. A table of resistance breakpoints and evaluated concentrations for antimicrobials of National Antimicrobial Resistance Monitoring System panel was presented in a previous study (Feldpausch *et al.*, 2016). *Enterococcus faecalis* ATCC 29212 (American Type Culture Collection, Manassas, VA) strain was included as the quality control for the susceptibility testing. Plates were incubated at 37°C for 18 h and then bacterial growth was assessed using Sensititre® ARIS and Vizion® systems (TREK Diagnostic Systems). Clinical and Laboratory Standards Institute (CLSI, 2018) guidelines were used to classify each bacterial isolate as resistant or nonresistant (intermediate and susceptible) according to the breakpoints established for each antimicrobial.

Statistical analysis

Responses on growth performance, water intake, and tylosin intake were measured at the pen (pig) level and were analyzed using general linear mixed models. The linear predictors included the fixed effects of tylosin administration route (CON, IN-FEED, IM, and IN-WATER), sex (gilt and barrow), and their interaction. The model also included the random effects of block and block × route cross-product. The latter random effect specified the pair of pens with 1 barrow pen and 1 gilt pen sharing the same treatment as the level of replication for tylosin administration route. Residual assumptions were checked using Studentized residuals.

For AMR data, frequency tables of resistant and nonresistant isolates for each antibiotic were initially evaluated. For gentamicin, kanamycin, streptomycin and vancomycin, none of the fecal isolates were categorized as resistant and thus no further statistical analyses were performed for these antibiotics. For each remaining antibiotic, frequency tables on resistant and non-resistant isolates were further evaluated by tylosin administration route, sampling day, and their combination. These tables were used to identify potential extreme category problems during model fitting. Subcategories with all resistant or nonresistant isolates or frequencies close to these extremes can lead to model fitting problems due to quasi-complete separation of data points, also known as extreme category problem.

For each antibiotic, the probability of AMR was estimated using a generalized linear mixed model with a Bernoulli distribution on the AMR responses and a logit link function. The linear predictor included the fixed effects of tylosin administration route, sex, sampling day, enterococcal species, and their interactions, as well as the random blocking effect and its cross-products with tylosin administration route and with gender to identify the proper level of replication for each fixed effect factor. Due to the presence of extreme category problems, it was not possible to fit the 3-way interaction for chloramphenicol, linezolid, nitrofurantoin, penicillin, quinupristin/dalfopristin, tigecycline, ciprofloxacin, daptomycin, erythromycin, lincomycin, tetracycline and tylosin. For similar reasons, it was also not possible to fit 2-way interactions between administration route and sampling day for linezolid, nitrofurantoin, penicillin, quinupristin/dalfopristin, and tigecycline, as well as any interaction involving sex for ciprofloxacin, daptomycin, erythromycin, lincomycin, tetracycline, and tylosin. Overdispersion was assessed using the maximum-likelihood-based fit statistic Pearson Chi-Square over degree of freedom. In all cases, final models used for inference showed no evidence for overdispersion.

Pairwise comparisons were conducted using a Tukey-Kramer or Bonferroni adjustment, as appropriate in each case. Statistical models were fit using the GLIMMIX procedure of SAS (Version 9.4; SAS Inst. Inc., Cary, NC). In all cases, the final model used for inference was fit using residual (pseudo-) likelihood implemented with a Newton-Raphson optimization with ridging. Least square mean estimates of growth responses and of probability of AMR are presented, along with corresponding SEM or 95% confidence intervals. Results were considered significant at $P \leqslant 0.05$, and marginally significant with at $0.05 < P \leqslant 0.10$.

Results

Growth performance

No evidence of route × sex interaction ($P > 0.55$) was observed for any of the growth responses during treatment, post-treatment, or overall periods (Table 4.2). During the treatment period (d 0 to 21), the main effect of administration route marginally contributed to ADG response ($P = 0.098$). Pigs that received CON and IN-FEED had greater ($P < 0.05$) ADG than those receiving IM tylosin, with IN-WATER pigs showing intermediate ADG. For the main effect of sex, barrows grew marginally faster ($P = 0.094$) than gilts during the treatment period regardless of tylosin administration route. Average daily feed intake was greater ($P = 0.031$) in barrows than in gilts, but there was no evidence for any effect of tylosin administration route on ADFI ($P = 0.219$). Overall, there was no evidence of any effect of IN-FEED tylosin on G:F relative to CON pigs. In contrast, administration of tylosin through IM or IN-WATER decreased G:F ($P < 0.05$) compared with pigs from CON. No evidence of sex effect was observed for G:F during the treatment period. During the post-treatment period (d 21 to 35), no evidence for any effects of administration route or sex was observed for any growth responses ($P > 0.26$). Overall (d 0 to 35), there was no evidence that growth performance was influenced by the tylosin administration route; barrows had marginally greater ($P = 0.068$) ADFI than gilts but no evidence of differences in ADG or G:F were observed.

Concerning average daily water intake, there was no evidence (*P* > 0.10) for any effects of tylosin administration route or sex (Table 4.2). Among the medicated pigs, total tylosin dose administrated per pig was the greatest through IM, second highest through IN-FEED, with the IN-WATER route being the lowest (*P* < 0.01).

Prevalence of fecal enterococci and *erm*(B) gene

A total of 480 enterococcal isolates consisting of 120 isolates per treatment group (control, feed, water and injectable) and sampling day (days 0, 7, 14, 21, 28, and 35) were obtained. Of these, a total of 292 (292/480; 60.8%) and 188 (188/480; 39.2%) isolates were *E. faecium* and *E. faecalis*. Both, treatment and sampling days did not affect the prevalence of either species significantly (*P* > 0.05). No evidence of route × day interaction or the main effect of administration route was observed for the prevalence of *erm*(B) gene among treatments (*P* > 0.54). The prevalence of *erm*(B) gene increased (*P* < 0.001) during the treatment period (22.7 and 59.6% on d 0 and 21, respectively) but then decreased (*P* < 0.001) to baseline level on d 35 (13.8%; Table 4.5).

Antimicrobial resistance

There was no evidence for any effects of either *E. faecium* and or *E. faecalis* on the antimicrobial susceptibilities of all antibiotics tested. Table 4.3 illustrates the estimated probability of AMR – among enterococcal isolates in response to tylosin administration route and sampling day – to antibiotics critically important to human medicine (WHO, 2012); namely, ciprofloxacin, daptomycin, erythromycin, gentamicin, kanamycin, linezolid, penicillin, streptomycin, tigecycline, tylosin, and vancomycin. No enterococcal isolates showed resistance to gentamicin, kanamycin, streptomycin, or vancomycin for the duration of the study. For ciprofloxacin, there was no evidence of interaction or main effects involving tylosin administration route, sex, or sampling day on AMR in the study period. For daptomycin, only the main effect of sampling day was evident on AMR ($P < 0.001$), whereby the probability of AMR decreased during the treatment period and increased thereafter regardless of administration route or sex. For erythromycin, no evidence of route × sampling day interaction was apparent; however, both main effects significantly ($P < 0.05$) contributed to explain AMR. Overall, the probability of AMR to erythromycin was marginally greater ($P < 0.10$) when pigs received tylosin via either IN-FEED or IM relative to IN-WATER, with that of CON pigs being intermediate. Moreover, the probability of AMR to erythromycin increased from d 0 to d 21 and d 35 regardless of tylosin administration route. For linezolid, penicillin, and tigecycline, there was no evidence for any effects of tylosin administration route, sex, or sampling day on AMR. For tylosin, the main effect of administration route marginally contributed to explain AMR ($P = 0.068$), whereby the probability of AMR to tylosin was greater ($P < 0.05$) in enterococcal isolates collected from pigs receiving tylosin via IN-FEED and IM (69 and 70% of isolates, respectively) compared with CON pigs and those receiving tylosin through IN-WATER (50 and 50%, respectively). The probability of AMR to tylosin increased ($P < 0.01$) from d 0 to d 21 and d 35.

Table 4.4 shows the estimated probability of AMR of enterococcal isolates to antibiotics considered highly important or important to human medicine; namely, chloramphenicol, quinupristin/dalfopristin, lincomycin, tetracycline and nitrofurantoin (WHO, 2012). *E. faecalis* is intrinsically resistant to quinupristin/dalfopristin (synercid), so we removed these isolates from the final analyses. There was no evidence for any effects of tylosin administration route, sex, and sampling day on AMR to chloramphenicol, lincomycin, or tetracycline. For quinupristin/dalfopristin susceptibility data among *E. faecium* isolates, we didn't find any evidence of tylosin administration route, sex, and sampling day (*P* > 0.05). For nitrofurantoin, only the main effect of sampling day significantly contributed to explain AMR (*P* = 0.002), whereby the probability of AMR to nitrofurantoin was not significantly modified during the treatment period but decreased (*P* < 0.01) thereafter (22, 27, and 2% on d 0, 21, and 35, respectively) regardless of sex or tylosin administration routes.

Discussion

In this study, we evaluated the effects of tylosin administration route on the growth performance and the selection and expansion of AMR among fecal enterococci of finishing pigs. Tylosin was selected as the antibiotic treatment because of its widespread use in the U.S. swine industry and its varying formulations that can be administered through different routes. It has been reported in studies (NCR-89 Committee on Confinement Management of Swine, 1986; Pilcher *et al.*, 2015) that feeding tylosin at a low dosage (44 or 22 ppm) promoted ADG and G:F of growing-finishing pigs. However, other studies (Lillie *et al.*, 1997; Dritz *et al.*, 2002; Van Lunen *et al.*, 2003) have suggested a lack of growth-promoting response of tylosin when fed to finishing pigs according to these regimens. In the present study, the tylosin in-feed regimen was approved for control of porcine proliferative enteropathies at 100 g/ton (110 mg/kg of feed). As of January 1, 2017, all indications for improved feed efficiency or rate of gain were removed from the labels of medically important antimicrobials used in food animals. At the label therapeutic dose used in this study, we did not observe any evidence for differences in growth performance among pigs fed tylosin-medicated feed and those with no antibiotic treatment. A potential reason for this observation is that pigs in the present study were individually housed and had approximately 15% greater ADFI and 20% greater ADG than the normally group-housed pigs of similar weight range and raised on the same research site. Moreover, the treatment period in the study was only 21 days, which is relatively a short duration to see differences in growth performance. In addition, the good hygienic condition of the university research environment may have also contributed to the lack of any observed growth response to this feed antibiotic due to lack of disease occurrence. Pigs from the IM group had decreased ADG and G:F than control pigs, which may be a result of pig reaction to the handling and injection procedure. However, it remains unclear why pigs offered medicated water were less feed efficient than control pigs.

Because tylosin has a significant Gram positive antibacterial spectrum component, fecal enterococci were chosen to evaluate the impact of administration route on AMR development. Enterococci are considered as major nosocomial pathogens and also as a reservoir of AMR genes (Jackson et al., 2004). Macrolide resistance in swine enterococci and its cross-resistance to erythromycin are thought to be due to tylosin use (Jackson et al., 2004). In enterococci, resistance to macrolides has been very well documented (Aarestrup et al., 2000). Evidence from earlier studies suggests that, *erm*(B) is most widely distributed macrolide resistance gene in piglets (Jackson et al., 2004; Patterson et al., 2007). Consistent with this spectrum, in this study that tylosin and erythromycin resistance were observed among enterococcal isolates and their prevalence was sensitive to tylosin administration route. Alteration in the efflux pumps that remove antibiotics from the cell or the modification of the bacterial target structure induces acquired resistance to macrolides, including tylosin and erythromycin (Roberts *et al.,* 1999). Acquisition and expansion of macrolide resistance among enterococci due to tylosin use in swine production has been well documented (Aarestrup *et al.*, 2000; Jackson *et al.*, 2004).

With regard to administration route, we initially hypothesized that oral administration would expose gut bacteria to higher concentrations of antibiotics and thus would promote greater expansion of AMR. Indeed, using a mouse model, Zhang *et al.* (2013) reported that when the same doses of tetracycline or ampicillin were administered, enrichment of corresponding AMR gene pools in gut microbiota were greater and faster via oral administration compared with intravenous injection. However, results from the present study suggest that IM or IN-FEED tylosin equally promote the development of enterococcal resistance to erythromycin and tylosin to a greater extent relative to oral water administration. Two readily identified reasons might explain this finding. The first is bile excretion of injected tylosin and its metabolites into the gastrointestinal tract of pigs that exerted selection pressure on gut bacteria. Both secretion from the liver into the gastrointestinal tract and urinary excretion of absorbed tylosin and the metobolite desmycosin have been reported (Worth, 1971; Wal and Bories, 1973). Secondly, the effects of administration route on the development of AMR in this study may be dose-dependent (Zhang *et al.,* 2013). The treatment dose and procedure administrated in each tested route followed the precise label regimen of the corresponding tylosin product formulation. Based on these dosages, pigs provided the WATER treatment received only 21 and 43% of the total tylosin doses administrated to those on the IM and FEED treatments, respectively (Table 4.2). However, label regimen for tylosin injection is not always followed in common practices, which results in a lower dose of tylosin intake. Future research is needed to verify the AMR response to lower dose of tylosin administration through IM. Moreover, a recent review by Pyörälä *et al.* (2014) suggested that applying macrolide antibiotics in feed or through injections creates long-acting concentrations of active substance in pigs, which may contribute to the expansion of AMR. The slow absorption and release of tylosin in injected pigs and the uninterrupted tylosin administration through feed may have created a continuous selection pressure on resistant bacteria in contrast to the lower dosage and intermittently administered tylosin treatment effected through water.

In addition, it was unexpected that no evidence of a route × day interaction was apparent for the development of resistance to tylosin and erythromycin. Given the significant main effects of sampling day and route, this would suggest an increase in the resistance between sampling days among enterococcal isolates collected from pigs that received no tylosin treatment. It is possible that resistant bacteria could have been transmitted from the tylosin-treated pigs to control pigs through fecal contamination; this, even though isolation measures were put in place between pens. Indirect physical contact of pigs via personnel movement across pens could also lead to cross-contamination of resistant bacteria. Remaining unexplained is the reason why resistance of enterococcal isolates to daptomycin decreased from baseline (d 0) to the end of the treatment period (d 21) and then increased back to baseline levels after 2 wk (d 35) of the wash-out period (Table 4.3).

Conclusions

In summary, we found no evidence that feeding tylosin promotes the growth performance of finishing pigs in the absence of the disease challenge for which it is labeled at the regimen administered in this study; in contrast, tylosin injection reduced ADG and G:F compared with untreated pigs. The likely reason for this is stress reaction to the injection and handling of pigs. Tylosin administration through injection and feed resulted in an increased probability of detecting resistance to erythromycin and tylosin among fecal enterococcal isolates compared with those collected from pigs that received either no or oral tylosin through the water. However, no evidence of selection of resistance to other antimicrobial groups was apparent in the population of pigs and enteric bacteria in this study.

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Tables

Table 4.1. Diet composition (as-fed basis)

	Non-medicated	Medicated
Corn	85.95	85.90
Soybean meal	11.91	11.91
Monocalcium P (21% P)	0.40	0.40
Limestone	0.90	0.90
Salt	0.35	0.35
L-Lysine-HCl	0.23	0.23
L-Threonine	0.06	0.06
Trace mineral premix*	0.10	0.10
Vitamin premix†	0.08	0.08
Phytase‡	0.02	0.02
Tylan 100§	-	0.05
Total	100.00	100.00
Calculated composition		
Standardized ileal digestible amino acid, %		
Lysine	0.65	0.65
Isoleucine:Lysine	65	65
Leucine:Lysine	169	169
Methionine:Lysine	31	31
Methionine & Cystine:Lysine	62	61
Threonine:Lysine	67	67
Tryptophan:Lysine	17	17
Valine:Lysine	77	77
Total Lysine, %	0.74	0.74
Crude protein, %	13.02	13.02
Net energy, kcal/kg	2,555	2,553
Calcium, %	0.45	0.45
Phosphorous, %	0.39	0.39
Digestible P with phytase, %	0.28	0.28
Analyzed composition, %		
Dry matter	89.69	89.60
Crude protein	12.80	12.65
Ether extract	2.75	2.25
Calcium	0.52	0.47
Phosphorous	0.35	0.31

* Provided per kilogram of diet: 27 mg Mn from manganese oxide, 110 mg Fe from iron

sulfate, 110 mg Zn from zinc sulfate, 11 mg Cu from copper sulfate, 0.20 mg I from calcium iodate, and 0.20 mg Se from sodium selenite.

† Provided per kilogram of diet: 4,409 IU vitamin A, 661 IU vitamin D3, 18 IU vitamin E, 1.8 mg vitamin K, 3.3 mg riboflavin, 11.0 mg pantothenic acid, 19.8 mg niacin, and 0.02 mg vitamin B_{12}.

‡ Ronozyme Hiphos 2700 (DSM Nutritional Products, Inc., Parsippany, NJ), providing 184.3 phytase units (FTU)/lb and an estimated release of 0.10% available P.

§ Elanco Animal Health (Indianapolis, IN).

Table 4.2. Effects of tylosin administration route and sex on growth performance of finisher pigs*

	Tylosin administration route†					Sex			*P* <		
	CON	IN-FEED	IM	IN-WATER	SEM	Barrow	Gilt	SEM	Route	Sex	Route × sex
Treatment (d 0 to 21)											
ADG, kg	1.26^{a}	1.26^{a}	1.15^{b}	1.22^{ab}	0.034	1.25	1.20	0.023	0.098	0.094	0.554
ADFI, kg	3.64	3.72	3.55	3.82	0.099	3.78	3.59	0.071	0.219	0.031	0.822
G:F	0.347^{a}	0.339^{ab}	0.324^{b}	0.322^{b}	0.0067	0.331	0.335	0.0046	0.041	0.606	0.652
Post-treatment (d 21 to 35)											
ADG, kg	1.20	1.21	1.16	1.17	0.033	1.19	1.18	0.024	0.601	0.844	0.987
ADFI, kg	3.74	3.69	3.53	3.67	0.087	3.70	3.61	0.067	0.292	0.269	0.879
G:F	0.322	0.330	0.327	0.322	0.0079	0.322	0.329	0.0060	0.844	0.381	0.750
Overall (d 0 to 35)											
ADG, kg	1.23	1.24	1.15	1.20	0.027	1.23	1.19	0.018	0.117	0.155	0.756
ADFI, kg	3.68	3.71	3.54	3.76	0.086	3.75	3.60	0.066	0.262	0.068	0.837
G:F	0.337	0.335	0.326	0.322	0.0057	0.328	0.332	0.0035	0.195	0.257	0.472
Water intake, L/d‡	6.14	6.45	6.87	6.06	0.287	6.56	6.20	0.241	0.179	0.310	0.566
Tylosin intake, g	-	8.61^{b}	18.00^{a}	3.69^{c}	0.148	10.20	10.01	0.123	0.001	0.262	0.425

* There were 40 barrows and 40 gilts (Line 600 Duroc × Line 241, DNA, Columbus, NE; initially 94 ± 3.6 kg) housed with 1 pig per pen and 10 replicate pens per treatment per sex.

† CON = pigs received no antibiotic; IN-FEED = pigs received 110 mg tylosin per kg feed for 21 d; IM = pigs received 8.82 mg tylosin per kg body weight through intramuscular injection twice daily for the first 3 d of each week during the 3-week treatment period; IN-WATER = 66 mg tylosin per liter of drinking water for the first 3 d of each week during treatment period.

‡ Measured during treatment period only.

^{abcd} Means with different superscripts within a row differ ($P < 0.05$).

ADG = Average Daily Gain; ADFI = Average Daily Feed Intake; G:F = Gain to Feed ratio ; SEM = Standard Error of Mean

Table 4.3. Effects of tylosin administration route and sampling day on the probability of antimicrobial resistance of fecal enterococci isolates to critically important antimicrobials*,§

Antibiotics and treatment period	Tylosin administration route†				Probability, *P* <		
	CON	IN-FEED	IM	IN-WATER	Route	Day	Route × day
Ciprofloxacin					0.318	0.904	0.986
Baseline (d 0)	10 [2, 33]‡	20 [8, 43]	20 [8, 43]	0 [.]			
Treatment (d 21)	10 [2, 33]	25 [11, 48]	20 [8, 43]	15 [5, 38]			
Post-treatment (d 35)	10 [2, 33]	25 [11, 48]	10 [2, 33]	15 [5, 38]			
Daptomycin					0.312	0.001	0.708
Baseline (d 0)	70 [47, 86]	55 [33, 75]	60 [38, 79]	40 [21, 62]			
Treatment (d 21)	40 [21, 62]	25 [11, 48]	25 [11, 48]	20 [8, 43]			
Post-treatment (d 35)	50 [29, 71]	40 [21, 62]	40 [21, 62]	55 [33, 75]			
Erythromycin					0.025	0.004	0.258
Baseline (d 0)	55 [33, 76]	65 [42, 83]	45 [24, 67]	35 [17, 58]			
Treatment (d 21)	50 [28, 71]	80 [57, 93]	95 [72, 99]	50 [28, 71]			
Post-treatment (d 35)	65 [42, 83]	80 [57, 93]	75 [51, 90]	70 [46, 87]			
Linezolid					0.688	0.942	-
Baseline (d 0)	0 [0]	20 [8, 42]	10 [2, 35]	0 [0]			
Treatment (d 21)	20 [7, 47]	10 [2, 35]	0 [0]	0 [0]			
Post-treatment (d 35)	15 [5, 37]	10 [3, 32]	10 [3, 32]	0 [0]			
Penicillin					0.697	0.187	-
Baseline (d 0)	5 [0.7, 27]	10 [2, 33]	0 [0]	0 [0]			
Treatment (d 21)	0 [0]	5 [0.7, 27]	0 [0]	0 [0]			
Post-treatment (d 35)	10 [2, 33]	10 [2, 33]	10 [2, 33]	0 [0]			
Tigecycline					0.279	0.832	-
Baseline (d 0)	85 [63, 95]	90 [68, 98]	95 [71, 99]	100			
Treatment (d 21)	90 [68, 98]	90 [68, 98]	100	95 [74, 99]			
Post-treatment (d 35)	90 [68, 98]	90 [68, 98]	100	85 [62, 95]			

Tylosin					0.068	0.001	0.233
Baseline (d 0)	45 [24, 68]	55 [32, 76]	30 [13, 54]	35 [17, 58]			
Treatment (d 21)	50 [28, 72]	75 [51, 90]	90 [67, 98]	50 [28, 72]			
Post-treatment (d 35)	55 [32, 76]	75 [51, 89]	75 [51, 89]	65 [41, 83]			

* Values represent the estimated probability of resistance among 20 enterococcal isolates per sampling day (d 0, 21, or 35); susceptibility was determined according to National Antimicrobial Resistance Monitoring System (CLSI, 2018; https://www.fda.gov/downloads/AnimalVeterinary/SafetyHealth/AntimicrobialResistance/NationalAntimicrobialResistanceMonitoringSystem/UCM581395.pdf) established breakpoints. One fecal sample was collected per pen per day and 1 enterococcal isolate per fecal sample was assessed. There was a total of 80 pigs (Line 600 × 241, DNA, Columbus, NE; initially 94 ± 3.6 kg) housed with 1 pig per pen and 10 replicates per treatment route.

§ None of the enterococcal isolates were identified as resistant to gentamicin, kanamycin, streptomycin, and vancomycin.

† CON = pigs received no antibiotic; IN-FEED = pigs received 110 mg tylosin per kg feed for 21 d; IM = pigs received 8.82 mg tylosin per kg body weight through intramuscular injection twice daily for the first 3 d of each week during the 3-week treatment period; IN-WATER = 66 mg tylosin per liter of drinking water for the first 3 d of each week during treatment period.

‡ Values in parenthesis indicate 95% confidence intervals.

Table 4.4. Effects of tylosin administration route and sampling day on the probability of antimicrobial resistance of fecal enterococci isolates to highly important and important antimicrobials*

	Tylosin administration route†				Probability, *P* <		
	CON	IN-FEED	IM	IN-WATER	Route	Day	Route × day
Chloramphenicol					0.331	0.234	0.935
Baseline (d 0)	19 [7, 44]‡	14 [4, 38]	3 [0.3, 26]	4 [0.4, 28]			
Treatment (d 21)	10 [2, 33]	9 [2, 32]	4 [0.4, 28]	5 [0.4, 28]			
Post-treatment (d 35)	19 [7, 44]	14 [4, 38]	19 [7, 44]	8 [2, 32]			
Lincomycin					0.996	0.555	0.340
Baseline (d 0)	95 [72, 99]	86 [61, 96]	76 [52, 90]	91 [67, 98]			
Treatment (d 21)	100 [.]	91 [67, 98]	95 [71, 99]	81 [56, 93]			
Post-treatment (d 35)	86 [62, 96]	95 [72, 99]	95 [72, 99]	95 [72, 99]			
Nitrofurantoin					0.331	0.002	-
Baseline (d 0)	20 [7, 43]	10 [2, 33]	35 [17, 58]	25 [10, 49]			
Treatment (d 21)	25 [10, 49]	30 [13, 54]	15 [5, 38]	40 [20, 63]			
Post-treatment (d 35)	0 [0]	0 [0]	0 [0]	10 [3, 31]			
Quinupristin/Dalfopristin					0.688	0.942	-
Baseline (d 0)	0 [0]	20 [8, 42]	10 [2, 35]	0 [0]			
Treatment (d 21)	20 [7, 47]	10 [2, 35]	0 [0]	0 [0]			
Post-treatment (d 35)	15 [5, 37]	10 [3, 32]	10 [3, 32]	0 [0]			
Tetracycline					0.753	0.104	0.747
Baseline (d 0)	80 [55, 93]	80 [55, 93]	75 [50, 90]	80 [55, 93]			
Treatment (d 21)	80 [55, 93]	90 [65, 98]	95 [70, 99]	80 [55, 93]			
Post-treatment (d 35)	90 [65, 98]	85 [60, 96]	95 [70, 99]	90 [65, 98]			

* Values represent the estimated probability of resistance among 20 enterococcal isolates per sampling day (d 0, 21, or 35); susceptibility was determined according to National Antimicrobial Resistance Monitoring System (CLSI, 2018; https://www.fda.gov/downloads/AnimalVeterinary/SafetyHealth/AntimicrobialResistance/NationalAntimicrobialResistanceMonitoringSystem/UCM581395.pdf) established breakpoints for human medicine. Clindamycin breakpoints is used as an indicator for interpretation of Lincomycin. One fecal sample was collected per pen per day and 1 enterococcal isolate per fecal sample was

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assessed. There was a total of 80 pigs (Line 600 × 241, DNA, Columbus, NE; initially 94 ± 3.6 kg) housed with 1 pig per pen and 10 replicates per treatment route.

