Inclusion of excess dietary calcium in diets for 100- to 130-kg growing pigs reduces feed intake and daily gain if dietary phosphorus is at or below the requirement[1]

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ABSTRACT: An experiment was conducted to test the hypothesis that the requirement for standardized total tract digestible (STTD) Ca by pigs from 100 to 130 kg depends on the concentration of STTD P in the diet. Ninety pigs (average initial BW: 99.89 ± 3.34 kg) were randomly allotted to 15 experimental diets. Each diet was fed to 6 replicate pigs using a randomized complete block design. Fifteen corn and soybean meal-based diets were formulated and phytate and Na were constant among treatments. Diets were formulated using a 3 × 5 factorial design with diets containing 0.11%, 0.21%, or 0.31% STTD P and 0.12%, 0.29%, 0.46%, 0.61%, or 0.78% total Ca (0.08%, 0.18%, 0.29%, 0.38%, or 0.49% STTD Ca). The P concentrations ranged from 48 to 152% of the STTD P requirement for 100- to 125-kg pigs and the Ca concentrations ranged from 27 to 173% of the total Ca requirement. Experimental diets were fed for 28 d and pigs were individually housed. Pig and feeder weights were recorded at the beginning and at the conclusion of the experiment to calculate ADFI, ADG, and G:F. On d 28, all pigs were euthanized and the right femur was extracted. Ash, Ca, and P concentrations were determined from the de-fatted, dried femurs. Results indicated that as dietary concentrations of STTD Ca increased, ADFI decreased (main effect of Ca, $P < 0.05$), regardless of the dietary concentration of P. The model to predict ADFI (ADFI = 3.6782 – 1.2722 × STTD Ca [%]; $P = 0.001$) was dependent only on the concentration of dietary STTD Ca, but not on the concentration of dietary STTD P. In contrast, the model to predict ADG depended on both STTD Ca and STTD P (1.4556 – 1.4192 × STTD Ca [%] – 1.0653 × STTD P [%] + 4.2940 STTD Ca [%] × STTD P [%]; $P = 0.002$). There were no effects of STTD Ca or STTD P on G:F. Linear increases were observed for bone ash, bone Ca, and bone P as dietary concentrations of STTD Ca increased for all concentrations of STTD P, but the increase was greater at the greatest concentration of STTD P than at lower concentrations (interaction, $P < 0.001$). In conclusion, results indicate that the estimated requirement for dietary STTD Ca by 100- to 130-kg pigs needed to maximize ADG, bone ash, and bone Ca depends on the concentration of STTD P in the diet. Results also indicate that feeding Ca in excess of the current requirement for total Ca is detrimental to growth performance of pigs from 100 to 130 kg unless P is also included above the requirement.

Key words: bone ash, calcium, digestible calcium, phosphorus, pigs, requirements

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INTRODUCTION

Inclusion of Ca and P in diets fed to pigs needs to be adequate to optimize growth performance and at the same time minimize nutrient excretion from pigs. Diets are most accurately formulated by using values for standardized total tract digestible (**STTD**) concentrations of Ca and P in feed ingredients to meet the requirements for these minerals at each stage of production (NRC, 2012). The current requirements for P are indicated on the basis of STTD P, but the requirements

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for Ca are estimated as total Ca due to a lack of data for the digestibility of Ca in feed ingredients (NRC, 2012). The STTD P requirements were estimated based on a modeling approach, and the requirements for Ca by growing pigs were obtained using a fixed ratio of 2.15 to 1 between total Ca and STTD P (NRC, 2012).

Recently, values for digestibility of Ca have been reported in inorganic supplements (64 to 77%; González-Vega et al., 2014; 2015b; Merriman and Stein, 2016), plant ingredients (40 to 78%; Bohlke et al., 2005; González-Vega et al., 2013; Zhang et al., 2016), and ingredients of animal origin (58 to 96%; Kim et al., 2012; Sulabo and Stein, 2013; González-Vega et al., 2015a; Merriman et al., 2016). Diets can, therefore, now be formulated using values for digestibility of Ca in feed ingredients, but there are no current estimates for the requirement of STTD Ca by pigs with a BW of 100 to 130 kg.

