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Effects of Standardized Total Tract Digestible Phosphorus on Growth Performance, Carcass Characteristics, Bone Mineralization, and Economics of 53- to 287-lb Pigs

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Abstract

A total of 1,130 barrows and gilts (PIC; 359 × Camborough, initial pen average BW of 53.2 ± 1.61 lb) were used in a 111-d growth trial to determine the standardized total tract digestible (STTD) P requirement of growing-finishing pigs from 53 to 287 lb. Pens of pigs were randomly assigned to 1 of 6 dietary treatments in a randomized complete block design with BW as a blocking factor. There were 7 replicate pens per treatment and 26 to 27 pigs per pen (at least 13 barrows and gilts per pen). The experimental diets were corn-soybean meal-based and were fed in 4 phases. The 6 dietary treatments were formulated to contain 80, 90, 100, 115, 130, and 150% of the NRC publication STTD P requirement for growing-finishing pigs within each phase. The STTD P levels were achieved by increasing the amount of limestone and monocalcium phosphate at the expense of corn, maintaining a similar 1.14 to 1.16:1 total Ca:P ratio across treatments, with no added phytase. Overall, increasing STTD P resulted in a quadratic response in ADG, F/G, and final BW ($P < 0.05$). The greatest improvement was observed with STTD P at 130% of NRC for ADG and final BW and 115% STTD P of the NRC recommendation for F/G. Average daily feed intake increased linearly with the inclusion of STTD P ($P < 0.05$). Increasing STTD P resulted in a linear increase in fat-free bone ash weight and percentage ash ($P < 0.05$). Barrows had significantly higher percentage ash compared to gilts ($P < 0.05$). Increasing STTD P resulted in an increase in HCW and carcass ADG, with the greatest response observed with STTD P at 130% of NRC (quadratic, $P < 0.05$). There was a marginally significant quadratic response in carcass F/G, with the greatest improvement with STTD P at 115% of NRC ($P < 0.10$). Carcass yield decreased with increasing STTD P (linear, $P < 0.05$), while there was a marginally significant decrease in backfat and increase in fat-free lean (linear, $P < 0.10$). No difference was observed for loin depth ($P > 0.05$). Feed cost per pig increased linearly with increasing STTD ($P < 0.05$). Contrarily, gain value per pig and IOFC increased quadratically, with the greatest profit observed with STTD P at 130% of NRC ($P < 0.05$). For ADG and feed efficiency, the quadratic model demonstrated the best fit. The maximum response in ADG was estimated at 122% of NRC STTD P, and the maximum response in feed efficiency was estimated at 116% of NRC STTD P. The broken-line linear model best fitted the data for ash as a percentage of fat-free dried bone, with a plateau achieved at 131% of the NRC STTD P requirement. In conclusion, the estimated STTD P requirement for growing-finishing pigs from 53 to 287 lb ranged from 116 to 131% of the NRC publication recommendations for each phase, depending on the response criteria and statistical model.

Keywords

phosphorus, finishing pigs, growth, bone mineralization

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Cover Page Footnote

Appreciation is expressed to Genus PIC for partial funding, to New Horizon Farms for use of the feed mill and animal facilities, and to Marty Heintz and Heath Houselog for technical assistance.

Authors

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This finishing pig nutrition and management is available in Kansas Agricultural Experiment Station Research Reports: https://newprairiepress.org/kaesrr/vol3/iss7/44

Effects of Standardized Total Tract Digestible Phosphorus on Growth Performance, Carcass Characteristics, Bone Mineralization, and Economics of 53- to 287-lb Pigs[1]

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Summary

A total of 1,130 barrows and gilts (PIC; 359 × Camborough, initial pen average BW of 53.2 ± 1.61 lb) were used in a 111-d growth trial to determine the standardized total tract digestible (STTD) P requirement of growing-finishing pigs from 53 to 287 lb. Pens of pigs were randomly assigned to 1 of 6 dietary treatments in a randomized complete block design with BW as a blocking factor. There were 7 replicate pens per treatment and 26 to 27 pigs per pen (at least 13 barrows and gilts per pen). The experimental diets were corn-soybean meal-based and were fed in 4 phases. The 6 dietary treatments were formulated to contain 80, 90, 100, 115, 130, and 150% of the NRC[4] publication STTD P requirement for growing-finishing pigs within each phase. The STTD P levels were achieved by increasing the amount of limestone and monocalcium phosphate at the expense of corn, maintaining a similar 1.14 to 1.16:1 total Ca:P ratio across treatments, with no added phytase. Overall, increasing STTD P resulted in a quadratic response in ADG, F/G, and final BW ($P < 0.05$). The greatest improvement was observed with STTD P at 130% of NRC for ADG and final BW and 115% STTD P of the NRC recommendation for F/G. Average daily feed intake increased linearly with the inclusion of STTD P ($P < 0.05$). Increasing STTD P resulted in a linear increase in fat-free bone ash weight and percentage ash ($P < 0.05$). Barrows had significantly higher percentage ash compared to gilts ($P < 0.05$). Increasing STTD P resulted in an increase in HCW and carcass ADG, with the greatest response observed with STTD P at 130% of NRC (quadratic, $P < 0.05$). There was a marginally significant quadratic response in carcass F/G, with the greatest improvement with STTD P at 115% of NRC

[1] Appreciation is expressed to Genus PIC for partial funding, to New Horizon Farms for use of the feed mill and animal facilities, and to Marty Heintz and Heath Houselog for technical assistance.

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[4] NRC. 2012. Nutrient requirements of swine. 11th rev. ed. Natl. Acad. Press, Washington, D.C.

($P < 0.10$). Carcass yield decreased with increasing STTD P (linear, $P < 0.05$), while there was a marginally significant decrease in backfat and increase in fat-free lean (linear, $P < 0.10$). No difference was observed for loin depth ($P > 0.05$). Feed cost per pig increased linearly with increasing STTD ($P < 0.05$). Contrarily, gain value per pig and IOFC increased quadratically, with the greatest profit observed with STTD P at 130% of NRC ($P < 0.05$). For ADG and feed efficiency, the quadratic model demonstrated the best fit. The maximum response in ADG was estimated at 122% of NRC STTD P, and the maximum response in feed efficiency was estimated at 116% of NRC STTD P. The broken-line linear model best fitted the data for ash as a percentage of fat-free dried bone, with a plateau achieved at 131% of the NRC STTD P requirement. In conclusion, the estimated STTD P requirement for growing-finishing pigs from 53 to 287 lb ranged from 116 to 131% of the NRC publication recommendations for each phase, depending on the response criteria and statistical model.