† CON = pigs received no antibiotic; IN-FEED = pigs received 110 mg tylosin per kg feed for 21 d; IM = pigs received 8.82 mg tylosin per kg body weight through intramuscular injection twice daily for the first 3 d of each week during the 3-week treatment period; IN-WATER = 66 mg tylosin per liter of drinking water for the first 3 d of each week during treatment period.

‡ Values in parenthesis indicate 95% confidence intervals.

Table 4.5. Effects of tylosin administration route and sampling day on the prevalence of *erm*(B) gene[*]

Antibiotics and treatment period	Tylosin administration route[†]				Probability, *P* <		
	CON	IN-FEED	IM	IN-WATER	Route	Day	Route × day
Erm(B)					0.661	0.001	0.545
Baseline (d 0)	24 [10, 49][‡]	24 [10, 49]	15 [5, 38]	30 [13, 54]			
Treatment (d 21)	45 [24, 68]	66 [41, 84]	75 [51, 90]	50 [28, 72]			
Post-treatment (d 35)	9 [2, 32]	19 [7, 43]	20 [7, 44]	10 [2, 33]			

[*] Values represent the estimated prevalence of erm(B) gene among 20 enterococcal isolates per sampling day (d 0, 21, or 35); susceptibility was determined according to National Antimicrobial Resistance Monitoring System (CLSI, 2018; https://www.fda.gov/downloads/AnimalVeterinary/SafetyHealth/AntimicrobialResistance/NationalAntimicrobialResistanceMonitoringSystem/UCM581395.pdf)) established breakpoints. One fecal sample was collected per pen per day and 1 enterococcal isolate per fecal sample was assessed. There was a total of 80 pigs (Line 600 × 241, DNA, Columbus, NE; initially 94 ± 3.6 kg) housed with 1 pig per pen and 10 replicates per treatment route.

[†] CON = pigs received no antibiotic; IN-FEED = pigs received 110 mg tylosin per kg feed for 21 d; IM = pigs received 8.82 mg tylosin per kg body weight through intramuscular injection twice daily for the first 3 d of each week during the 3-week treatment period; IN-WATER = 66 mg tylosin per liter of drinking water for the first 3 d of each week during treatment period.

[‡] Values in parenthesis indicate 95% confidence intervals.

Chapter 5 - A retrospective analysis of seasonal growth patterns of nursery and finishing pigs in commercial production[1]

Summary

Objective: To determine seasonal patterns of nursery and finisher growth performance in three commercial US production systems located in the midwest.

Materials and methods: Five years of production records, including 5039 nursery and 5354 finisher production batches, were collected from three production systems. Explanatory variables include system, site, pig-flow type, feeder type, batch size, week of placement, average days-on-feed, fill length, number of sow farm sources, dietary energy, mortality, and initial body weight. Week of placement served as the unit for seasonal patterns. Nursery and finisher performance (average daily gain [ADG], average daily feed intake [ADFI], and gain to feed ratio [G:F]) were analyzed in separate datasets using multi-level linear mixed models. A guided stepwise selection approach was used to select fixed variables and their interactions. Seasonality curves were generated using rolling averages of least-squares means with a 5-week window and step-size of 1 week.

Results: For nursery, the seasonality effect was significant (P <.001) for ADG, ADFI, but not for G:F. Nursery ADG and ADFI decreased as week of placement progressed from the 1st to 20th week of a year but increased thereafter. All finisher growth responses were affected by week of placement (P <.001) but the pattern and magnitude of seasonal variability differed among systems (system × week interactions, P <.02).

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Implications: Seasonal variability of nursery and finisher performance can be quantified using production records in a multi-level linear mixed model. Seasonality effects on finisher performance was system dependent, while nursery seasonality shared more similarity among investigated systems.

Keywords: swine, seasonality, growth performance, nursery, finisher

It is widely documented that pig production has seasonal variations.[1-3] Pigs have a limited ability to thermoregulate, thus extreme temperatures result in increased reproductive difficulties, reduced growth performance, and elevated mortality.[1] Seasonal heat stress loss estimates indicate a nearly $300 million annual cost to the US swine industry.[4]

An accurate estimate of seasonal variability in feed consumption and growth rate is essential for commercial producers to estimate feed usage and marketing projections. Coarse estimations of the seasonality curve are sometimes generated based on raw means of weekly production performance. However, the precision of this method may be questioned as it does not account for factors confounded with seasonality. For instance, some nutritional programs feed pigs with increased dietary energy during the summer to counteract the decreased feed intake. Additionally, pigs grow slower and, therefore, producers likely extend their feeding period and change their marketing strategy in the summer compared with other times of the year. These confounding factors along with other production variables, such as different pig flows, feeder types, ventilation designs, and stocking densities, are also known to cause variations in growth and, therefore, need to be accounted for in a seasonality analysis. In a retrospective study conducted in 1995 by Bahnson and Dial,[3] seasonal patterns of finisher average daily gain (ADG) and average daily feed intake (ADFI) in commercial swine production were determined using multiple linear regression models. However, the inference scope of this study is limited to a single production system and such seasonal patterns require validation and an update using current data from modern production systems.

The objective of this study was to develop a systematic modeling approach to estimate the seasonality effects (expressed as the week of placement in a year) on growth performance of nursery and finishing pigs using retrospective commercial production records.

Material and methods

Data collection

Five years of production records from January 2013 to December 2017 were collected from three swine production systems located in the midwestern United States. A total of 5039 nursery and 5354 finisher production batches representing nearly 28 million market pigs were included in the raw dataset. The dataset structure consists of three levels: system, site, and batch. The batch was defined as a cohort of pigs per airspace within a site. In most cases the airspace was defined at the barn level. Some sites consisted of multiple barns, of which production records were reported as separate batches; however, the size of sites (eg, number of barns per site or rooms per batch) was not available for analysis. There were 25, 49, and 126 nursery sites; 513, 142, and 126 finisher sites; and 398, 52, and 130 wean-to-finish sites in systems A, B, and C, respectively. Explanatory variables collected at the site level were types of pig flow and feeder design. Nursery flow types included conventional nursery (nursery), nursery phase of wean-to-finish flow (WF-nursery), and wean-to-finish facilities that only housed nursery flows (converted-nursery). Finisher flow types included conventional finishing (finishing) and finishing phase of wean-to-finish flow (WF-finishing). At the batch level, data collected included starting and ending inventory, start date, close date, average days on feed (DOF), length of fill period, number of sow farm sources (sowfarm), average dietary net energy (NE), mortality, initial body weight (BW), final BW, ADG, ADFI, and gain to feed ratio (G:F). The final BW of WF-nursery batches and the initial BW of WF-finishing batches were determined based on pigs that were loaded onto trucks, weighed, and transferred from the wean-to-finish barn to another finisher; it is assumed that the batch of pigs that stayed in the wean-to-finish barn had similar average BW as those that were transferred out. Start date and close date referred to the first and last day, respectively, that pigs of the batch were in the facility. Average DOF was calculated as the sum of pig days (defined as one live pig being fed for one day) divided by the total number of pigs started. Average dietary NE was calculated based on major ingredient usage per batch and estimated energy density of ingredients.

Data processing

The raw dataset was divided into two subsets for separate analysis of nursery and finisher performance. Because dietary NE data was only available since 2015 in system A, the finisher dataset analysis was limited to 3 years (2015 to 2017) of observations to avoid confounded effects between system and year. However, given that the nutritional programs of the three systems did not alter energy content of nursery diets over seasons, NE was not considered in the nursery models so that the nursery dataset could include 5 years of data and provide an increased number of replications for seasonality analysis.

Initial diagnosis was performed using scatter plots for each explanatory and outcome variable to identify outliers. Screening criteria and the number of observations removed are presented in Table 5.1. For the nursery dataset, observations with suspected errors in BW estimation (ie, ADG < 0), recorded feed usage (G:F > 1000 g/kg), or date recording (fill length > DOF) as well as inaccurate pig counts (ie, mortality < 0) were removed from the dataset. Additionally, observations were removed if DOF < 21 d or final BW > 50 kg because they did not represent the standard pig flow among the systems. For the finisher dataset, observations with suspected errors in recorded feed usage (ie, ADFI > 4 kg, ADFI < 1.5 kg, or G:F > 1000 g/kg) were removed. Finisher observations with initial BW < 10 kg or > 70 kg, or final BW < 100 kg or > 150 kg, were considered non-normal production flows and were removed from the dataset. Feed delivery recording errors were identified when feed allocation was inaccurately recorded between consecutive batches resulting in abnormal G:F variability (eg, G:F < 300 g/kg in a batch and G:F > 1000 g/kg in the subsequent batch due to carry over or misallocation of feed among batches or when there was an extreme high and extreme low value among batches within a site). The ADFI and G:F values of these observations were deleted, but ADG values were unchanged. For each observation, week of placement (week; calendar year beginning January 1) was designated according to the start date and served as the unit for seasonality effect. Pig inventory counts were categorized to form batch size classes to avoid multicollinearity with fill length because batches with greater inventory often required a longer fill period. Sizes of nursery batches include < 3000, 3000 to 6000, and > 6000, and sizes of finisher batches include < 1500, 1500 to 3500, and > 3500. These inventory categories were selected to represent common commercial facility capacities. However, information regarding space allowance, stocking density, or pen or barn dimension was not available from every production system for analysis. In addition, feeder designs were categorized into 3 types: dry, tube, and wet-dry. Facilities equipped with mixed feeder types were assigned a missing value due to the limited number of observations (n = 137) with mixed types of feeders.

Statistical analysis

Finisher and nursery datasets were analyzed separately. Average daily gain, ADFI, and G:F were evaluated as response variables. System, flow, size, year, feeder type, and week were treated as categorical variables, while fill length, DOF, mortality, sowfarm, and dietary NE were treated as continuous variables. Quadratic terms of DOF and mortality were evaluated for potential non-linear effects on pig growth responses. Dietary NE was only available for finisher models. In the nursery dataset, converted-nursery was exclusive to system A, resulting in confounded effects between system and flow. Thus, the system and flow variables were merged in the nursery dataset to form a 7-category variable termed system-flow.

For each response variable, first-order ordinary least squares regression models, involving predictor variables of system (or system-flow in the nursery dataset), year, week, size, fill length, DOF, initial BW, mortality, NE (only for finisher dataset), and feeder type, were constructed for regression diagnostics following procedures described by Chen et al.[5] Observation leverage was estimated and evaluated in a leverage versus residual squared plot to identify influential observations. Suspected observations were assessed for biological accuracy and recorded in the screening list if removed from the dataset (Table 5.1). Multicollinearity among predictor variables was tested using variance inflation factor (VIF); variables with VIF values greater than 6 were further diagnosed using two-way scatter plots. There was evidence showing multicollinearity between finisher initial BW and DOF due to a strong, negative linear correlation (r = -0.83). Because the alteration of DOF was often considered a part of the seasonality change in finishing pig production (eg, pigs raised during the summer had a longer feeding period than in the winter), initial BW was included in the finisher models. However, DOF of nursery batches did not vary significantly over seasons and thus was used in the nursery models. Studentized residuals versus fitted values and studentized residuals versus each categorical descriptive variable plot were examined for heteroscedasticity. Heteroscedasticity was found among systems as observations from system A had consistently greater residual variance compared with systems B and C across all response variables; therefore, a dummy variable ("variance group"; variance group = 1 if system = A, variance group = 0 if system = B or C) was created and accounted for in the analysis.

Multi-level linear mixed models for each response variable were constructed with batch serving as the observational unit, site as a random effect, and system (system-flow in nursery dataset) as a fixed effect. A random residual term of batch within variance group was included in all models to account for heterogeneous variance among systems. A guided stepwise selection approach was employed to select variables and their interaction terms. Specifically, a saturated first-order model was first fit involving all candidate fixed variables. This model was then reduced in a stepwise manner based on variable significance level ($P > .10$) and improvement in Bayesian information criterion (BIC). Possible two-way interactions among remaining fixed variables were introduced to form a saturated two-way model. The final model was achieved by stepwise removal of interaction terms based on their significance level ($P > .10$) and improvement in model BIC. Bayesian information criterion was used as an indicator of model suitability.[6] Restricted maximum likelihood method was used in the model selection to evaluate the significance of fixed effect terms. The Kenward-Roger's procedure was used to estimate degrees of freedom and adjust estimated SE for bias correction. Also, at each model selection step, studentized residuals were evaluated. All analyses were performed using Stata Statistical Software (Release 15; StataCorp LLC, College Station, Texas).

Least-squares means for week of placement were generated using the margins command with "asbalanced" and "emptycells(reweight)" options.[7] To generate a smooth seasonality curve for each growth response, rolling averages of the least-squares means were calculated using a centered 5-week window with step-size of 1 week. Rolling averages for weeks 1, 2, 51, and 52 were generated by recursive extension of the week series (eg, rolling average of week 1 represents the mean of weeks 51, 52, 1, 2, and 3). Finally, seasonal patterns were standardized using growth responses in week 1 as a benchmark and that of other weeks were expressed as changes in response relative to week 1.

Results

Descriptive statistics

Explanatory variable frequencies and histograms are presented in Table 5.2 and Figures 5.1, 5.2, and 5.3. The majority (> 80%) of the nursery batches were filled within 20 days with system A having a longer average fill length than systems B and C. In contrast, the majority of finisher batches were filled within two days. In both nursery and finisher datasets, more than 65% of the production batches sourced pigs from a single sow farm, while about 30% of the batches obtained pigs from 2 to 6 sow farm sources. The number of observations per week of placement varied throughout the year and averaged 95 and 101 batches per week in nursery and finisher datasets, respectively. Descriptive statistics for initial and final BW, DOF, mortality, and growth responses along with US industry benchmarks[8] are shown in Table 5.3. The mean values of initial BW were 5.5 and 27.0 kg, final BW were 26.6 and 125.3 kg, DOF were 55.3 and 112.4 days, and mortalities were 4.1% and 4.0% in nursery and finisher datasets, respectively. The mean values of ADG were 370 and 871 g, ADFI were 630 and 2436 g, and G:F were 602 and 358 g/kg in nursery and finisher, respectively. These growth responses were reasonably in line with average industry levels for the same time period.

Nursery seasonality

A total of 4960 nursery observations were used in the final model for ADG and 4365 observations were used in the ADFI and G:F models (observations with descriptive variables coded as missing values were unavailable for analysis if the descriptive variables were included in the model; Table 5.4). Effects of system-flow, size, year, week, fill length, DOF, mortality, sowfarm, and feeder type as well as some of their interactions significantly ($P < .10$) contributed to the variability in growth responses among observations. Parameter coefficients and statistics for each model are provided in the supplementary material (Appendix A). Because there was no evidence of system-flow × week or size × week interactions for ADG and ADFI ($P > .10$), only main effects of week ($P < .001$) were reported. Plots of week of placement least-squares means for ADG (Figure 5.4A) and ADFI (Figure 5.5A) indicated considerable variation among contiguous weeks. Thus, a rolling average was adopted to describe the seasonal patterns (Figures 5.4B and 5.5B), similar to the approach of Bahnson and Dial.[3]

Nursery ADG and ADFI progressively decreased as the time of placement transitioned from the 1st to 15th week of the year. Both ADG and ADFI remained low during week 15 to 22 but increased thereafter and became equal to week 1 values by the 43rd and 33rd week of the year, respectively. Interestingly, a second but short period of decrease and recovery in both ADG and ADFI was observed during week 35 to 40 with a diminished magnitude. For G:F, there was no evidence of a week effect in nursery growth performance.

Finisher seasonality

A total of 4747 finisher observations were used in the final model for ADG and 4743 observations were used in the ADFI and G:F models (Table 5.5). Effects of system, flow, size, year, week, fill length, initial BW, mortality, sowfarm, feeder, and NE as well as some of their interactions significantly (*P* < .10) contributed to the finisher models. System × week interactions (*P* < .001) were observed for ADG, ADFI, and G:F (Figures 5.6, 5.7, and 5.8, respectively).

In system A, ADG decreased as the time of placement transitioned from week 1 to 15, remained low from week 15 to 20, and increased thereafter; shortly after a plateau around week 33, a second period of decrease and recovery in ADG was observed during week 33 to 45 with diminished magnitude. In systems B and C, ADG decreased during the first 10 weeks of the year, followed by a period of low ADG from week 10 to 20; thereafter, ADG increased, reached a plateau around week 30, and then decreased to the performance level observed in week 1.

For ADFI, seasonal patterns were generally similar among systems. Average daily feed intake decreased as the time of placement transitioned during the first 15 weeks of a year, increased for pigs placed from week 20 to 35, reached a plateau, and then decreased to week 1 level. However, the magnitude of the first period of decrease was greater in system B compared with systems A and C (200, 140, and 120 g, respectively). Moreover, the plateau of the ADFI curve remained longer in system C (approximately 15 weeks from week 35 to 50) compared with systems A and B (approximately 7 weeks occurring primarily around weeks 35 to 40).

Distinct seasonal patterns for G:F were observed among systems. In system A, two short periods of G:F decrease and recovery was observed from week 10 to 25 and from week 30 to 50, with the magnitude of decrease smaller during the first than the second period. In systems B and C, G:F increased during the first 20 to 25 weeks of the year and then decreased to the week 1 level by week 35.

Discussion

Seasonal variations have been widely observed in swine production, primarily due to the seasonal changes in environmental temperature.[1-3] In this study, we constructed a multi-level linear mixed model that determined the seasonal patterns of ADG, ADFI, and G:F in three US production systems while controlling for variability in growth performance resulting from differences in system, type of pig flow, batch size, year, strategy of barn filling, feeder type, and dietary NE. Because the three systems were generally located nearby and within the midwestern United States, geographic factors were not considered in the model due to data availability and similar seasonal patterns among systems were initially hypothesized. In addition, because genetic information was not available at the batch level for analysis, it was assumed that genetic lines and rate of improvement were consistent within system and the genetic variability could be controlled by the fixed effects of system and year. It is also worth noting that even though our datasets provided a large number of observations per week (average 95 and 101 batches per week in nursery and finisher datasets, respectively), within site replication per week was limited because relatively few sites are filled during the same week in multiple years. Therefore, site and week of placement were confounded, which might have contributed to the variability in least-squares means among contiguous weeks (Figures 5.4A, 5.5A, 5.6A, 5.7A, and 5.8A). However, such differences among week of placement means were not always biologically significant from a production perspective.[2]

To evaluate the impact of increasing replications over year on the finisher seasonality models, a separate analysis was conducted using five years (2013 to 2017) of finisher data from systems B and C (system A was excluded because of lacking NE data from 2013 to 2014). Seasonality curves generated from the 5-year dataset (data not shown) followed similar patterns as those generated from the 3-year dataset. Moreover, ventilation design (tunnel versus curtain) was included in the 5-year (systems B and C only) models; there was no evidence that seasonal patterns for finisher growth performance was dependent on ventilation type.

In this analysis, there were seasonal patterns in ADG and ADFI for both nursery and finisher datasets. In general, ADG decreased as the time of placement progressed during the first 15 weeks of the year and remained at that level for another 5 to 10 weeks, which was driven by a similar decrease in ADFI. In another retrospective study conducted in 1995, Bahnson and Dial[3] determined the seasonal growth patterns in a commercial swine production system located in the midwestern United States; interestingly, the seasonal changes in finisher ADG and ADFI reported by these authors shared a nearly identical pattern and magnitude as that in system A and was generally in agreement with the other two systems from the present study. It was not surprising that ADG and ADFI decreased as the time of placement transitioned from winter to spring, because the average ambient temperature likely increased during the corresponding feeding periods. For instance, pigs that were placed in the barn around week 10 to 20 would have experienced the summer weather during June, July, and August, corresponding to the hottest season of a year in that region. It has been well demonstrated that pigs reduce voluntary feed intake in response to high ambient temperature.[9-11] As expected, the seasonal ADG and ADFI curves reached the minimum approximately 5 weeks later in nursery than in finisher due to a shorter feeding length and delayed time of entry during the summer weather. However, finisher growth performance recovered faster than nursery and further increased beyond the week 1 level as the week of placement transitioned into fall (after week 25). Interestingly, a second period of decrease in nursery ADG and ADFI was observed from week 35 to 40; even though the magnitude of this decrease was marginal, it was consistently observed across systems. A similar pattern was also observed in finishing pigs from system A. Assuming a lactation period of 21 days, nursery pigs that were placed around week 35 to 40 would have been born and nursed during August and might have also experienced in-utero heat stress during June and July. It is possible that extreme temperatures during the summer may have negatively affected late-gestation and lactating sow performance and subsequently decreased growth performance of piglets. Heat stress during late gestation has been demonstrated to decrease the number of piglets born alive and piglet birth weight,[12] and many studies have reported decreased lactating sow feed intake and piglet weaning weight during lactation under heat stress.[13-15]

The magnitude of seasonal variability (difference between the highest and lowest performance of the year) represented approximately 5% of the mean ADG or ADFI in nursery, in contrast to approximately 9% in finisher growth performance. A greater seasonality impact on finisher performance is expected because heavier pigs are more sensitive to high ambient temperature and express greater reduction in appetite and growth during the summer compared with nursery pigs.[1,9] Nevertheless, seasonality effects on G:F were observed in finisher but not in nursery pigs. In systems B and C, G:F increased in finishing pigs fed during the summer. This observation is consistent with findings of another retrospective study using data from nearly 60,000 commercial gilts over 2.5 years, where greater G:F was observed in pigs raised during the summer than winter (357 vs. 312 g/kg, respectively).[2] Improved G:F during the summer may be attributed to the decreased voluntary feed intake and the potential for pigs to utilize less feed for fat deposition (thermal insulation) and maintenance of body temperature.[10] However, it merits further investigation on the reason why system A expressed less seasonal change in G:F compared with systems B and C.

Our models suggest that seasonal patterns for nursery responses were similar among systems and different pig-flow types, while finisher performance patterns were system dependent (system ×

week interaction). In nurseries, tight regulation of barn temperature and a relatively consistent diet regimen over time might have resulted in systems sharing similar seasonal patterns. In contrast, for finishers, different systems responded to seasonal change by employing different feeding strategies; for example, a considerable portion of pigs from systems A and C received summer diets with increased dietary NE, while system B did not change dietary NE over season. However, including dietary NE in the finisher models did not fully explain the differences in seasonal patterns among systems. Other factors that might have led to this interaction include management practice, marketing strategy, and other nutritional interventions (eg, addition of ractopamine). Moreover, it is possible that assumptions that the effects of genetic differences and geographical locations are negligible among systems may have been violated and partly contributed to the system × week interaction.

In commercial swine production, application of seasonality curves for growth performance include, but are not limited to, feed usage estimation and marketing projection. Users can predict ADFI of a production batch at the time of placement based on observed ADFI of pigs from a benchmark week along with the standardized differences among weeks presented as the rolling average curve. Total feed usage of a batch of pigs can be estimated by multiplying the predicted ADFI by pig inventory. Likewise, pig ADG can be estimated at the time of placement and thus the length of feeding period and marketing date can be determined by dividing the difference between targeted market weight and initial BW by the estimated ADG. For more precise estimation of growth responses, users need to adjust for other descriptive factors, eg, pig flow, dietary NE, feeder type, and pig initial BW, using the coefficients presented in the supplementary material (Appendix A).

In addition, caution is needed when applying a uniform seasonality curve to various finisher production systems because seasonal growth patterns of finishing pigs appear to be system dependent (system × week interaction). Systems that share little similarity (eg, geographic location) with the systems studied herein can generate their seasonal growth patterns using the methodology described in this study along with the code for the statistical analysis provided in the supplementary material (Appendix A).

In summary, this retrospective analysis depicts the seasonal patterns of nursery and finisher growth performance in three commercial swine production systems located in the midwestern United States. Nursery ADG and ADFI expressed prominent seasonal variations and were similar among systems, whereas nursery G:F was not affected by season. Finisher ADG, ADFI, and G:F varied over seasons but the magnitudes and patterns of change were system dependent. This study also presents concepts underlying the implementation of a multi-level linear mixed model of production records to analyze seasonality and potentially other decision factors in commercial systems.

Implications

- Seasonal variabilities in pig growth performance were observed in both commercial nurseries and finishers and can be quantified using a modeling approach based on production records.
- Seasonal patterns for nursery growth performance were similar among investigated systems, while seasonality effects on finisher performance was system dependent.

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Tables and figures

Table 5.1. Screening criteria for exclusion of nursery and finisher batches from three swine production systems located in the midwestern United States from January 2013 to December 2017

	Production system		
Item	**A**	**B**	**C**
Nursery dataset			
Production batches in the raw dataset, No.	2632	1125	1282
Observation removal, No.			
Inaccurate pig counts[*]	1	1	9
Average DOF < 21 d	14	2	0
Final BW > 50 kg	26	0	2
Suspected BW estimation errors (ie, biologically abnormal ADG)	7	2	0
Suspected feed accounting errors (ie, G:F > 1,000 g/kg)	11	1	0
Suspected date recording errors (ie, fill length > DOF)	1	2	0
Production batches in the final dataset, No.	2572	1117	1271
Value removal, No.			
Feed delivery recording errors[†]	45	0	4
Removal rate	4.0%	0.7%	1.2%
Finisher dataset			
Production batches in the raw dataset, No.	2862	1076	1416
Observation removal, No.			
Unusual pig flow[‡]	2	0	1
Initial BW < 10 kg	9	1	1
Initial BW >70 kg	30	1	0
Final BW < 100 kg	16	6	0
Final BW > 150 kg	1	0	0
Suspected feed accounting errors[§]	14	1	2
Production batches in the final dataset, No.	2790	1067	1412
Value removal, No.			
Feed delivery recording errors[¶]	2	1	0
Suspected dietary energy recording errors[#]	23	0	0
Removal rate	3.4%	0.9%	0.3%

* Including batches with abnormal inventory and mortality < 0.