To determine requirements for digestible Ca, the concentration that results in optimum growth performance of the pigs or the greatest bone mineral concentration needs to be determined. The influence of P on Ca requirements also needs to be considered because P influences both growth performance and bone ash concentration. Therefore, the objective of this experiment was to test the hypothesis that the requirement for STTD Ca by 100- to 130-kg pigs to maximize ADG, ADFI, G:F, bone ash, bone Ca, and bone P is dependent on the dietary concentration of STTD P.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol describing animal procedures for the experiment. Pigs used in the experiment were the offspring of Line 359 boars mated to C46 females (Pig Improvement Company, Hendersonville, TN).

Animals and Housing

Ninety barrows (average initial BW: 99.89 ± 3.34 kg) were randomly allotted to a randomized complete block design with 15 experimental diets. Each diet was fed to 6 replicate pigs per diet. Pigs were allotted to experimental diets using The Experimental Animal Allotment Program (Kim and Lindemann, 2007). Pens had fully slatted floors and pigs had free access to water via a nipple waterer and feed from an individual feeder. Pigs were housed in environmentally controlled buildings at the University of Illinois Swine Research Center, Champaign, IL.

Diets and Feeding

Fifteen corn-soybean meal based diets were formulated to contain different Ca and P concentrations, but to keep the concentration of phytate constant, all diets contained the same amount of corn and soybean meal (Tables 1–3). Diets were formulated using a 3 × 5 factorial design with diets containing 0.11%, 0.21%, or 0.31% STTD P and 0.12%, 0.29%, 0.46%, 0.61%, or 0.78% total Ca (0.08%, 0.18%, 0.29%, 0.38%, or 0.49% STTD Ca). Values for STTD of P were from NRC (2012), and values for STTD Ca were from Stein et al. (2016). Concentrations of STTD P ranged from 48% to 152% of the requirement (NRC, 2012), and the total Ca concentrations ranged from 27% to 173% of the Ca requirement (NRC, 2012). All diets had the same concentrations of Na, which was accomplished by reducing the sodium bicarbonate inclusion as the concentration of monosodium phosphate increased in diets to provide increasing concentrations of dietary P. Concentrations of NE and standardized ileal digestible AA were also constant among diets.

Pigs were allowed ad libitum access to experimental diets for 28 d, and daily feed provisions were recorded. Pig weights were recorded at the beginning and at the conclusion of the experiment. Feeder weights were also recorded on these days to calculate feed disappearance during the experiment, and ADFI, ADG, and G:F were calculated from these data.

Sample Analyses

On the last day of the experiment, barrows were euthanized at the Meats Science Laboratory at the University of Illinois. The right femur from each barrow was removed, cleaned, and stored at -20°C. Bones were broken and soaked in petroleum ether under a chemical hood to remove marrow and fat for 72 h and then dried overnight at 130°C.

Diets were analyzed for DM using a drying oven at 135°C for 2 h (Method 930.15; AOAC, 2007) and diets and bones were analyzed for ash (Method 942.05; AOAC, 2007). Diets were also analyzed for N using the combustion procedure (Method 990.03; AOAC, 2007) on an Elementar Rapid N-cube protein/nitrogen apparatus (Elementar Americas Inc., Mt. Laurel, NJ), and CP was calculated as N × 6.25. Diets were analyzed for crude fat using ether extraction (Method 920.39 [A]; AOAC, 2007), ADF (Method 973.18; AOAC, 2007), and NDF (Holst, 1973). Diets and bone ash samples were analyzed for Ca and P by inductively coupled plasma (**ICP**) spectroscopy (Method 985.01 A, B, and C; AOAC, 2007) after wet ash sample preparation (Method 975.03 B[b]; AOAC, 2007).