Introduction

Phosphorus (P) is an inorganic element that is essential for growth performance and development and maintenance of the skeletal system. It is the second most abundant mineral in the body after calcium. Besides bone mineralization, phosphorus is involved in different biological functions such as energy metabolism, synthesis of nucleic acids, and structure of cell membranes. Diets formulated with excess P can lead to an increase P excretion, negatively impacting the environment. In addition, this mineral is the third most expensive component in swine diets after energy and protein. Thus, diets are typically formulated to avoid excess P, with low margins of safety.

Establishing the optimum amount of P to supplement swine diets remains an important issue. Since 2012, the NRC[4] adopted the concept of standardized total tract digestibility (STTD) to report the requirements for P, which are based on a factorial approach. The NRC emphasized a need for empirical data to validate the model-derived digestible P requirement. However, to our knowledge there is still a lack of experiments on STTD P requirements of finishing pigs.

Furthermore, current statistical capabilities for modeling dose-response studies has allowed for a more precise estimation of the concentration of P needed to optimize different response criteria. Therefore, the objective of this study was to determine the effects of STTD P on growth performance, bone mineralization, carcass characteristics, and economics of growing-finishing pigs housed under commercial conditions.

Procedures

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. The study was conducted at a commercial research-finishing site in southwestern Minnesota. The barn was naturally ventilated and double-curtain-sided. Pens had completely slatted flooring and deep pits. Each pen was equipped with a 5-hole stainless steel feeder and cup waterer to allow ad libitum access to feed and water. The facility was equipped with a computerized feeding system (FeedPro; Feedlogic Corp., Willmar, MN) capable of measuring and recording daily feed additions to individual pens.

A total of 1,130 barrows and gilts (PIC; 359 × Camborough, initial pen average BW of 53.2 ± 1.61 lb) were used in a 111-d growth trial. After placement in the finishing facility, pigs were fed a common diet until the initiation of the trial. On d 0, pigs were weighed in pens and pens were ranked by average pig BW. Pens were then randomly assigned to 1 of 6 dietary treatments in a randomized complete block design, with BW as a blocking factor. There were 7 replicate pens per treatment and 26 to 27 pigs per pen (at least 13 barrows and gilts per pen).

The experimental diets were corn-soybean-meal-based, and fed in 4 different phases (Tables 1, 2, 3, and 4). The diets were formulated to contain 80, 90, 100, 115, 130, and 150% of the NRC[4] publication requirement for finishing pigs within each phase. The NRC requirement for phases 1, 2, 3, and 4 are estimated as 0.31, 0.27, 0.24, and 0.21% STTD P, respectively. Phase 1 diets were fed from d 0 to 29 (53.2 to 108.2 lb); phase 2 diets were fed from d 29 to 56 (108.3 to 166.5 lb); phase 3 diets were fed from d 56 to 70 (166.6 to 197.8 lb); and phase 4 diets were fed from d 70 to 111 (197.9 to 287.5 lb). The STTD P concentrations were achieved by increasing the amount of calcium carbonate and monocalcium phosphate at the expense of corn. A similar total Ca:P ratio of 1.14:1 to 1.16:1 was maintained across the dietary treatments in all phases with no added phytase. Experimental diets were manufactured at the New Horizon Farms Feed Mill (Pipestone, MN) and fed in meal form. Representative samples of treatment diets were taken from 6 feeders per dietary treatment 3 d after the beginning and 3 d before the end of the phase and stored at -4°F. After blending, subsamples were analyzed for DM, CP, crude fiber, ash, ether extract, Ca, and P (Ward Laboratories, Inc., Kearney, NE, Tables 5 and 6).

Pens of pigs were weighed and feed disappearance was recorded on d 0, 29, 56, 70, 99, and 111 to determine ADG, ADFI, F/G, grams of STTD P intake per kilogram of gain, and grams of STTD P intake per day. The formulated STTD P values were multiplied by ADFI to calculate grams of STTD P intake per day within phases. The total grams of STTD P intake were divided by total BW gain to calculate the grams of STTD P intake per kilogram of gain.

On d 99, the 2 heaviest pigs in each pen were selected, weighed, and sold according to standard farm procedures. On d 111, final pen weights were taken and one barrow and one gilt with intermediate weights were selected, tattooed with a pen ID and marked for bone data collection. These pigs were transported to a commercial abattoir in northwest Iowa (Natural Foods, Sioux Center, IA) for processing and collection of metacarpal bone samples for analysis of bone mineral content. The remaining pigs were individually tattooed with the specific pen identity on the shoulder to allow for carcass measurements to be recorded on a pen basis. These pigs were transported to a commercial packing plant in southwestern Minnesota (JBS Swift and Company, Worthington, MN) for processing and carcass data collection. Carcass measurements included HCW, loin depth, backfat depth, and percentage lean. Percentage carcass yield was calculated by dividing the average pen HCW by the average final live weight at the farm. Carcass ADG was calculated by multiplying the overall ADG by percentage carcass yield. Carcass F/G was calculated by dividing the overall ADFI by carcass ADG.

Bones were collected following processing for bone mineralization analysis. The left front feet were separated at the junction of carpals and radius and ulna, and individually placed in a zip-lock plastic bag with a permanent identification tag within the bag, being stored at -20°C. Feet were thawed overnight, and then were autoclaved for 1 h at 121°C. The third and fourth metacarcapals of each foot were removed. These bones were cleaned of extraneous soft tissue, and refrozen. The third metacarpal was dried at ambient temperature for 24 h, cut in half, and weighed. They were wrapped in cheesecloth to keep their tag ID, and defatted by petroleum ether using a Soxhlet extraction apparatus for 7 d. Defatted metacarpals were placed in a 105°C drying oven for 24 h to determine the dry fat-free weight. Bones were then ashed in a muffle furnace at 600°C for another 24 h to determine percentage ash. Ash is expressed as a percentage of dried fat-free bone weight.

For the economic analysis, total feed cost per pig, cost per lb of gain, gain value, and income over feed cost (IOFC) were calculated. The total feed cost per pig was calculated by multiplying ADFI by feed cost per pound and number of days the diet was fed in each respective period, then taking the sum of these values for each period. Cost per lb of gain was calculated by dividing total feed cost per pig by total gain per pig. Gain value per pig was calculated by multiplying carcass gain by an assumed carcass value of $67.32 per cwt. To calculate IOFC, total feed cost was subtracted from gain value. For all economic evaluations, price of ingredients during fall of 2016 was used with corn valued at $3.30/bu ($152.50/ton), soybean meal at $300/ton, L-lysine HCL at $0.70/lb, DL-methionine at $1.66/lb, L-threonine at $0.98/lb, L-tryptophan at $4.09/lb, L-valine at $5.00/lb, monocalcium phosphate at $0.32/lb, and calcium carbonate at $0.02/lb.

