

Standardized Total Tract Digestible Phosphorus Requirement of 13- to 28-lb Pigs Fed Diets With or Without Phytase¹

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Summary

A total of 1,080 nursery pigs (PIC 280 × 1050, initially 13.0 ± 2.38 lb BW) were housed in 3 commercial research rooms and used in a 46-d study to determine the effects of increasing standardized total tract digestible (STTD) phosphorus (P) concentrations in diets with and without phytase on growth performance and percentage bone ash. Pens of pigs (10 pigs per pen, 9 pens per treatment) were balanced for equal pen weights and allotted randomly to 1 of 12 treatments. Dietary treatments were arranged in 2 sets of dose titration with 6 levels of STTD P with and without 2,000 phytase unit (FYT) of phytase (DSM Nutritional Products, Inc., Parsippany, NJ). The STTD P levels were expressed as percentage of the NRC (2012)³ requirement estimates (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 phase 1 (d 0 to 11) and phase 2 (d 11 to 25), followed by a common phase 3 diet from d 25 to 46. On d 25, 1 median-weight gilt from each pen was euthanized and radius samples were collected for analysis of bone ash. During the treatment period (d 0 to 25), increasing STTD P from 80 to 140% of NRC in diets without phytase improved average daily gain (ADG) (quadratic, $P = 0.005$), average daily feed intake (ADFI) (quadratic, $P = 0.043$), and feed efficiency (F/G) (linear, $P < 0.001$; quadratic, $P = 0.063$). 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 ranged from 102 to >140% of NRC for maximum feed efficiency using BLL, broken-line quadratic, and linear models. When diets contained phytase, increasing STTD P from 100 to 170% of NRC improved ADG (quadratic, $P = 0.031$) and F/G (linear, $P = 0.005$; quadratic, $P = 0.065$). Estimated STTD P requirement

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³NRC. 2012. Nutrient Requirements of Swine. 11th rev. ed. Natl. Acad. Press, Washington, DC.

in diets containing phytase was 138% for maximum ADG (QP model) and was 147 (QP model) and 116% (BLL model) of NRC for maximum feed efficiency. Increasing STTD P increased (linear, $P < 0.001$) percentage bone ash regardless of phytase addition. Comparing diets containing the same STTD P levels, adding phytase improved ($P < 0.001$) ADG, ADFI, and F/G. In summary, estimated STTD P requirements varied depending on the response criteria and statistical models and ranged from 91 to >140% of the NRC in diets containing no phytase, and from 116 to >170% of NRC for diets containing 2,000 FYT phytase. The high dose of phytase promoted growth performance and improved the dose responses to dietary STTD P for ADG and feed efficiency in 13- to 28-lb nursery pigs.

Introduction

Dietary P concentration can greatly affect pig growth performance 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 number of published studies; thus, empirical data are needed to validate these STTD P requirement estimates. In a recent dose titration study, Vier et al. (2017a⁴) reported that feeding STTD P concentrations above the NRC (2012) requirement estimate improved growth performance and percentage bone ash in 25- to 50-lb nursery pigs. However, to our knowledge, limited research has been published that investigated the STTD P requirement of early nursery pigs from weaning to 25 lb body weight (BW).

In current pig production, phytase has been commonly added in diets to increase availability of phytate-bound P. Feeding high dose of phytase has also been reported to promote growth performance of nursery pigs^{5,6,7} by reducing the anti-nutritional factors of phytate and increasing availability of extra-phosphoric nutrients, such as amino acids (AA), trace minerals, and dietary energy.⁸ It can be hypothesized that the growth-promoting effect of 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.

Furthermore, updated statistical methodology for modeling dose-response studies has been developed and allows for a more precise estimation of the nutrient concentra-

⁴Vier, 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. DeRouche. 2017a. Standardized total tract digestible phosphorus requirement of 11- to 25-kg pigs. *J. Anim. Sci.* 95(Suppl. 2):56. (Abstr.). doi:10.2527/asasmw.2017.119

⁵Zeng, Z. K., D. Wang, X. S. Piao, P. F. Li, H. Y. Zhang, C. X. Shi, and S. K. Yu. 2014. Effects of adding super dose phytase to the phosphorus-deficient diets of young pigs on growth performance, bone quality, minerals and amino acids digestibilities. *Asian-Austral J Anim Sci* 27:237–246. doi:10.5713/ajas.2013.13370

⁶Zeng, Z., Q. Li, Q. Tian, P. Zhao, X. Xu, S. Yu, and X. Piao. 2015. Super high dosing with a novel Buttiauxella phytase continuously improves growth performance, nutrient digestibility, and mineral status of weaned pigs. *Biol. Trace Elem. Res.* doi:10.1007/s12011-015-0319-2

⁷Patience, J. F., S. A. Gould, D. Koehler, B. Corrigan, A. Elsbernd, and C. L. Holloway. 2015. Super-dosed phytase improves rate and efficiency of gain in nursery pigs. *Iowa State University Animal Industry Report*. 611:98.

⁸Cowieson, A. J., P. Wilcock, and M. R. Bedford. 2011. Super-dosing effects of phytase in poultry and other monogastrics. *World's Poult. Sci. J.* 67:225–235. doi: 10.1017/S0043933911000250

tion needed to optimize different response criteria.⁹ Therefore, the objective of this study was to determine the effects of increasing STTD P concentration in diets with or without high levels (2,000 phytase unit; FYT) of phytase on growth performance and percentage bone ash of nursery pigs from 13- to 28-lb BW.

Procedures

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in the experiment. The study was conducted at the Cooperative Research Farm's Swine Research Nursery (Kalmbach Feeds, Inc., Sycamore, OH). Each pen (5 × 6 ft²) 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 × 1050) were housed in each pen and were allowed *ad libitum* access to feed and water throughout the experiment.

A total of 1,080 weaned pigs with initial BW of 13.0 ± 2.38 lb were used from 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 then allotted to 1 of 12 dietary treatments (9 replications per treatment) in a completely randomized manner. The dietary treatments were arranged in 2 sets of dose titrations with 6 levels of STTD P in diets contained 0 or 2,000 FYT phytase (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 designed weight range and different STTD P levels (0.45 and 0.40%, respectively) were recommended for 11 to 15 and 15 to 24 lb pigs. 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% of 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, respectively (Table 1). For diets containing phytase, the experimental STTD P levels were: 100, 110, 125, 140, 155, and 170% of NRC; including the manufacturer's suggested release value of 0.158% STTD P and 0.105% STTD calcium (Ca) for 2,000 FYT phytase, the tested 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 to contain negligible (0.02%) amounts of inorganic P source. Phase 1 diets (Table 3) were offered from d 0 to 11 and phase 2 diets (Table 4) were offered from d 11 to 25. A common phase 3 diet containing 0.45% STTD P was then fed to all pigs from d 25 to 46. Ingredient loading values, standardized ileal digestible AA digestibility coefficients, and STTD coefficients for P were obtained from NRC (2012). All ingredients containing Ca and P were sampled 4 times and sent to 2 laboratories (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). The average of the 16 laboratory results for each sampled ingredient was used in the diet formulation. All diets were balanced for a total Ca:total P ratio of 1.20:1. Phase 1 diets were prepared in pellet form and phases 2 and 3 diets were provided in

⁹Gonçalves, 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. *J. Anim. Sci.* 94(5): 1940-1950.

meal form. Pigs and feeders were weighed on d 0, 11, 25, and 46 to determine ADG, ADFI, and F/G.

Complete diet samples were obtained and delivered to the Kansas State University Swine Laboratory, Manhattan, KS, and stored at -4°F until analysis. Feed samples were analyzed for dry matter, crude protein, 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. The means of analyzed nutrient values are presented in Tables 3 and 4.