Table 1. Ingredient composition and nutrient analysis of experimental diets containing 0.11% standardized total tract digestible (STTD) P, as-fed basis[1]

	0.11% STTD P				
Total Ca, %	0.12	0.29	0.46	0.61	0.78
STTD Ca, %	0.08	0.18	0.29	0.38	0.49
STTD Ca: STTD P	0.73:1.00	1.64:1.00	2.64:1.00	3.45:1.00	4.45:1.00
Item					
Corn, %	65.00	65.00	65.00	65.00	65.00
Soybean meal, %	20.00	20.00	20.00	20.00	20.00
Cornstarch, %	13.55	12.31	10.95	9.80	8.56
Soybean oil, %	–	0.80	1.70	2.45	3.25
Calcium carbonate, %	–	0.44	0.90	1.30	1.74
Sodium bicarbonate, %	1.05	1.05	1.05	1.05	1.05
Sodium chloride, %	0.20	0.20	0.20	0.20	0.20
Vitamin mineral premix,[2] %	0.20	0.20	0.20	0.20	0.20
Analyzed composition					
CP, %	14.49	15.55	14.68	14.81	14.29
AEE,[3] %	2.57	2.21	3.14	3.48	4.63
ADF, %	2.76	2.65	3.01	3.43	3.97
NDF, %	6.46	5.68	6.69	5.88	7.22
DM, %	90.56	90.53	90.41	90.60	90.26
Ash, %	2.46	2.75	3.03	3.46	3.94
Ca, %	0.14	0.25	0.39	0.62	0.71
P, %	0.27	0.26	0.27	0.29	0.29
Phytate P, %	0.10	0.10	0.13	0.15	0.16
Calculated composition					
NE, kcal/kg	2,629	2,629	2,629	2,629	2,629
Na, %	0.37	0.37	0.37	0.37	0.37
Cl, %	0.15	0.15	0.15	0.15	0.15
Total Ca:total P	0.43:1.00	1.04:1.00	1.64:1.00	2.18:1.00	2.79:1.00
Total Ca:STTD P	1.09:1.00	2.64:1.00	4.18:1.00	5.55:1.00	7.09:1.00
STTD Ca:STTD P	0.73:1.00	1.64:1.00	2.64:1.00	3.45:1.00	4.45:1.00

[1]All diets were formulated to have the following concentrations of standardized ileal digestible AA: Arg, 0.86%; His, 0.36%; Ile, 0.53%; Leu, 1.18%; Lys, 0.65%; Met, 0.22%; Phe, 0.64%; Thr, 0.55%; Trp, 0.15%; and Val, 0.59%.

[2]The vitamin-micromineral premix provided the following quantities of vitamins and microminerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate; Fe, 126 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganous sulfate; Se, 0.25 mg as sodium selenite and selenium yeast; and Zn, 124.9 mg as zinc sulfate.

[3]AEE = acid hydrolyzed ether extract.

Statistical Analyses

Normality of residuals and identification of outliers were determined by the UNIVARIATE procedure of SAS (SAS Inst. Inc., Cary, NC). Data for BW, ADG, ADFI, G:F, bone ash, bone Ca, and bone P were analyzed using the Proc MIXED procedure of SAS (SAS Inst. Inc., Cary, NC). The fixed effects of the model were dietary concentration of STTD Ca, dietary concentration of STTD P, and the interaction between Ca and STTD P; the random effect was block. Effects of dietary STTD Ca, STTD P, and the interaction between STTD Ca and STTD P were considered significant at $P \leq 0.05$. If the interaction or the main effects were significant, the program NLREG version 5.2 (Sherrod, 2008) was used to determine parameter estimates for the surface response model to increasing concentrations of STTD Ca and STTD P (Khuri and Cornell, 1996). The parameter estimates of the model that were not significant and were not included in a significant interaction were removed from the model and the estimates were recalculated. The surface response full model was

$$Y = a + b \times \text{STTD Ca} + c \times \text{STTD Ca}^2 + d \times \text{STTD P} + e \times \text{STTD P}^2 + f \times \text{STTD Ca} \times \text{STTD P},$$

where Y was the dependent variable; a was the intercept; b, c, d, e, and f were the coefficients; and STTD Ca and STTD P were the percentage concentrations of dietary STTD Ca and STTD P.