Experimental growth data were analyzed as a randomized complete block design, with pen serving as the experimental unit and BW as a blocking factor. The study was structured as a split-plot design in a randomized complete block design for the bone data. The whole-plot treatments included the different STTD P concentrations. Within each of the dietary treatments, there was a one-way treatment structure with gender as the factor level. A random effect of block by treatment was used to identify the pair of pigs (one barrow and one gilt) within each pen as the experimental unit for gender. The two-way interaction between dietary treatments and gender was tested, and no significant interactions were observed. Response variables were analyzed using generalized linear and non-linear mixed models. Polynomial contrasts were implemented to evaluate the functional form of the dose response to increasing dietary STTD P on ADG, ADFI, BW, F/G, feed cost/pig, feed cost/lb of gain, gain value/pig, IOFC, and grams of STTD P intake per day. The coefficients for the unequally spaced linear and quadratic contrasts were derived using the IML procedure in SAS. Statistical models were fitted using GLIMMIX procedure of SAS (Version 9.3, SAS Institute Inc., Cary, NC). Results were considered significant at $P \leq 0.05$ and marginally significant at $0.05 \leq P \leq 0.10$.

The effects of STTD P dose response on ADG, feed efficiency (modeled as gain to feed, G:F), and percentage bone ash were fit using GLIMMIX and NLMIXED procedure of

SAS according to Gonçalves et al.[5] Models were expanded to account for heterogeneous residual variances when needed. For the percentage ash analysis, models were expanded to account for a significant gender effect. Competing statistical models included a 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.[6] A decrease in BIC greater than 2 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.

Results and Discussion

Analysis of DM, CP, crude fiber, fat, and ash contents of experimental diets (Tables 5 and 6) showed that values were reasonably consistent with formulated estimates. Although some variation in analyzed P existed, analyzed P content still increased with increasing STTD P treatments. Chemical analysis of dietary Ca is typically more variable, with a higher coefficient of variation than P.

From d 0 to 56 (phases 1 and 2), which corresponded to the grower period, increasing the STTD P increased ADG driven by an increase in ADFI, both in a quadratic manner ($P < 0.05$; Table 7). The greatest improvement occurred as the STTD P increased from 80 to 115% of the NRC[4] requirement estimate, with no improvement thereafter. Contrarily, feed efficiency was not statistically affected by the dietary treatment ($P > 0.05$). From d 56 to 111 (phases 3 and 4), which corresponded to the finisher period, increasing STTD P increased ADG driven by an improvement in F/G, both in a quadratic manner ($P < 0.05$). The greatest improvement occurred as the STTD P increased from 80 to 115% for F/G and from 80 to 130% of the NRC requirement for ADG, with no improvement thereafter. Contrarily, feed intake was not statistically affected by the dietary treatment ($P > 0.05$).

For the overall period, increasing STTD P increased ADG and final BW (quadratic, $P < 0.05$). The greatest increase in ADG and final BW was observed as STTD P increased from 80 to 130% of NRC[4] requirement estimates, with no further improvement. Similarly, feed efficiency improved as STTD P increased from 80 to 115% of the requirement and started to worsen thereafter (quadratic, $P < 0.05$). On the other hand, ADFI increased linearly as STTD P increased. Similarly, grams of STTD P intake per kilogram of gain increased linearly ($P < 0.05$) for the grower and finisher periods, with a marginal quadratic response during the finisher period ($P < 0.10$). The grams of STTD P intake per day increased in a quadratic fashion ($P < 0.05$) during the grower period, and in a linear manner during the finisher period ($P < 0.05$).

[5] Gonçalves, M., N. Bello, S. Dritz, M. Tokach, J. DeRouchey, J. Woodworth, and R. Goodband. 2016. An update on modeling dose–response relationships: Accounting for correlated data structure and heterogeneous error variance in linear and nonlinear mixed models. Journal of Animal Science. 94(5): 1940-1950.

[6] G. A. Milliken, and D. E. Johnson. 2009. Analysis of messy data: designed experiments. Vol. 1, 2nd ed., CRC Press, Boca Raton, FL.

For carcass characteristics, HCW increased as STTD P increased up to 130% of the NRC[4] requirement estimate, with no further increase thereafter (quadratic, $P < 0.05$). Similarly, carcass ADG increased in a quadratic manner, with the greatest response observed with STTD P at 130% of the NRC requirement estimate (quadratic, $P < 0.05$). There was also a marginally significant response in carcass F/G, with the greatest improvement with STTD P at 115% of the requirement estimate ($P < 0.10$). Carcass yield decreased with increasing STTD P (linear, $P < 0.05$), while there was a marginally significant linear decrease in backfat and increase in fat-free lean ($P < 0.10$). No statistically significant differences were observed for loin depth measurements.

For bone characteristics, increasing STTD P resulted in a linear improvement in fat-free bone ash weight ($P < 0.05$; Table 9). However, there was no statistically significant difference in fat-free bone ash weight due to gender when the model was adjusted to account for differences in HCW between barrows and gilts ($P > 0.05$). Similarly, ash as a percentage of fat-free dried bone increased linearly as STTD P increased ($P < 0.05$), with barrows presenting significantly greater percentage bone ash than gilts ($P < 0.05$).

Feed cost per pig increased linearly with increasing STTD P, with the highest feed cost observed when STTD P was at 130% of the NRC[4] requirement estimate ($P < 0.05$). On the contrary, feed cost per pound of gain was fairly flat across the treatments up to the diet with STTD P at 130% of the requirement, with the greatest feed cost per pound of gain when STTD P was at 150% of the NRC requirement estimate (quadratic, $P < 0.05$). This was probably due to a high feed cost per pig and poor growth performance observed with this STTD P concentration. Gain value per pig increased with the greatest revenue for pigs fed diets with STTD P at 130% of the NRC requirement estimate, which is a result of the quadratic improvement in ADG and final BW (quadratic, $P < 0.05$). Similarly, IOFC increased in a quadratic manner, with the greatest improvement being observed as STTD P increased from 80 to 130% of the NRC requirement estimate ($P < 0.05$).

Homogeneous variance was used for ADG and percentage bone ash models and heterogeneous variance was used for feed efficiency models. For ADG (Figure 1), the best fitting model was the QP (BIC: 361). The STTD P concentration for maximum ADG was estimated at 122% (95% CI: [104, 143%]) of the NRC[4] requirement estimates within phases. Based on the best fitting model, the estimated regression equation was ADG, lb = $1.436 + 1.171 \times (\text{STTD P}) - 0.478 \times (\text{STTD P})^2$ or ADG, g = $651.36 + 531.33 \times (\text{STTD P}) - 216.90 \times (\text{STTD P})^2$ in the metric system. Similarly, the best fitting model for feed efficiency (Figure 2), modeled as G:F in g/kg, was the QP (BIC: 284). Based on this model, the estimated regression equation was G:F = $338.34 + 108.98 \times (\text{STTD P}) - 46.7864 \times (\text{STTD P})^2$. The STTD P concentration for maximum G:F was estimated at 116% (95% CI: [90, >150%]) of the NRC requirement for each phase. The percentage bone ash (Figure 3) model that best fitted the data was the BLL (BIC: 185). The STTD P concentration for maximum bone percentage ash was estimated at 131% (95% CI: [113, 148%]) of the NRC requirement estimate for each phase.