At the end of treatment period (d 25), 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 -4°F until analysis. After thawing at room temperature (75°F) in plastic bags for 24 h, bones were autoclaved for 60 min, adhering tissue and cartilage caps were removed, then dried at 221°F for 7 d. Dried radiuses were ashed in a muffle furnace at $1,112^{\circ}\text{F}$ for 24 h to determine total ash weight and percentage bone ash.

Growth performance and bone ash data were analyzed in a randomized complete block design with pen as the experimental unit and room as a blocking factor. Effects of phytase and phytase \times STTD P interaction were analyzed in a 2×4 factorial treatment structure, with main effects of phytase (0 or 2,000 FYT) and STTD P levels (100, 110, 125, and 140% of NRC), which represented the dose treatments that were overlapped between the 2 titration sets. Within each set of the dose titration, single degree-of-freedom contrasts were performed to test the linear and quadratic dose response to increasing STTD P. Coefficients for the unequally spaced linear and quadratic contrasts were derived using the IML procedure in SAS (Version 9.4, SAS Institute Inc., Cary, NC). Statistical models were fit using the GLIMMIX procedure of SAS. Means were reported as least-squares means. Results were considered significant at $P < 0.05$ and marginally significant at $0.05 < P < 0.10$.

Separately for each set (with or without phytase) of STTD P titration, the effects of STTD P dose response on ADG, ADFI, and feed efficiency (modeled as gain to feed, G:F) during treatment period (d 0 to 25), as well as percentage bone ash, were fit using GLIMMIX and NLMIXED procedures of SAS according to Gonçalves et al. (2016)⁸ Models were expanded to account for heterogeneous residual variances when needed. For the percentage bone ash analysis, sample pig BW was included in the statistical models as a covariate. 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.¹⁰ 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.

¹⁰Milliken, G. A., and D. E. Johnson. 2009. Analysis of messy data: designed experiments. Vol. 1, 2nd ed., CRC Press, Boca Raton, FL.

Results

Analyzed total P concentrations of dietary treatments were reasonably consistent with calculated levels and followed similar patterns as the designed treatment structure (Tables 3 and 4). Analysis of total Ca was more variable than P. Analyzed Ca concentrations were similar to formulated levels in phase 1 diets but were slightly greater in phase 2 diets containing 80, 90, 100, and 125% of NRC STTD P without phytase and 100, 140, and 170% of NRC STTD P with phytase. However, the analyzed Ca:analyzed P ratios in diets were within 1.13:1 to 1.57:1 range and should not impact pig performance and percentage bone ash.

Phytase × STTD P interactions were assessed using the 8 treatments with overlapped STTD P levels between the 2 sets of dose titration. No phytase × STTD P interactions were observed for any growth response or percentage bone ash except for ADG ($P = 0.083$) during treatment period (d 0 to 25), whereby increasing STTD P from 100 to 140% of NRC in diets containing phytase increased (linear, $P = 0.017$) ADG, but no evidence of different ADG was observed when diets contained no phytase (Table 5). Feeding phytase increased ($P < 0.001$) ADG from d 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 marginal phytase × STTD P interaction on ADG, STTD P requirements were modeled separately for diets with and without phytase.

During the treatment period (d 0 to 25), increasing STTD P from 80 to 140% of NRC in diets without phytase increased ADG (quadratic, $P = 0.005$; Figure 1) and d 25 BW (quadratic, $P = 0.019$). The best fitting models for ADG were QP (BIC = 481.7) and BLL (BIC = 479.0). The QP model estimated the maximum ADG at 117% (95% CI: [86, >140%]) of NRC level of STTD P, with 99% of maximum ADG achieved at 106%; the estimated QP regression equation was: $ADG, g = -8.45 + 4.74 \times (\text{STTD P, \% NRC}) - 0.02 \times (\text{STTD P, \% NRC})^2$. The BLL model suggested that the ADG response was plateaued at 91% (95% CI: [76, 107%]) of NRC. When diets contained 2,000 FYT phytase, increasing STTD P from 100 to 170% of NRC increased ADG (quadratic, $P = 0.031$; Figure 2) and marginally increased d 25 BW (quadratic, $P = 0.084$). The QP model estimated the maximum ADG at 138% (95% CI: [110, >170%]) of NRC, with 99% of maximum ADG achieved at 122%; the estimated QP regression equation was: $ADG, g = 76.18 + 3.31 \times (\text{STTD P, \% NRC}) - 0.012 \times (\text{STTD P, \% NRC})^2$.

For ADFI during treatment period, pigs fed diets containing phytase had greater ($P < 0.001$) ADFI than those fed diets without phytase regardless of STTD P levels (0.84 vs. 78 lb, respectively). Increasing STTD P from 80 to 140% of NRC increased (quadratic, $P = 0.043$) ADFI when phytase was not included in the diets (Figure 3). The QP model suggested that the maximum ADFI was achieved when diets contained STTD P of 109% (95% CI: [80, 140%]) of NRC, with 99% of maximum ADFI achieved at 97%; the estimated QP regression equation was: $ADFI, g = 80.91 + 5.16 \times (\text{STTD P, \% NRC}) - 0.024 \times (\text{STTD P, \% NRC})^2$. When diets contained phytase, dietary STTD P did not affect ADFI.

Feed efficiency (F/G) during treatment period was improved ($P < 0.001$) by adding phytase to diets regardless of STTD P levels (1.28 vs. 1.32, respectively; Table 5). Requirements of STTD P to maximize feed efficiency were modeled based on G:F ratio. Increasing STTD P from 80 to 140% of NRC in diets without phytase improved (linear, $P < 0.001$; quadratic, $P = 0.063$) G:F (Figure 4), with LM (BIC = 505.2), BLL (BIC = 503.3), and BLQ (BIC = 504.5) being competing models. The LM model estimated the maximum G:F at greater than 140% of NRC; the estimated LM regression equation was: $G:F, g/kg = 644.57 + 0.90 \times (\text{STTD P, \% NRC})$. 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, $P = 0.005$; quadratic, $P = 0.065$) G:F (Figure 5). 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%; the estimated QP regression equation was: $G:F, g/kg = 534.32 + 3.48 \times (\text{STTD P, \% NRC}) - 0.012 \times (\text{STTD P, \% NRC})^2$. The BLL plateau was estimated at 116.4% (95% CI: [85.2, 147.7%]).

During the post-treatment period (d 25 to 46), all pigs received the same common diet containing 0.45% STTD P (approximately 136% of NRC requirement estimate). Pigs previously fed diets containing phytase had poorer ($P < 0.05$) ADG (1.45 vs. 1.58 lb, respectively), ADFI (2.41 vs. 2.32 lb, respectively), and F/G (1.52 vs. 1.55, 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 decreased when STTD P content of previous diets increased from 100 to 110% of NRC and ADFI increased thereafter (quadratic, $P = 0.080$).

Percentage bone ash was not affected by adding phytase in the diets but was increased (linear, $P < 0.001$) 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 6); the estimated LM regression equation was: $\text{bone ash, \%} = 28.79 + 0.095 \times (\text{STTD P, \% NRC}) + 0.56 \times (\text{BW, kg})$. When diets contained phytase, the LM model (BIC = 257.6) estimated the maximum percentage bone ash achieved at greater than 170% of NRC (Figure 7); the estimated LM regression equation was: $\text{bone ash, \%} = 32.27 + 0.084 \times (\text{STTD P, \% NRC}) + 0.37 \times (\text{BW, kg})$.