† Only ADFI and G:F values were removed.

‡ Half of the total inventory was filled 90 days after filling of the first half.

§ Including batches with ADFI > 4 kg, ADFI < 1.5 kg, or G:F > 1,000 g/kg.

¶ Feed allocation was inaccurately recorded between consecutive batches resulting in abnormal variability in G:F. Only ADFI and G:F values were removed from the dataset.

Only energy values were removed.

DOF = days on feed; BW = body weight; ADG = average daily gain; G:F = gain to feed ratio; ADFI = average daily feed intake.

Table 5.2. Frequency of nursery and finisher batches from three swine production systems located in the midwestern United States from January 2013 to December 2017 for each explanatory variable

	Production system		
Item	**A**	**B**	**C**
Nursery dataset			
Year			
2013	574	212	201
2014	401	211	235
2015	552	226	246
2016	562	222	279
2017	483	246	310
Type of pig flow			
Converted-nursery*	601	0	0
Nursery	816	802	619
WF-nursery†	1155	315	652
Batch size			
< 3000 pigs	1198	583	436
3000 to 6000 pigs	396	237	288
> 6000 pigs	978	297	547
Feeder type			
Dry	543	981	786
Tube	718	12	81
Wet-dry	965	27	295
Missing‡	346	97	109
Finisher dataset			
Year			
2015	908	343	442
2016	986	345	463
2017	896	379	507
Type of pig flow			
Finishing	2084	877	955
WF-finishing§	706	190	457
Batch size			
< 1500 pigs	45	115	143
1500 to 3500 pigs	1231	540	959
> 3500 pigs	1514	412	310
Feeder type			
Dry	95	598	664
Tube	634	289	283
Wet-dry	1787	85	378
Missing‡	274	95	87

* Wean-to-finish facilities that were used for traditional nursery pig flow.

† Nursery phase of wean-to-finish flow.

Table 5.3. Descriptive analysis of explanatory and outcome variables for nursery and finisher batches from three swine production systems located in the midwestern United States from January 2013 to December 2017

Item	**N**	**Mean (SD)**	**Minimum**	**Median**	**Maximum**	**Industry average**[*]
Nursery dataset						
Initial BW, kg	4960	5.5 (0.49)	2.8	5.4	9.1	NA
Final BW, kg	4960	26.6 (6.71)	8.0	26.2	49.6	23.6
Average DOF, No.	4960	55.3 (12.06)	22.8	53.4	115.2	46.3
Mortality, %	4960	4.1 (4.84)	0.0	2.6	53.4	4.8
ADG, g	4960	370 (67.5)	86	376	603	376
ADFI, g	4846	630 (140.8)	186	617	1270	570
G:F, g/kg	4846	602 (90.4)	185	617	974	660
Finisher dataset						
Initial BW, kg	5269	27.0 (8.1)	10.1	25.9	68.6	NA
Final BW, kg	5269	125.3 (3.87)	101.6	125.3	138.4	128.0
Average DOF, No.	5269	112.4 (14.8)	57.2	114.3	162.2	111.2
Mortality, %	5269	4.0 (2.57)	0.0	3.4	26.3	4.6
Dietary NE, kcal/kg	5191	2626 (144.8)	2423	2577	2949	NA
ADG, g	5269	871 (75.4)	594	862	1347	926
ADFI, g	5264	2436 (229.2)	1769	2413	3683	2386
G:F, g/kg	5264	358 (20.6)	255	359	471	388

[*] Average of US swine industry productivity from 2013 to 2016.[8]

BW = body weight; NA = not available; DOF = days on feed; ADG = average daily gain; ADFI = average daily feed intake; G:F = gain to feed ratio; NE = net energy.

Table 5.4. Multi-level linear mixed model components for nursery ADG, ADFI, and G:F in three swine production systems located in the midwestern United States from January 2013 to December 2017

Source of variation	***P* value**[*]		
	ADG (n = 4960)	**ADFI** (n = 4365)	**G:F** (n = 4365)
System-flow[†]	< .001	< .001	< .001
Batch size	< .001	< .001	NS
Year	< .001	< .001	< .001
Week of placement (week)	< .001	< .001	NS
Length of fill period (fill)	.24	.017	NS
Average DOF	< .001	< .001	< .001
Mortality	< .001	< .001	< .001
Number of sow farm sources (sowfarm)	< .001	< .001	NS
Feeder type	NS	< .001	< .001
System-flow × size	NS	< .001	NS
System-flow × year	< .001	< .001	< .001
System-flow × fill	< .001	< .002	NS
System-flow × DOF	< .001	< .001	< .001
System-flow × mortality	< .001	<.001	< .001
Size × year	.004	NS	NS
Size × fill	NS	.02	NS
Size × sowfarm	< .001	< .001	NS

[*] Multi-level linear mixed models for nursery dataset; model components were selected using a guided stepwise selection method with $P < .10$ considered statistically significant.

[†] The system and flow variables were merged in the nursery dataset to form a 7-category variable termed system-flow: system A-converted_nursery, system A-nursery, system A-WF_nursery, system B-nursery, system B-WF_nursery, system C-nursery, and system C-WF_nursery.

ADF = average daily gain; ADFI = average daily feed intake; G:F = gain to feed ratio; NS = not selected by the model; DOF = days on feed; WF = wean-to-finish.

Table 5.5. Multi-level linear mixed model components for finisher ADG, ADFI, and G:F in three swine production systems located in the midwestern United States from January 2015 to December 2017

Source of variation	***P* value**[*]		
	ADG (n = 4747)	**ADFI** (n =4743)	**G:F** (n = 4743)
System	< .001	< .001	< .001
Flow	.002	.003	< .001
Batch size	.02	.018	.04
Year	< .001	.04	< .001
Week of placement (week)	< .001	< .001	< .001
Length of fill period (fill)	NS	.24	.99
Initial BW	< .001	< .001	< .001
Mortality	< .001	< .001	< .001
Number of sow farm sources (sowfarm)	.68	.11	< .001
Dietary NE	< .001	< .001	< .001
Feeder type	< .001	< .001	NS
System × flow	< .001	< .001	< .001
System × size	< .001	.018	< .001
System × year	.004	< .001	< .001
System × week	< .001	< .001	< .001
System × fill	NS	.095	< .001
System × initial BW	< .001	< .001	< .001
System × mortality	.01	NS	< .001
System × sowfarm	< .001	< .001	NS
System × NE	-	< .001	< .001
System × feeder	.002	.004	NS
Flow × size	NS	NS	< .001
Flow × year	< .001	< .001	NS
Flow × fill	NS	< .001	NS
Flow × initial BW	.04	NS	NS
Flow × mortality	< .001	< .001	NS
Flow × sowfarm	NS	< .001	< .001
Flow × NE	.015	.002	NS
Size × fill	NS	.01	NS
Size × initial BW	NS	NS	NS
Size × mortality	NS	NS	.09
Size × sowfarm	.007	.006	.006
Size × feeder	NS	< .001	NS

[*] Multi-level linear mixed models for the finisher dataset; model components were selected using a guided stepwise selection method with $P < .10$ considered statistically significant.

ADG = average daily gain; ADFI = average daily feed intake; G:F = gain to feed ratio; NS = not selected by the model; BW = body weight; NE = net energy.

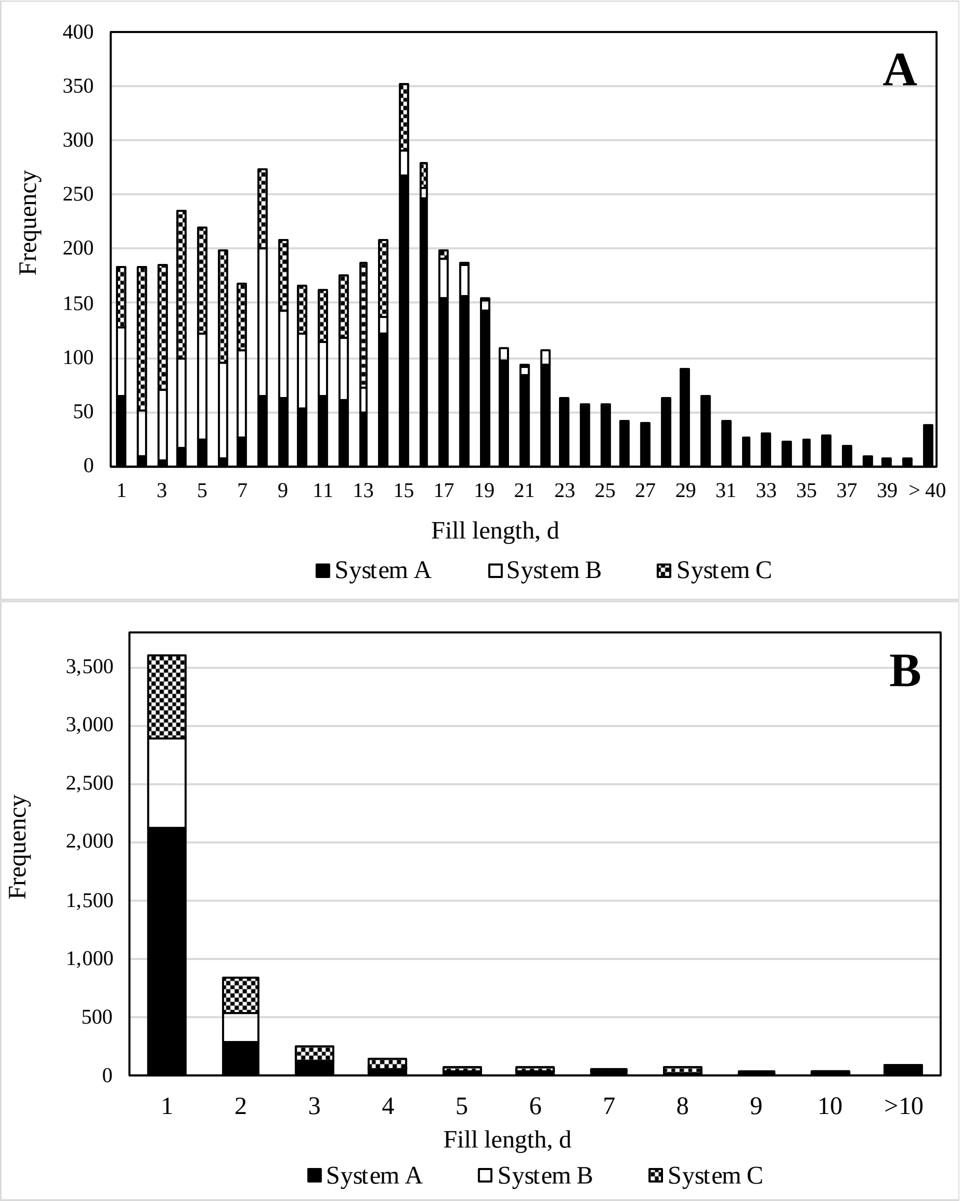

Figure 5.1. Frequency distribution of fill length for (A) nursery and (B) finisher batches from three swine production systems located in the midwestern United States from January 2013 to December 2017.

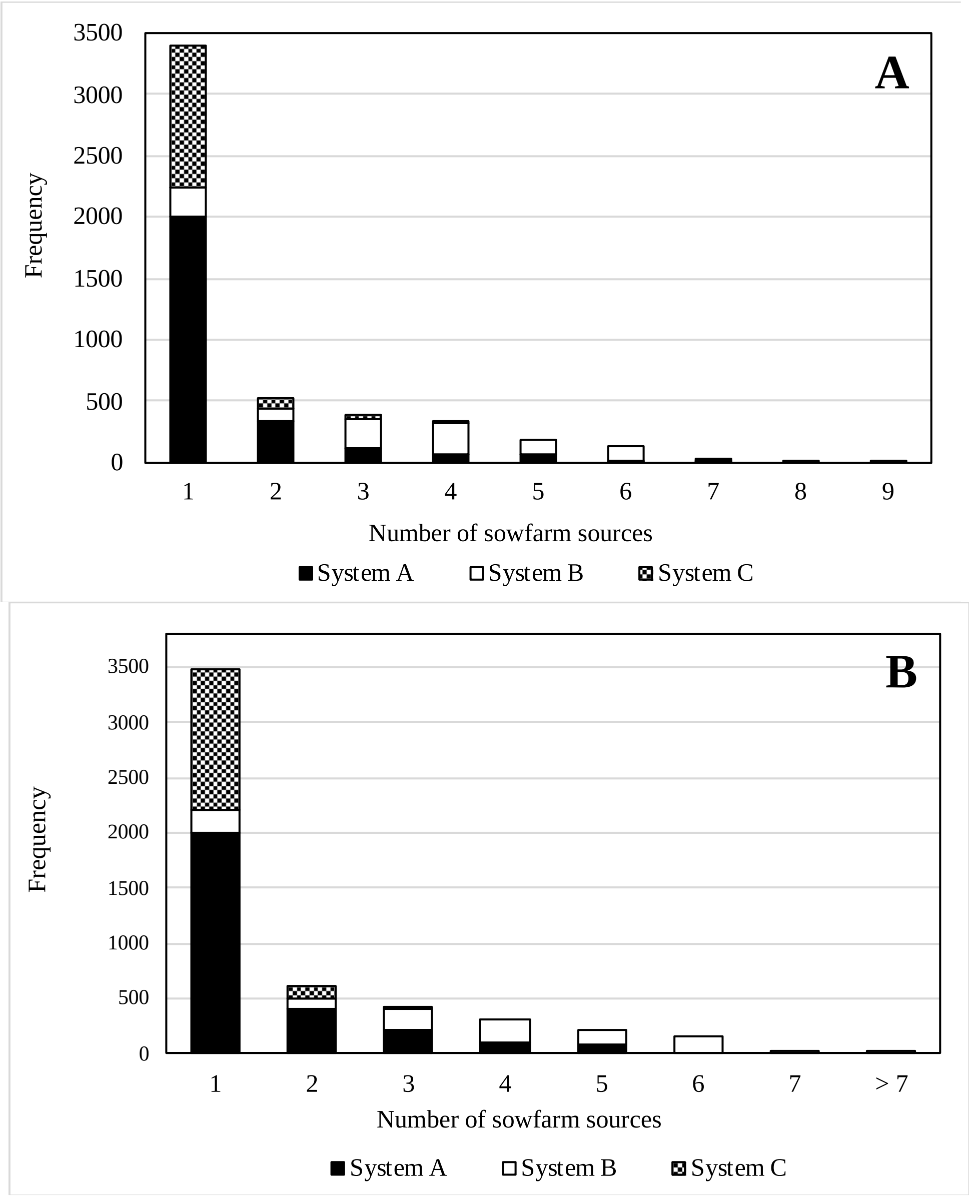

Figure 5.2. Frequency distribution of number of sow farm sources for (A) nursery and (B) finisher batches from three swine production systems located in the midwestern United States from January 2013 to December 2017.

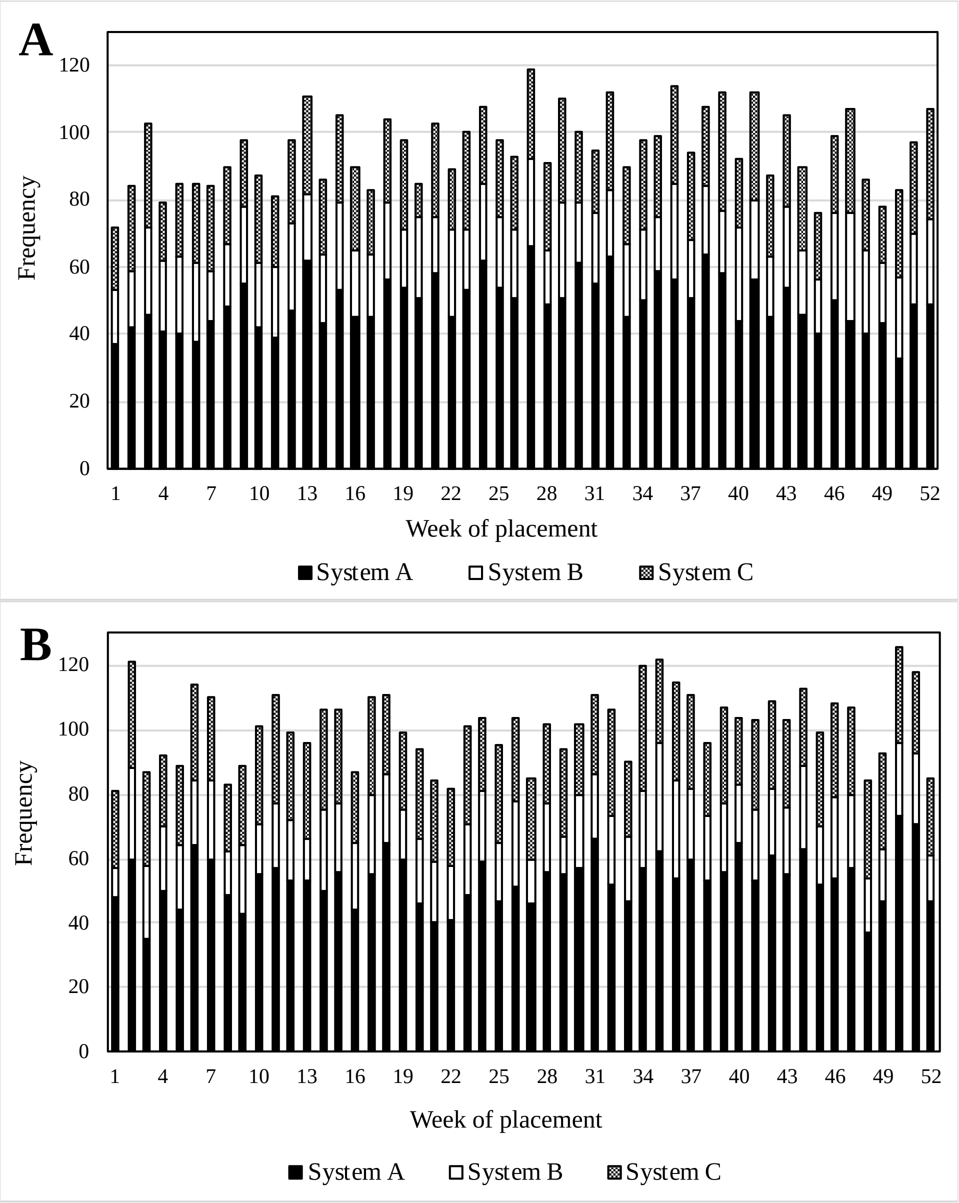

Figure 5.3. Frequency distribution of week of placement for (A) nursery and (B) finisher batches from three swine production systems located in the midwestern United States from January 2013 to December 2017.

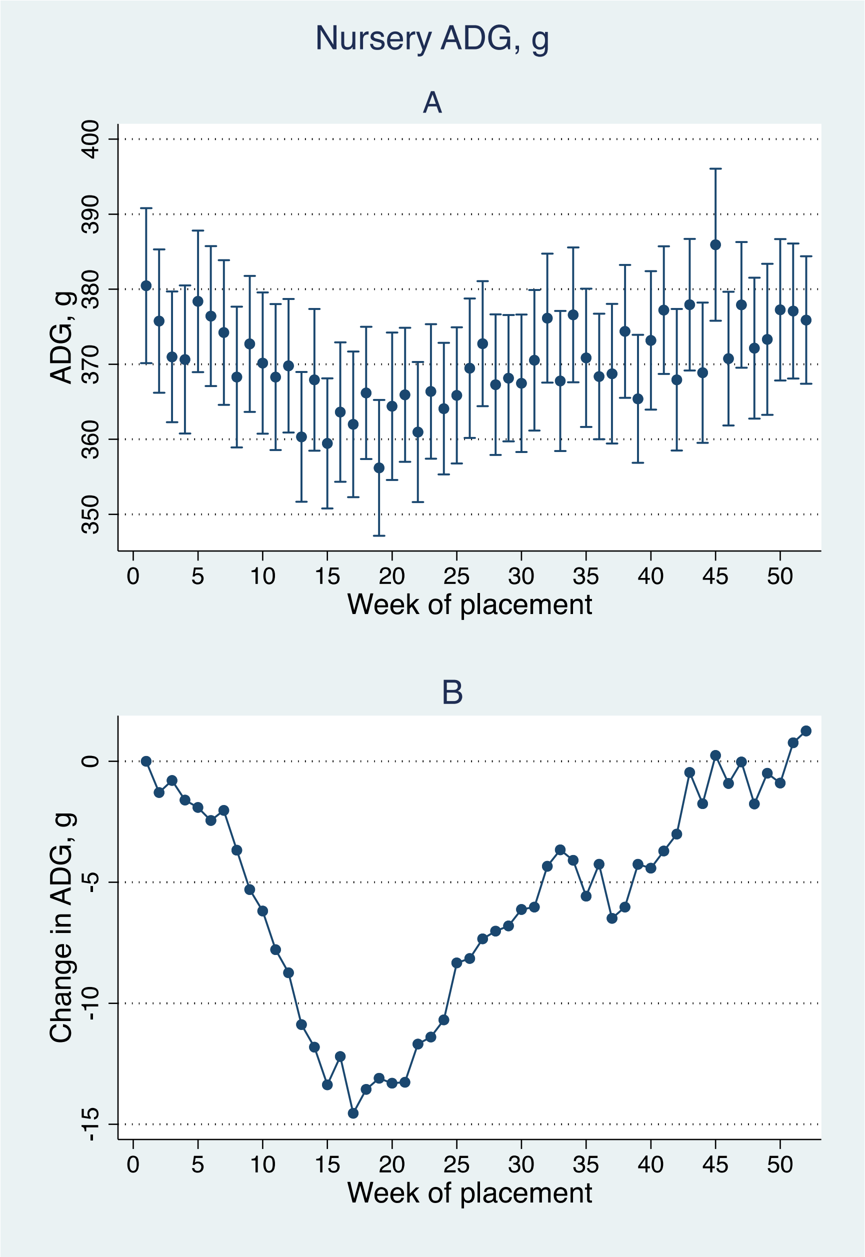

Figure 5.4. Effect of week of placement on nursery ADG in three swine production systems located in the midwestern United States from January 2013 to December 2017. Values are presented as (A) least-squares means with 95% confidence interval and (B) rolling average (window = 5, step size = 1) for changes in ADG relative to week 1. ADG = Average daily gain.

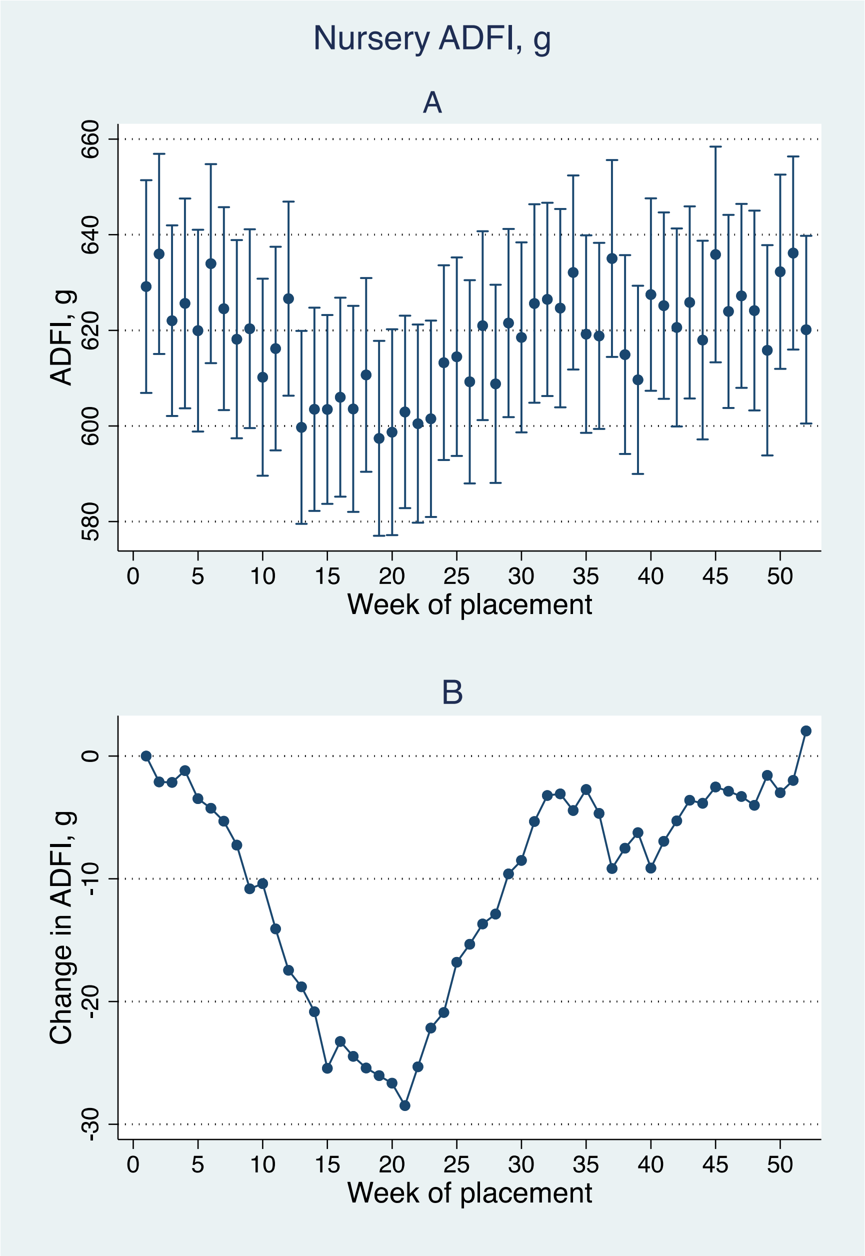

Figure 5.5. Effect of week of placement on nursery ADFI in three swine production systems located in the midwestern United States from January 2013 to December 2017. Values are presented as (A) least-squares means with 95% confidence interval and (B) rolling average (window = 5, step size = 1) for changes in ADFI relative to week 1. ADFI = average daily feed intake.