Phosphorus specifications based on the data generated in the present trial and a STTD P nursery phase 3 trial[7] were used to generate STTD P requirement equations for nursery and growing-finishing pigs (Table 10). Based on the nursery data, 130% of the NRC[4] requirement was used for the nursery phase 3, and 122% of the NRC requirements for growing-finishing phases 1, 2, 3, and 4. The resulting regression equation is STTD P, % = $0.0000020072 \times (\text{body weight, lb})^2 - 0.0014032410 \times (\text{body weight, lb}) + 0.4816400603$. The regression equation in the metric version is STTD P = $0.0000020072 \times (\text{body weight, kg} \times 2.2046)^2 - 0.0014032410 \times (\text{body weight, kg} \times 2.2046) + 0.4816400603$.

In summary, increasing STTD P improved ADG, F/G, final BW, HCW, as well as carcass ADG and carcass F/G in a quadratic fashion. Although feed cost increased with the increasing STTD P, the improved value in gain was sufficient to overcome the increase in diet cost. Thus, the return over the feed cost increased quadratically with increasing STTD P. Ash as a percentage of fat-free dried bone, and bone ash weight increased linearly with increasing STTD P, with higher mean values for barrows than gilts. In conclusion, the estimated STTD P requirement for finishing pigs from 53 to 287 lb ranged from 116 to 131% of the NRC[4] publication recommendations for each phase, depending on the response criteria and statistical model.

[7] Vier, C.M., F. Wu, S.S. Dritz, M.D. Tokach, M.A.D Gonçalves, U.A.D. Orlando, J.C. Woodworth, R.D. Goodband, and J.M. DeRouchey. 2017. Standardized total tract digestible phosphorus requirement of 11- to 25-kg pigs. J. Anim. Sci. 95 (supplement 2):56.

Table 1. Diet composition for phase 1 diets (as-fed basis)[1]

	Phase 1					
	STTD P, % of NRC[2]					
Item	80	90	100	115	130	150
Ingredient, %						
Corn	66.71	66.53	66.28	65.97	65.65	65.25
Soybean meal (46.5% CP)	30.78	30.79	30.81	30.83	30.85	30.88
Limestone	0.95	0.98	1.03	1.08	1.13	1.18
Monocalcium P (21% P)	0.45	0.60	0.78	1.02	1.27	1.59
Salt	0.35	0.35	0.35	0.35	0.35	0.35
L-Lys HCl	0.35	0.35	0.35	0.35	0.35	0.35
DL-Met	0.12	0.12	0.12	0.12	0.12	0.12
L-Thr	0.11	0.11	0.11	0.11	0.11	0.11
L-Trp	0.01	0.01	0.01	0.01	0.01	0.01
Trace mineral premix	0.08	0.08	0.08	0.08	0.08	0.08
Vitamin premix	0.10	0.10	0.10	0.10	0.10	0.10
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis						
Standardized ileal digestible (SID) amino acids, %						
Lys	1.21	1.21	1.21	1.21	1.21	1.21
Ile:Lys	61	61	61	61	61	61
Leu:Lys	127	127	127	127	127	126
Met:Lys	33	33	33	33	33	33
Met and Cys:Lys	56	56	56	56	56	56
Thr:Lys	61	61	61	61	61	61
Trp:Lys	18.7	18.7	18.7	18.7	18.7	18.7
Val:Lys	67	66	66	66	66	66
Total Lys, %	1.35	1.35	1.35	1.35	1.35	1.35
ME, kcal/lb	1,499	1,496	1,493	1,488	1,484	1,478
NE, kcal/lb	1,109	1,107	1,104	1,101	1,097	1,092
SID Lys:ME, g/Mcal	3.66	3.67	3.68	3.69	3.70	3.71
CP, %	20.7	20.7	20.7	20.6	20.6	20.6
Ca, %	0.56	0.59	0.64	0.70	0.76	0.84
P, %	0.49	0.52	0.56	0.61	0.66	0.73
Standardized total tract digestible P, %	0.25	0.28	0.31	0.36	0.40	0.46
Available P, %	0.17	0.20	0.24	0.29	0.35	0.42
Ca:P	1.14	1.14	1.15	1.15	1.15	1.15

[1] Phase 1 diets were fed from d 0 to 29 (53.3 to 108.2 lb).

[2] Assuming an ADFI of 3.48 lb and dietary NE of 1,122 kcal/lb, the NRC (2012) estimate of STTD P requirement for growing pigs from 25 to 55 lb expressed as dietary concentration is 0.31% STTD P. Therefore, treatment concentrations represented 80, 90, 100, 115, 130, and 150% of this NRC (2012) requirement.

Table 2. Diet composition for phase 2 diets (as-fed basis)[1]

	Phase 2					
	STTD P, % of NRC[2]					
Item	80	90	100	115	130	150
Ingredient, %						
Corn	77.45	77.27	77.10	76.81	76.53	76.17
Soybean meal (46.5% CP)	20.15	20.17	20.18	20.20	20.22	20.24
Limestone	0.90	0.93	0.95	1.00	1.05	1.10
Monocalcium P (21% P)	0.43	0.56	0.70	0.92	1.13	1.42
Salt	0.35	0.35	0.35	0.35	0.35	0.35
L-Lys HCl	0.35	0.35	0.35	0.35	0.35	0.35
DL-Met	0.07	0.07	0.07	0.07	0.07	0.07
L-Thr	0.12	0.12	0.12	0.12	0.12	0.12
L-Trp	0.02	0.02	0.02	0.02	0.02	0.02
Trace mineral premix	0.08	0.08	0.08	0.08	0.08	0.08
Vitamin premix	0.10	0.10	0.10	0.10	0.10	0.10
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis						
Standardized ileal digestible (SID) amino acids, %						
Lys	0.95	0.95	0.95	0.95	0.95	0.95
Ile:Lys	59	59	59	59	59	59
Leu:Lys	136	136	135	135	135	135
Met:Lys	32	32	32	32	32	32
Met and Cys:Lys	57	57	57	57	57	57
Thr:Lys	63	63	63	63	63	63
Trp:Lys	18.2	18.2	18.2	18.2	18.2	18.2
Val:Lys	67	67	66	66	66	66
Total Lys, %	1.07	1.07	1.07	1.07	1.07	1.07
ME, kcal/lb	1,505	1,502	1,500	1,496	1,492	1,486
NE, kcal/lb	1,138	1,136	1,134	1,131	1,127	1,123
SID Lys:ME, g/Mcal	2.86	2.87	2.87	2.88	2.89	2.90
CP, %	16.5	16.5	16.5	16.4	16.4	16.4
Ca, %	0.50	0.53	0.57	0.62	0.68	0.75
P, %	0.44	0.46	0.49	0.54	0.59	0.65
Standardized total tract digestible P, %	0.22	0.24	0.27	0.31	0.35	0.40
Available P, %	0.15	0.18	0.21	0.26	0.30	0.37
Ca:P	1.15	1.15	1.15	1.15	1.16	1.15

[1] Phase 2 diets were fed from d 29 to 56 (108.3 to 166.5 lb).