Feed cost per pig increased (quadratic, $P = 0.050$) as STTD P content increased in diets containing no phytase, but remained unchanged for diets containing phytase (Table 6). Gain value and income over feed cost increased (quadratic, $P < 0.05$) as dietary STTD P increased in both formulation sets; however, the pattern of dose response differed among diets with and without phytase (phytase \times STTD P interaction, $P < 0.10$) and closely follow the same pattern as that for ADG during d 0 to 25.

Intake of STTD P per kg of gain was increased (linear, $P < 0.001$) by increasing STTD P in both sets of formulations but was decreased ($P < 0.001$) by adding phytase to the diets (Figure 8).

Discussion

The STTD P requirements estimated in the present study varied depending on the response criteria and statistical models. In diets without phytase addition, QP and BLL models resulted in distinct STTD P requirement estimates based on ADG. The BLL estimate of 91% of NRC (2012) likely represents the minimal STTD P level required without reduction in ADG, while QP model tends to be more sensitive to detecting the STTD P level that maximizes the response and, therefore, results in a higher requirement estimate of 117% of NRC (2012). It is worthwhile to note that, 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 considerably lower STTD P levels. In this case, 95 and 99% of the maximum ADG can be achieved at STTD P levels of 92 and 106% of NRC (2012), respectively. These results suggest that the NRC (2012) recommendations are reasonably accurate for ADG response when diets do not contain phytase. Likewise, the estimated STTD P requirements in diets not containing phytase using ADFI and G:F as response criteria ranged from 102 to greater than 140% of NRC (2012) depending on statistical models.

When 2,000 FYT phytase was added in the diets, the estimated plateau levels of STTD P for ADG (138% of NRC (2012)) and G:F (147 and 116% of NRC (2012) using QP and BLL models, respectively) increased compared with that for diets without phytase. It is possible that the better ADG and G:F responses to increasing STTD P dose were driven by the improved growth performance when phytase was added to diets. Comparing diets that contained the same STTD P contents, positive effects of feeding 2,000 FYT phytase were observed for ADG (Figure 9), ADFI, and F/G (Figure 10). Additionally, STTD P intake per kg of gain was reduced 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.^{5,6,7} Proposed mechanisms for the “super-dose” effect of phytase include the near-complete destruction of anti-nutritional effects of phytate and generation of other nutrients such as inositol, as well as better availability of other nutrients like AA, minerals, or energy.¹¹

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. To our knowledge, this observation has not been reported in other studies for nursery pigs. We hypothesize that pigs previously fed high phytase diets had not been exposed to anti-nutritional factors of phytate, thus when switched to a diet without phytase the digestive function of these pigs was 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.

Regardless of phytase addition, increasing STTD P concentration linearly increased percentage of bone ash, suggesting the STTD P requirement greater than 140% of NRC (2012) in no phytase diets and 170% of NRC (2012) in phytase-containing diets

¹¹Adeola, O., and A. J. Cowieson. 2011. Board-Invited Review: Opportunities and challenges in using exogenous enzymes to improve nonruminant animal production. *J. Anim. Sci.* 89:3189-3218. doi:10.2527/jas.2010-3715

is needed for maximizing bone mineralization. This observation is consistent with other studies (Ekpe et al., 2002;¹² Saraiva et al., 2012;¹³ Vier et al., 2017b¹⁴) where greater dietary P is needed for maximizing percentage bone ash than that for growth performance. It is also worthwhile to note that, when diets contained the same STTD P levels (100, 110, 125, and 140% of NRC diets), feeding diets with or without phytase resulted in similar percentage of bone ash. Because percentage bone ash is a sensitive indicator of dietary available P, this observation suggests that the P and Ca releasing ability of 2,000 FYT phytase used in the present study was accurately estimated.

In summary, increasing dietary STTD P improved ADG, ADFI, F/G, and percentage bone ash. The estimated STTD P requirements varied based on the response criteria and statistical models, and ranged from 91 to greater than 140% of the NRC (2012) requirement estimates in diets containing no phytase, and from 116 to greater than 170% of NRC (2012) for diets containing 2,000 FYT phytase. The high dose of phytase exerted an extra-phosphoric effect on promoting growth performance and improved the dose responses of ADG and feed efficiency to dietary STTD P in 13- to 28-lb nursery pigs.

¹²Ekpe, E. D., R. T. Zijlstra, and J. F. Patience. 2002. Digestible phosphorus requirement of grower pigs. *Can. J. Anim. Sci.* 82:541–549. doi: 10.4141/A02-006

¹³Saraiva, A., J. L. Donzele, R. F. M. Oliveira, M. L. T. Abreu, F. C. O. Silva, S. E. F. Guimarães, and S. W. Kim. 2012. Phosphorus requirements for 60- to 100-kg pigs selected for high lean deposition under different thermal environments. *J. Anim. Sci.* 90:1499-1505. doi:10.2527/jas.2010-3623

¹⁴Vier, C. M., F. Wu, M. B. Menegat, H. S. Cemin, S. S. Dritz, M. D. Tokach, M. A. Gonçalves, U. A. Orlando, J. C. Woodworth, R. D. Goodband, and J. M. DeRouchey. 2017b. Effects of standardized total tract digestible phosphorus on growth performance, carcass characteristics, bone mineralization, and economics of 53-to 287-lb pigs. *Kansas Agricultural Experiment Station Research Reports: Vol. 3: Iss. 7.* doi:10.4148/2378-5977.7497

Table 1. Diet treatment structure (as-fed basis)

	Phytase ¹ :		0 FTU/kg diet				2,000 FTU/kg diet							
	STTD ² P, % NRC ³ :		80	90	100	110	125	140	100	110	125	140	155	170
Phase 1 (d 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, 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 (d 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 (d 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

P = phosphorus. Ca = calcium. FYT = phytase unit. STTD = standardized total tract digestible.

¹Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ).

²Digestibility coefficients for P content of feed ingredients were from NRC (2012) and that of Ca content were from Stein (2016).

³The NRC (2012) requirement estimates for nursery pigs from 11 to 15 lb and 15 to 24 lb, 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.

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

Table 2. Analyzed Ca and P concentrations in feed ingredients (as-fed basis)

	Ca, %			P, %		
	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	37.11	41.76	39.44	<0.01	0.01	0.01

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

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

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

Table 3. Diet formulation, phase 1 (d 0 to 11; as-fed basis)

Ingredients, %	Phytase ¹ :	0 FTU/kg diet						2,000 FTU/kg diet					
	STTD ² P, % NRC ³ :	80	90	100	110	125	140	100	110	125	140	155	170
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-Lys 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-Met	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-Thr	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-Trp	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-Val	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 (20,000 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	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	

continued

Table 3. Diet formulation, phase 1 (d 0 to 11; as-fed basis)

	Phytase ¹ :	0 FTU/kg diet					2,000 FTU/kg diet						
	STTD ² P, % NRC ³ :	80	90	100	110	125	140	100	110	125	140	155	170
Calculated composition													
Standardized ileal digestible AA, %													
Lys	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40	1.40
Ile:Lys	57	57	57	57	57	57	57	57	57	57	57	57	57
Leu:Lys	111	111	110	110	110	110	111	111	111	110	110	110	110
Met:Lys	38	38	38	38	38	38	38	38	38	38	38	38	38
Met and Cys:Lys	58	58	58	58	58	58	58	58	58	58	58	58	58
Thr:Lys	64	64	64	64	64	64	64	64	64	64	64	64	64
Trp:Lys	19	19	19	19	19	19	19	19	19	19	19	19	19
Val:Lys	71	71	71	71	71	71	71	71	71	71	71	71	71
Total Lys, %	1.53	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	21.02
NE, kcal/lb	1,167	1,167	1,167	1,167	1,167	1,167	1,167	1,167	1,167	1,167	1,167	1,167	1,167
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	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	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	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	0.86

¹Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ).