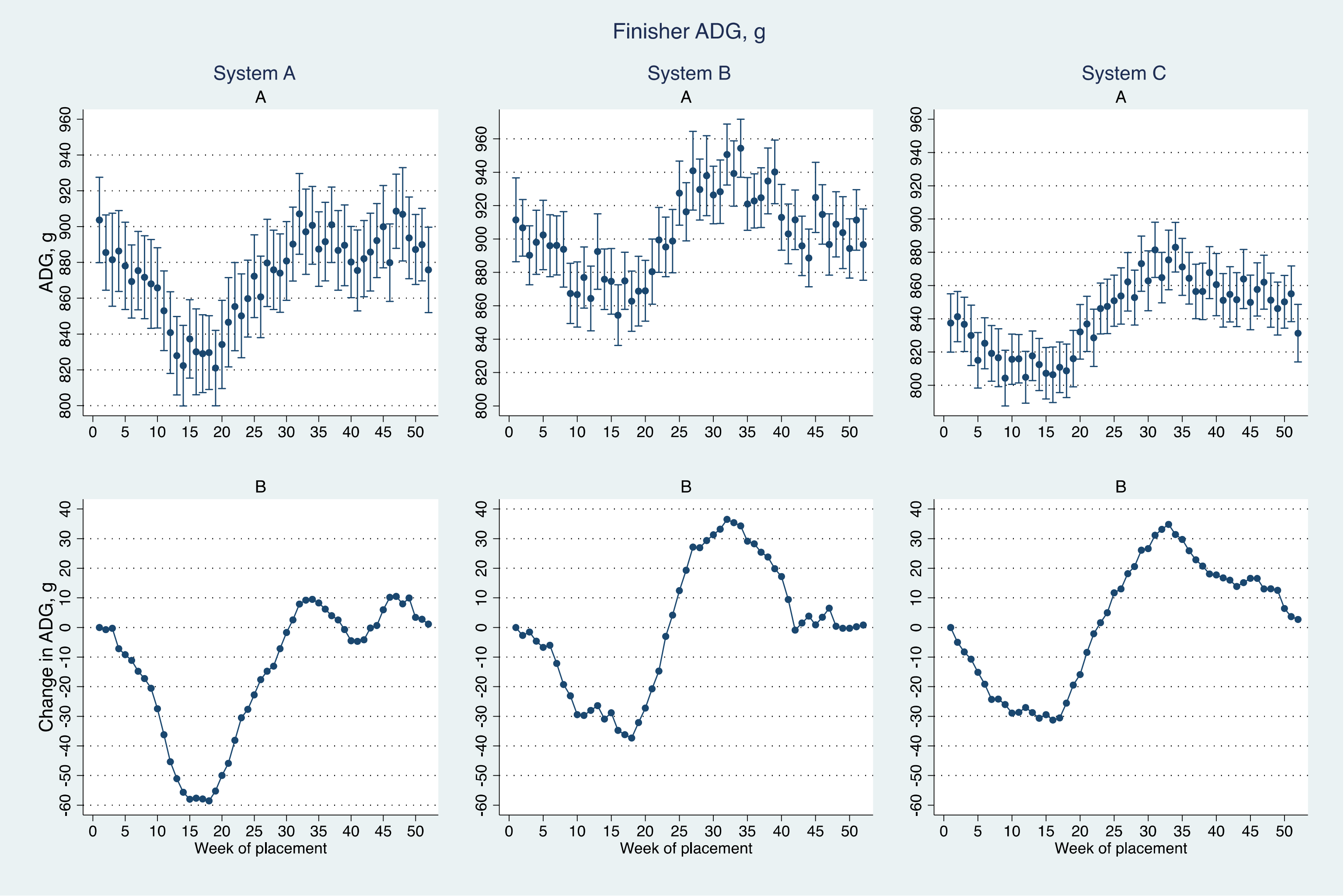

Figure 5.6. Effect of week of placement on finisher ADG in three swine production systems located in the midwestern United States from January 2015 to December 2017. Values are presented as (A) least-squares means with 95% confidence interval and (B) rolling average (window = 5, step size = 1) for changes in ADG relative to week 1. ADG = average daily gain.

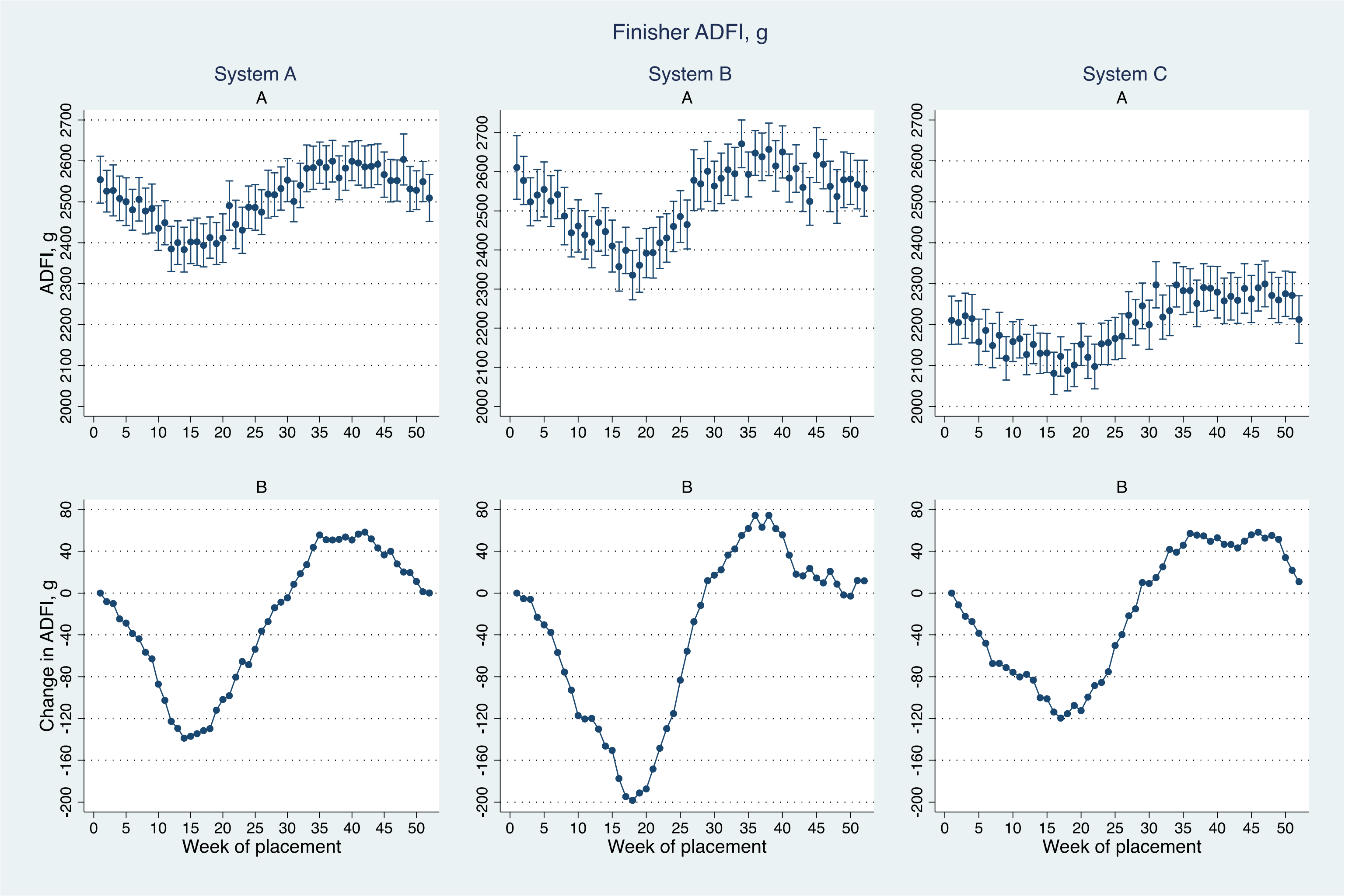

Figure 5.7. Effect of week of placement on finisher ADFI in three swine production systems located in the midwestern United States from January 2015 to December 2017. Values are presented as (A) least-squares means with 95% confidence interval and (B) rolling average (window = 5, step size = 1) for changes in ADFI relative to week 1. ADFI = average daily feed intake.

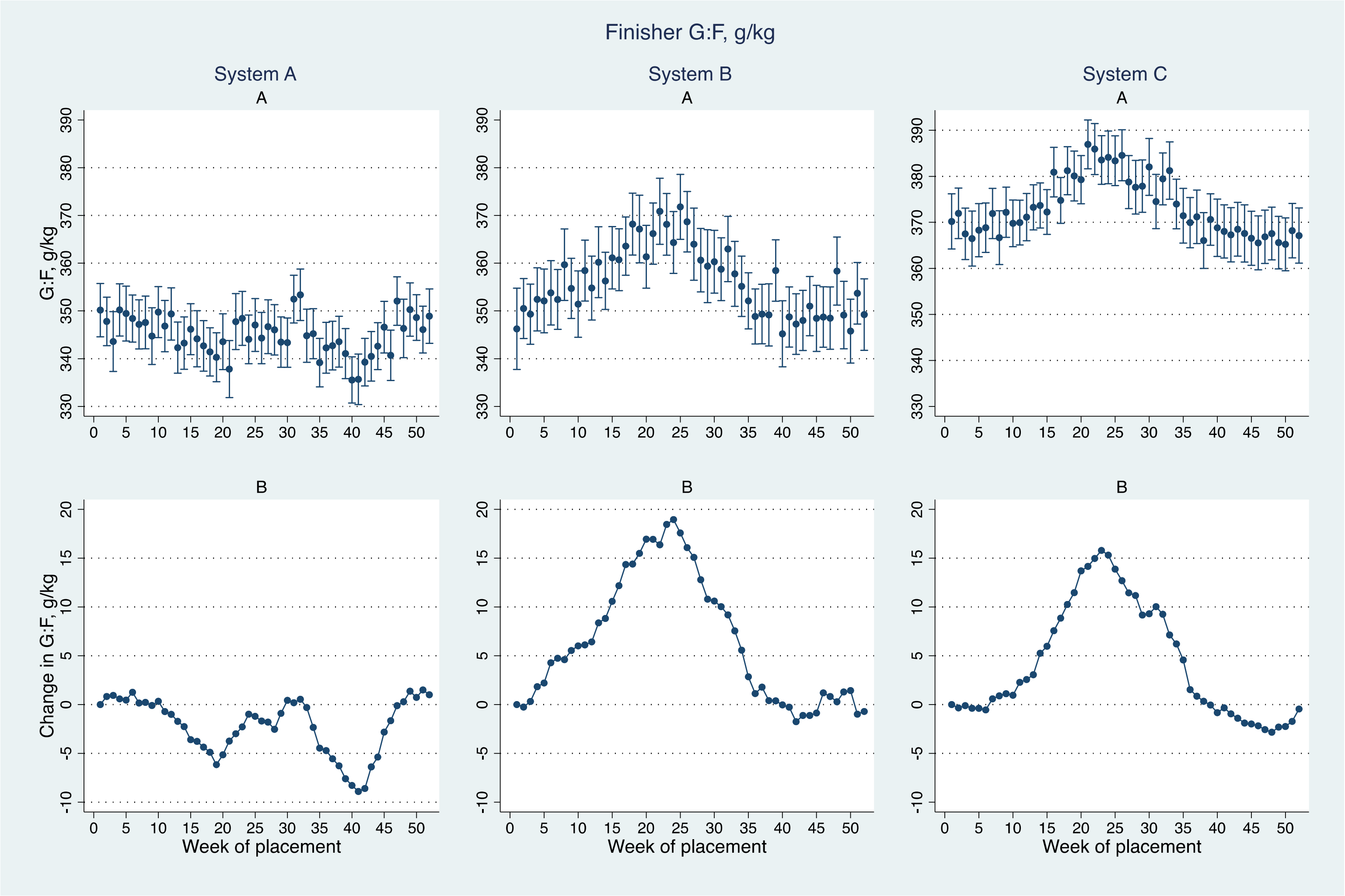

Figure 5.8. Effects of week of placement on finisher G:F in three swine production systems located in the midwestern United States from January 2015 to December 2017. Values are presented as (A) least-squares means with 95% confidence interval and (B) rolling average (window = 5, step size = 1) for changes in G:F relative to week 1. G:F = gain to feed ratio.

Chapter 6 - Strategy to blend leftover finisher feed to nursery pigs in a wean-to-finish production system[1]

ABSTRACT: In wean-to-finish pig production, leftover finisher feed from the previous group is commonly blended with nursery diets as weanling pigs enter the facility. Two experiments were conducted to evaluate feeding the last finisher diet to nursery pigs. The timing (phase) and dose was evaluated. Each experiment used 1,260 pigs from two commercial research rooms with 21 pigs per pen and 30 pens per room (15 pens per treatment). Pigs were fed commercial nursery diets in a 5-phase feeding program, and phase changes were based on a feed budget. In experiment 1, pens of pigs (initially 5.83 kg) were blocked by body weight, gender, and room and allotted to 1 of 4 treatments. Treatments included: standard nursery diets throughout (control); or standard diets with 2.5 kg/pig of the last finisher feed blended at the beginning of phase 2, 3, or 4. Growth responses during the intermediate periods were promptly decreased ($P < 0.05$) once the finisher feed was introduced regardless of phase in which it was blended. However, during the overall nursery period, blending the finisher diet into phase 2 decreased ($P < 0.05$) average daily gain (ADG) and average daily feed intake (ADFI), but did not affect gain:feed ratio (G:F), compared with control pigs or those that had blended diet in phase 4 with blending of phase 3 diet intermediate. In experiment 2, weaned pigs were fed common phase 1 and 2 diets before the start of the experiment. At the beginning of phase 3, pens of pigs (initially 10.6 kg) were blocked by body weight and room and allotted to 1 of 4 treatments. Treatments consisted of a dose-titration of blending increasing amounts of finisher feed (0, 1.25, 2.50, and

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[1] This work has been accepted for 2019 publication and is available online in the *Translational Animal Science*: F. Wu, K. F. Coble, C. W. Hastad, M. D. Tokach, J. C. Woodworth, J. M. DeRouchey, S. S. Dritz, and R. D. Goodband. 2019. Strategy to blend leftover finisher feed to nursery pigs in a wean-to-finish production system. Transl. Anim. Sci., https://doi.org/10.1093/tas/txy143.

3.75 kg/pig) into the phase 3 nursery diet. Overall, blending increasing amounts of the last finisher feed with phase 3 nursery diet decreased ADG (linear, $P = 0.050$) and tended to decrease (linear, $P < 0.07$) ADFI and final body weight. However, there was no evidence for difference in overall G:F. In conclusion, blending finisher feed into the early nursery diets decreased overall ADG and ADFI; however, pigs greater than 11 kg had improved ability to compensate for the negative effects of blending the last finisher feed on overall growth performance. Nevertheless, increasing the amounts of finisher feed fed to 11-kg pigs from 0 to 3.75 kg/pig resulted in a linear decrease in overall ADG and ADFI. Economic analysis indicated no change in income-over-feed-cost due to the timing and dose of blending finisher feed into nursery diets.

Keywords: finisher feed, growth, nursery pig, wean-to-finish

INTRODUCTION

In a wean-to-finish pig production, one of the challenges in feed management is to determine what to do with feed remaining in the bin at the end of the finishing phase after pigs have been marketed. The precision of budgeting finisher feed based on predicted feed intake and closeout dates is not perfect. Thus, there is often feed remaining in the bins that must be removed and transported to another site or fed to the next group of pigs. However, in a wean-to-finish barn, the next group happens to be weanling pigs. One strategy is to remove the feed. However, this is time consuming and expensive if the feed is disposed. If the feed is transferred to another group of pigs this poses a biosecurity risk. Thus, a common strategy is to blend leftover finisher feed into the later stage nursery diets, which requires prolonged feed storage and may result in tandem blending of the early nursery phase diets. Therefore, information regarding the timing and maximum dose of the last finisher feed blended into nursery diets is needed to quantify and mitigate its negative effects. To address this problem, two experiments were designed to replicate a commercial production scenario where up to 7.5 metric tons of the last finisher diet was left in the bins at a 2,000-head barn; thus, up to 3.75 kg per pig of the last finisher feed would have to be fed to each nursery pig in the subsequent turn. Therefore, the objective of this study was to determine the effects of feeding finisher feed blended into different phases of nursery diet (experiment 1), and the dose effect of increasing the quantity of finisher feed blended (experiment 2), on nursery pig growth performance and production economics.

MATERIALS AND METHODS

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in these studies. The studies were conducted at New Fashion Pork's nursery research facility located in southwest Minnesota. Both of the experiments used two adjoining research rooms. Each room was equipped with 30 pens (2.59 × 5.56 m) that contained a 3-hole dry self-feeder and a cup waterer to allow ad libitum access to feed and water. Diets were manufactured at the New Fashion Pork feed mill located in Worthington, MN.

During each of the experiments, feed additions to each pen were delivered and recorded by a robotic feeding system (FeedPro; Feedlogic Corp., Wilmar, MN). Pens of pigs were weighed and feed disappearance measured every 7 days to determine average daily gain (ADG), average daily feed intake (ADFI), and gain:feed ratio (G:F).

Experiment 1

A total of 1,260 weaned pigs [initially 5.8 kg; PIC TR4 × (Fast LW × PIC L02); PIC, Hendersonville, TN, USA; Fast Genetics, Saskatoon, SK, Canada] were used. Pens of pigs (21 pigs per pen, 30 pens of barrows and 30 pens of gilts) were blocked by initial pen weight, gender, and room. Within blocks, pens were allotted randomly to 1 of 4 treatments with 15 replications per treatment. Pigs were fed commercial nursery diets in a 5-phase feeding program (Table 6.1) with phase changes made by using a prescribed feed budget (Table 6.2). Treatments consisted of a standard 5-phase nursery diet program (control) and the standard program with 2.5 kg/pig of a last finisher diet blended in phase 2, 3, or 4 diets. The finisher feed did not contain ractopamine. In the blended diets, feed delivery followed the sequence of 1.25 kg/pig of the finisher diet, then a 50:50% blend of the finisher and standard diet, and ended with the remaining allocation of the budgeted nursery diet.

Experiment 2

A total of 1,260 pigs [initially 10.6 kg; PIC TR4 × (Fast LW × PIC L02); PIC, Hendersonville, TN, USA; Fast Genetics, Saskatoon, SK, Canada] were used. Before the start of the experiment, newly weaned pigs were placed into pens with 21 pigs per pen and 30 pens per room. Barrows and gilts were mixed in a pen with a constant sex ratio balanced across pens. Pigs were fed commercial nursery diets in a 5-phase feeding program (Table 6.3) with phases 1 and 2 fed during the pre-treatment period. Phase changes were made again by using a feed budget (Table 6.4). At the beginning of phase 3 (d 0 of the experiment), pens of pigs were blocked by pen weight and room. The reason for selecting phase 3 to initiate this experiment was based on findings from experiment 1. Each room contained seven complete blocks and a 2-pen incomplete block (two incomplete blocks from the adjoining rooms formed a complete block). Within blocks, pens were allotted randomly to 1 of 4 treatments with 15 replications per treatment. Treatments consisted of a dose-titration of blending increasing amounts of the last finisher diet (0, 1.25, 2.50, and 3.75 kg per pig, corresponding to 0, 2.5, 5, and 7.5 metric tons of leftover finisher feed per 2,000-head barn, respectively) into the phase 3 nursery diet. The last finisher diet did not contain ractopamine. When the finisher feed was blended with nursery diet, feed delivery followed the sequence of: half of the finisher feed budget, a 50:50% blend the last finisher and phase 3 nursery diets and ended with the remaining budget of the phase 3 nursery diet.

Chemical Analysis

Nine feed samples (five standard nursery diets, one finisher diet, and three blended diets) from experiment 1 and seven feed samples (five nursery diets, one finisher diet, and one blended diet) from experiment 2 were collected directly from the feed robot delivery outlet. Feed samples were delivered to the Kansas State University Swine Laboratory, stored at -20°C until they were analyzed for dry matter, crude protein, and mineral content (Ward Laboratories, Inc., Kearney, NE). Standard procedures from AOAC (2006) were followed for analysis of moisture (Method 934.01) and crude protein (Method 990.03). To determine the moisture content, samples were weighed, dried to approximately 90% dry matter at 64 °C, and then mixed and ground through a 1 mm sieve, followed by another drying under 105 °C for 3 hours. Crude protein was calculated by multiplying N concentration by 6.25 in which percentage N was determined based on thermal conductivity with combustion method. Calcium, phosphorous, zinc, and copper concentrations were analyzed by iCAP 6000 series ICP Emission Spectrometer (Thermo Electron Corporation, Marietta, OH) using methods outlined by AOAC (2012).

Economic Analysis

Calculation of economics were based on a gain value of $1.32 per kg body weight (BW) and feed prices of $0.574, $0.495, $0.429, $0.327, $0.292, and $0.190 per kg of nursery phase 1, 2, 3, 4, 5, and last finisher diets, respectively. Feed prices consisted of costs for ingredients excluding manufacturing and delivery costs. Economic response variables included and were calculated using:

Feed cost = diet cost × feed consumption;

gain value = total BW gain × $1.32/kg;

feed cost per kg of gain = feed cost / (ADG × period length, d);

Income-over-feed-cost = gain value – feed cost.

Statistical Analysis

All data were analyzed using the GLIMMIX procedure of SAS (SAS Institute, Inc., Cary, NC) with pen as the experimental unit. The statistical models for experiment 1 included the fixed effect of treatment (blending phases) and the random effects of weight block, gender, and room. Means were reported as least-squares means and separated by the PDIFF option. For experiment 2, the statistical models included the fixed effect of treatment (finisher feed amount) and the random effects of weight block and room. Contrasts were used to determine the linear and quadratic effects of increasing finisher feed dose. Results were considered significant at $P < 0.05$ and marginally significant at $0.05 < P < 0.10$.

RESULTS

Diet Analysis, experiments 1 and 2

As expected, the finisher diet contained lower crude protein, Ca, and P concentrations than nursery diets (Table 6.5). Nutrient concentrations in blended diets approximated the average between the finisher diet and the corresponding nursery diet phase, indicating that diets were properly blended.

Experiment 1

From d 0 to 7, there were no differences in growth performance as expected ($P > 0.16$; Table 6.6) because all pigs received standard phase 1 diet. From d 7 to 14 (phase 2 diets), pigs that received finisher feed blended into the phase 2 diet had decreased ($P < 0.01$) ADG, ADFI, G:F, and d 14 BW compared with pigs in other treatment groups. From d 14 to 21, blending finisher feed into the phase 3 diet resulted in decreased ($P < 0.01$) ADG and G:F compared with other treatments, but no differences in ADFI were observed. Body weights of pigs fed the finisher diet blended into phase 2 or phase 3 were lower ($P < 0.05$) than pigs from control and phase 4 blending treatments on d 21.

Between d 21 and 28 the switch from the phase 3 to phase 4 budgets occurred in the majority of the pens. During this period, ADG for pigs fed finisher feed blended into the phase 3 or phase 4 diets was lower ($P < 0.05$) than that of pigs from control with phase 2 blending treatment intermediate. No evidence for differences in ADG among pigs from control and phase 2 blending treatment were observed. Pigs with finisher feed blended into the phase 3 diet had decreased ($P = 0.002$) ADFI compared with pigs from the phase 4 blending treatment with pigs from the control and phase 2 blending treatments having intermediate ADFI. Pigs receiving finisher feed blended into the phase 4 diet had poorer ($P < 0.01$) G:F than pigs from other treatments. Also, G:F of pigs from phase 2 blending treatment was lower ($P = 0.025$) than that of pigs from the control, but was not different from pigs from the phase 3 blending treatment. On d 28, BW of pigs fed finisher feed blended into the phase 2 or phase 3 diets was lower ($P < 0.05$) than those from control and phase 4 blending treatments.

From d 28 to 35, the majority of the pens were fed their phase 4 budgets with the diet change from phase 4 to 5 occurring at the end of this week. A marginal treatment effect ($P = 0.067$) was observed for ADG with pigs that had received finisher feed blended into the phase 2 diet having decreased ($P < 0.05$) ADG compared with pigs from other treatment groups. However, no evidence of differences in ADFI and G:F were observed. On d 35, BW of pigs that received finisher feed blended during phase 2 was decreased ($P < 0.01$) compared with those from control and phase 4 blending treatments, but was not different from pigs from phase 3 blending treatment. Pigs that received finisher feed blended into the phase 3 diet also had lower ($P = 0.013$) BW than pigs fed the control treatment. Pigs fed the last finisher diet blended into the phase 4 diet had similar BW compared with control pigs on d 35.

From d 35 to 47, all pigs were fed a standard phase 5 diet. Average daily gain was similar among treatments. Pigs fed finisher feed blended into the phase 2 or phase 3 diets had decreased ($P < 0.05$) ADFI compared with control pigs, but they were not different from pigs from phase 4 blending treatment. Gain:feed ratio increased ($P < 0.01$) in pigs that previously had finisher feed blended into their diets compared with the control. Pigs from phase 3 blending treatment also had better ($P = 0.020$) G:F than pigs from phase 4 blending treatment.

Overall, blending finisher diet during phase 2 resulted in decreased ($P < 0.05$) ADG, ADFI, and final body weight, but did not affect G:F compared with control pigs or pigs that had finisher diet blended into the nursery phase 4. No evidence for differences in growth performance were observed among pigs from control, phase 3 blending, and phase 4 blending treatments.

Blending the last finisher feed into phase 2 or 3 decreased ($P < 0.05$) feed cost relative to control pigs and pigs that received blended diet in phase 4, which can be explained by the slightly decreased overall feed intake and lower cost of the finisher diet (Table 6.7). The lower final BW also resulted in pigs that received the finisher diet treatment during phase 2 to have lower ($P < 0.05$) gain value than pigs from control and phase 4 blending treatments with blending of phase 3 diet intermediate. No treatment effect was observed for feed cost per kg of gain. Income-over-feed-cost was numerically decreased for pigs fed blended diets, and the magnitude is greater when pigs received the blended diet at a younger age; however, no statistically significant difference was detected.