Table 2. Ingredient composition and nutrient analysis of experimental diets containing 0.21% standardized total tract digestible (STTD) P, as-fed basis[1]

	0.21% STTD P				
Total Ca, %	0.12	0.29	0.46	0.61	0.78
STTD Ca, %	0.08	0.18	0.29	0.38	0.49
STTD Ca: STTD P	0.38:1.00	0.86:1.00	1.38:1.00	1.81:1.00	2.33:1.00
Item					
Corn, %	65.00	65.00	65.00	65.00	65.00
Soybean meal, %	20.00	20.00	20.00	20.00	20.00
Cornstarch, %	13.23	11.93	10.63	9.48	8.19
Soybean oil, %	0.20	1.05	1.90	2.65	3.50
Calcium carbonate, %	–	0.45	0.90	1.30	1.74
Sodium bicarbonate, %	0.72	0.72	0.72	0.72	0.72
Monosodium phosphate, %	0.45	0.45	0.45	0.45	0.45
Sodium chloride, %	0.20	0.20	0.20	0.20	0.20
Vitamin mineral premix[2], %	0.20	0.20	0.20	0.20	0.20
Analyzed composition					
CP, %	15.32	13.73	15.50	12.99	15.23
AEE[3], %	2.17	3.17	3.37	3.64	4.46
ADF, %	3.29	3.46	3.46	3.46	3.38
NDF, %	7.7	6.53	8.64	8.18	10.26
DM, %	90.71	90.94	90.84	90.69	90.36
Ash, %	2.79	3.74	3.54	3.16	3.74
Ca, %	0.09	0.29	0.51	0.51	0.65
P, %	0.34	0.39	0.43	0.39	0.39
Phytate P, %	0.10	0.10	0.10	0.15	0.16
Calculated composition					
NE, kcal/kg	2,629	2,629	2,629	2,629	2,629
Na, %	0.37	0.37	0.37	0.37	0.37
Cl, %	0.15	0.15	0.15	0.15	0.15
Total Ca:total P	0.31:1.00	0.74:1.00	1.18:1.00	1.56:1.00	2.00:1.00
Total Ca:STTD P	0.57:1.00	1.38:1.00	2.19:1.00	2.90:1.00	3.71:1.00
STTD Ca:STTD P	0.38:1.00	0.86:1.00	1.38:1.00	1.81:1.00	2.33:1.00

[1]All diets were formulated to have the following concentrations of standardized ileal digestible AA: Arg, 0.86%; His, 0.36%; Ile, 0.53%; Leu, 1.18%; Lys, 0.65%; Met, 0.22%; Phe, 0.64%; Thr, 0.55%; Trp, 0.15%; and Val, 0.59%.

[2]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate; Fe, 126 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganous sulfate; Se, 0.25 mg as sodium selenite and selenium yeast; and Zn, 124.9 mg as zinc sulfate.

[3]AEE = acid hydrolyzed ether extract.

RESULTS AND DISCUSSION

All pigs remained healthy throughout the experiment and consumed their respective diets without apparent problems. Interactions between STTD Ca and STTD P were not significant for ADFI or G:F (Table 4). For ADFI, the reduced model contained only STTD Ca and excluded all terms containing STTD P as well as the quadratic term for STTD Ca. Feed intake was greatest by pigs consuming the least concentration of STTD Ca, and a reduction ($P < 0.01$) in ADFI occurred as dietary concentrations of STTD Ca increased. These results demonstrate that if pigs are fed diets containing Ca below the current requirement (NRC, 2012), and if STTD P is at or below the requirement, they will increase ADFI, which results in the greatest estimated ADG. In contrast, if dietary P is above the requirement, the ADG of pigs is not reduced by including Ca above the requirement as indicated by the interaction ($P < 0.05$) between Ca and P in the model to predict ADG of pigs.

Neither Ca nor P could be used to predict G:F, indicating that the efficiency of feed utilization for gain was not modified by dietary Ca or P concentration. Instead, the growth potential was limited by pigs fed diets with the greater concentrations of STTD Ca because of reduced ADFI. This is different from pigs between 25 and 50 kg BW where G:F may be predicted using linear and quadratic coefficients for dietary Ca and P (González-Vega et al., 2016b). Likewise for pigs from 11 to 25 kg BW, G:F was quadratically influenced by the dietary

Table 3. Ingredient composition and nutrient analysis of experimental diets containing 0.31% standardized total tract digestible (STTD) P, as-fed basis[1]