²STTD = standardized total tract digestible.

³The NRC (2012) requirement estimate for nursery pigs from 11 to 15 lb, 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.

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

⁵Provided 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, and 1600 mg I from calcium iodate.

⁶Provided per kg of premix: 28,659,800 IU vitamin A, 4,409,200 IU vitamin D₃, 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 B₁₂, 4,409 mg folic acid, 44 mg thiamin, 44 mg pyridoxine, and 4.4 mg biotin.

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

Table 4. Diet formulation, phases 2 and 3 (d 11 to 25 and d 25 to 46, respectively; as-fed basis)

Ingredients, %	Phytase ¹ : STTD ² P, % NRC ³ :	Phase 2												Phase 3
		0 FTU/kg diet						2,000 FTU/kg diet						
		80	90	100	110	125	140	100	110	125	140	155	170	
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-Lys 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-Met	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-Thr	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-Trp	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-Val	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	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	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	

continued

Table 4. Diet formulation, phases 2 and 3 (d 11 to 25 and d 25 to 46, respectively; as-fed basis)

Phytase ¹ : STTD ² P, % NRC ³ :	Phase 2												Phase 3
	0 FTU/kg diet						2,000 FTU/kg diet						
	80	90	100	110	125	140	100	110	125	140	155	170	
Calculated composition													
Standardized ileal digestible AA, %													
Lys	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
Ile:Lys	60	60	60	60	60	60	60	60	60	60	60	60	59
Leu:Lys	118	118	118	118	117	117	119	119	118	118	118	117	120
Met:Lys	37	36	36	36	36	36	37	37	36	36	36	36	35
Met and Cys:Lys	58	58	58	58	58	58	58	58	58	58	58	58	58
Thr:Lys	64	64	64	64	64	64	64	64	64	64	64	64	64
Trp:Lys	19	19	19	19	19	19	19	19	19	19	19	19	19
Val:Lys	71	71	71	71	71	71	71	71	71	71	71	71	71
Total Lys, %	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
NE, kcal/lb	1,129	1,129	1,129	1,129	1,129	1,129	1,129	1,129	1,129	1,129	1,129	1,129	1,103
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

¹Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ).

²STTD = standardized total tract digestible.

³The NRC (2012) requirement estimate for nursery pigs from 15 to 24 lb, 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.

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

⁵Provided 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, and 1600 mg I from calcium iodate.

⁶Provided per kg of premix: 28,659,800 IU vitamin A, 4,409,200 IU vitamin D₃, 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 B₁₂, 4,409 mg folic acid, 44 mg thiamin, 44 mg pyridoxine, and 4.4 mg biotin.

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

Table 5. Effects of standardized total tract digestible (STTD) P and phytase on growth performance and percentage bone ash¹

	BW, lb			Treatment (d 0 to 25)			Post-treatment (d 25 to 46)			Overall (d 0 to 46)			Bone ash, %
	d 0	d 25	d 46	ADG, lb	ADFI, lb	F/G	ADG, lb	ADFI, lb	F/G	ADG, lb	ADFI, lb	F/G	
P level with 0 FTU phytase ²													
80%	13.0	26.2	58.5	0.53	0.75	1.42	1.54	2.35	1.52	0.96	1.43	1.49	43.3
90%	13.0	27.5	60.2	0.58	0.80	1.38	1.56	2.36	1.51	1.00	1.47	1.47	44.8
100%	13.0	27.7	61.0	0.59	0.78	1.33	1.60	2.42	1.51	1.02	1.48	1.45	45.3
110%	13.0	27.9	60.9	0.59	0.80	1.34	1.57	2.42	1.54	1.02	1.50	1.47	47.2
125%	13.0	27.5	60.1	0.58	0.77	1.32	1.56	2.37	1.52	1.00	1.46	1.46	48.9
140%	13.0	27.7	60.9	0.58	0.76	1.30	1.59	2.41	1.52	1.01	1.46	1.45	48.7
P level with 2,000 FTU phytase ²													
100%	13.0	29.0	60.9	0.63	0.83	1.31	1.52	2.35	1.54	1.01	1.48	1.46	45.5
110%	13.0	29.4	60.0	0.65	0.84	1.29	1.46	2.28	1.56	1.00	1.46	1.46	45.9
125%	13.1	29.4	61.0	0.65	0.83	1.27	1.50	2.34	1.56	1.02	1.48	1.45	48.5
140%	13.0	29.8	61.6	0.67	0.85	1.26	1.51	2.33	1.54	1.03	1.49	1.44	49.3
155%	13.0	29.6	61.4	0.66	0.85	1.27	1.52	2.37	1.56	1.03	1.50	1.46	50.2
170%	13.0	29.1	61.7	0.64	0.82	1.27	1.55	2.40	1.55	1.03	1.50	1.45	50.6
SEM	0.37	1.09	1.81	0.030	0.032	0.022	0.043	0.076	0.019	0.035	0.050	0.013	0.84
Source of variation, ³ <i>P</i> <													
Phytase	0.159	0.001	0.808	0.001	0.001	0.001	0.001	0.006	0.014	0.801	0.981	0.668	0.687
0 FTU phytase													
P, linear	0.119	0.018	0.096	0.018	0.823	0.001	0.487	0.366	0.826	0.175	0.721	0.033	0.001
P, quadratic	0.439	0.019	0.147	0.005	0.043	0.063	0.578	0.420	0.774	0.082	0.155	0.604	0.251
2,000 FTU phytase													
P, linear	0.206	0.689	0.210	0.448	0.724	0.005	0.160	0.080	0.996	0.125	0.178	0.435	0.001
P, quadratic	0.425	0.084	0.960	0.031	0.262	0.065	0.304	0.348	0.648	0.845	0.842	0.542	0.220

¹A total of 1,080 barrows and gilts (PIC 280 × 1050, Hendersonville, TN) with initial BW of 13.0 ± 2.38 lb were used in a 46-d trial with 10 pigs per pen and 9 replications (pen) per treatment.

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

³Phytase 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 2,000 FTU). No P × phytase interaction was observed for any response criteria (*P* > 0.22) except for ADG of treatment period (*P* = 0.083), whereby ADG was increased (linear, *P* = 0.017) by increasing STTD P in diets containing phytase, but not in diets not containing phytase.

Table 6. Effects of increasing dietary standard total tract digestible (STTD) P and phytase on production economics during treatment period (d 0 to 25)¹

	Feed price, \$/ton		Economics, ² \$/pig			
	Phase 1	Phase 2	Feed cost	Gain value	Feed cost/ lb gain	IOFC
P level with 0 FTU phytase ³						
80%	537	380	3.81	9.21	0.291	5.40
90%	539	382	4.08	10.14	0.283	6.05
100%	541	384	4.03	10.28	0.274	6.26
110%	543	386	4.13	10.40	0.278	6.27
125%	546	388	3.99	10.15	0.276	6.15
140%	549	391	3.99	10.23	0.273	6.24
P level with 2000 FTU phytase ³						
100%	535	378	4.19	11.04	0.267	6.84
110%	537	380	4.27	11.45	0.262	7.17
125%	540	383	4.23	11.41	0.261	7.17
140%	543	386	4.35	11.78	0.260	7.41
155%	547	389	4.38	11.63	0.265	7.24
170%	549	392	4.26	11.22	0.267	6.95
SEM	---	---	0.164	0.542	0.0043	0.379
Source of variation, ⁴ <i>P</i> <						
Phytase × P interaction						
Linear	---	---	0.241	0.083	0.456	0.075
Quadratic	---	---	0.628	0.897	0.239	0.647
Phytase	---	---	0.001	0.001	0.001	0.001
0 FTU phytase						
P, linear	---	---	0.425	0.018	0.001	0.004
P, quadratic	---	---	0.050	0.005	0.030	0.004
2000 FTU phytase						
P, linear	---	---	0.315	0.448	0.660	0.562
P, quadratic	---	---	0.330	0.031	0.043	0.013

¹A total of 1,080 barrows and gilts (PIC 280 × 1050, Hendersonville, TN) with initial BW of 13.0 ± 2.38 lb were used in a 46-d trial with 10 pigs per pen and 9 replications (pen) per treatment.