Experiment 2

From d 0 to 14, feeding increasing finisher feed amounts tended to decrease (quadratic, $P < 0.09$) ADG and d 14 BW (Table 6.8). Average daily gain was unaffected as the last finisher diet quantity increased from 0 to 1.25 kg/pig but decreased thereafter. There was no strong evidence that ADFI was affected by feeding the finisher diet. However, G:F decreased (linear, $P < 0.001$) as more finisher feed was blended into the phase 3 nursery diet.

From d 14 to 28, pigs previously fed increasing finisher diet amounts had increased (linear, $P < 0.05$) ADG and G:F. Average daily feed intake was unaffected by the finisher feed quantity fed. Overall (d 0 to 28), blending increasing amounts of finisher feed with phase 3 nursery diet decreased ADG (linear, $P = 0.050$) and tended to decrease ADFI and final BW (linear, $P < 0.07$). However, there were no evidences of any linear or quadratic effects of increasing the quantity of finisher feed on overall G:F.

Feed cost, gain value, and feed cost per kg of gain decreased (linear, $P < 0.05$) as the quantity of finisher feed fed in phase 3 increased from 0 to 3.75 kg/pig (Table 6.9). However, no evidence of statistical differences in income-over-feed-cost was observed among treatments.

DISCUSSIONS

In a series of two experiments, we evaluated the feeding phase and dose of finisher feed fed to nursery pigs. To our knowledge, this is the first published study that offered a model for wean-to-finish production systems to evaluate the strategy of managing leftover finisher feed.

In experiment 1, blending the finisher diet in phase 2 decreased growth performance immediately and the negative effects persisted during the subsequent periods. The last finisher diet does not contain specialty protein ingredients and is less palatable, which may be responsible for a low ADFI when fed to young pigs. This is supported by many studies (Skinner et al., 2014; Collins et al., 2017; Tekeste et al., 2017) where reducing diet complexity has led to decreased growth performance during the early nursery phase. In addition, the last finisher diet is deficient in amino acids, calcium, and phosphorus concentrations for nursery pigs. These diets also contain growth-promoting levels of zinc, copper, and phytase. Lack of these nutrients has been reported to prevent nursery pigs from achieving maximum growth performance (Hill et al., 2000; Nemechek et al., 2018; Wu et al., 2018). It is worth noting that the last finisher feed used in the present study did not contain fibrous ingredients, such as distiller's dried grains with solubles and wheat middlings, or ractopamine; otherwise, more severe reduction in nursery growth responses may be expected.

When finisher feed was blended in phase 3 or phase 4, an immediate decrease in growth performance was also observed. However, these pigs were able to maintain or increase feed intake to compensate partly for the negative impact of consuming the finisher diet and, therefore, resumed growth performance to levels similar to the control faster and to a greater degree compared with those receiving the finisher diet during phase 2. Interestingly, pigs that previously received blended diets expressed greater G:F from d 35 to 47 compared with control pigs that never received any finisher feed, which might be a result of the decreased feed intake and compensatory gain.

According to the results from experiment 1, blending 2.5 kg finisher feed per pig into phase 3 nursery diet resulted in no observed impact on overall growth performance. The next question was to determine the maximum amount of the last finisher diet blended with phase 3 (initially 12 kg BW) nursery diets without affecting pig performance. Therefore, the second experiment was designed to characterize the dose-response to increasing the leftover finisher diet quantity. The doses evaluated ranged from 0 to 3.75 kg per pig (corresponding to 0 to 7.5 metric tons per 2,000-head barn) blended into nursery phase 3. Based on feed intake, pigs that were budgeted 1.25 kg/pig finisher feed had completed their finisher feed budgets by d 4. These pigs were able to fully compensate for any initial lost gain by d 14, but with a slightly poorer G:F, compared with those that did not receive finisher feed. However, pigs that received 2.50 and 3.75 kg/pig finisher feed completed their finisher feed budgets around d 8 and 11, respectively, and thus had less time for compensatory gain by the end of the first growth period (d 0 to 14).

Pigs that previously received finisher feed had compensatory growth during the second growth period (d 14 to 28), and the degree of compensation linearly related to the quantity of finisher feed fed previously. Compensatory growth after a short period of nutrient deficiency has been widely documented in nursery pigs. Stein and Kil (2006) and Nemechek et al. (2018) both reported that pigs that received early nursery diets with deficient amino acids (or crude protein), but late nursery diets with adequate nutrients, were able to fully compensate for overall ADG with unaffected, or even improved, G:F. Although the mechanism behind compensatory growth is not fully understood, Prince et al. (1983) and Kamalakar et al. (2009) suggested that the magnitude of compensatory gain may be influenced by the degree of amino acid restriction and the length of time that pigs are subjected to the restriction. In the present study, pigs that received 2.50 or 3.75 kg/pig finisher feed might have experienced prolonged nutrient deficiency and, therefore, had decreased overall ADG and ADFI compared with those allocated 0 or 1.25 kg/pig finisher feed.

In summary, growth performance of nursery pigs was promptly influenced when fed the last finisher feed blended into nursery diets, and its magnitude of change depended on which phase the finisher feed was blended into. When BW was greater than 11 kg (phase 3 in the present study), pigs had improved ability to compensate for the negative effects of feeding finisher feed on overall ADG and ADFI. However, increasing the amounts of finisher feed fed to 11-kg pigs resulted in a linear decrease in overall ADG and ADFI.

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TABLES

Table 6.1. Composition of experimental diets (as-fed basis; experiment 1)[1]

Items	Phase 2	Phase 3	Phase 4	Phase 5	Finisher
Ingredients, %					
Corn	43.14	39.27	37.07	38.39	79.00
Soybean meal (48% crude protein)	23.75	27.05	32.60	29.30	14.75
Corn distiller's dried grains with solubles	7.50	15.00	20.00	25.00	-
Whey permeate	4.58	2.91	-	-	-
Steamed-rolled oats	3.93	2.49	-	-	-
Corn gluten meal	0.95	0.60	-	-	-
Yeast protein meal[2]	2.24	1.43	-	-	-
Enzymatically-treated soy product[3]	1.65	1.05	-	-	-
Limestone	0.85	1.05	1.05	1.28	0.70
Monocalcium phosphate (22% P)	0.84	0.83	0.60	0.65	0.15
Sodium chloride	0.35	0.38	0.26	0.31	0.53
Vitamin and mineral premix	0.08[4]	0.10[4]	0.15[4]	0.15[4]	0.10[5]
L-lysine HCl	0.55	0.55	0.46	0.49	0.35
L-threonine	0.20	0.18	0.12	0.12	0.12
L-tryptophan	0.07	0.07	0.05	0.05	0.02
DL-methionine	0.07	0.10	0.17	0.14	0.08
L-valine	0.09	0.06	-	-	-
L-isoleucine	0.04	0.03	-	-	-
Choline chloride	0.01	-	-	-	-
Beef tallow	1.95	2.95	4.45	3.60	3.85
Vegetable oil	0.88	0.56	-	-	-
Phytase[6]	0.04	0.04	0.02	0.02	-
AV-E Digest[7]	5.00	2.50	2.50	-	-
XFE Liquid Energy[8]	-	-	0.50	0.50	0.25
Tri-basic copper chloride	0.01	0.04	-	-	-
Zinc oxide	0.32	0.21	-	-	-
Other additives	0.91	0.58	-	-	0.10
Total	100.00	100.00	100.00	100.00	100.00
Calculated analysis					
Standardized ileal digestible amino acids, %					
Lysine	1.40	1.40	1.41	1.32	0.81
Isoleucine:lysine	57	58	62	62	56
Methionine and cysteine:lysine	58	58	58	58	60
Threonine:lysine	63	63	62	62	66
Tryptophan:lysine	20	20	20	20	18
Valine:lysine	67	67	68	68	66
Total lysine, %	1.56	1.56	1.58	1.48	0.89
Crude protein, %	22.10	22.78	24.18	22.84	12.45
Net energy, kcal/kg	2,295	2,385	2,469	2,491	2,712
Calcium, %	0.78	0.78	0.75	0.75	0.37

Phosphorus, %	0.71	0.71	0.68	0.68	0.34
Available phosphorus, %	0.43	0.43	0.45	0.45	0.19

[1] Phase 1 diet formulation is not available.

[2] ProPlex DY (ADM Animal Nutrition, Quincy, IL).

[3] HP 300 (Hamlet Protein, Inc., Findlay, OH).

[4] Provided per kg of premix: 3,933,333 IU vitamin A, 266,667 IU vitamin D_3, 440,920 IU vitamin D, 26,455 IU vitamin E, 1,609 mg vitamin K, 5,512 mg riboflavin, 13,228 mg pantothenic acid, 17,637 mg niacin, 16,169 mcg vitamin B_{12}, 39,683 ppm Mn, 111,700 ppm Fe, 132,276 ppm Zn, 220,460 ppm Cu, 558 ppm I, and 441 ppm Se.

[5] Provided per kg of premix: 4,739,890 IU vitamin A, 250,000 IU vitamin D_3, 485,012 IU vitamin D, 33,069 IU vitamin E, 2,094 mg vitamin K, 4,409 mg riboflavin, 15,432 mg pantothenic acid, 22,046 mg niacin, 16,535 mcg vitamin B_{12}, 59,524 ppm Mn, 143,299 ppm Fe, 198,414 ppm Zn, 330,690 ppm Cu, 441 ppm I, and 661 ppm Se.

[6] Ronozyme HiPhos (DSM Nutritional Products, Inc., Parsippany, NJ).

[7] AV-E Digest (XFE Products, Des Moines, IA).

[8] Liquid Energy (XFE Products, Des Moines, IA).

Table 6.2. Feed budgets (kg per pig) of treatments (experiment 1)

Phase	Control	Blended diets[1]		
		Phase 2	Phase 3	Phase 4
Phase 1	2.48 (2.41)[2]	2.48 (2.37)	2.48 (2.60)	2.48 (2.70)
Phase 2	3.66 (3.72)	1.25 (1.21) last finisher diet, 2.50 (2.25) 50:50% blend, 2.50 (2.28) standard phase 2	3.66 (3.73)	3.66 (3.72)
Phase 3	3.66 (3.70)	3.66 (3.71)	1.25 (1.30) last finisher diet, 2.50 (2.48) 50:50% blend, 2.50 (2.53) standard phase 3	3.66 (3.72)
Phase 4	9.53 (9.33)	9.53 (9.30)	9.53 (9.42)	1.25 (1.30) last finisher diet, 2.50 (2.46) 50:50% blend, 8.28 (8.11) standard phase 4
Phase 5	9.53 (15.22)	7.03 (12.07)	7.03 (11.64)	7.03 (12.25)

[1] Finisher feed was blended with standard nursery diets in different phases; blended diets were delivered in the sequence of: finisher feed, 50% finisher and 50% standard blended diet, and standard diet.

[2] Values in the parenthesis indicate the actual amount (kg per pig) of diet consumed.

Table 6.3. Composition of experimental diets (as-fed basis; experiment 2)[1]

Items	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Finisher
Ingredients, %						
Corn	41.47	44.45	40.13	44.75	45.53	80.77
Soybean meal (48% crude protein)	16.30	23.05	26.00	29.20	27.15	14.90
Corn DDGS[2]	5.00	7.50	15.00	16.75	20.00	-
Spray dried whey	5.50	-	-	-	-	-
Whey permeate	5.82	4.37	2.91	-	-	-
Steamed-rolled oats	4.99	3.74	2.49	-	-	-
Corn gluten meal	1.20	0.90	0.60	-	-	-
Yeast protein meal[3]	2.85	2.14	1.43	-	-	-
Enzymatically-treated soy product[4]	2.10	1.58	1.05	-	-	-
Limestone	0.67	0.84	0.10	-	1.30	0.88
Monocalcium phosphate (22% P)	0.45	0.68	-	0.15	1.03	0.40
Sodium chloride	0.38	0.38	-	0.03	0.34	0.43
Vitamin and mineral premix[5]	0.30[5]	0.30[5]	0.30[5]	0.15[5]	0.15[5]	0.10[6]
Nursery mineral premix	-	-	2.50	2.50	-	-
L-lysine HCl	0.56	0.57	0.22	0.18	0.54	0.28
L-threonine	0.20	0.22	0.20	0.17	0.17	0.11
L-tryptophan	0.07	0.06	0.06	0.04	0.03	0.03
DL-methionine	0.14	0.14	0.16	0.22	0.21	0.05
L-valine	0.12	0.09	0.06	0.06	0.08	-
L-isoleucine	0.05	0.04	0.03	-	-	-
Choline chloride	0.04	0.01	-	-	-	-
Phytase[7]	-	-	-	-	0.07	-
Protease[8]	-	-	-	0.05	0.05	-
AV-E Digest[9]	7.50	5.00	2.50	2.50	-	-
XFE Liquid Energy[10]	0.75	-	-	0.75	0.75	0.75
Choice white grease	0.85	1.90	2.90	2.50	2.60	1.20
Vegetable oil	1.12	0.84	0.56	-	-	-
Tri-basic copper chloride	0.01	0.03	0.01	-	-	-
Zinc oxide	0.41	0.31	0.21	-	-	-
Other additives	1.15	0.86	0.58	-	-	0.10
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis						
Standardized ileal digestible amino acids, %						
Lysine	1.35	1.40	1.40	1.38	1.32	0.74
Isoleusine:lysine	0.58	0.57	0.58	0.57	0.56	0.57
Methionine and Cystein:lysine	0.62	0.58	0.58	0.58	0.58	0.56
Threonine:lysine	0.63	0.63	0.63	0.62	0.62	0.66
Tryptophan:lysine	0.20	0.19	0.19	0.19	0.18	0.20
Valine:lysine	0.69	0.67	0.66	0.67	0.68	0.65
Total lysine, %	1.51	1.56	1.56	1.55	1.47	0.82
Crude protein, %	21.30	22.27	22.94	22.99	21.73	12.74
Net energy, kcal/kg	2,412	2,443	2,476	2,535	2,535	2,601
Calcium, %	0.70	0.71	0.73	0.79	0.77	0.46
Phosphorus, %	0.64	0.65	0.66	0.68	0.67	0.40
Available phosphorus, %	0.45	0.43	0.43	0.45	0.45	0.24

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[1] Phases 1 and 2 diets were fed before the start of experiment.

[2] Distiller's dried grains with solubles.

[3] ProPlex DY (ADM Animal Nutrition, Quincy, IL).

[4] HP 300 (Hamlet Protein, Inc., Findlay, OH).

[5] Provided per kg of premix: 3,933,333 IU vitamin A, 266,667 IU vitamin D_3, 440,920 IU vitamin D, 26,455 IU vitamin E, 1,609 mg vitamin K, 5,512 mg riboflavin, 13,228 mg pantothenic acid, 17,637 mg niacin, 16,169 mcg vitamin B_{12}, 39,683 ppm Mn, 111,700 ppm Fe, 132,276 ppm Zn, 220,460 ppm Cu, 558 ppm I, and 441 ppm Se.

[6] Provided per kg of premix: 4,739,890 IU vitamin A, 250,000 IU vitamin D_3, 485,012 IU vitamin D, 33,069 IU vitamin E, 2,094 mg vitamin K, 4,409 mg riboflavin, 15,432 mg pantothenic acid, 22,046 mg niacin, 16,535 mcg vitamin B_{12}, 59,524 ppm Mn, 143,299 ppm Fe, 198,414 ppm Zn, 330,690 ppm Cu, 441 ppm I, and 661 ppm Se.

[7] Ronozyme HiPhos (DSM Nutritional Products, Inc., Parsippany, NJ).

[8] CIBENZA® DP100 (Novus International, Saint Charles, MO)

[9] AV-E Digest (XFE Products, Des Moines, IA).

[10] Liquid Energy (XFE Products, Des Moines, IA).

Table 6.4. Feed budgets (kg per pig) of treatments (experiment 2)

	Finisher feed budget[1], kg/pig			
Phase	0	1.25	2.50	3.75
Phase 1	2.48 (2.54)[2]			
Phase 2	2.00 (1.78)			
Phase 3	3.74 (3.93)	0.63 (0.74) last finisher diet, 1.25 (1.36) 50:50% blend, 3.12 (3.21) standard phase 3	1.25 (1.37) last finisher diet, 2.50 (2.71) 50:50% blend, 2.50 (2.59) standard phase 3	1.87 (1.99) last finisher diet, 3.74 (3.90) 50:50% blend, 1.87 (1.02) standard phase 3
Phase 4	9.53 (10.11)	9.53 (9.65)	9.53 (9.74)	9.53 (9.82)
Phase 5	9.53 (7.67)	8.28 (7.33)	7.03 (4.57)	5.78 (4.01)

[1] The budgeted amount of finisher diet was blended into phase 3 nursery diet; blended diets were delivered in the sequence of: finisher feed, 50% finisher and 50% standard blended diet, and standard diet.

[2] Values in the parenthesis indicate the actual amount (kg per pig) of diet consumed.

Table 6.5. Analyzed nutrient composition of experimental diets[1]

	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Finisher	50% Phase 2: 50% finisher blend	50% Phase 3: 50% finisher blend	50% Phase 4: 50% finisher blend
Experiment 1									
Dry matter, %	89.2	89.6	89.1	88.5	87.2	87.8	88.5	88.7	87.7
Crude protein, %	22.3	23.8	23.8	24.5	19.1	13.6	19.2	18.5	18.8
Calcium, %	1.02	1.01	0.95	0.96	0.87	0.62	0.80	0.87	0.79
Phosphorous, %	0.71	0.88	0.70	0.70	0.52	0.31	0.53	0.54	0.49
Zinc, ppm	2,335	3,466	1,733	151	117	114	1,529	821	137
Copper, ppm	88	209	246	186	141	155	219	184	185
Experiment 2									
Dry matter, %	90.0	90.8	90.1	88.4	88.7	88.5	-	89.4	-
Crude protein, %	20.2	21.8	23.3	23.4	23.0	14.5	-	18.8	-
Calcium, %	0.97	1.12	1.03	0.73	1.01	1.18	-	1.06	-
Phosphorous, %	0.54	0.55	0.63	0.64	0.69	0.45	-	0.53	-
Zinc, ppm	2,605	2,169	2,260	265	169	123	-	847	-
Copper, ppm	100	216	215	98	155	135	-	135	-

[1] Multiple samples of each diet were collected, blended and subsampled, and analyzed (Ward Laboratories, Inc., Kearney, NE).

Table 6.6. Effects of blending finisher feed into different phases of nursery diets on growth performance (experiment 1)[1]

		Blended diets[2]				
	Control	Phase 2	Phase 3	Phase 4	SEM	*P*-value
Body weight, kg						
d 0	5.8	5.8	5.8	5.8	0.05	0.984
d 7	7.0	7.1	7.0	7.0	0.07	0.979
d 14	9.8^{a}	9.4^{b}	9.9^{a}	9.9^{a}	0.13	0.001
d 21	12.7^{a}	12.2^{b}	12.3^{b}	12.8^{a}	0.16	0.001
d 28	16.2^{a}	15.5^{b}	15.5^{b}	16.0^{a}	0.17	0.001
d 35	20.8^{a}	19.8^{c}	20.1^{bc}	20.6^{ab}	0.22	0.003
d 47	30.0^{a}	29.1^{b}	29.4^{ab}	29.9^{a}	0.26	0.017
d 0 to 7						
ADG, g	174	176	169	171	8.5	0.880
ADFI, g	174	164	171	179	6.4	0.368
G:F, g/kg	1026	1097	1004	947	54.5	0.161
d 7 to 14						
ADG, g	398^{a}	329^{b}	405^{a}	415^{a}	11.9	0.001
ADFI, g	448^{a}	412^{b}	446^{a}	459^{a}	13.1	0.002
G:F, g/kg	886^{a}	804^{b}	907^{a}	905^{a}	13.7	0.001
d 14 to 21						
ADG, g	414^{a}	402^{a}	346^{b}	409^{a}	10.9	0.001
ADFI, g	560	556	556	559	10.9	0.991
G:F, g/kg	741^{a}	722^{a}	622^{b}	733^{a}	15.8	0.001
d 21 to 28						
ADG, g	498^{a}	475^{ab}	467^{b}	454^{b}	8.1	0.003
ADFI, g	655^{ab}	653^{ab}	631^{b}	673^{a}	9.3	0.018
G:F, g/kg	762^{a}	728^{b}	741^{ab}	674^{c}	9.9	0.001
d 28 to 35						
ADG, g	648^{a}	616^{b}	648^{a}	647^{a}	10.5	0.067
ADFI, g	884	868	884	913	15.7	0.235
G:F, g/kg	734	712	735	709	10.3	0.146
d 35 to 47						
ADG, g	769	768	780	776	8.3	0.644
ADFI, g	1298^{a}	1246^{b}	1254^{b}	1276^{ab}	15.6	0.048
G:F, g/kg	594^{c}	616^{ab}	623^{a}	608^{b}	4.3	0.001
d 0 to 47						
ADG, g	514^{a}	493^{b}	502^{ab}	509^{a}	5.4	0.031
ADFI, g	736^{a}	711^{b}	720^{ab}	738^{a}	8.3	0.045
G:F, g/kg	699	693	698	690	3.6	0.132

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[1] A total of 1,260 weaned pigs [PIC TR4 × (Fast LW × PIC L02); PIC, Hendersonville, TN, USA; Fast Genetics, Saskatoon, SK, Canada] were used in a 47-day growth trial with 21 pigs per pen and 15 replications (pen) per treatment. Growth responses include average daily gain (ADG), average daily feed intake (ADFI), and gain:feed ratio (G:F).

[2] Approximately 2.5 kg/pig of finisher feed was blended with standard nursery diets at the beginning of different phases (as feed budgets presented in Table 2).

[abc] Means with different superscripts within a row differ ($P < 0.05$).

Table 6.7. Effects of blending finisher feed into different phases of nursery diets on production economics (experiment 1)[1]

		Blended diets[2]				
Item	Control	Phase 2	Phase 3	Phase 4	SEM	*P*-value
Economics, $/pig						
Feed cost[3]	12.37^{a}	11.74^{b}	12.01^{b}	12.39^{a}	0.134	<0.001
Gain value[4]	31.95^{a}	30.64^{b}	31.18^{ab}	31.64^{a}	0.334	0.031
Feed cost/kg gain[5]	0.511	0.509	0.507	0.516	0.0044	0.410
IOFC[6]	19.58	18.89	19.16	19.26	0.261	0.317

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[1] A total of 1,260 weaned pigs [PIC TR4 × (Fast LW × PIC L02); PIC, Hendersonville, TN, USA; Fast Genetics, Saskatoon, SK, Canada] with initial body weight of 5.9 kg were used in a 47-day growth trial with 21 pigs per pen and 15 replications (pen) per treatment.

[2] Approximately 2.5 kg/pig of finisher feed was blended with standard nursery diets at the beginning of different phases (as feed budgets presented in Table 2).

[3] Feed cost = diet cost × feed consumption.

[4] Gain value = total body weight gain × $1.32/kg.

[5] Feed cost per kg of gain = feed cost / (average daily gain × period length, d).

[6] Income-over-feed-cost = gain value – feed cost.

[ab] Means with different superscripts within a row differ ($P < 0.05$).

Table 6.8. Effects of blending increasing doses of finisher feed into nursery diets on growth performance (experiment 2)[1]

	Finisher feed budget[2], kg/pig					*P*-value, <	
Item	0	1.25	2.50	3.75	SEM	Linear	Quadratic
Body weight, kg							
d 0	10.6	10.6	10.6	10.5	0.18	0.828	0.817
d 14	16.5	16.6	16.1	15.7	0.25	0.001	0.087
d 28	25.1	25.3	25.0	24.7	0.35	0.068	0.195
d 0 to 14							
ADG, g	426	432	395	368	10.9	0.001	0.090
ADFI, g	575	601	566	554	16.2	0.105	0.169
G:F, g/kg	741	722	699	664	9.6	0.001	0.418
d 14 to 28							
ADG, g	612	620	630	638	12.2	0.029	0.993
ADFI, g	980	994	949	960	23.5	0.175	0.947
G:F, g/kg	624	626	667	667	8.6	0.001	0.934
d 0 to 28							
ADG, g	518	526	512	502	8.4	0.050	0.216
ADFI, g	777	797	756	755	14.8	0.052	0.367
G:F, g/kg	668	661	678	666	4.7	0.566	0.535

[1] A total of 1,260 weaned pigs [PIC TR4 × (Fast LW × PIC L02); PIC, Hendersonville, TN, USA; Fast Genetics, Saskatoon, SK, Canada] were used in a 28-day growth trial with 21 pigs per pen and 15 replications (pen) per treatment. Growth responses include average daily gain (ADG), average daily feed intake (ADFI), and gain:feed ratio (G:F).

[2] The budgeted amounts of finisher feed blended into phase 3 nursery diet.

Table 6.9. Effects of blending increasing does of finisher feed into nursery diets on production economics (experiment 2)[1]

	Finisher feed budget[2], kg/pig					*P*-value, <	
Item	0	1.25	2.50	3.75	SEM	Linear	Quadratic
Economics, \$/pig							
Feed cost[3]	7.23	7.24	6.73	6.40	0.135	0.001	0.113
Gain value[4]	19.19	19.49	18.95	18.59	0.313	0.050	0.215
Feed cost/kg gain[5]	0.499	0.491	0.469	0.454	0.0041	0.001	0.289
IOFC[6]	11.96	12.25	12.22	12.20	0.1983	0.384	0.380

[1] A total of 1,260 weaned pigs [PIC TR4 × (Fast LW × PIC L02); PIC, Hendersonville, TN, USA; Fast Genetics, Saskatoon, SK, Canada] with initial body wegiht of 10.6 kg were used in a 28-day growth trial with 21 pigs per pen and 15 replications (pen) per treatment.