	0.31% STTD P				
Total Ca, %	0.12	0.29	0.46	0.61	0.78
STTD Ca, %	0.08	0.18	0.29	0.38	0.49
STTD Ca: STTD P	0.26:1.00	0.58:1.00	0.94:1.00	1.23:1.00	1.58:1.00
Item					
Corn, %	65.00	65.00	65.00	65.00	65.00
Soybean meal, %	20.00	20.00	20.00	20.00	20.00
Cornstarch, %	12.85	11.55	10.25	9.12	7.81
Soybean oil, %	0.45	1.30	2.15	2.90	3.75
Calcium carbonate, %	–	0.45	0.90	1.28	1.74
Sodium bicarbonate, %	0.40	0.40	0.40	0.40	0.40
Monosodium phosphate, %	0.90	0.90	0.90	0.90	0.90
Sodium chloride, %	0.20	0.20	0.20	0.20	0.20
Vitamin mineral premix[2], %	0.20	0.20	0.20	0.20	0.20
Analyzed composition					
CP, %	14.70	15.02	14.54	14.41	14.37
AEE[3], %	2.15	2.81	3.29	3.78	4.21
ADF, %	3.09	3.47	3.49	3.61	3.65
NDF, %	8.09	8.14	8.97	9.65	9.98
DM, %	90.75	91.10	90.94	90.40	90.57
Ash, %	3.20	3.50	3.57	3.96	4.12
Ca, %	0.13	0.27	0.50	0.72	0.95
P, %	0.50	0.45	0.51	0.54	0.52
Phytate P, %	0.10	0.11	0.14	0.14	0.16
Calculated composition					
NE, kcal/kg	2,629	2,629	2,629	2,629	2,629
Na, %	0.37	0.37	0.37	0.37	0.37
Cl, %	0.15	0.15	0.15	0.15	0.15
Total Ca:total P	0.24:1.00	0.58:1.00	0.92:1.00	1.22:1.00	1.56:1.00
Total Ca:STTD P	0.39:1.00	0.94:1.00	1.48:1.00	1.97:1.00	2.52:1.00
STTD Ca:STTD P	0.26:1.00	0.58:1.00	0.94:1.00	1.23:1.00	1.58:1.00

[1]All diets were formulated to have the following concentrations of standardized ileal digestible AA: Arg, 0.86%; His, 0.36%; Ile, 0.53%; Leu, 1.18%; Lys, 0.65%; Met, 0.22%; Phe, 0.64%; Thr, 0.55%; Trp, 0.15%; and Val, 0.59%.

[2]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate; Fe, 126 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganous sulfate; Se, 0.25 mg as sodium selenite and selenium yeast; and Zn, 124.9 mg as zinc sulfate.

[3]AEE = acid hydrolyzed ether extract.

concentrations of STTD Ca (González-Vega et al., 2016a). The reason G:F was not influenced by dietary Ca and P in the current experiment may be that older pigs have a greater capacity to regulate the composition of body gain than younger pigs. Another possibility is that pigs were not fed the deficient diets long enough to create a depletion of body stores of Ca and P.

The current requirements for pigs from 100 to 125 kg BW are 0.46% total Ca and 0.21% STTD P (NRC, 2012). Using the digestibility values for STTD of Ca in soybean meal and calcium carbonate that have been published (Stein et al., 2016), the STTD of Ca in the diet containing 0.46% total Ca was calculated to be 0.29% STTD Ca. The greatest ADG was achieved by pigs fed diets containing 0.29% or less STTD Ca and 0.21% STTD P. Addition of either Ca or P above those concentrations have resulted in a reduction in growth performance (Reinhart and Mahan, 1986; Hall et al., 1991; NRC, 2012), and results from this experiment are in agreement with the previous observations. This indicates that the current requirements for STTD Ca and STTD P represent the maximum dietary concentrations that should be fed to pigs from 100 to 130 kg BW.

Growth response curves typically have a positive linear relationship to increased concentrations of the limiting nutrient being tested if nutrient intake is below the requirement (Robbins et al., 2006). This experiment and other experiments evaluating concentrations of dietary Ca below the presumed requirement have failed to demonstrate such a response for Ca (González-Vega

Table 4. Growth performance of pigs fed experimental diets with varying concentrations of standardized total tract digestible (STTD) Ca and P for 28 d