²Calculation of economics were based on a gain value of \$0.70/lb. Feed cost = diet cost × feed consumption; gain value = total BW gain × \$0.70/lb; feed cost per pound of gain = feed cost / (ADG × period length, d); income over feed cost (IOFC) = gain value – feed cost.

³Dietary STTD P levels expressed as percentage of NRC (2012) requirement estimates.

⁴Phytase × P interaction and the main effect of phytase were analyzed in a 2 × 4 factorial with the main effects of P (100, 110, 125, or 140%) and phytase (0 or 2,000 FTU).

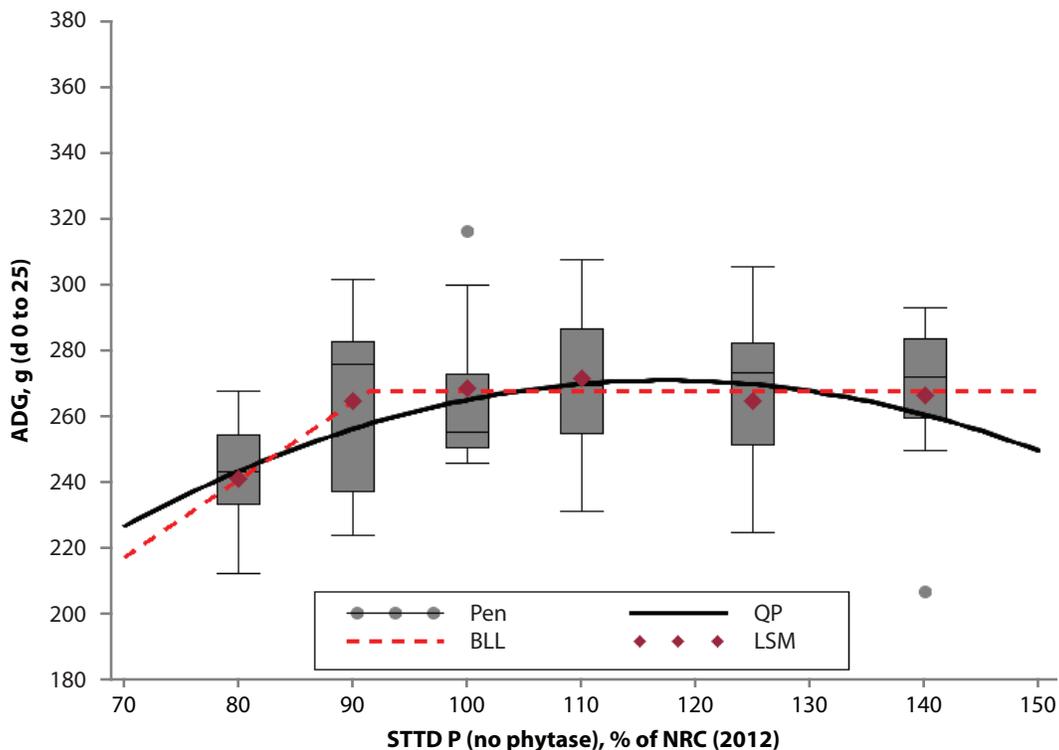


Figure 1. Fitted quadratic polynomial (QP; BIC = 481.7) and broken-line linear (BLL; BIC = 479.0) regression models on d 0 to 25 average daily gain (ADG) as a function of increasing standardized total tract digestible (STTD) P as percentage of NRC (2012) requirement estimate in 6- to 13-kg pigs. The LSM represents least square means. The QP model estimated the maximum mean ADG at 117% (95% CI: [86, >140%]), with 99% of maximum ADG achieved at 106%; the estimated QP regression equation was: $ADG, g = -8.45 + 4.74 \times (STTD P, \% NRC) - 0.02 \times (STTD P, \% NRC)^2$. The BLL plateau was estimated at 91% (95% CI: [76, 107%]).

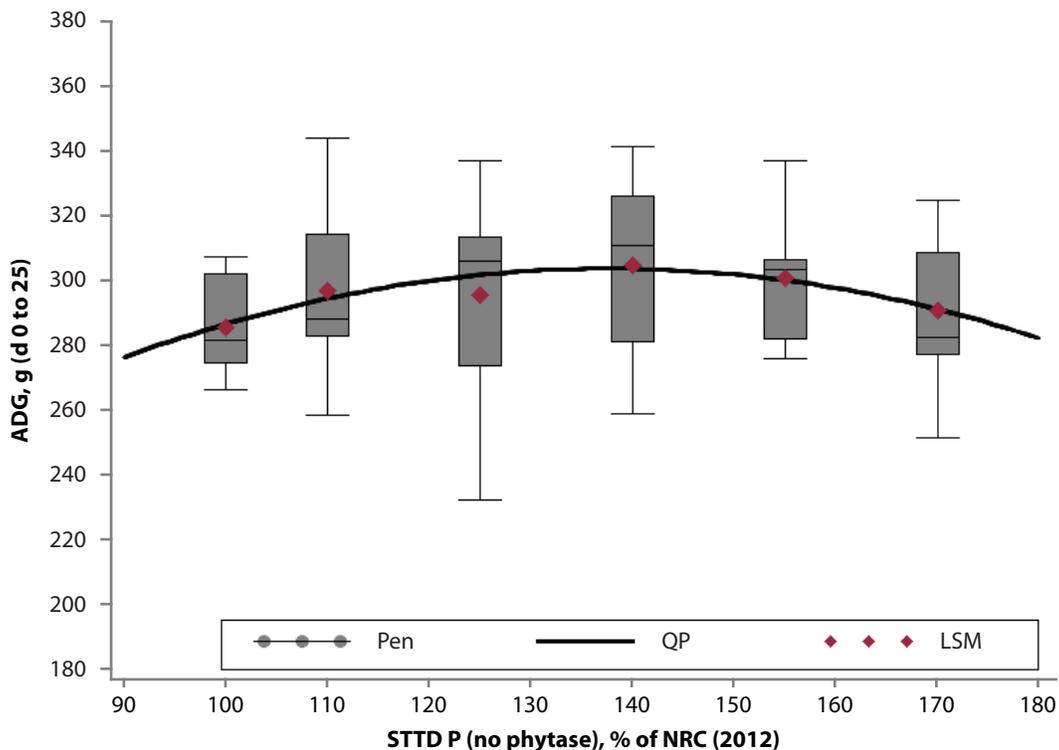


Figure 2. Fitted quadratic polynomial (QP; BIC = 470.1) regression models on d 0 to 25 average daily gain (ADG) as a function of increasing standardized total tract digestible (STTD) P (including P release by phytase) as percentage of NRC (2012) requirement estimate in 6- to 13-kg pigs. The LSM represents least square means. The QP model estimated the maximum mean ADG at 138% (95% CI: [110, >170%]), with 99% of maximum ADG achieved at 122%; the estimated QP regression equation was: $ADG, g = 76.18 + 3.31 \times (STTD P, \% NRC) - 0.012 \times (STTD P, \% NRC)^2$.