[2] Assuming an ADFI of 4.91 lb and dietary NE of 1,122 kcal/lb, the NRC (2012) estimate of STTD P requirement for growing pigs from 110 to 165 lb expressed as dietary concentration is 0.31% STTD P. Therefore, treatment concentrations represented 80, 90, 100, 115, 130, and 150% of this NRC (2012) requirement.

Table 3. Diet composition for phase 3 diets (as-fed basis)[1]

	Phase 3					
	STTD P, % of NRC[2]					
Item	80	90	100	115	130	150
Ingredient, %						
Corn	84.24	84.08	83.91	83.65	83.40	83.09
Soybean meal (46.5% CP)	13.58	13.59	13.60	13.62	13.64	13.66
Limestone	0.85	0.88	0.90	0.95	1.00	1.03
Monocalcium P (21% P)	0.38	0.50	0.63	0.82	1.01	1.27
Salt	0.35	0.35	0.35	0.35	0.35	0.35
L-Lys HCl	0.30	0.30	0.30	0.30	0.30	0.30
DL-Met	0.02	0.02	0.02	0.02	0.02	0.02
L-Thr	0.10	0.10	0.10	0.10	0.10	0.10
L-Trp	0.02	0.02	0.02	0.02	0.02	0.02
Trace mineral premix	0.08	0.08	0.08	0.08	0.08	0.08
Vitamin premix	0.10	0.10	0.10	0.10	0.10	0.10
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis						
Standardized ileal digestible (SID) amino acids, %						
Lys	0.75	0.75	0.75	0.75	0.75	0.75
Ile:Lys	60	60	60	60	60	60
Leu:Lys	151	151	151	151	151	151
Met:Lys	30	30	30	30	30	30
Met and Cys:Lys	58	58	58	58	58	58
Thr:Lys	65	65	65	65	65	65
Trp:Lys	18.2	18.2	18.2	18.2	18.2	18.2
Val:Lys	70	70	70	70	70	70
Total Lys, %	0.85	0.85	0.85	0.85	0.85	0.85
ME, kcal/lb	1,509	1,506	1,504	1,500	1,497	1,492
NE, kcal/lb	1,156	1,154	1,152	1,149	1,146	1,143
SID Lys:ME, g/Mcal	2.26	2.26	2.26	2.27	2.27	2.28
CP, %	13.8	13.8	13.8	13.8	13.8	13.7
Ca, %	0.45	0.48	0.52	0.57	0.62	0.67
P, %	0.40	0.42	0.45	0.49	0.53	0.59
Standardized total tract digestible P, %	0.19	0.22	0.24	0.28	0.31	0.36
Available P, %	0.13	0.16	0.19	0.23	0.27	0.32
Ca:P	1.14	1.15	1.15	1.16	1.16	1.15

[1] Phase 1 diets were fed from d 56 to 70 (166.6 to 197.8 lb).

[2] Assuming an ADFI of 3.48 lb and dietary NE of 1,122 kcal/lb, the NRC (2012) estimate of STTD P requirement for growing pigs from 165 to 220 lb expressed as dietary concentration is 0.24% STTD P. Therefore, treatment concentrations represented 80, 90, 100, 115, 130, and 150% of this NRC (2012) requirement.

Table 4. Diet composition for phase 4 diets (as-fed basis)[1]

	Phase 4					
	STTD P, % of NRC[2]					
Item	80	90	100	115	130	150
Ingredient, %						
Corn	84.91	84.77	84.62	84.40	84.18	83.93
Soybean meal (46.5% CP)	13.13	13.14	13.15	13.17	13.18	13.20
Limestone	0.83	0.85	0.88	0.91	0.95	0.98
Monocalcium P (21% P)	0.26	0.37	0.48	0.65	0.81	1.03
Salt	0.35	0.35	0.35	0.35	0.35	0.35
L-Lys HCl	0.25	0.25	0.25	0.25	0.25	0.25
DL-Met	0.01	0.01	0.01	0.01	0.01	0.01
L-Thr	0.08	0.08	0.08	0.08	0.08	0.08
L-Trp	0.01	0.01	0.01	0.01	0.01	0.01
Trace mineral premix	0.08	0.08	0.08	0.08	0.08	0.08
Vitamin premix	0.10	0.10	0.10	0.10	0.10	0.10
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis						
Standardized ileal digestible (SID) amino acids, %						
Lys	0.70	0.70	0.70	0.70	0.70	0.70
Ile:Lys	64	64	64	64	63	63
Leu:Lys	161	161	161	161	160	160
Met:Lys	31	31	31	31	31	31
Met and Cys:Lys	60	60	60	60	60	60
Thr:Lys	67	67	67	67	67	67
Trp:Lys	18.5	18.5	18.5	18.5	18.5	18.5
Val:Lys	74	74	74	74	74	74
Total Lys, %	0.80	0.80	0.80	0.80	0.80	0.80
ME, kcal/lb	1,511	1,509	1,506	1,503	1,500	1,496
NE, kcal/lb	1,159	1,157	1,155	1,153	1,150	1,147
SID Lys:ME, g/Mcal	2.10	2.10	2.11	2.11	2.12	2.12
CP, %	13.6	13.6	13.6	13.5	13.5	13.5
Ca, %	0.42	0.45	0.48	0.52	0.56	0.61
P, %	0.37	0.39	0.42	0.45	0.49	0.53
Standardized total tract digestible P, %	0.17	0.19	0.21	0.24	0.27	0.31
Available P, %	0.11	0.13	0.15	0.19	0.23	0.27
Ca:P	1.14	1.15	1.15	1.15	1.16	1.15

[1] Phase 1 diets were fed from d 70 to 111 (197.9 to 287.5 lb).

[2] Assuming an ADFI of 6.47 lb and dietary NE of 1,122 kcal/lb, the NRC (2012) estimate of STTD P requirement for growing pigs from 220 to 298 lb expressed as dietary concentration is 0.21% STTD P. Therefore, treatment concentrations represented 80, 90, 100, 115, 130, and 150% of this NRC (2012) requirement.