	Total Ca (STTD Ca), %				
Item	0.12	0.29	0.46	0.61	0.78
STTD Ca, %:	(0.08)	(0.18)	(0.29)	(0.38)	(0.49)
Initial BW, kg					
0.11% STTD P	98.83	100.28	101.75	97.62	99.23
0.21% STTD P	99.42	98.38	101.07	98.47	100.45
0.31% STTD P	101.13	99.15	99.25	102.60	100.72
ADG,[1,2] kg					
0.11% STTD P	1.21	1.14	1.17	0.89	0.83
0.21% STTD P	1.16	1.20	1.17	1.15	0.96
0.31% STTD P	1.11	1.10	1.08	1.00	1.10
ADFI,[3,4] kg					
0.11% STTD P	3.70	3.29	3.27	3.16	2.88
0.21% STTD P	3.72	3.58	3.31	3.32	3.16
0.31% STTD P	3.46	3.32	3.27	3.16	3.16
GF,[5,6] d 1–28					
0.11% STTD P	0.33	0.35	0.37	0.28	0.29
0.21% STTD P	0.32	0.34	0.36	0.35	0.31
0.31% STTD P	0.33	0.33	0.34	0.32	0.35
Final BW,[7,8] kg					
0.11% STTD P	132.68	132.33	134.48	122.42	122.52
0.21% STTD P	132.02	131.85	133.75	130.77	127.32
0.31% STTD P	132.33	129.90	129.62	130.57	131.47

[1]Results indicated that ADG from d 1 to 28 at different combinations of STTD Ca and STTD P can be described by the following model: 1.4556– 1.4192 × STTD Ca– 1.0653 × STTD P + 4.2940 STTD Ca × STTD P (P = 0.002).

[2]Standard error of the within treatment least squares means = 0.09.

[3]Results indicated that ADFI from d 1 to 28 at different concentrations of STTD Ca can be described by the following model: 3.6782– 1.2722 × STTD Ca (P = 0.001).

[4]Standard error of the within treatment least squares means = 0.23.

[5]Results indicated that G:F from d 1 to 28 could not be predicted using STTD Ca or STTD P.

[6]Standard error of the within treatment least squares means = 0.02.

[7]Results indicated that final BW at different combinations of STTD Ca and STTD P can be described by the following model: 140.4729– 42.9212 × STTD Ca– 30.3919 × STTD P + 140.2884 STTD Ca × STTD P (P = 0.006).

[8]Standard error of the within treatment least squares means = 2.87.

Table 5. Least squares means (g per femur) for bone ash, bone Ca, and bone P in pigs fed diets containing from 0.12 to 0.78% standardized total tract digestible (STTD) Ca and from 0.11 to 0.31% STTD P

	Total Ca, %				
Item	0.12	0.29	0.46	0.61	0.78
STTD Ca, %:	0.08	0.18	0.29	0.38	0.49
Bone ash,[1,2] g per femur					
0.11% STTD P	73.32	72.94	73.99	70.62	76.08
0.21% STTD P	69.04	72.42	84.26	83.32	83.81
0.31% STTD P	73.87	75.43	78.18	81.16	87.68
Bone Ca,[3,4] g per femur					
0.11% STTD P	26.98	27.27	25.41	25.01	28.14
0.21% STTD P	25.47	27.15	30.79	31.37	31.20
0.31% STTD P	27.26	27.83	28.98	30.63	33.03
Bone P,[5,6] g per femur					
0.11% STTD P	12.86	13.06	12.06	11.84	13.03
0.21% STTD P	12.19	13.06	14.52	14.98	14.65
0.31% STTD P	13.00	13.24	13.71	14.47	15.58
Ca:P in bone					
0.11% STTD P	2.10:1.00	2.09:1.00	2.11:1.00	2.11:1.00	2.16:1.00
0.21% STTD P	2.09:1.00	2.08:1.00	2.12:1.00	2.10:1.00	2.13:1.00
0.31% STTD P	2.10:1.00	2.10:1.00	2.11:1.00	2.12:1.00	2.12:1.00

[1]Results indicated that bone ash at different combinations of STTD Ca and STTD P can be described by the following model: 72.4527– 5.4437 × STTD Ca– 12.2622 × STTD P + 146.6110 × STTD Ca × STTD P (P < 0.001).

[2]Standard error of the within treatments least squares means = 3.31.

[3]Results indicated that bone Ca at different combinations of STTD Ca and STTD P can be described by the following model: 26.6645– 4.7992 × STTD Ca– 4.8919 × STTD P + 69.7578 × STTD Ca × STTD P (P < 0.001).