[2] The budgeted amounts of finisher feed blended into phase 3 nursery diet.

[3] Feed cost = diet cost × feed consumption.

[4] Gain value = total body wegiht gain × \$1.32/kg.

[5] Feed cost per kg of gain = feed cost / (average daily gain × period length, d).

[6] Income-over-feed-cost = gain value – feed cost.

Appendix A - Supplementary material for Chapter 5

Code for statistical analysis

Nursery ADG

```
mixed adg fill avg_dof mortality sowfarm i.sysflow i.size i.year i.startwk ///
i.sysflow#c.fill i.sysflow#c.avg_dof i.sysflow#c.mortality i.sysflow#i.year ///
i.size#c.sowfarm i.size#i.year ///
|| site: || closeout: vargrp, nocons base reml dfmethod(kroger)
estat ic
```

Nursery ADFI

```
mixed adfi fill avg_dof mortality sowfarm i.sysflow i.size i.feeder i.year i.startwk ///
i.sysflow#c.fill i.sysflow#c.avg_dof i.sysflow#c.mortality i.sysflow#i.size i.sysflow#i.year ///
i.size#c.fill i.size#c.sowfarm ///
|| site: || closeout: vargrp, nocons base reml dfmethod(kroger)
estat ic
```

Nursery G:F

```
mixed gf avg_dof mortality i.sysflow i.feeder i.year ///
i.sysflow#c.avg_dof i.sysflow#c.mortality i.sysflow#i.year ///
|| site: || closeout: vargrp, nocons base reml dfmethod(kroger)
estat ic
```

Finisher ADG

```
mixed adg startwt mortality sowfarm NE i.system i.flow i.size i.feeder i.year i.startwk ///
i.system#c.startwt i.system#c.mortality i.system#c.sowfarm i.system#i.flow i.system#i.size
i.system#i.feeder i.system#i.year i.system#i.startwk ///
```

```
i.flow#c.startwt i.flow#c.mortality i.flow#c.NE i.flow#i.year ///
i.size#c.sowfarm ///
|| site: || closeout: vargrp, nocons base reml dfmethod(kroger)
estat ic
```

Finisher ADFI

```
mixed adfi fill startwt mortality sowfarm NE i.system i.flow i.size i.feeder i.year i.startwk ///
i.system#c.fill i.system#c.startwt i.system#c.sowfarm i.system#c.NE i.system#i.flow
i.system#i.size i.system#i.feeder i.system#i.year i.system#i.startwk ///
i.flow#c.fill i.flow#c.mortality i.flow#c.sowfarm i.flow#c.NE i.flow#i.year ///
i.size#c.fill i.size#c.sowfarm i.size#i.feeder ///
|| site: || closeout: vargrp, nocons base reml dfmethod(kroger)
estat ic
```

Finisher G:F

```
mixed gf fill startwt mortality sowfarm NE i.system i.flow i.size i.year i.startwk ///
i.system#c.fill i.system#c.startwt i.system#c.mortality i.system#c.NE i.system#i.flow
i.system#i.size i.system#i.year i.system#i.startwk ///
i.flow#c.sowfarm i.flow#i.size  ///
i.size#c.mortality i.size#c.sowfarm ///
|| site: || closeout: vargrp, nocons base reml dfmethod(kroger)
estat ic
```

Table A.10. List of variables and corresponding codes and descriptions used in multi-level linear mixed models for nursery and finisher ADG, ADFI, and G:F in three swine production systems located in the midwestern United States from January 2013 to December 2017

Variable	**Code**	**Description**
Year	year	2013-2017
System	system	-
Pig flow	flow	Converted-nursery, Nursery, WF_nursery; Finisher, WF_finisher
System-pigflow	sysflow	One-way factor merged from system and flow variables
Site	site	-
Batch	closeout	-
Batch size	size	Size of closeouts based on head counts
Feeder	feeder	Dry, tube, wet-dry
Dietary NE, kcal/kg	NE	Dietary net energy
DOF	avg_dof	Average days on feed
Fill length	fill	Length of fill period (continuous)
Sowfarm	sowfarm	Number of sowfarms souces (continuous)
Initial BW, kg	startwt	Average initial body weight
Final BW, kg	finalwt	Average final body weight
Mortality, %	mortality	-
ADG, g	adg	Average daily gain
ADFI, g	adfi	Average daily feed intake
G:F, g/kg	gf	Gain:feed ratio

WF = wean-to-finish; NE = net energy; DOF = days on feed; BW = body weight; ADG = average daily gain; ADFI = average daily feed intake; G:F = gain to feed ratio.

Table A.11. Parameter coefficients and statistics for nursery ADG

ADG	**Coefficient**	**SE**	***t***	***P* > *t***	**95% LCL**	**95% UCL**
fill	0.517	0.436	1.190	0.236	-0.338	1.372
average_DOF	3.845	0.226	17.030	0.000	3.402	4.288
mortality	-3.959	0.316	-12.530	0.000	-4.579	-3.339
sowfarm	-5.060	1.000	-5.060	0.000	-7.022	-3.099
sysflow						
A-Converted-Nursery	0.000	(base)				
A-Nursery	100.445	17.887	5.620	0.000	65.372	135.518
A-WF_nursery	142.460	16.725	8.520	0.000	109.663	175.256
B-Nursery	86.569	19.339	4.480	0.000	48.656	124.482
B-WF_nursery	111.032	22.433	4.950	0.000	67.053	155.012
C-Nursery	98.926	18.367	5.390	0.000	62.918	134.935
C-WF_nursery	70.956	19.518	3.640	0.000	32.692	109.221
size						
3000 - 6000 pigs	0.000	(base)				
< 3000	10.589	5.323	1.990	0.047	0.152	21.025
> 6000	-16.441	4.715	-3.490	0.000	-25.685	-7.196
year						
2013	0.000	(base)				
2014	-2.867	6.148	-0.470	0.641	-14.923	9.188
2015	-14.673	6.247	-2.350	0.019	-26.922	-2.424
2016	-7.128	7.563	-0.940	0.346	-21.958	7.701
2017	-34.449	9.381	-3.670	0.000	-52.845	-16.053
startwk						
1	0.000	(base)				
2	-4.710	6.826	-0.690	0.490	-18.092	8.672
3	-9.488	6.472	-1.470	0.143	-22.177	3.201
4	-9.840	6.926	-1.420	0.155	-23.419	3.739
5	-2.086	6.774	-0.310	0.758	-15.367	11.194
6	-4.051	6.748	-0.600	0.548	-17.280	9.178
7	-6.241	6.833	-0.910	0.361	-19.638	7.156
8	-12.170	6.737	-1.810	0.071	-25.378	1.038
9	-7.757	6.642	-1.170	0.243	-20.778	5.264
10	-10.312	6.744	-1.530	0.126	-23.533	2.909
11	-12.181	6.868	-1.770	0.076	-25.646	1.284
12	-10.680	6.566	-1.630	0.104	-23.553	2.193
13	-20.146	6.494	-3.100	0.002	-32.878	-7.414
14	-12.540	6.788	-1.850	0.065	-25.848	0.767
15	-21.015	6.521	-3.220	0.001	-33.799	-8.230
16	-16.837	6.725	-2.500	0.012	-30.022	-3.653
17	-18.471	6.867	-2.690	0.007	-31.934	-5.007
18	-14.293	6.543	-2.180	0.029	-27.121	-1.465
19	-24.281	6.648	-3.650	0.000	-37.315	-11.248
20	-16.061	6.898	-2.330	0.020	-29.584	-2.538
21	-14.540	6.587	-2.210	0.027	-27.453	-1.626
22	-19.505	6.753	-2.890	0.004	-32.746	-6.265

23	-14.097	6.607	-2.130	0.033	-27.050	-1.143
24	-16.386	6.542	-2.500	0.012	-29.211	-3.560
25	-14.614	6.652	-2.200	0.028	-27.656	-1.572
26	-10.996	6.730	-1.630	0.102	-24.190	2.198
27	-7.732	6.419	-1.200	0.228	-20.317	4.853
28	-13.189	6.757	-1.950	0.051	-26.436	0.058
29	-12.323	6.421	-1.920	0.055	-24.910	0.265
30	-13.006	6.677	-1.950	0.052	-26.097	0.085
31	-9.933	6.714	-1.480	0.139	-23.095	3.230
32	-4.330	6.482	-0.670	0.504	-17.038	8.378
33	-12.693	6.737	-1.880	0.060	-25.901	0.515
34	-3.888	6.615	-0.590	0.557	-16.856	9.080
35	-9.615	6.720	-1.430	0.153	-22.790	3.559
36	-12.100	6.411	-1.890	0.059	-24.670	0.470
37	-11.734	6.739	-1.740	0.082	-24.946	1.477
38	-6.088	6.561	-0.930	0.353	-18.951	6.774
39	-15.076	6.454	-2.340	0.020	-27.729	-2.423
40	-7.296	6.666	-1.090	0.274	-20.365	5.774
41	-3.251	6.433	-0.510	0.613	-15.863	9.361
42	-12.542	6.798	-1.840	0.065	-25.870	0.787
43	-2.534	6.535	-0.390	0.698	-15.347	10.279
44	-11.594	6.746	-1.720	0.086	-24.819	1.632
45	5.455	7.014	0.780	0.437	-8.296	19.206
46	-9.719	6.574	-1.480	0.139	-22.608	3.169
47	-2.559	6.419	-0.400	0.690	-15.143	10.025
48	-8.323	6.739	-1.240	0.217	-21.536	4.889
49	-7.153	6.999	-1.020	0.307	-20.876	6.569
50	-3.214	6.779	-0.470	0.636	-16.505	10.078
51	-3.377	6.628	-0.510	0.610	-16.373	9.618
52	-4.584	6.449	-0.710	0.477	-17.228	8.060
sysflow#c.fill						
A-Nursery	0.266	0.498	0.530	0.593	-0.711	1.243
A-WF_nursery	0.779	0.487	1.600	0.109	-0.175	1.733
B-Nursery	-1.874	0.544	-3.440	0.001	-2.940	-0.807
B-WF_nursery	-1.438	0.656	-2.190	0.028	-2.724	-0.152
C-Nursery	-0.270	0.633	-0.430	0.669	-1.511	0.971
C-WF_nursery	-0.312	0.624	-0.500	0.617	-1.535	0.911
sysflow#c.avg_DOF						
A-Nursery	-1.639	0.308	-5.330	0.000	-2.242	-1.036
A-WF_nursery	-2.207	0.259	-8.520	0.000	-2.715	-1.699
B-Nursery	0.061	0.341	0.180	0.858	-0.608	0.730
B-WF_nursery	-0.090	0.354	-0.250	0.800	-0.785	0.605
C-Nursery	-0.168	0.342	-0.490	0.624	-0.839	0.503
C-WF_nursery	0.445	0.341	1.300	0.192	-0.223	1.113
sysflow#c.mortality						
A-Nursery	1.554	0.548	2.840	0.005	0.480	2.628
A-WF_nursery	0.382	0.436	0.880	0.381	-0.473	1.237
B-Nursery	-1.104	0.581	-1.900	0.057	-2.242	0.034
B-WF_nursery	-5.405	1.257	-4.300	0.000	-7.869	-2.942

C-Nursery	-6.235	0.575	-10.840	0.000	-7.363	-5.108
C-WF_nursery	-5.529	0.523	-10.580	0.000	-6.554	-4.505
sysflow#year						
A-Nursery#2014	-13.915	9.407	-1.480	0.139	-32.359	4.529
A-Nursery#2015	-14.504	9.010	-1.610	0.108	-32.170	3.161
A-Nursery#2016	-35.093	9.969	-3.520	0.000	-54.639	-15.546
A-Nursery#2017	0.991	11.263	0.090	0.930	-21.094	23.077
A-WF_nursery#2014	5.343	8.724	0.610	0.540	-11.764	22.449
A-WF_nursery#2015	19.364	8.343	2.320	0.020	3.005	35.724
A-WF_nursery#2016	-1.733	8.965	-0.190	0.847	-19.312	15.846
A-WF_nursery#2017	3.730	10.607	0.350	0.725	-17.068	24.529
B-Nursery#2014	2.121	7.630	0.280	0.781	-12.837	17.080
B-Nursery#2015	10.004	7.737	1.290	0.196	-5.165	25.172
B-Nursery#2016	6.295	8.846	0.710	0.477	-11.047	23.637
B-Nursery#2017	48.058	10.370	4.630	0.000	27.727	68.390
B-WF_nursery#2014	-8.347	9.114	-0.920	0.360	-26.214	9.521
B-WF_nursery#2015	7.675	9.118	0.840	0.400	-10.200	25.551
B-WF_nursery#2016	9.846	10.206	0.960	0.335	-10.162	29.854
B-WF_nursery#2017	53.614	11.604	4.620	0.000	30.865	76.363
C-Nursery#2014	-10.391	8.682	-1.200	0.231	-27.411	6.629
C-Nursery#2015	-7.852	8.731	-0.900	0.369	-24.969	9.265
C-Nursery#2016	-7.356	9.682	-0.760	0.447	-26.337	11.625
C-Nursery#2017	33.872	10.899	3.110	0.002	12.503	55.240
C-WF_nursery#2014	-7.381	8.189	-0.900	0.367	-23.436	8.674
C-WF_nursery#2015	-6.175	8.168	-0.760	0.450	-22.187	9.838
C-WF_nursery#2016	-6.873	9.190	-0.750	0.455	-24.889	11.143
C-WF_nursery#2017	28.294	10.885	2.600	0.009	6.953	49.634
size#c.sowfarm						
< 3000	-8.088	2.541	-3.180	0.001	-13.072	-3.105
> 6000	2.857	1.198	2.380	0.017	0.507	5.206
size#year						
< 3000#2014	3.266	5.823	0.560	0.575	-8.150	14.682
< 3000#2015	9.668	5.788	1.670	0.095	-1.680	21.016
< 3000#2016	-3.193	5.818	-0.550	0.583	-14.599	8.214
< 3000#2017	-13.305	5.742	-2.320	0.021	-24.562	-2.048
> 6000#2014	6.963	5.030	1.380	0.166	-2.898	16.825
> 6000#2015	5.401	4.865	1.110	0.267	-4.136	14.938
> 6000#2016	0.332	4.775	0.070	0.945	-9.030	9.694
> 6000#2017	-8.695	4.716	-1.840	0.065	-17.940	0.550
_Constant	156.441	14.510	10.780	0.000	127.992	184.891
Random-effects Parameters	**Estimate**	**SE**	**95% LCL**	**95% UCL**		
site: Identity						
var(cons)	256.660	33.000	199.487	330.218		
closeout: Identity						
var(vargrp)	1256.468	84.403	1101.469	1433.278		
var(Residual)	1264.230	39.659	1188.842	1344.399		

Model	**Observations**	***df***	**AIC**	**BIC**		
Nursery ADG	4960	123	51348.65	52149.28		

ADG = average daily gain; CI = confidence interval; DOF = days on feed; WF = wean-to-finish; AIC = Akaike information criterion; BIC = Bayesian information criterion; LCL = lower confidence limit; UCL = upper confidence limit.

Table A.12. Parameter coefficients and statistics for nursery ADFI

ADFI	**Coefficient**	**SE**	***t***	***P* > *t***	**95% LCL**	**95% UCL**
fill	2.103	0.880	2.390	0.017	0.377	3.829
avg_DOF	8.433	0.417	20.220	0.000	7.615	9.251
mortality	-1.950	0.574	-3.400	0.001	-3.075	-0.824
sowfarm	-6.592	1.926	-3.420	0.001	-10.369	-2.814
sysflow						
A-Converted-Nursery	0.000	(base)				
A-Nursery	1.957	51.250	0.040	0.970	-98.545	102.459
A-WF_nursery	163.937	34.072	4.810	0.000	97.123	230.751
B-Nursery	80.037	37.369	2.140	0.032	6.774	153.301
B-WF_nursery	58.301	40.538	1.440	0.150	-21.176	137.778
C-Nursery	142.040	34.979	4.060	0.000	73.463	210.617
C-WF_nursery	51.172	35.590	1.440	0.151	-18.603	120.948
size						
3000 - 6000	0.000	(base)				
< 3000	129.213	24.020	5.380	0.000	82.118	176.309
> 6000	-26.202	96.363	-0.270	0.786	-215.175	162.770
feeder						
Dry	0.000	(base)				
Tube	14.420	7.759	1.860	0.064	-0.829	29.668
Wetdry	25.641	6.427	3.990	0.000	13.002	38.280
year						
2013	0.000	(base)				
2014	-17.754	12.045	-1.470	0.141	-41.376	5.868
2015	-50.339	12.212	-4.120	0.000	-74.289	-26.389
2016	-36.115	14.363	-2.510	0.012	-64.282	-7.947
2017	-88.405	17.598	-5.020	0.000	-122.917	-53.893
startwk						
1	0.000	(base)				
2	6.812	11.831	0.580	0.565	-16.386	30.009
3	-7.143	11.267	-0.630	0.526	-29.234	14.948
4	-3.518	12.227	-0.290	0.774	-27.491	20.456
5	-9.222	11.889	-0.780	0.438	-32.534	14.089
6	4.805	11.780	0.410	0.683	-18.291	27.902
7	-4.635	11.924	-0.390	0.698	-28.013	18.744
8	-11.019	11.676	-0.940	0.345	-33.913	11.875
9	-8.818	11.695	-0.750	0.451	-31.748	14.113
10	-18.973	11.708	-1.620	0.105	-41.930	3.983
11	-12.973	12.023	-1.080	0.281	-36.546	10.600
12	-2.535	11.471	-0.220	0.825	-25.027	19.957
13	-29.450	11.432	-2.580	0.010	-51.864	-7.036
14	-25.675	11.973	-2.140	0.032	-49.151	-2.198
15	-25.696	11.303	-2.270	0.023	-47.858	-3.534
16	-23.149	11.784	-1.960	0.050	-46.254	-0.044
17	-25.600	12.089	-2.120	0.034	-49.302	-1.898

18	-18.485	11.497	-1.610	0.108	-41.026	4.057
19	-31.751	11.576	-2.740	0.006	-54.449	-9.053
20	-30.457	12.105	-2.520	0.012	-54.191	-6.722
21	-26.232	11.461	-2.290	0.022	-48.703	-3.762
22	-28.670	11.747	-2.440	0.015	-51.702	-5.638
23	-27.650	11.664	-2.370	0.018	-50.520	-4.780
24	-15.919	11.575	-1.380	0.169	-38.615	6.776
25	-14.674	11.763	-1.250	0.212	-37.737	8.390
26	-19.906	11.971	-1.660	0.096	-43.376	3.565
27	-8.176	11.334	-0.720	0.471	-30.399	14.047
28	-20.352	11.848	-1.720	0.086	-43.582	2.878
29	-7.638	11.291	-0.680	0.499	-29.776	14.499
30	-10.644	11.671	-0.910	0.362	-33.527	12.239
31	-3.541	11.736	-0.300	0.763	-26.552	19.471
32	-2.680	11.537	-0.230	0.816	-25.300	19.940
33	-4.509	11.859	-0.380	0.704	-27.761	18.744
34	2.946	11.588	0.250	0.799	-19.774	25.666
35	-9.948	11.787	-0.840	0.399	-33.059	13.162
36	-10.329	11.274	-0.920	0.360	-32.434	11.775
37	5.867	11.773	0.500	0.618	-17.215	28.950
38	-14.239	11.823	-1.200	0.229	-37.420	8.943
39	-19.516	11.237	-1.740	0.083	-41.548	2.517
40	-1.678	11.505	-0.150	0.884	-24.236	20.881
41	-3.987	11.201	-0.360	0.722	-25.949	17.976
42	-8.564	11.836	-0.720	0.469	-31.771	14.644
43	-3.323	11.429	-0.290	0.771	-25.732	19.086
44	-11.196	11.750	-0.950	0.341	-34.234	11.842
45	6.704	12.546	0.530	0.593	-17.895	31.303
46	-5.198	11.547	-0.450	0.653	-27.838	17.443
47	-1.950	11.100	-0.180	0.861	-23.714	19.815
48	-5.022	11.827	-0.420	0.671	-28.211	18.167
49	-13.338	12.273	-1.090	0.277	-37.401	10.724
50	3.103	11.726	0.260	0.791	-19.888	26.093
51	7.004	11.544	0.610	0.544	-15.629	29.638
52	-9.022	11.235	-0.800	0.422	-31.050	13.006
sysflow#c.fill						
A-Nursery	-0.201	1.287	-0.160	0.876	-2.725	2.323
A-WF_nursery	0.171	1.115	0.150	0.878	-2.015	2.357
B-Nursery	-3.284	1.074	-3.060	0.002	-5.389	-1.179
B-WF_nursery	-0.380	1.224	-0.310	0.756	-2.778	2.019
C-Nursery	-0.260	1.376	-0.190	0.850	-2.958	2.438
C-WF_nursery	-1.763	1.330	-1.330	0.185	-4.371	0.845
sysflow#c.avg_DOF						
A-Nursery	0.120	0.702	0.170	0.864	-1.257	1.497
A-WF_nursery	-1.791	0.477	-3.760	0.000	-2.727	-0.856
B-Nursery	0.667	0.609	1.100	0.273	-0.526	1.861
B-WF_nursery	1.437	0.604	2.380	0.017	0.252	2.621
C-Nursery	-0.751	0.605	-1.240	0.215	-1.938	0.435
C-WF_nursery	1.079	0.587	1.840	0.066	-0.072	2.230

sysflow#c.mortality						
A-Nursery	1.466	1.046	1.400	0.161	-0.585	3.517
A-WF_nursery	-0.554	0.791	-0.700	0.484	-2.106	0.998
B-Nursery	-5.035	1.359	-3.700	0.000	-7.700	-2.370
B-WF_nursery	-9.317	2.035	-4.580	0.000	-13.308	-5.326
C-Nursery	-10.818	0.969	-11.160	0.000	-12.719	-8.918
C-WF_nursery	-12.217	0.879	-13.890	0.000	-13.941	-10.493
sysflow#size						
A-Nursery# ≤ 3000	-90.332	39.526	-2.290	0.022	-167.843	-12.821
A-Nursery# > 6000	8.100	99.575	0.080	0.935	-187.177	203.377
A-WF_nursery#≤3000	-134.303	24.941	-5.380	0.000	-183.213	-85.392
A-WF_nursery#>6000	-12.275	93.779	-0.130	0.896	-196.187	171.638
B-Nursery#≤3000	-79.393	25.429	-3.120	0.002	-129.260	-29.525
B-Nursery#>6000	29.081	95.349	0.300	0.760	-157.904	216.066
B-WF_nursery#≤3000	-51.644	35.313	-1.460	0.144	-120.964	17.676
B-WF_nursery#>6000	26.455	95.119	0.280	0.781	-160.079	212.990
C-Nursery#≤3000	-87.459	23.538	-3.720	0.000	-133.610	-41.308
C-Nursery#>6000	-11.116	95.361	-0.120	0.907	-198.126	175.894
C-WF_nursery#≤3000	-67.273	25.776	-2.610	0.009	-117.807	-16.738
C-WF_nursery#>6000	10.669	95.096	0.110	0.911	-175.822	197.160
sysflow#year						
A-Nursery#2014	6.443	18.606	0.350	0.729	-30.046	42.933
A-Nursery#2015	15.495	18.007	0.860	0.390	-19.820	50.810
A-Nursery#2016	-23.042	19.846	-1.160	0.246	-61.964	15.879
A-Nursery#2017	39.221	21.796	1.800	0.072	-3.525	81.967
A-WF_nursery#2014	42.182	16.271	2.590	0.010	10.272	74.091
A-WF_nursery#2015	33.812	15.790	2.140	0.032	2.846	64.779
A-WF_nursery#2016	0.716	16.950	0.040	0.966	-32.525	33.957
A-WF_nursery#2017	69.773	19.910	3.500	0.000	30.727	108.819
B-Nursery#2014	30.375	14.167	2.140	0.032	2.598	58.153
B-Nursery#2015	46.127	14.305	3.220	0.001	18.079	74.175
B-Nursery#2016	25.962	16.153	1.610	0.108	-5.710	57.634
B-Nursery#2017	99.122	19.080	5.200	0.000	61.710	136.534
B-WF_nursery#2014	8.694	15.749	0.550	0.581	-22.183	39.570
B-WF_nursery#2015	54.438	15.896	3.420	0.001	23.272	85.603
B-WF_nursery#2016	62.917	17.753	3.540	0.000	28.111	97.723
B-WF_nursery#2017	129.704	20.510	6.320	0.000	89.491	169.916
C-Nursery#2014	9.116	15.391	0.590	0.554	-21.059	39.291
C-Nursery#2015	22.222	15.309	1.450	0.147	-7.792	52.236
C-Nursery#2016	2.801	17.001	0.160	0.869	-30.532	36.134
C-Nursery#2017	66.045	19.584	3.370	0.001	27.646	104.444
C-WF_nursery#2014	2.477	14.102	0.180	0.861	-25.173	30.126
C-WF_nursery#2015	16.046	14.232	1.130	0.260	-11.859	43.951
C-WF_nursery#2016	13.532	16.070	0.840	0.400	-17.977	45.041
C-WF_nursery#2017	60.816	19.388	3.140	0.002	22.801	98.830
size#c.fill						
≤ 3000	-3.484	1.262	-2.760	0.006	-5.959	-1.010
> 6000	-0.646	0.741	-0.870	0.384	-2.099	0.808
size#c.sowfarm						

≤ 3000	-18.217	4.957	-3.670	0.000	-27.939	-8.496
> 6000	3.186	2.730	1.170	0.243	-2.168	8.539
Constant	125.627	28.608	4.390	0.000	69.531	181.722
Random-effects Parameters	**Estimate**	**SE**	**95% LCL**	**95% UCL**		
site: Identity						
var(_cons)	1000.371	124.630	783.638	1277.047		
closeout: Identity						
var(vargrp)	4964.350	280.025	4444.762	5544.678		
var(Residual)	3076.755	99.856	2887.136	3278.828		
Model	**Observations**	***df***	**AIC**	**BIC**		
Nursery ADFI	4365	131	49477.22	50313.18		

ADFI = average daily feed intake; CI = confidence interval; DOF = days on feed; WF = wean-to-finish; AIC = Akaike information criterion; BIC = Bayesian information criterion; LCL = lower confidence limit; UCL = upper confidence limit.