Table 5. Analyzed composition of experimental diets (as-fed-basis)[1]

	Phase 1[2]					
	STTD P, % of NRC					
Item, %	80	90	100	115	130	150
DM	89.60	88.40	88.30	88.46	88.74	88.67
CP	18.95	19.90	19.00	20.25	20.05	19.55
Crude fiber	2.15	2.45	2.15	1.95	2.00	2.00
Ether extract	2.70	2.50	2.25	2.30	2.35	2.15
Ash	4.01	4.04	4.18	4.16	4.21	4.81
Ca	0.74	0.74	0.76	0.79	0.73	0.91
P	0.40	0.43	0.47	0.49	0.56	0.62
	Phase 2[3]					
	STTD P, % of NRC					
	80	90	100	115	130	150
DM	89.56	88.76	87.98	88.03	88.84	88.38
CP	19.75	17.40	20.05	16.80	20.40	19.75
Crude fiber	2.25	2.55	2.65	2.35	2.40	2.55
Ether extract	2.45	2.70	2.45	2.25	2.30	2.60
Ash	3.08	3.33	4.08	4.07	4.79	4.52
Ca	0.51	0.55	0.59	0.74	0.91	0.84
P	0.31	0.43	0.48	0.49	0.57	0.57

[1] Representative samples of treatment diets were taken from 6 feeders per dietary treatment 3 d after the beginning and 3 d before the end of the phase and stored at -4°F. After blending, subsamples were submitted to Ward Laboratories, Inc. (Kearney, NE) and were analyzed for DM, CP, CF, ash, ether extract, Ca, and P.

[2] Phase 1 calculated standardized total tract digestible (STTD) P were 0.25, 0.28, 0.31, 0.36, 0.40, and 0.46%, and calculated total P were 0.49, 0.52, 0.56, 0.61, 0.66, and 0.73% for 80, 90, 100, 115, 130, and 150% of the NRC (2012) requirement, respectively.

[3] Phase 2 calculated STTD P were 0.22, 0.24, 0.27, 0.31, 0.35, and 0.40% and calculated total P were 0.44, 0.46, 0.49, 0.54, 0.59, and 0.65% for 80, 90, 100, 115, 130, and 150% of the NRC (2012) requirement, respectively.

Table 6. Analyzed composition of experimental diets (as-fed-basis)[1]

	Phase 3[2]					
	STTD P, % of NRC					
Item, %	80	90	100	115	130	150
DM	88.11	89.57	87.42	88.25	87.39	88.38
CP	13.65	13.35	12.05	13.65	13.05	13.90
C	2.25	1.40	1.20	1.50	1.35	2.55
Ether extract	2.35	2.30	2.05	2.15	2.15	2.60
Ash	3.12	3.10	3.18	3.39	3.41	4.52
Ca	0.58	0.54	0.57	0.59	1.11	0.84
P	0.33	0.36	0.36	0.44	0.46	0.57
	Phase 4[3]					
	STTD P, % of NRC					
	80	90	100	115	130	150
DM	87.31	86.98	87.47	88.55	88.22	86.99
CP	16.75	11.00	19.15	17.45	19.10	18.50
C	1.60	1.70	1.70	1.70	1.80	2.15
Ether extract	1.90	2.20	1.90	1.90	1.75	1.60
Ash	3.77	2.95	4.01	4.43	4.56	4.56
Ca	0.53	0.58	0.85	0.89	0.67	0.69
P	0.39	0.31	0.48	0.53	0.54	0.58

[1] Representative samples of treatment diets were taken from 6 feeders per dietary treatment 3 d after the beginning and 3 d before the end of the phase and stored at -4°F. After blending, subsamples were submitted to Ward Laboratories, Inc. (Kearney, NE) and were analyzed for DM, CP, CF, ash, ether extract, Ca, and P.

[2] Phase 3 calculated standardized total tract digestible (STTD) P were 0.19, 0.22, 0.24, 0.28, 0.31, and 0.36%, and calculated total P were 0.40, 0.42, 0.45, 0.49, 0.53, and 0.59 % for 80, 90, 100, 115, 130, and 150% of the NRC requirement, respectively.

[3] Phase 4 calculated STTD P were 0.17, 0.19, 0.21, 0.24, 0.27, and 0.31% and calculated total P were 0.37, 0.39, 0.42, 0.45, 0.49, and 0.53% for 80, 90, 100, 115, 130, and 150% of the NRC requirement, respectively.

Table 7. Effects of standardized total tract digestible (STTD) P on growth performance, carcass characteristics, and economics of growing-finishing pigs[1]

	STTD P, % of NRC requirement[2]							Probability, *P*<	
Item	80	90	100	115	130	150	SEM	Linear	Quadratic
Grower period (d 0 to 56)									
ADG, lb	1.95	2.00	1.99	2.06	2.05	2.02	0.026	0.001	0.003
ADFI, lb	4.13	4.24	4.23	4.37	4.37	4.26	0.078	0.017	0.004
F/G	2.13	2.12	2.14	2.14	2.15	2.12	0.022	0.827	0.237
STTD P intake, g/d	4.3	5.0	5.5	6.6	7.4	8.3	0.12	0.001	0.009
STTD P intake, g/kg gain	4.9	5.4	6.1	7.0	7.9	9.1	0.07	0.001	0.351
Finisher period (d 56 to 111)									
ADG, lb	2.21	2.21	2.23	2.25	2.30	2.20	0.028	0.208	0.006
ADFI, lb	6.39	6.42	6.42	6.33	6.52	6.45	0.059	0.254	0.792
F/G	2.94	2.94	2.90	2.84	2.86	2.99	0.028	0.747	0.001
STTD P intake, g/d	5.0	5.7	6.5	7.1	8.3	9.5	0.07	0.001	0.842
STTD P intake, g/kg gain	5.0	5.7	6.4	7.1	7.9	9.4	0.09	0.001	0.063
Overall period (d 0 to 111)									
ADG, lb	2.08	2.10	2.11	2.15	2.17	2.11	0.014	0.001	0.001
ADFI, lb	5.23	5.31	5.29	5.33	5.41	5.32	0.051	0.033	0.102
F/G	2.56	2.55	2.54	2.50	2.53	2.57	0.020	0.998	0.004
BW, lb									
d 0	53.2	53.2	53.3	53.3	53.2	53.2	1.61	0.992	0.954
d 56	162.6	165.6	165.3	169.2	169.7	166.7	2.78	0.001	0.001
d 111	281.9	285.0	286.9	290.8	294.6	285.9	2.47	0.002	0.001

continued

Table 7, *continued*. Effects of standardized total tract digestible (STTD) P on growth performance, carcass characteristics, and economics of growing-finishing pigs[1]