[4]Standard error of the within treatments least squares means = 1.31.

[5]Results indicated that bone P at different combinations of STTD Ca and STTD P can be described by the following model: 12.9522– 3.4175 × STTD Ca– 2.9441 × STTD P + 35.5359 × STTD Ca × STTD P (P < 0.001).

[6]Standard error of the within treatments least squares means = 0.63.

et al., 2016a, 2016b). The reason for this observation may be that pigs used in the current experiment were provided diets containing adequate concentrations of Ca and P prior to the initiation of the experiment; therefore, these pigs may have had sufficient quantities of stored Ca and P in the bones to manage the deficiencies subjected to them during the experiment. The possibility that the outcome could have been different if the pigs had been fed deficient diets through the entire growth period cannot be excluded, but further research is needed to verify this hypothesis.

Significant interactions ($P < 0.05$) were observed between STTD Ca and STTD P for bone ash, bone Ca, and bone P (Table 5). However, due to the positive linear nature of the predicted equations, a maximum value could not be estimated. Bone ash (Fig. 1), bone Ca (Fig. 2), and bone P (Fig. 3) increased ($P < 0.05$) as dietary concentrations of Ca and P increased, and the greatest bone ash, bone Ca, and bone P concentrations were observed at the greatest levels of STTD Ca and STTD P. In previous experiments (González-Vega et al., 2016a, 2016b), bone responses were curvilinear and bone responses plateaued at the greatest levels of Ca, but that was not the case in the present experiment. Despite the detrimental impact on growth performance, pigs continued to deposit Ca and P in the bones as Ca or P or both Ca and P in the diets increased, which may reflect the greater storage capacity in the femurs of the bigger pigs used in this experiment compared with the pigs used in previous experiments.

In the diets used in this experiment, the ratio between STTD Ca and STTD P was between 0.26:1 and 4.45:1. In pigs at 25 to 50 kg of BW, the estimated ratio needed to maximize ADG and G:F was between 1.16:1

and 1.43:1 (González-Vega et al., 2016b). In the present experiment, the STTD Ca: STTD P ratio in the diet that met requirements for total Ca and STTD P according to NRC (2012) is 1.38:1. Results of this experiment strongly indicate that if dietary Ca exceeds this ratio, growth performance will be reduced unless P is also included above the requirement. In contrast, there appears to be no negative implications of including dietary Ca below 0.46% and a ratio between STTD Ca and STTD P at 1.10:1 may be sufficient to maximize growth of pigs from 100 to 130 kg. This conclusion is based on data from pigs that have had adequate provisions of Ca and P before they reached 100 kg. Calcium to P ratios in diets are important if dietary concentrations of P are limiting, but may be of less importance if an adequate concentration of dietary P is provided (Crenshaw, 2001) and results of the present experiment support this hypothesis.

The ratio between Ca and P in bone ash was close to 2.1:1 for all dietary treatments, which is consistent with previous data (Gutzwiller et al., 2014; González Vega et al., 2016b). The observation that this ratio did not change based on the intake of Ca and P indicates that Ca and P are deposited in bones at a fixed ratio. If one or both minerals are provided below the requirement, pigs will respond by reducing the size of the bones, but not by changing the composition of the bone, which is also in agreement with published data (González Vega et al., 2016b).

In contrast to results for ADG and ADFI, results indicated that the estimated concentrations of STTD Ca needed to maximize bone ash, bone Ca, and bone P may be greater than the current requirement (NRC, 2012). Likewise, the concentrations of Ca and P that were estimated to maximize bone ash were also greater than those estimated to maximize growth performance. These observations are in agreement with previous data (Nimmo et al., 1980; Kornegay et al., 1981; Maxson and Mahan, 1983; González-Vega et al., 2016a, 2016b). The implications of these observations are that pigs can utilize dietary Ca and P to synthesize bone tissue at levels above that required to maximize growth performance. As a consequence, if the objective is to maximize bone ash, inclusion of Ca and P likely needs to exceed current requirements (NRC, 2012). This may be of importance in the feeding of developing boars and gilts that are raised for the breeding herd where it may be the objective to maximize bone ash prior to the reproductive age of the animals.