Table A.13. Parameter coefficients and statistics for nursery G:F

G:F	**Coefficient**	**SE**	***t***	***P* > *t***	**95% LCL**	**95% UCL**
avg_DOF	-1.830	0.304	-6.020	0.000	-2.425	-1.234
mortality	-5.291	0.416	-12.710	0.000	-6.107	-4.475
sysflow						
A-Converted-Nursery	0.000	(base)				
A-Nursery	18.062	27.475	0.660	0.511	-35.817	71.940
A-WF_nursery	80.921	20.478	3.950	0.000	40.762	121.080
B-Nursery	107.901	24.097	4.480	0.000	60.658	155.144
B-WF_nursery	39.921	25.244	1.580	0.114	-9.570	89.412
C-Nursery	75.322	23.244	3.240	0.001	29.752	120.891
C-WF_nursery	119.219	23.440	5.090	0.000	73.266	165.173
feeder						
Dry	0.000	(base)				
Tube	-13.183	4.728	-2.790	0.006	-22.474	-3.892
Wetdry	-21.828	3.842	-5.680	0.000	-29.384	-14.271
year						
2013	0.000	(base)				
2014	15.040	8.538	1.760	0.078	-1.703	31.783
2015	29.496	8.619	3.420	0.001	12.593	46.399
2016	30.056	10.172	2.950	0.003	10.107	50.005
2017	46.027	12.610	3.650	0.000	21.298	70.757
sysflow#c.avg_dof						
A-Nursery	0.351	0.512	0.680	0.493	-0.653	1.355
A-WF_nursery	-1.106	0.344	-3.220	0.001	-1.780	-0.432
B-Nursery	-1.177	0.434	-2.710	0.007	-2.028	-0.326
B-WF_nursery	-0.529	0.431	-1.230	0.220	-1.374	0.316
C-Nursery	-0.205	0.436	-0.470	0.638	-1.060	0.649
C-WF_nursery	-1.052	0.425	-2.480	0.013	-1.885	-0.219
sysflow#c.mortality						
A-Nursery	0.316	0.746	0.420	0.672	-1.148	1.779
A-WF_nursery	2.240	0.574	3.900	0.000	1.114	3.367
B-Nursery	-0.333	0.878	-0.380	0.705	-2.055	1.390
B-WF_nursery	0.247	1.410	0.180	0.861	-2.516	3.011
C-Nursery	0.820	0.702	1.170	0.242	-0.556	2.197
C-WF_nursery	4.054	0.633	6.400	0.000	2.813	5.296
sysflow#year						
A-Nursery#2014	10.351	13.124	0.790	0.430	-15.386	36.089
A-Nursery#2015	6.006	12.529	0.480	0.632	-18.565	30.576
A-Nursery#2016	5.900	13.621	0.430	0.665	-20.812	32.613
A-Nursery#2017	-35.541	15.503	-2.290	0.022	-65.944	-5.139
A-WF_nursery#2014	-30.425	11.577	-2.630	0.009	-53.128	-7.723
A-WF_nursery#2015	-13.249	11.041	-1.200	0.230	-34.900	8.402
A-WF_nursery#2016	-25.476	11.893	-2.140	0.032	-48.799	-2.154
A-WF_nursery#2017	-88.069	14.141	-6.230	0.000	-115.801	-60.338
B-Nursery#2014	-20.443	10.125	-2.020	0.044	-40.294	-0.592
B-Nursery#2015	-26.531	10.153	-2.610	0.009	-46.437	-6.625
B-Nursery#2016	-21.127	11.492	-1.840	0.066	-43.659	1.405
B-Nursery#2017	-39.709	13.681	-2.900	0.004	-66.535	-12.883
B-WF_nursery#2014	-18.436	11.252	-1.640	0.101	-40.496	3.624
B-WF_nursery#2015	-33.821	11.301	-2.990	0.003	-55.977	-11.664
B-WF_nursery#2016	-45.574	12.653	-3.600	0.000	-70.380	-20.767

B-WF_nursery#2017	-54.968	14.708	-3.740	0.000	-83.804	-26.131
C-Nursery#2014	-27.759	10.965	-2.530	0.011	-49.256	-6.262
C-Nursery#2015	-29.893	10.903	-2.740	0.006	-51.270	-8.516
C-Nursery#2016	-27.638	12.081	-2.290	0.022	-51.324	-3.951
C-Nursery#2017	-44.041	14.031	-3.140	0.002	-71.553	-16.529
C-WF_nursery#2014	-9.770	10.062	-0.970	0.332	-29.497	9.958
C-WF_nursery#2015	-23.971	10.108	-2.370	0.018	-43.789	-4.152
C-WF_nursery#2016	-33.135	11.423	-2.900	0.004	-55.533	-10.738
C-WF_nursery#2017	-36.688	13.918	-2.640	0.008	-63.978	-9.399
Constant	697.724	17.562	39.730	0.000	663.285	732.163
Random-effects Parameters	**Estimate**	**SE**	**95% LCL**	**95% UCL**		
site: Identity						
var(_cons)	284.8505	40.00879	216.3023	375.1223		
closeout: Identity						
var(vargrp)	2819.26	150.1316	2539.843	3129.417		
var(Residual)	1668.38	53.37558	1566.978	1776.343		
Model	**Observations**	***df***	**AIC**	**BIC**		
Nursery G:F	4365	54	47101.78	47446.38		

G:F = gain to feed ratio; CI = confidence interval; DOF = days on feed; WF = wean-to-finish; AIC = Akaike information criterion; BIC = Bayesian information criterion; LCL = lower confidence limit; UCL = upper confidence limit.

Table A.14. Parameter coefficients and statistics for finisher ADG

ADG	**Coefficient**	**SE**	***t***	***P* > *t***	**95% LCL**	**95% UCL**
startwt	1.967	0.182	10.780	0.000	1.609	2.325
mortality	-9.689	0.574	-16.880	0.000	-10.814	-8.563
sowfarm	-0.726	1.776	-0.410	0.683	-4.208	2.756
NE	0.162	0.022	7.440	0.000	0.119	0.204
system						
A	0.000	(base)				
B	30.373	22.333	1.360	0.174	-13.410	74.157
C	-42.422	20.505	-2.070	0.039	-82.622	-2.222
flow						
Finishing	0.000	(base)				
WF_finishing	244.875	80.550	3.040	0.002	86.955	402.795
size						
1500-3500	0.000	(base)				
< 1500	-21.002	16.667	-1.260	0.208	-53.687	11.682
> 3500	-10.319	4.019	-2.570	0.010	-18.200	-2.437
feeder						
Dry	0.000	(base)				
Tube	-17.819	9.878	-1.800	0.071	-37.199	1.560
Wetdry	10.363	9.451	1.100	0.273	-8.178	28.904
year						
2015	0.000	(base)				
2016	4.593	3.483	1.320	0.187	-2.237	11.424
2017	21.709	4.753	4.570	0.000	12.389	31.029
startwk						
1	0.000	(base)				
2	-18.181	13.862	-1.310	0.190	-45.363	9.002
3	-22.222	15.840	-1.400	0.161	-53.283	8.840
4	-17.373	14.513	-1.200	0.231	-45.832	11.086
5	-25.651	15.134	-1.690	0.090	-55.329	4.027
6	-34.385	13.709	-2.510	0.012	-61.267	-7.502
7	-28.313	14.233	-1.990	0.047	-56.223	-0.403
8	-32.001	14.685	-2.180	0.029	-60.798	-3.204
9	-35.699	15.318	-2.330	0.020	-65.738	-5.660
10	-37.956	14.275	-2.660	0.008	-65.948	-9.964
11	-50.736	14.310	-3.550	0.000	-78.799	-22.674
12	-62.931	14.624	-4.300	0.000	-91.608	-34.253
13	-75.821	14.184	-5.350	0.000	-103.635	-48.007
14	-81.384	14.582	-5.580	0.000	-109.979	-52.789
15	-66.476	14.157	-4.700	0.000	-94.237	-38.715
16	-73.647	14.945	-4.930	0.000	-102.954	-44.340
17	-74.720	14.125	-5.290	0.000	-102.420	-47.021
18	-74.086	13.657	-5.420	0.000	-100.868	-47.304
19	-82.728	13.835	-5.980	0.000	-109.858	-55.599
20	-69.550	15.229	-4.570	0.000	-99.414	-39.686
21	-57.157	15.423	-3.710	0.000	-87.402	-26.913
22	-48.404	15.459	-3.130	0.002	-78.719	-18.088
23	-53.560	14.666	-3.650	0.000	-82.321	-24.799
24	-43.955	14.057	-3.130	0.002	-71.521	-16.389
25	-31.424	14.668	-2.140	0.032	-60.187	-2.660
26	-42.969	14.683	-2.930	0.003	-71.762	-14.176

27	-23.996	15.258	-1.570	0.116	-53.917	5.924
28	-27.858	14.337	-1.940	0.052	-55.972	0.255
29	-29.689	14.304	-2.080	0.038	-57.740	-1.638
30	-22.891	14.277	-1.600	0.109	-50.888	5.105
31	-13.472	13.679	-0.980	0.325	-40.296	13.352
32	3.396	14.498	0.230	0.815	-25.035	31.827
33	-6.605	15.015	-0.440	0.660	-36.049	22.840
34	-2.988	14.142	-0.210	0.833	-30.720	24.744
35	-16.268	13.890	-1.170	0.242	-43.507	10.970
36	-12.102	14.268	-0.850	0.396	-40.081	15.876
37	-2.688	13.957	-0.190	0.847	-30.057	24.681
38	-16.961	14.348	-1.180	0.237	-45.097	11.174
39	-14.147	14.487	-0.980	0.329	-42.557	14.262
40	-23.512	13.640	-1.720	0.085	-50.260	3.237
41	-28.212	14.623	-1.930	0.054	-56.887	0.464
42	-21.619	14.136	-1.530	0.126	-49.339	6.100
43	-17.943	14.247	-1.260	0.208	-45.881	9.995
44	-11.511	13.850	-0.830	0.406	-38.671	15.648
45	-3.748	14.671	-0.260	0.798	-32.518	25.021
46	-23.868	14.130	-1.690	0.091	-51.576	3.840
47	4.907	13.930	0.350	0.725	-22.409	32.222
48	3.169	15.961	0.200	0.843	-28.131	34.468
49	-10.006	14.687	-0.680	0.496	-38.807	18.795
50	-16.496	13.274	-1.240	0.214	-42.526	9.534
51	-13.782	13.506	-1.020	0.308	-40.266	12.703
52	-27.897	14.965	-1.860	0.062	-57.243	1.448
system#c.startwt						
B	-1.237	0.291	-4.250	0.000	-1.808	-0.666
C	0.041	0.292	0.140	0.887	-0.531	0.614
system#c.mortality						
B	-2.289	1.057	-2.160	0.030	-4.362	-0.216
C	-2.216	0.841	-2.640	0.008	-3.864	-0.568
system#c.sowfarm						
B	-2.086	1.774	-1.180	0.240	-5.564	1.393
C	-15.831	3.541	-4.470	0.000	-22.774	-8.889
system#flow						
B-WF_finishing	-24.930	9.558	-2.610	0.009	-43.669	-6.190
C-WF_finishing	-47.389	8.697	-5.450	0.000	-64.439	-30.339
system#size						
B#≤1500	72.233	17.442	4.140	0.000	38.027	106.440
B#>3500	1.974	6.591	0.300	0.765	-10.957	14.905
C#≤1500	44.422	17.246	2.580	0.010	10.598	78.246
C#>3500	8.774	5.898	1.490	0.137	-2.802	20.349
system#feeder						
B#Tube	14.820	11.154	1.330	0.184	-7.068	36.709
B#Wetdry	33.639	12.168	2.760	0.006	9.757	57.521
C#Tube	30.537	11.043	2.770	0.006	8.867	52.206
C#Wetdry	34.827	10.314	3.380	0.001	14.589	55.064
system#year						
B#2016	-6.132	4.438	-1.380	0.167	-14.832	2.569
B#2017	-7.985	5.192	-1.540	0.124	-18.163	2.194
C#2016	2.113	4.164	0.510	0.612	-6.051	10.277
C#2017	-10.622	5.355	-1.980	0.047	-21.122	-0.123

system#startwk						
B# 2	13.373	19.599	0.680	0.495	-25.051	51.798
B# 3	1.008	21.317	0.050	0.962	-40.785	42.801
B# 4	3.931	20.616	0.190	0.849	-36.488	44.350
B# 5	16.616	21.496	0.770	0.440	-25.528	58.760
B# 6	18.901	19.907	0.950	0.342	-20.126	57.929
B# 7	13.023	20.061	0.650	0.516	-26.307	52.353
B# 8	14.342	21.586	0.660	0.506	-27.979	56.663
B# 9	-8.383	21.039	-0.400	0.690	-49.631	32.864
B#10	-6.764	20.427	-0.330	0.741	-46.813	33.284
B#11	16.229	20.093	0.810	0.419	-23.163	55.622
B#12	15.866	20.807	0.760	0.446	-24.926	56.657
B#13	56.864	21.247	2.680	0.007	15.209	98.518
B#14	45.811	20.399	2.250	0.025	5.818	85.803
B#15	29.655	20.410	1.450	0.146	-10.360	69.670
B#16	16.549	20.729	0.800	0.425	-24.090	57.188
B#17	38.203	19.884	1.920	0.055	-0.780	77.186
B#18	25.383	19.851	1.280	0.201	-13.536	64.302
B#19	40.017	20.575	1.940	0.052	-0.321	80.355
B#20	27.039	20.822	1.300	0.194	-13.782	67.861
B#21	26.149	21.379	1.220	0.221	-15.765	68.064
B#22	36.388	21.188	1.720	0.086	-5.151	77.927
B#23	37.371	20.326	1.840	0.066	-2.480	77.222
B#24	31.227	20.226	1.540	0.123	-8.427	70.881
B#25	47.457	20.799	2.280	0.023	6.681	88.232
B#26	47.797	20.314	2.350	0.019	7.972	87.623
B#27	53.411	22.179	2.410	0.016	9.928	96.893
B#28	46.052	20.232	2.280	0.023	6.387	85.717
B#29	56.164	21.745	2.580	0.010	13.532	98.796
B#30	37.819	19.981	1.890	0.058	-1.355	76.993
B#31	30.317	19.982	1.520	0.129	-8.859	69.492
B#32	35.733	20.202	1.770	0.077	-3.873	75.340
B#33	34.396	21.015	1.640	0.102	-6.806	75.597
B#34	45.897	19.944	2.300	0.021	6.796	84.997
B#35	25.775	19.376	1.330	0.184	-12.212	63.762
B#36	23.446	19.923	1.180	0.239	-15.613	62.506
B#37	15.972	19.969	0.800	0.424	-23.178	55.121
B#38	40.281	20.677	1.950	0.051	-0.256	80.817
B#39	42.855	20.498	2.090	0.037	2.668	83.042
B#40	25.018	20.152	1.240	0.214	-14.490	64.526
B#41	19.788	20.421	0.970	0.333	-20.248	59.825
B#42	21.650	20.032	1.080	0.280	-17.623	60.923
B#43	2.369	20.007	0.120	0.906	-36.855	41.593
B#44	-11.341	19.728	-0.570	0.565	-50.018	27.335
B#45	17.195	21.130	0.810	0.416	-24.231	58.621
B#46	27.125	20.037	1.350	0.176	-12.158	66.408
B#47	-19.617	20.081	-0.980	0.329	-58.986	19.752
B#48	-5.810	21.632	-0.270	0.788	-48.221	36.600
B#49	2.365	21.336	0.110	0.912	-39.464	44.194
B#50	-0.623	19.423	-0.030	0.974	-38.703	37.456
B#51	13.704	19.681	0.700	0.486	-24.881	52.289
B#52	13.100	21.357	0.610	0.540	-28.771	54.971
C# 2	22.003	17.089	1.290	0.198	-11.501	55.506

C# 3	21.417	18.961	1.130	0.259	-15.758	58.593
C# 4	9.902	18.284	0.540	0.588	-25.944	45.749
C# 5	3.201	18.481	0.170	0.863	-33.032	39.434
C# 6	22.190	17.083	1.300	0.194	-11.301	55.682
C# 7	10.018	17.863	0.560	0.575	-25.004	45.040
C# 8	11.067	18.435	0.600	0.548	-25.076	47.209
C# 9	2.547	18.677	0.140	0.892	-34.071	39.164
C#10	16.146	17.480	0.920	0.356	-18.125	50.416
C#11	29.192	17.383	1.680	0.093	-4.889	63.272
C#12	30.287	17.856	1.700	0.090	-4.721	65.296
C#13	56.050	17.383	3.220	0.001	21.970	90.130
C#14	56.376	17.806	3.170	0.002	21.466	91.287
C#15	36.217	17.519	2.070	0.039	1.870	70.564
C#16	42.515	18.455	2.300	0.021	6.333	78.696
C#17	48.050	17.409	2.760	0.006	13.919	82.181
C#18	45.314	17.284	2.620	0.009	11.428	79.200
C#19	61.264	17.610	3.480	0.001	26.738	95.789
C#20	64.220	18.556	3.460	0.001	27.840	100.600
C#21	56.555	18.716	3.020	0.003	19.861	93.250
C#22	39.462	18.854	2.090	0.036	2.497	76.427
C#23	62.236	17.785	3.500	0.000	27.366	97.105
C#24	53.907	17.644	3.060	0.002	19.315	88.498
C#25	44.799	17.836	2.510	0.012	9.830	79.768
C#26	59.208	18.219	3.250	0.001	23.490	94.927
C#27	48.741	18.797	2.590	0.010	11.890	85.593
C#28	43.142	17.872	2.410	0.016	8.103	78.181
C#29	65.356	17.737	3.680	0.000	30.582	100.130
C#30	48.250	18.059	2.670	0.008	12.846	83.655
C#31	57.456	17.253	3.330	0.001	23.631	91.282
C#32	23.920	17.489	1.370	0.171	-10.369	58.208
C#33	44.543	18.647	2.390	0.017	7.984	81.103
C#34	48.532	17.156	2.830	0.005	14.896	82.168
C#35	49.970	17.430	2.870	0.004	15.797	84.142
C#36	38.985	17.513	2.230	0.026	4.649	73.320
C#37	21.615	17.412	1.240	0.215	-12.522	55.753
C#38	35.949	17.880	2.010	0.044	0.895	71.004
C#39	44.421	17.679	2.510	0.012	9.761	79.082
C#40	46.589	17.757	2.620	0.009	11.776	81.401
C#41	41.825	17.865	2.340	0.019	6.800	76.851
C#42	38.839	17.541	2.210	0.027	4.450	73.228
C#43	31.946	17.574	1.820	0.069	-2.508	66.400
C#44	37.927	17.611	2.150	0.031	3.400	72.454
C#45	16.129	17.927	0.900	0.368	-19.017	51.276
C#46	44.056	17.421	2.530	0.011	9.902	78.210
C#47	19.613	17.342	1.130	0.258	-14.386	53.613
C#48	10.561	19.064	0.550	0.580	-26.815	47.938
C#49	18.685	17.883	1.040	0.296	-16.376	53.746
C#50	29.219	16.745	1.740	0.081	-3.611	62.048
C#51	31.339	17.218	1.820	0.069	-2.417	65.095
C#52	21.732	18.412	1.180	0.238	-14.365	57.829
flow#c.startwt						
WF_finishing	-0.560	0.268	-2.090	0.037	-1.085	-0.035
flow#c.mortality						

WF_finishing	-3.846	0.859	-4.480	0.000	-5.530	-2.163
flow#c.NE						
WF_finishing	-0.072	0.030	-2.430	0.015	-0.130	-0.014
flow#year						
WF_finishing#2016	10.985	3.623	3.030	0.002	3.881	18.089
WF_finishing#2017	20.048	3.823	5.240	0.000	12.552	27.544
size#c.sowfarm						
< 1500	-7.124	2.285	-3.120	0.002	-11.605	-2.643
> 3500	-0.348	1.318	-0.260	0.792	-2.932	2.236
Constant	456.970	61.902	7.380	0.000	335.608	578.331
Random-effects Parameters	**Estimate**	**SE**	**95% LCL**	**95% UCL**		
site: Identity						
var(_cons)	495.309	45.825	413.167	593.782		
closeout: Identity						
var(vargrp)	3006.807	133.037	2757.045	3279.195		
var(Residual)	1104.778	36.955	1034.671	1179.635		
Model	**Observations**	***df***	**AIC**	**BIC**		
Finisher ADG	4,747	197	49797.57	51071.23		

ADG = average daily gain; CI = confidence interval; BW = body weight; NE = net energy; WF = wean-to-finish; AIC = Akaike information criterion; BIC = Bayesian information criterion; LCL = lower confidence limit; UCL = upper confidence limit.

Table A.15. Parameter coefficients and statistics for finisher ADFI

ADFI	**Coefficient**	**SE**	***t***	***P > t***	**95% LCL**	**95% UCL**
fill	-1.968	1.670	-1.180	0.239	-5.243	1.306
startwt	15.058	0.413	36.490	0.000	14.248	15.867
mortality	-13.305	1.100	-12.100	0.000	-15.462	-11.149
sowfarm	-7.022	4.375	-1.610	0.109	-15.599	1.555
NE	-0.196	0.061	-3.200	0.001	-0.316	-0.076
system						
A	0.000	(base)				
B	-1298.527	422.704	-3.070	0.002	-2127.358	-469.696
C	1016.912	346.882	2.930	0.003	336.760	1697.064
flow						
Finishing	0.000	(base)				
WF_finishing	617.974	205.392	3.010	0.003	215.293	1020.654
size						
1500-3500	0.000	(base)				
< 1500	16.071	47.284	0.340	0.734	-76.665	108.807
> 3500	-54.461	20.027	-2.720	0.007	-93.765	-15.157
feeder						
Dry	0.000	(base)				
Tube	-67.961	26.480	-2.570	0.010	-119.926	-15.995
Wetdry	43.020	26.080	1.650	0.099	-8.161	94.201
year						
2015	0.000	(base)				
2016	2.230	8.278	0.270	0.788	-14.003	18.464
2017	31.139	12.406	2.510	0.012	6.812	55.466
startwk						
1	0.000	(base)				
2	-28.215	32.667	-0.860	0.388	-92.275	35.845
3	-26.351	37.308	-0.710	0.480	-99.511	46.810
4	-45.905	34.212	-1.340	0.180	-112.995	21.185
5	-53.822	35.654	-1.510	0.131	-123.739	16.095
6	-73.646	32.403	-2.270	0.023	-137.189	-10.104
7	-48.123	33.549	-1.430	0.152	-113.912	17.666
8	-76.537	34.610	-2.210	0.027	-144.408	-8.667
9	-70.522	36.104	-1.950	0.051	-141.322	0.278
10	-118.421	33.637	-3.520	0.000	-184.383	-52.458
11	-105.079	33.735	-3.110	0.002	-171.234	-38.924
12	-169.234	34.479	-4.910	0.000	-236.847	-101.620
13	-153.995	33.423	-4.610	0.000	-219.537	-88.453
14	-170.957	34.386	-4.970	0.000	-238.388	-103.527
15	-152.098	33.381	-4.560	0.000	-217.558	-86.638
16	-151.791	35.254	-4.310	0.000	-220.924	-82.658
17	-160.525	33.287	-4.820	0.000	-225.801	-95.249
18	-141.591	32.189	-4.400	0.000	-204.714	-78.468
19	-156.029	32.628	-4.780	0.000	-220.012	-92.046
20	-142.850	35.907	-3.980	0.000	-213.264	-72.436
21	-63.385	36.329	-1.740	0.081	-134.627	7.857
22	-109.469	36.417	-3.010	0.003	-180.882	-38.055
23	-123.499	34.532	-3.580	0.000	-191.216	-55.781
24	-67.167	33.118	-2.030	0.043	-132.112	-2.222
25	-67.862	34.563	-1.960	0.050	-135.640	-0.085

26	-79.263	34.635	-2.290	0.022	-147.183	-11.344
27	-35.258	35.983	-0.980	0.327	-105.822	35.305
28	-36.655	33.780	-1.090	0.278	-102.897	29.586
29	-21.755	33.724	-0.650	0.519	-87.888	44.378
30	-1.086	33.694	-0.030	0.974	-67.159	64.987
31	-53.051	32.222	-1.650	0.100	-116.238	10.135
32	-14.104	34.141	-0.410	0.680	-81.055	52.848
33	27.628	35.325	0.780	0.434	-41.644	96.900
34	29.378	33.477	0.880	0.380	-36.271	95.027
35	41.732	32.736	1.270	0.203	-22.463	105.928
36	29.957	33.623	0.890	0.373	-35.978	95.891
37	45.149	32.850	1.370	0.169	-19.269	109.568
38	4.424	33.785	0.130	0.896	-61.828	70.676
39	28.328	34.141	0.830	0.407	-38.624	95.279
40	45.028	32.136	1.400	0.161	-17.990	108.047
41	40.928	34.502	1.190	0.236	-26.730	108.586
42	31.259	33.304	0.940	0.348	-34.050	96.569
43	32.638	33.553	0.970	0.331	-33.159	98.435
44	37.543	32.671	1.150	0.251	-26.524	101.611
45	12.469	34.563	0.360	0.718	-55.310	80.247
46	-2.229	33.301	-0.070	0.947	-67.532	63.075
47	-2.137	32.881	-0.060	0.948	-66.615	62.342
48	49.539	37.614	1.320	0.188	-24.222	123.301
49	-22.606	34.652	-0.650	0.514	-90.558	45.345
50	-25.952	31.286	-0.830	0.407	-87.303	35.399
51	-4.884	31.811	-0.150	0.878	-67.266	57.497
52	-44.670	35.284	-1.270	0.206	-113.861	24.521
system#c.fill						
B	4.864	3.934	1.240	0.216	-2.851	12.579
C	4.511	2.303	1.960	0.050	-0.004	9.027
system#c.startwt						
B	-2.476	0.781	-3.170	0.002	-4.006	-0.946
C	1.867	0.716	2.610	0.009	0.462	3.271
system#c.sowfarm						
B	-13.635	4.464	-3.050	0.002	-22.387	-4.883
C	-48.629	9.876	-4.920	0.000	-67.994	-29.264
system#c.NE						
B	0.553	0.165	3.340	0.001	0.229	0.877
C	-0.513	0.138	-3.730	0.000	-0.783	-0.243
system#flow						
B-WF_finishing	-157.964	27.195	-5.810	0.000	-211.284	-104.644
C-WF_finishing	-102.061	22.487	-4.540	0.000	-146.146	-57.976
system#size						
B#≤1500	136.330	48.628	2.800	0.005	40.939	231.721
B#>3500	-26.107	21.138	-1.240	0.217	-67.584	15.369
C#≤1500	88.044	44.868	1.960	0.050	0.037	176.051
C#>3500	1.953	18.616	0.100	0.916	-34.585	38.491
system#feeder						
B#Tube	46.942	28.554	1.640	0.101	-9.102	102.987
B#Wetdry	75.933	31.508	2.410	0.016	14.082	137.784
C#Tube	98.361	28.528	3.450	0.001	42.370	154.352
C#Wetdry	73.824	27.203	2.710	0.007	20.435	127.213
system#year						