	STTD P, % of NRC requirement[2]							Probability, *P*<	
Item	80	90	100	115	130	150	SEM	Linear	Quadratic
Carcass characteristics[3]									
Pig count	147	146	139	152	143	150			
HCW, lb	205.1	208.3	208.3	210.4	212.8	207.0	1.58	0.012	0.001
Carcass ADG, lb[4]	1.51	1.54	1.53	1.56	1.57	1.53	0.010	0.029	0.001
Carcass F/G[5]	3.47	3.45	3.46	3.43	3.45	3.49	0.028	0.479	0.059
Carcass yield, %	72.8	73.1	72.6	72.3	72.2	72.4	0.24	0.027	0.368
Backfat, mm[6,7]	19.0	18.4	18.3	18.6	18.0	18.1	-	0.073	0.580
Fat-free lean, %[6,7]	55.0	55.4	55.4	55.3	55.6	55.5	-	0.097	0.519
Loin depth, mm[6,7]	64.1	64.7	64.2	64.5	64.7	64.3	-	0.796	0.651
Economics, $/pig									
Feed cost	50.63	51.52	51.61	52.25	53.40	52.92	0.502	0.001	0.106
Feed cost/lb gain[8]	0.220	0.221	0.221	0.220	0.221	0.226	0.0018	0.002	0.018
Gain value[9]	111.18	113.35	113.33	114.72	116.35	112.45	0.711	0.015	0.001
IOFC[10]	60.55	61.83	61.72	62.47	62.95	59.51	0.687	0.388	0.001

[1] A total of 1,130 pigs (337 × 1050, PIC, initially 53.2 lb BW) were used in a 111-d growth trial with 26 to 27 pigs per pen and 7 pens per treatment.

[2] All treatments contain variable concentrations of STTD P that represent 80, 90, 100, 115, 130, and 150% of the NRC requirement for pigs within phases.

[3] 877 pigs were transported to a commercial packing plant for processing and data collection (Swift and Company, Worthington, MN).

[4] Carcass average daily gain = overall average daily gain × carcass yield.

[5] Carcass F/G = overall average daily feed intake/carcass average daily gain.

[6] SEM for backfat were 0.370, 0370, 0.376, 0.373, and 0.367, SEM for % lean were 0.247, 0.247, 0.251, 0.244, 0.249, and 0.245, and SEM for loin depth were 6.17, 6.17, 6.29, 6.08, 6.23 and 6.10 for 80, 90, 100, 115, 130, and 150% of the NRC requirement, respectively.

[7] Adjusted for HCW.

[8] Feed cost/lb gain = total feed cost divided by total gain per pig.

[9] Gain value = (HCW × $0.6732) – (d 0 BW × 0.75 × $0.6732).

[10] Income over feed cost = gain value – feed cost.

Table 8. Effects of standardized total tract digestible (STTD) P on bone analysis of growing-finishing pigs[1,2,3]

	STTD P, % of NRC[4]						Gender		Probability, P<[6]		
									Treatment		
Item[5]	80	90	100	115	130	150	Barrow	Gilt	Linear	Quadratic	Gender
Ash bone wt, g	8.47	8.75	9.05	9.25	9.56	10.03	9.24	9.13	0.001	0.840	0.501
SEM	0.177	0.178	0.180	0.188	0.179	0.178	0.108	0.115			
Ash, %	60.76	60.74	61.12	61.45	61.94	61.93	61.50	61.15	0.001	0.373	0.036
SEM	0.184	0.186	0.187	0.196	0.186	0.185	0.107	0.116			

[1] A total of 1,130 pigs (337 × 1050, PIC, initially 53.2 lb BW) were used in a 111-d growth trial with 26 to 27 pigs per pen and 7 pens per treatment.

[2] Visually assumed to represent the mean live weight of the pen, 84 pigs (2 pigs/pen, 1 barrow/1 gilt) were subsampled and shipped to a separate processing facility for bone collection (Natural Foods Holdings, Inc., Sioux Center, IA).

[3] A total of 84 3rd metacarpals were autoclaved for 1 h. After cleaning, bones were placed in a Soxhlet extraction apparatus containing petroleum ether for 7 d as a means of removing water and fat. They were then dried at 105°C for 24 h, and then ashed at 600°C for 24 h.

[4] All treatments contain variable concentrations of STTD P that represent 80, 90, 100, 115, 130, and 150% of the NRC publication (2012) requirement for pigs within phases.

[5] Adjusted for HCW.

[6] The two-way interaction was tested and no evidence for significant interactions was observed for ash bone weight and bone percentage ash.

Table 9. Standardized total tract digestible (STTD) P requirement for nursery and growing-finishing pigs[1,2]

	Body weight range, lb						
Item	25-50	50-80	80-120	120-160	160-200	200-250	250-290
Average BW, lb	37.5	65	100	140	180	225	270
Diet NE, Kcal/lb	1,093	1,102	1,102	1,132	1,151	1,154	1,154
STTD P	0.43	0.40	0.36	0.32	0.29	0.27	0.25
STTD P:NE	3.93	3.63	3.27	2.83	2.52	2.34	2.17

[1] Phosphorus specifications are based on the data generated in the present trial and a STTD P nursery phase 3 trial; thus, 130% of the NRC requirements was used for the nursery phase 3, and 122% of the NRC for growing-finishing phases 1, 2, 3, and 4.

[2] The regression equation is STTD P = $0.0000020072 \times (\text{body weight, lb})^2 - 0.0014032410 \times (\text{body weight, lb}) + 0.4816400603$. The regression equation in the metric version is STTD P = $0.0000020072 \times (\text{body weight, kg} \times 2.2046)^2 - 0.0014032410 \times (\text{body weight, kg} \times 2.2046) + 0.4816400603$.