In conclusion, results from this experiment indicated that inclusion of more than 0.29% STTD Ca in diets for 100- to 130-kg pigs was detrimental to growth performance if dietary STTD P was at or less than 0.21%. Dietary Ca above the requirement resulted in reduced ADFI, and if dietary P was at or

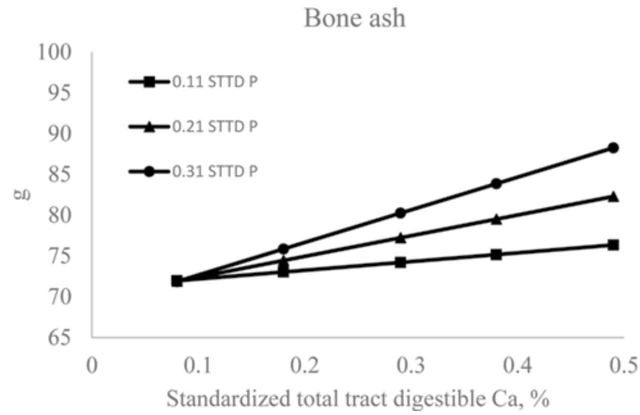

Figure 1. Predicted values, based on the interaction between standardized total tract digestible (STTD) Ca and STTD P ($P = 0.049$), for bone ash (g per femur) in pigs fed diets containing from 0.08% to 0.49% standardized total tract digestible (STTD) Ca and from 0.11% to 0.31% STTD P. All responses were linear and no maximum values could be estimated.

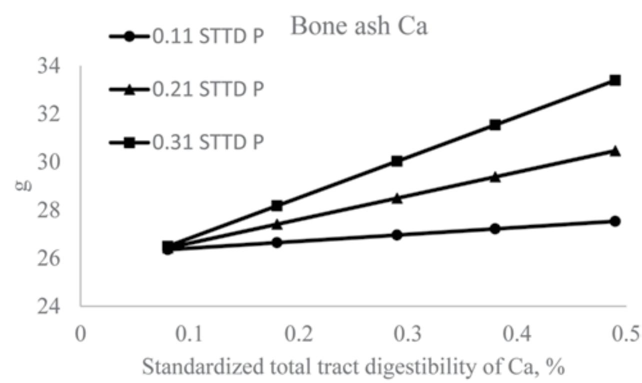

Figure 2. Predicted values, based on the interaction between standardized total tract digestible (STTD) Ca and STTD P ($P = 0.049$), for bone ash Ca (g per femur) in pigs fed diets containing from 0.08% to 0.49% standardized total tract digestible (STTD) Ca and from 0.11% to 0.31% STTD P. All responses were linear and no maximum values could be estimated.

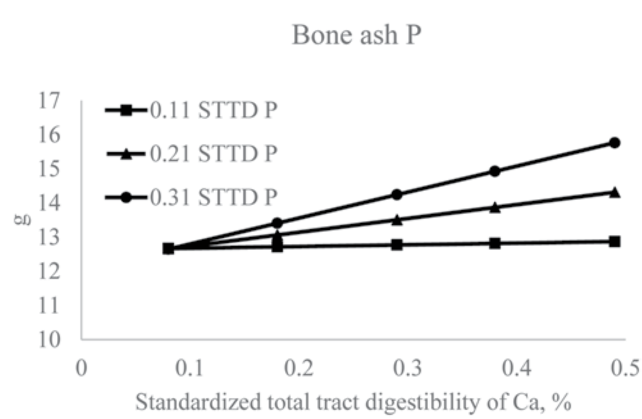

Figure 3. Predicted values, based on the interaction between standardized total tract digestible (STTD) Ca and STTD P ($P = 0.049$), for bone ash P (g per femur) in pigs fed diets containing from 0.08% to 0.49% standardized total tract digestible (STTD) Ca and from 0.11% to 0.31% STTD P. All responses were linear and no maximum values could be estimated.

below the requirement, increased dietary Ca also reduced ADG, whereas feed efficiency was not changed. However, including Ca and P in diets to maximize growth performance did not result in maximum bone ash. Growth performance of pigs weighing 100 to 130 kg appears to be maximized if the STTD Ca:STTD P ratio is between 1.10:1.0 and 1.38:1.0.

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