B#2016	-13.631	11.629	-1.170	0.241	-36.429	9.168
B#2017	-20.740	15.515	-1.340	0.181	-51.158	9.678
C#2016	-9.416	11.707	-0.800	0.421	-32.368	13.535
C#2017	-53.770	14.817	-3.630	0.000	-82.819	-24.721
system#startwk						
B# 2	-4.842	51.489	-0.090	0.925	-105.789	96.105
B# 3	-61.336	55.413	-1.110	0.268	-169.975	47.303
B# 4	-24.564	54.215	-0.450	0.651	-130.855	81.727
B# 5	-2.386	56.549	-0.040	0.966	-113.253	108.482
B# 6	-12.291	52.698	-0.230	0.816	-115.610	91.028
B# 7	-20.996	52.724	-0.400	0.690	-124.364	82.372
B# 8	-47.560	57.122	-0.830	0.405	-159.551	64.432
B# 9	-96.266	55.057	-1.750	0.080	-204.207	11.674
B#10	-31.231	53.871	-0.580	0.562	-136.849	74.387
B#11	-67.124	52.865	-1.270	0.204	-170.770	36.521
B#12	-21.759	54.775	-0.400	0.691	-129.148	85.630
B#13	13.445	56.400	0.240	0.812	-97.133	124.023
B#14	7.313	53.603	0.140	0.891	-97.780	112.405
B#15	-48.722	53.936	-0.900	0.366	-154.468	57.024
B#16	-101.395	54.255	-1.870	0.062	-207.764	4.975
B#17	-51.395	52.245	-0.980	0.325	-153.825	51.034
B#18	-133.641	52.369	-2.550	0.011	-236.314	-30.967
B#19	-93.807	54.677	-1.720	0.086	-201.006	13.392
B#20	-75.967	54.395	-1.400	0.163	-182.611	30.677
B#21	-154.523	56.046	-2.760	0.006	-264.404	-44.642
B#22	-83.038	55.399	-1.500	0.134	-191.650	25.574
B#23	-56.585	53.185	-1.060	0.287	-160.858	47.687
B#24	-83.409	53.338	-1.560	0.118	-187.981	21.164
B#25	-57.265	54.649	-1.050	0.295	-164.408	49.878
B#26	-66.581	53.158	-1.250	0.210	-170.800	37.639
B#27	2.811	58.594	0.050	0.962	-112.066	117.688
B#28	-5.067	53.161	-0.100	0.924	-109.292	99.157
B#29	12.089	57.866	0.210	0.835	-101.364	125.541
B#30	-46.024	52.432	-0.880	0.380	-148.819	56.771
B#31	25.471	52.794	0.480	0.630	-78.036	128.978
B#32	8.399	52.916	0.160	0.874	-95.346	112.144
B#33	-43.636	55.047	-0.790	0.428	-151.558	64.286
B#34	31.178	52.494	0.590	0.553	-71.739	134.095
B#35	-59.300	50.865	-1.170	0.244	-159.024	40.424
B#36	7.151	52.320	0.140	0.891	-95.425	109.726
B#37	-17.801	52.539	-0.340	0.735	-120.807	85.206
B#38	42.021	54.526	0.770	0.441	-64.880	148.923
B#39	-24.243	53.924	-0.450	0.653	-129.965	81.478
B#40	-5.097	53.350	-0.100	0.924	-109.694	99.499
B#41	-67.811	53.588	-1.270	0.206	-172.873	37.251
B#42	-33.895	52.653	-0.640	0.520	-137.125	69.334
B#43	-83.403	52.584	-1.590	0.113	-186.499	19.692
B#44	-124.228	51.893	-2.390	0.017	-225.968	-22.488
B#45	19.379	55.748	0.350	0.728	-89.919	128.677
B#46	10.662	52.662	0.200	0.840	-92.585	113.909
B#47	-46.114	53.022	-0.870	0.385	-150.067	57.838
B#48	-123.583	56.324	-2.190	0.028	-234.008	-13.157
B#49	-8.819	56.400	-0.160	0.876	-119.395	101.757

B#50	-3.458	51.383	-0.070	0.946	-104.198	97.282
B#51	-38.672	52.005	-0.740	0.457	-140.631	63.286
B#52	-8.588	56.216	-0.150	0.879	-118.803	101.627
C# 2	22.595	43.471	0.520	0.603	-62.631	107.821
C# 3	37.279	47.820	0.780	0.436	-56.474	131.032
C# 4	49.839	46.790	1.070	0.287	-41.893	141.571
C# 5	1.019	46.856	0.020	0.983	-90.844	92.882
C# 6	48.902	43.727	1.120	0.263	-36.825	134.630
C# 7	-13.740	45.752	-0.300	0.764	-103.437	75.957
C# 8	39.883	47.178	0.850	0.398	-52.611	132.376
C# 9	-22.402	47.552	-0.470	0.638	-115.629	70.824
C#10	66.132	44.702	1.480	0.139	-21.508	153.772
C#11	59.960	44.358	1.350	0.177	-27.005	146.925
C#12	85.582	45.635	1.880	0.061	-3.887	175.051
C#13	94.767	44.591	2.130	0.034	7.347	182.188
C#14	90.179	45.650	1.980	0.048	0.681	179.677
C#15	72.150	45.190	1.600	0.110	-16.447	160.746
C#16	22.135	47.446	0.470	0.641	-70.884	115.153
C#17	72.131	44.703	1.610	0.107	-15.511	159.772
C#18	18.891	44.748	0.420	0.673	-68.837	106.620
C#19	46.457	45.563	1.020	0.308	-42.870	135.784
C#20	83.868	47.400	1.770	0.077	-9.061	176.797
C#21	-27.137	47.774	-0.570	0.570	-120.799	66.525
C#22	-3.620	47.945	-0.080	0.940	-97.619	90.378
C#23	66.021	45.114	1.460	0.143	-22.426	154.467
C#24	12.616	45.403	0.280	0.781	-76.397	101.630
C#25	23.200	45.227	0.510	0.608	-65.467	111.868
C#26	40.258	46.507	0.870	0.387	-50.920	131.436
C#27	47.604	47.830	1.000	0.320	-46.166	141.375
C#28	31.589	45.564	0.690	0.488	-57.739	120.917
C#29	56.837	45.217	1.260	0.209	-31.812	145.486
C#30	-9.632	46.273	-0.210	0.835	-100.351	81.086
C#31	139.559	44.157	3.160	0.002	52.988	226.131
C#32	21.876	44.200	0.490	0.621	-64.779	108.530
C#33	-4.350	47.455	-0.090	0.927	-97.385	88.686
C#34	57.135	43.601	1.310	0.190	-28.345	142.616
C#35	30.614	44.586	0.690	0.492	-56.798	118.026
C#36	42.922	44.485	0.960	0.335	-44.292	130.136
C#37	-3.924	44.418	-0.090	0.930	-91.007	83.158
C#38	75.505	45.687	1.650	0.098	-14.065	165.075
C#39	49.901	44.909	1.110	0.267	-38.144	137.946
C#40	23.520	45.906	0.510	0.608	-66.479	113.520
C#41	6.383	45.451	0.140	0.888	-82.725	95.492
C#42	27.039	44.809	0.600	0.546	-60.809	114.887
C#43	16.096	44.750	0.360	0.719	-71.636	103.829
C#44	40.120	45.239	0.890	0.375	-48.572	128.811
C#45	39.621	45.593	0.870	0.385	-49.765	129.007
C#46	81.621	44.579	1.830	0.067	-5.777	169.018
C#47	90.955	44.271	2.050	0.040	4.161	177.750
C#48	11.162	48.150	0.230	0.817	-83.238	105.562
C#49	72.141	45.396	1.590	0.112	-16.859	161.141
C#50	90.773	42.872	2.120	0.034	6.722	174.824
C#51	65.647	44.143	1.490	0.137	-20.896	152.191

C#52	46.383	46.811	0.990	0.322	-45.390	138.156
flow#c.fill						
WF_finishing	13.806	2.335	5.910	0.000	9.227	18.385
flow#c.mortality						
WF_finishing	-8.194	2.107	-3.890	0.000	-12.325	-4.063
flow#c.sowfarm						
WF_finishing	28.861	4.787	6.030	0.000	19.475	38.247
flow#c.NE						
WF_finishing	-0.235	0.075	-3.150	0.002	-0.382	-0.089
flow#year						
WF_finishing#2016	25.881	9.919	2.610	0.009	6.433	45.330
WF_finishing#2017	39.555	11.082	3.570	0.000	17.826	61.284
size#c.fill						
<1500	-6.336	4.551	-1.390	0.164	-15.258	2.587
>3500	4.035	1.784	2.260	0.024	0.538	7.533
size#c.sowfarm						
<1500	-16.398	6.758	-2.430	0.015	-29.651	-3.145
>3500	5.479	3.655	1.500	0.134	-1.687	12.646
size#feeder						
≤1500#Tube	-66.377	27.919	-2.380	0.018	-121.181	-11.573
≤1500#Wetdry	-6.019	34.354	-0.180	0.861	-73.463	61.426
>3500#Tube	49.317	17.654	2.790	0.005	14.654	83.980
>3500#Wetdry	14.617	19.328	0.760	0.450	-23.328	52.562
Constant	2716.176	172.736	15.720	0.000	2377.460	3054.892
Random-effects Parameters	**Estimate**	**SE**	**95% LCL**	**95% UCL**		
site: Identity						
var(_cons)	3447.749	318.849	2876.181	4132.901		
closeout: Identity						
var(vargrp)	13410.910	761.781	11997.960	14990.260		
var(Residual)	9139.323	307.505	8556.068	9762.337		
Model	**Observations**	***df***	**AIC**	**BIC**		
Finisher ADFI	4,743	207	58351.92	59690.06		

ADFI = average daily feed intake; CI = confidence interval; BW = body weight; NE = net energy; WF = wean-to-finish; AIC = Akaike information criterion; BIC = Bayesian information criterion; LCL = lower confidence limit; UCL = upper confidence limit.

Table A.16. Parameter coefficients and statistics for finisher G:F

G:F	**Coefficient**	**SE**	***t***	***P > t***	**95% LCL**	**95% UCL**
fill	0.001	0.109	0.010	0.992	-0.212	0.214
startwt	-1.414	0.041	-34.650	0.000	-1.494	-1.334
mortality	-2.139	0.172	-12.450	0.000	-2.476	-1.803
sowfarm	1.286	0.266	4.830	0.000	0.764	1.809
NE	0.110	0.006	19.210	0.000	0.098	0.121
system						
A	0.000	(base)				
B	261.687	43.017	6.080	0.000	177.343	346.031
C	-22.978	35.524	-0.650	0.518	-92.630	46.675
flow						
Finishing	0.000	(base)				
WF_finishing	12.057	1.183	10.190	0.000	9.737	14.376
size						
1500-3500	0.000	(base)				
< 1500	-9.634	4.007	-2.400	0.016	-17.491	-1.776
> 3500	-1.646	1.568	-1.050	0.294	-4.720	1.427
year						
2015	0.000	(base)				
2016	1.838	0.784	2.340	0.019	0.301	3.375
2017	7.275	1.222	5.950	0.000	4.879	9.671
startwk						
1	0.000	(base)				
2	-2.365	3.260	-0.730	0.468	-8.757	4.027
3	-6.584	3.741	-1.760	0.079	-13.920	0.751
4	0.044	3.410	0.010	0.990	-6.644	6.732
5	-0.715	3.531	-0.200	0.840	-7.640	6.210
6	-1.754	3.216	-0.550	0.586	-8.061	4.553
7	-2.990	3.294	-0.910	0.364	-9.450	3.469
8	-2.590	3.416	-0.760	0.448	-9.288	4.108
9	-5.442	3.586	-1.520	0.129	-12.475	1.590
10	-0.418	3.338	-0.130	0.900	-6.963	6.127
11	-3.344	3.359	-1.000	0.320	-9.931	3.243
12	-0.804	3.435	-0.230	0.815	-7.539	5.931
13	-7.855	3.359	-2.340	0.019	-14.442	-1.268
14	-6.904	3.434	-2.010	0.044	-13.637	-0.170
15	-4.001	3.343	-1.200	0.231	-10.557	2.554
16	-6.006	3.557	-1.690	0.091	-12.982	0.969
17	-7.489	3.328	-2.250	0.025	-14.014	-0.964
18	-8.748	3.224	-2.710	0.007	-15.071	-2.426
19	-9.881	3.263	-3.030	0.002	-16.280	-3.482
20	-6.614	3.524	-1.880	0.061	-13.525	0.296
21	-12.349	3.608	-3.420	0.001	-19.425	-5.273
22	-2.410	3.594	-0.670	0.502	-9.457	4.636
23	-1.728	3.471	-0.500	0.619	-8.535	5.079
24	-6.119	3.273	-1.870	0.062	-12.537	0.298
25	-3.117	3.453	-0.900	0.367	-9.889	3.654
26	-5.863	3.423	-1.710	0.087	-12.575	0.850
27	-3.477	3.520	-0.990	0.323	-10.379	3.425
28	-4.127	3.363	-1.230	0.220	-10.722	2.468
29	-6.692	3.358	-1.990	0.046	-13.277	-0.108

30	-6.807	3.304	-2.060	0.040	-13.286	-0.327
31	2.306	3.221	0.720	0.474	-4.010	8.621
32	3.202	3.402	0.940	0.347	-3.468	9.872
33	-5.356	3.474	-1.540	0.123	-12.169	1.457
34	-4.944	3.334	-1.480	0.138	-11.482	1.595
35	-10.999	3.291	-3.340	0.001	-17.452	-4.546
36	-7.901	3.376	-2.340	0.019	-14.520	-1.281
37	-7.433	3.295	-2.260	0.024	-13.895	-0.972
38	-6.616	3.366	-1.970	0.049	-13.216	-0.016
39	-9.115	3.329	-2.740	0.006	-15.644	-2.587
40	-14.632	3.220	-4.540	0.000	-20.946	-8.317
41	-14.493	3.371	-4.300	0.000	-21.103	-7.882
42	-10.900	3.261	-3.340	0.001	-17.294	-4.505
43	-9.684	3.330	-2.910	0.004	-16.214	-3.154
44	-7.557	3.236	-2.340	0.020	-13.902	-1.212
45	-3.576	3.402	-1.050	0.293	-10.247	3.094
46	-9.477	3.365	-2.820	0.005	-16.075	-2.879
47	1.892	3.304	0.570	0.567	-4.587	8.370
48	-3.826	3.706	-1.030	0.302	-11.092	3.440
49	0.121	3.507	0.030	0.973	-6.756	6.998
50	-1.556	3.132	-0.500	0.619	-7.697	4.585
51	-4.075	3.160	-1.290	0.197	-10.272	2.122
52	-1.263	3.502	-0.360	0.718	-8.131	5.605
system#c.fill						
B	-0.329	0.372	-0.880	0.377	-1.059	0.401
C	-0.845	0.224	-3.770	0.000	-1.285	-0.405
system#c.startwt						
B	-0.151	0.080	-1.890	0.059	-0.309	0.006
C	-0.429	0.074	-5.770	0.000	-0.575	-0.284
system#c.mortality						
B	-1.546	0.308	-5.020	0.000	-2.150	-0.942
C	-0.944	0.248	-3.810	0.000	-1.429	-0.458
system#c.NE						
B	-0.101	0.017	-6.020	0.000	-0.134	-0.068
C	0.022	0.014	1.540	0.123	-0.006	0.049
system#flow						
B-WF_finishing	12.883	2.159	5.970	0.000	8.649	17.116
C-WF_finishing	-4.452	1.490	-2.990	0.003	-7.373	-1.530
system#size						
B#≤1500	10.682	4.180	2.560	0.011	2.485	18.880
B#>3500	7.186	2.018	3.560	0.000	3.227	11.145
C#≤1500	4.372	4.078	1.070	0.284	-3.626	12.370
C#>3500	3.666	1.755	2.090	0.037	0.224	7.109
system#year						
B#2016	-0.884	1.159	-0.760	0.446	-3.157	1.388
B#2017	-3.328	1.565	-2.130	0.033	-6.395	-0.260
C#2016	5.305	1.184	4.480	0.000	2.984	7.626
C#2017	2.036	1.491	1.370	0.172	-0.888	4.960
system#startwk						
B# 2	6.628	5.285	1.250	0.210	-3.734	16.991
B# 3	9.662	5.684	1.700	0.089	-1.482	20.806
B# 4	6.136	5.547	1.110	0.269	-4.739	17.012
B# 5	6.578	5.626	1.170	0.242	-4.452	17.608

B# 6	9.307	5.425	1.720	0.086	-1.329	19.944
B# 7	9.155	5.385	1.700	0.089	-1.403	19.712
B# 8	16.027	5.834	2.750	0.006	4.589	27.466
B# 9	13.923	5.623	2.480	0.013	2.898	24.948
B#10	5.603	5.563	1.010	0.314	-5.304	16.510
B#11	15.547	5.435	2.860	0.004	4.890	26.203
B#12	9.356	5.603	1.670	0.095	-1.628	20.340
B#13	21.810	5.804	3.760	0.000	10.432	33.188
B#14	16.948	5.460	3.100	0.002	6.243	27.652
B#15	18.899	5.482	3.450	0.001	8.151	29.646
B#16	20.480	5.612	3.650	0.000	9.478	31.483
B#17	24.829	5.389	4.610	0.000	14.264	35.394
B#18	30.691	5.412	5.670	0.000	20.081	41.301
B#19	30.801	5.635	5.470	0.000	19.754	41.849
B#20	21.716	5.578	3.890	0.000	10.780	32.652
B#21	32.301	5.683	5.680	0.000	21.161	43.442
B#22	27.039	5.691	4.750	0.000	15.881	38.196
B#23	23.629	5.491	4.300	0.000	12.863	34.394
B#24	24.210	5.393	4.490	0.000	13.637	34.783
B#25	28.671	5.627	5.100	0.000	17.639	39.703
B#26	28.308	5.428	5.220	0.000	17.667	38.950
B#27	21.213	5.845	3.630	0.000	9.753	32.673
B#28	18.516	5.472	3.380	0.001	7.788	29.245
B#29	19.820	5.849	3.390	0.001	8.352	31.287
B#30	20.866	5.386	3.870	0.000	10.305	31.426
B#31	10.202	5.413	1.880	0.060	-0.410	20.814
B#32	13.538	5.467	2.480	0.013	2.819	24.257
B#33	16.885	5.579	3.030	0.002	5.947	27.823
B#34	13.855	5.405	2.560	0.010	3.259	24.451
B#35	16.871	5.247	3.220	0.001	6.585	27.157
B#36	10.497	5.363	1.960	0.050	-0.017	21.010
B#37	10.541	5.426	1.940	0.052	-0.096	21.179
B#38	9.547	5.517	1.730	0.084	-1.269	20.364
B#39	21.337	5.453	3.910	0.000	10.646	32.028
B#40	13.599	5.508	2.470	0.014	2.800	24.397
B#41	16.988	5.472	3.100	0.002	6.260	27.716
B#42	11.903	5.409	2.200	0.028	1.297	22.508
B#43	11.452	5.399	2.120	0.034	0.867	22.038
B#44	12.323	5.301	2.320	0.020	1.930	22.716
B#45	5.772	5.592	1.030	0.302	-5.191	16.736
B#46	11.953	5.419	2.210	0.027	1.330	22.576
B#47	0.359	5.448	0.070	0.947	-10.321	11.040
B#48	15.929	5.782	2.750	0.006	4.593	27.266
B#49	2.763	5.738	0.480	0.630	-8.487	14.013
B#50	1.092	5.312	0.210	0.837	-9.323	11.506
B#51	11.529	5.357	2.150	0.031	1.027	22.032
B#52	4.261	5.809	0.730	0.463	-7.129	15.651
C# 2	4.130	4.375	0.940	0.345	-4.448	12.708
C# 3	3.888	4.803	0.810	0.418	-5.528	13.304
C# 4	-3.762	4.658	-0.810	0.419	-12.894	5.371
C# 5	-1.178	4.698	-0.250	0.802	-10.389	8.033
C# 6	0.402	4.391	0.090	0.927	-8.207	9.011
C# 7	4.717	4.518	1.040	0.297	-4.141	13.574

C# 8	-0.936	4.733	-0.200	0.843	-10.215	8.343
C# 9	7.438	4.776	1.560	0.119	-1.926	16.802
C#10	0.018	4.504	0.000	0.997	-8.812	8.847
C#11	3.089	4.446	0.690	0.487	-5.627	11.804
C#12	1.741	4.607	0.380	0.705	-7.290	10.772
C#13	10.932	4.523	2.420	0.016	2.065	19.798
C#14	10.373	4.553	2.280	0.023	1.447	19.300
C#15	6.057	4.550	1.330	0.183	-2.863	14.977
C#16	16.718	4.834	3.460	0.001	7.241	26.195
C#17	12.067	4.507	2.680	0.007	3.232	20.903
C#18	19.783	4.545	4.350	0.000	10.873	28.693
C#19	19.759	4.586	4.310	0.000	10.768	28.749
C#20	15.705	4.670	3.360	0.001	6.550	24.860
C#21	29.099	4.783	6.080	0.000	19.723	38.476
C#22	18.153	4.751	3.820	0.000	8.838	27.468
C#23	15.083	4.572	3.300	0.001	6.120	24.047
C#24	20.049	4.571	4.390	0.000	11.087	29.011
C#25	16.303	4.569	3.570	0.000	7.346	25.261
C#26	20.232	4.605	4.390	0.000	11.204	29.259
C#27	12.041	4.704	2.560	0.011	2.819	21.263
C#28	11.562	4.582	2.520	0.012	2.579	20.546
C#29	14.364	4.514	3.180	0.001	5.514	23.215
C#30	18.649	4.608	4.050	0.000	9.615	27.682
C#31	2.025	4.453	0.450	0.649	-6.704	10.755
C#32	6.054	4.454	1.360	0.174	-2.679	14.786
C#33	16.409	4.712	3.480	0.001	7.170	25.647
C#34	8.732	4.352	2.010	0.045	0.200	17.265
C#35	12.239	4.483	2.730	0.006	3.451	21.028
C#36	7.648	4.475	1.710	0.088	-1.126	16.423
C#37	8.448	4.453	1.900	0.058	-0.282	17.177
C#38	2.470	4.619	0.530	0.593	-6.585	11.525
C#39	9.540	4.475	2.130	0.033	0.768	18.313
C#40	13.256	4.579	2.890	0.004	4.279	22.233
C#41	12.324	4.533	2.720	0.007	3.438	21.210
C#42	8.001	4.452	1.800	0.072	-0.727	16.728
C#43	7.992	4.508	1.770	0.076	-0.845	16.829
C#44	4.948	4.515	1.100	0.273	-3.903	13.800
C#45	-0.081	4.527	-0.020	0.986	-8.956	8.793
C#46	4.824	4.520	1.070	0.286	-4.037	13.685
C#47	-5.222	4.493	-1.160	0.245	-14.031	3.587
C#48	1.196	4.781	0.250	0.803	-8.178	10.570
C#49	-4.718	4.595	-1.030	0.305	-13.726	4.290
C#50	-3.419	4.331	-0.790	0.430	-11.910	5.071
C#51	2.073	4.440	0.470	0.641	-6.632	10.778
C#52	-1.812	4.702	-0.390	0.700	-11.031	7.407
flow#c.sowfarm						
WF_finishing	-3.423	0.494	-6.930	0.000	-4.392	-2.454
flow#size						
WF_finishing#≤1500	-9.362	3.495	-2.680	0.007	-16.215	-2.508
WF_finishing#>3500	-3.493	1.338	-2.610	0.009	-6.115	-0.870
size#c.mortality						
<1500	0.694	0.334	2.080	0.038	0.038	1.349
>3500	0.213	0.208	1.030	0.304	-0.194	0.621

size#c.sowfarm						
<1500	0.187	0.618	0.300	0.763	-1.025	1.398
>3500	-1.098	0.367	-2.990	0.003	-1.817	-0.378
Constant	105.857	16.055	6.590	0.000	74.375	137.339
Random-effects Parameters	**Estimate**	**SE**	**95% LCL**	**95% UCL**		
site: Identity						
var(_cons)	54.994	4.374	47.056	64.270		
closeout: Identity						
var(vargrp)	150.880	8.130	135.758	167.687		
var(Residual)	101.601	3.377	95.193	108.441		
Model	**Observations**	***df***	**AIC**	**BIC**		
Finisher G:F	5187	194	41777.78	43049.24		

G:F = gain to feed ratio; CI = confidence interval; BW = body weight; NE = net energy; WF = wean-to-finish; AIC = Akaike information criterion; BIC = Bayesian information criterion; LCL = lower confidence limit; UCL = upper confidence limit.