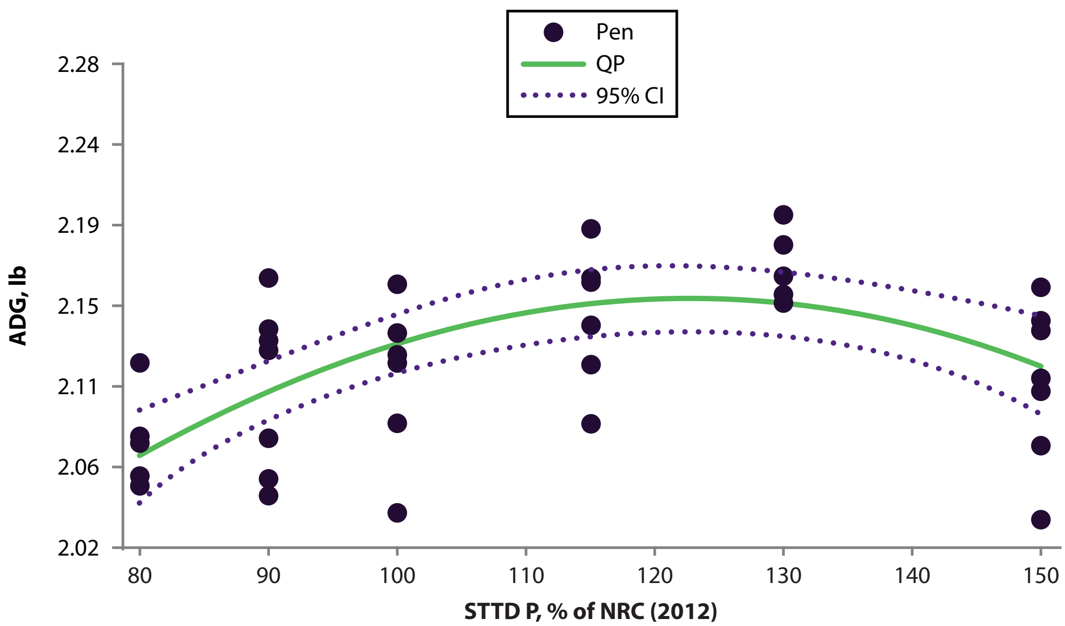

Figure 1. Fitted quadratic polynomial (QP) regression model on ADG as a function of increasing standardized total tract digestible (STTD) P in 53- to 287-lb pigs. The QP model estimated the maximum mean ADG at 122% (95% CI: [104, 143%]) of the NRC (2012) recommendations within phases. Based on the best-fitting model, the estimated regression equation was or ADG, lb = $1.436 + 1.171 \times (\text{STTD P}) - 0.478 \times (\text{STTD P})^2$ or ADG, g = $651.36 + 531.33 \times (\text{STTD P}) - 216.90 \times (\text{STTD P})^2$ in the metric system.

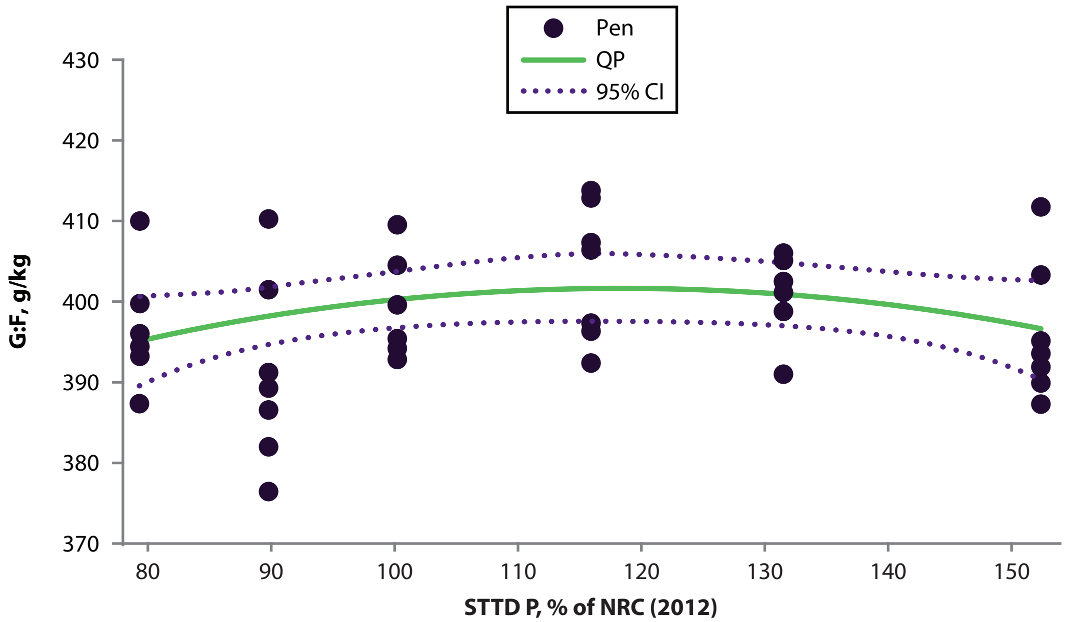

Figure 2. Fitted quadratic polynomial (QP) regression model on G:F as a function of increasing standardized total tract digestible (STTD) P in 53- to 287-lb pigs. The QP model estimated the maximum mean ADG at 122% (95% CI: [104, 143%]) of the NRC (2012) recommendations within phases. Based on the QP model, the estimated regression equation was G:F = 338.34 + 108.98 × (STTD P) – 46.7864 × (STTD P)^2.

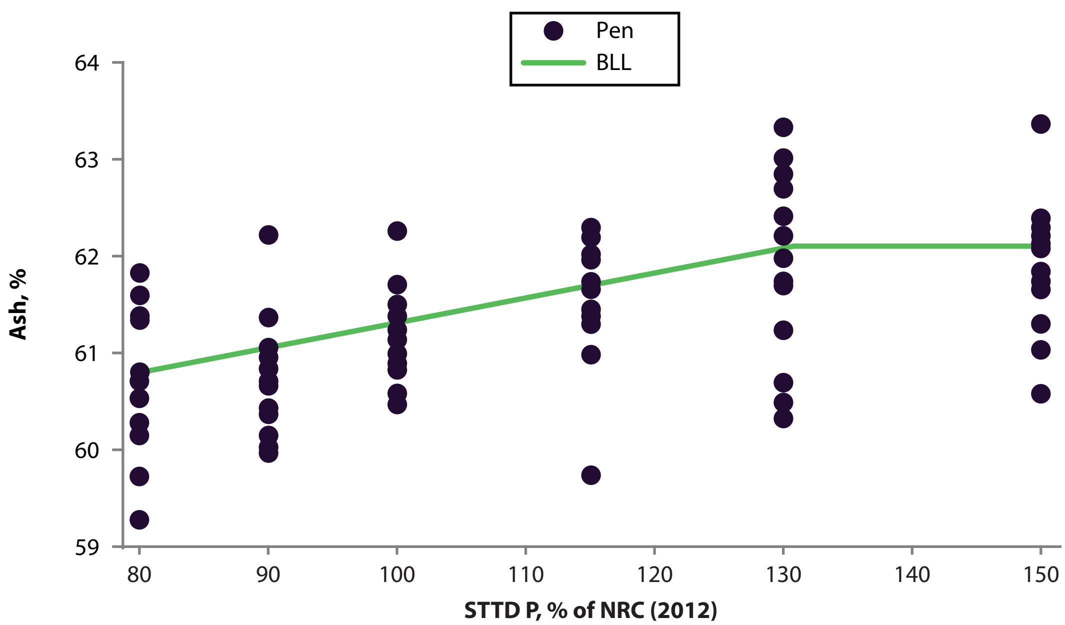

Figure 3. Fitted broken line linear (BLL) regression model on bone percentage ash as a function of increasing standardized total tract digestible (STTD) P in 53- to 287-lb pigs. The BLL model estimated the maximum mean percentage ash at 131% (95% CI: [113, 148%]) of the NRC (2012) recommendations within phases.