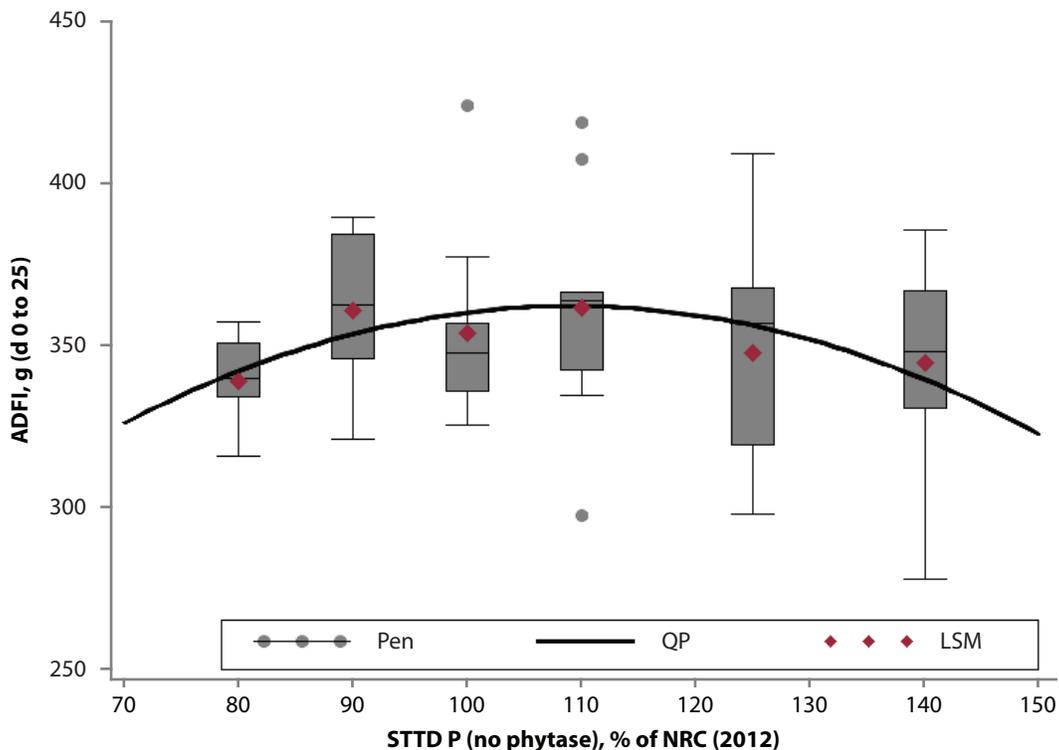


Figure 3. Fitted quadratic polynomial (QP; BIC = 502.2) regression models on d 0 to 25 average daily feed intake (ADFI) as a function of increasing standardized total tract digestible (STTD) P as percentage of NRC (2012) requirement estimate in 6- to 13-kg pigs. The LSM represents least square means. The QP model estimated the maximum mean ADFI at 109% (95% CI: [80, 140%]), with 99% of maximum ADFI achieved at 97%; the estimated QP regression equation was: $ADFI, g = 80.91 + 5.16 \times (STTD P, \% NRC) - 0.024 \times (STTD P, \% NRC)^2$.

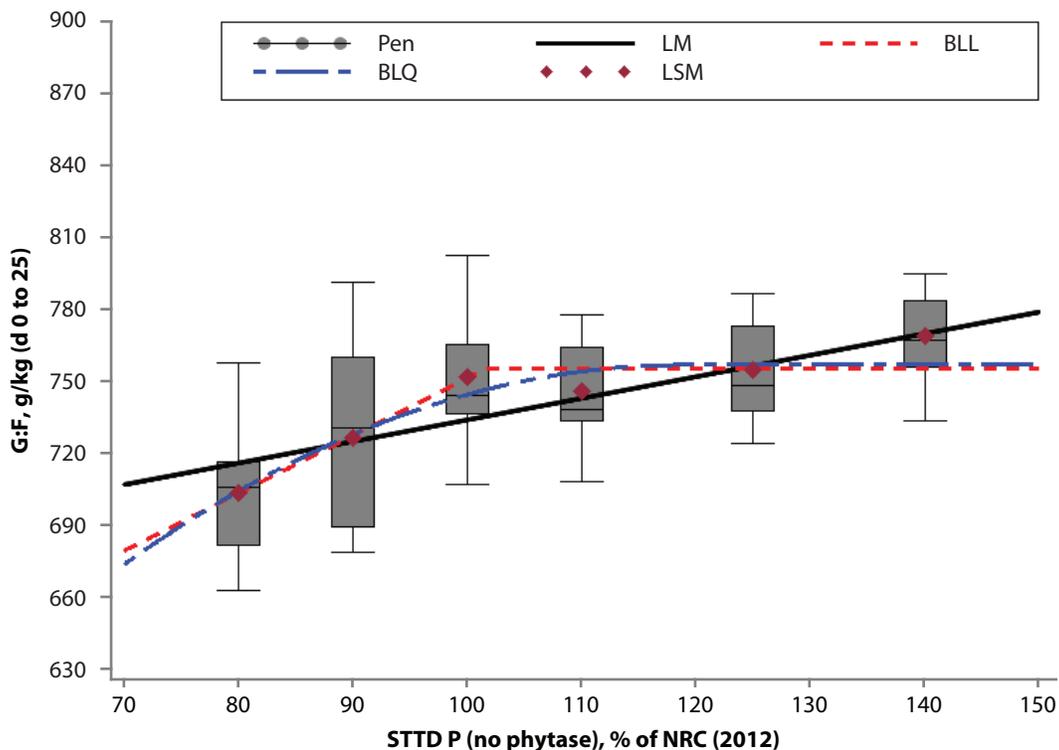


Figure 4. Fitted linear (LM; BIC = 505.2), broken-line linear (BLL; BIC = 503.3), and broken-line quadratic (BLQ; BIC = 504.5) regression models on d 0 to 25 gain to feed ratio (G:F) as a function of increasing standardized total tract digestible (STTD) P as percentage of NRC (2012) requirement estimate in 6- to 13-kg pigs. The LSM represents least square means. The LM model estimated the maximum mean G:F at greater than 140%; the estimated LM regression equation was: $G:F, g/kg = 644.57 + 0.90 \times (STTD P, \% NRC)$. The BLL plateau was estimated at 102% (95% CI: [85, 118%]). The BLQ plateau was estimated at 119% (95% CI: [24, 213%]).

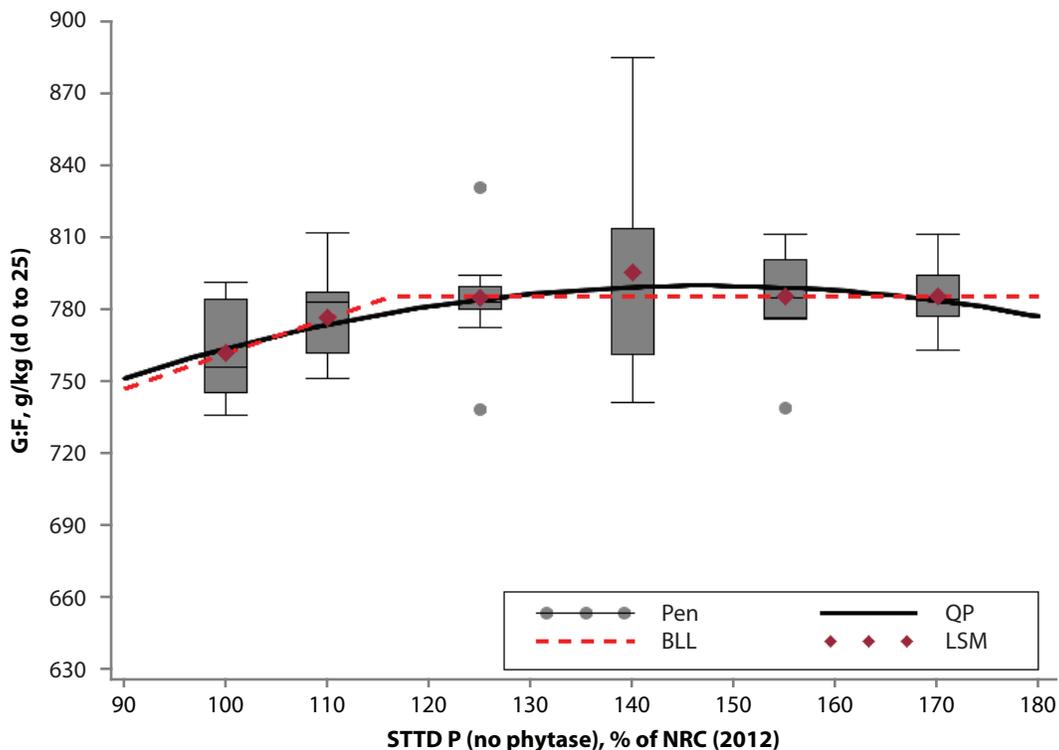


Figure 5. Fitted quadratic polynomial (QP; BIC = 489.8) and broken-line linear (BLL; BIC = 489.2) regression models on d 0 to 25 gain to feed ratio (G:F) as a function of increasing standardized total tract digestible (STTD) P (including P release by phytase) as percentage of NRC (2012) requirement estimate in 6- to 13-kg pigs. The LSM represents least square means. The QP model estimated the maximum mean G:F at 147% (95% CI: [120, >170%]), with 99% of maximum G:F achieved at 122%; the estimated QP regression equation was: $G:F, g/kg = 534.32 + 3.48 \times (STTD P, \% NRC) - 0.012 \times (STTD P, \% NRC)^2$. The BLL plateau was estimated at 116% (95% CI: [85, 148%]).

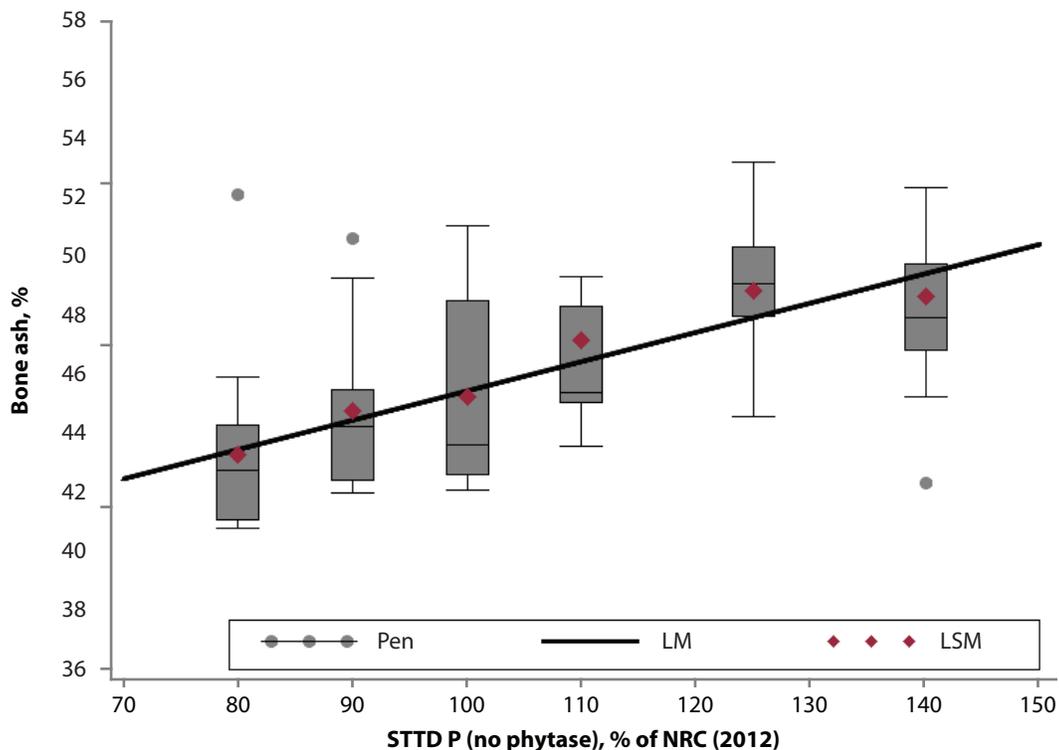


Figure 6. Fitted linear (LM; BIC = 264.3) regression models on percentage bone ash as a function of increasing standardized total tract digestible (STTD) P as percentage of NRC (2012) requirement estimate in 13-kg pigs. The LSM represents least square means. The LM model estimated the maximum mean percentage bone ash at greater than 140%; the estimated LM regression equation was: bone ash, % = 28.79 + 0.095 × (STTD P, % NRC) + 0.56 × (BW, kg).

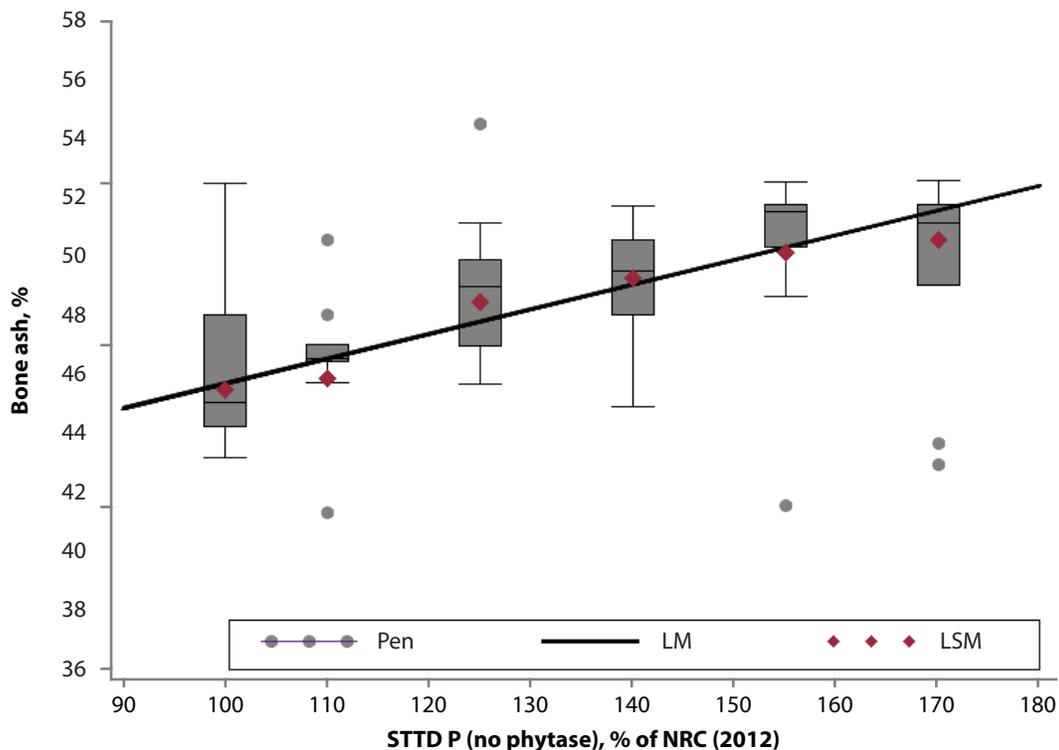


Figure 7. Fitted linear (LM; BIC = 257.6) regression models on percentage bone ash as a function of increasing standardized total tract digestible (STTD) P (including P release by phytase) as percentage of NRC (2012) requirement estimate in 13-kg pigs. The LSM represents least square means. The LM model estimated the maximum mean percentage bone ash at greater than 170%; the estimated LM regression equation was: bone ash, % = $32.27 + 0.084 \times (\text{STTD P, \% NRC}) + 0.37 \times (\text{BW, kg})$.

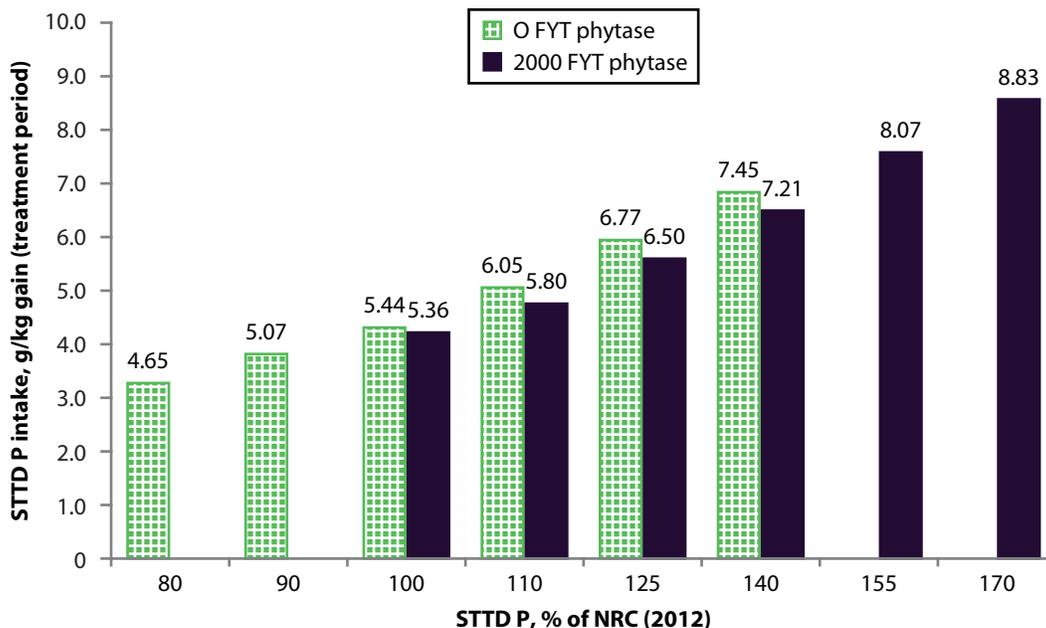


Figure 8. Effects of standardized total tract digestible (STTD) P and 2,000 phytase unit (FYT) of Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ) on STTD P intake (g) per kg gain during treatment period (d 0 to 25).

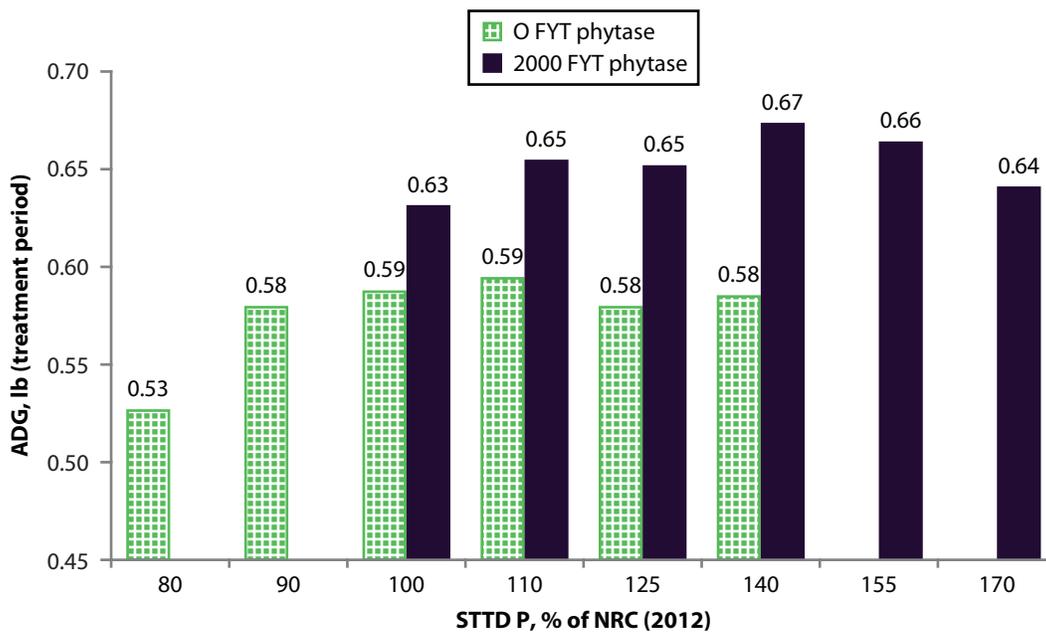


Figure 9. Effects of standardized total tract digestible (STTD) P and 2,000 phytase unit (FYT) of Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ) on average daily gain (ADG) during treatment period (d 0 to 25).

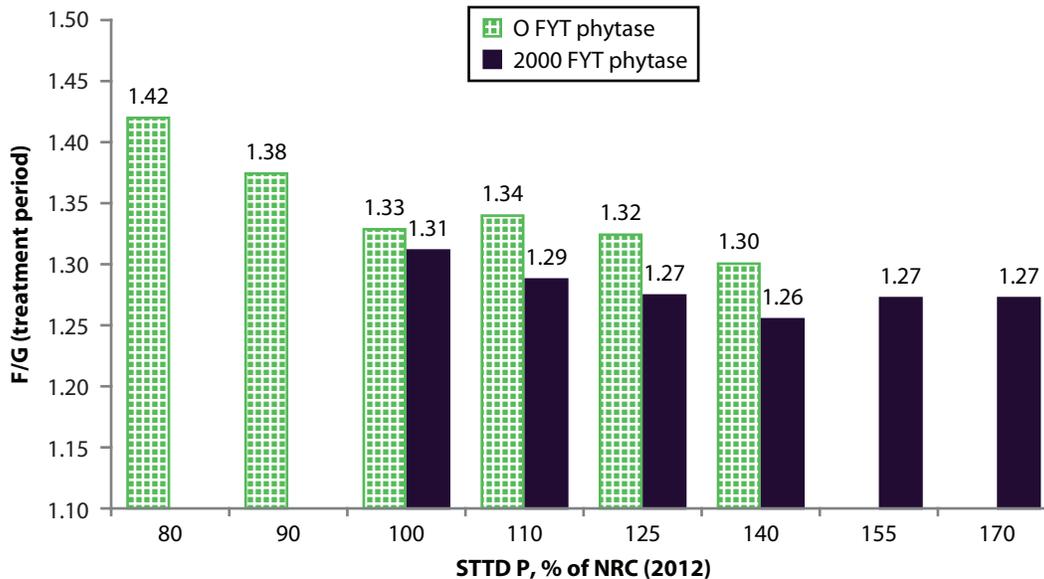


Figure 10. Effects of standardized total tract digestible (STTD) P and 2,000 phytase unit (FYT) of Ronozyme HiPhos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ) on feed efficiency (F/G) during treatment period (d 0 to 25).