Published November 20, 2014

Effects of dietary sulfur and distillers dried grains with solubles on carcass characteristics, loin quality, and tissue concentrations of sulfur, selenium, and copper in growing–finishing pigs[1]

B. G. Kim,*[2] D. Y. Kil,†[2] D. C. Mahan,‡ G. M. Hill,§ and H. H. Stein#[3]

*Department of Animal Science and Environment, Konkuk University, Seoul 143-701, Republic of Korea; †Department of Animal Science and Technology, Chung-Ang University, Anseong-si, Gyeonggi-do 456-756, Republic of Korea; ‡Department of Animal Science, The Ohio State University, Columbus 43210-1095; §Department of Animal Science, Michigan State University, East Lansing 48824-125; and #Department of Animal Sciences, University of Illinois, Urbana 61801

ABSTRACT: Inclusion of up to 0.38% S in diets that contain 30% distillers dried grains with solubles (DDGS) has no negative effect on growth performance of growing–finishing pigs, but there is no information about the effects of dietary S on accumulation of S in tissues in pigs. Therefore, the objective of this experiment was to determine if the concentration of S in diets containing DDGS affects carcass characteristics, loin quality, or tissue mineral concentrations in growing–finishing pigs. A total of 120 barrows (34.2 ± 2.3 kg BW) were allotted to 3 dietary treatments with 10 replicate pens and 4 pigs per pen in a randomized complete block design. Pigs were fed grower diets for 42 d and finisher diets for 42 d. At the conclusion of the experiment, the pig in each pen with the BW closest to the pen average was slaughtered. The control diet was based on corn and soybean meal and the finisher diet contained 0.14% S, 0.19 mg/kg Se, and 15.3 mg/kg Cu. The DDGS diet was formulated with corn, soybean meal, and 30% DDGS and the finisher diet with DDGS contained 0.16% S, 0.32 mg/kg Se, and 14.0 mg/kg Cu. The DDGS plus S (DDGS-S) diet was similar to the DDGS diet, except that 1.10% $CaSO_4$ (16.2% S) was included in this diet, and the finisher diet with DDGS-S contained 0.37% S, 0.35 mg/kg Se, and 13.8 mg/kg Cu. Results indicated that organ weights and loin quality, 24-h pH, drip loss, loin subjective color, marbling, and firmness did not differ among treatments, but loin a* was greater ($P < 0.05$) for pigs fed the control diet than for pigs fed the DDGS-S diet. Concentrations of S in hair, liver, heart, loin, and all other tissues did not differ among treatments, but urinary S concentration was greater ($P < 0.05$) for pigs fed the DDGS-S diet than for pigs fed the other diets. Pigs fed the DDGS diet or the DDGS-S diet had greater ($P < 0.01$) concentrations of Se in hair, liver, heart, and loin than pigs fed the control diet, but liver concentrations of Cu did not differ among treatments. In conclusion, inclusion of 30% DDGS in diets fed to growing–finishing pigs did not influence carcass characteristics or tissue S concentrations regardless of S concentration in the diet, and excess dietary S was excreted in the urine. However, because of the greater concentration of Se in DDGS than in corn and soybean meal and, therefore, greater concentrations in DDGS-containing diets, tissue concentrations of Se were increased in pigs fed diets that contained DDGS. In contrast, dietary DDGS did not influence liver concentrations of Cu.

Key words: carcass characteristics, copper, distillers dried grains with solubles, pigs, selenium, sulfur

 J. Anim. Sci. 2014.92:4486–4493
doi:10.2527/jas2013-6323

INTRODUCTION

Distillers dried grains with solubles (**DDGS**) may contain relatively large quantities of S, but the concentration of S in DDGS vary among DDGS sources due to different production strategies in ethanol plants (Kerr et al., 2008; Kim et al., 2012). It is suggested that cattle should not be fed more than 0.40% S on a DM basis

[1]This manuscript is based on research funded by the National Pork Board (Des Moines, IA) and the Nutritional Efficiency Consortium (Des Moines, IA).
[2]These authors equally contributed to this work.
[3]Corresponding author: hstein@illinois.edu
Received January 31, 2013.
Accepted July 29, 2014.

(NRC, 1996), but there are limited data on the tolerable concentration of S in diets fed to pigs. In our recent experiments using both weanling pigs and growing–finishing pigs, neither growth nor feed palatability was influenced by up to 0.38% S in diets containing DDGS (Kim et al., 2012). However, whether or not elevated concentrations of dietary S results in increased concentrations of S in the tissues of pigs, changes in carcass characteristics, or reduced quality of pork loins is not known.

Increased dietary concentrations of Se and Cu may increase tissue concentrations of Se and Cu in pigs (Mahan et al., 2005). Concentrations of Se and Cu in DDGS are greater than in corn (NRC, 2012). Therefore, it is expected that inclusion of DDGS in diets fed to pigs will increase concentrations of Se and Cu in diets containing DDGS and subsequently in body tissues of pigs fed DDGS-containing diets, but this hypothesis has not been tested. However, elevated concentrations of dietary S apparently reduced absorption and retention of Se and Cu in rats (Halverson et al., 1962; Ardüser et al., 1985) and in ruminant animals (Suttle, 1991; Ivancic and Weiss, 2001), but to our knowledge, no data on the effect of dietary S on retention of Se and Cu in pigs have been reported. The objective of this experiment, therefore, was to test the hypothesis that DDGS influences retention of S, Se, and Cu in growing–finishing pigs and to investigate if an elevated level of dietary S affects carcass composition and quality and tissue concentrations of S, Se, and Cu.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois approved the protocol for the experiment.

Animals and Diets

The procedure for animal care and handling, experimental design, and dietary treatments were described in detail by Kim et al. (2012). Briefly, a total of 120 growing barrows with an average initial BW of 34.2 kg (SD = 2.3) were allotted to 3 dietary treatments with 10 replicate pens per treatment and 4 pigs per pen. Pigs were blocked in a randomized complete block design using the Experimental Animal Allotment Program (Kim and Lindemann, 2007) with initial BW as the blocking factor. Pigs were fed the experimental diets in a 2-phase program with grower and finisher diets being provided during the initial 42 d and the last 42 d, respectively. Three diets were prepared in each phase (Table 1). The control diet contained corn and soybean meal, whereas the DDGS diet contained corn, soybean meal, and 30% DDGS (as-fed basis). The third diet DDGS plus S (**DDGS-S**) diet was similar to the DDGS diet, but included 1.10% (as-fed basis) calcium sulfate ($CaSO_4$; 21.9% Ca and 16.2% S) at the expense of corn and limestone. The same batch of DDGS was used for preparing the 2 DDGS-containing diets in both phases. The concentration of S in DDGS used in this experiment was 0.30%, which is considered the least concentration that is observed in commercial DDGS (Kim et al., 2012). Inclusion of 1.10% $CaSO_4$ to diets containing 30% DDGS contributed an additional 0.18% S to the diets and analyzed concentrations of S in the diet for growing and finishing pigs were 0.38 and 0.37%, respectively (Table 2). These concentrations of S correspond to the concentrations of S that would have been expected in the diets if a source of DDGS that contained 0.90% S had been used. Concentrations of S in DDGS vary between 0.30 and 0.90% (as-fed basis; Kerr et al., 2008; Kim et al., 2012). By using a low-S source of DDGS either without or with added S, we attempted to specifically investigate the effects of dietary S on response parameters.

Table 1. Ingredient composition of experimental diets, 1 as-is basis[1]

	Diet[2]					
	Growing period (0 to 42 d)			Finishing period (43 to 84 d)		
Ingredient, %	Control	DDGS	DDGS-S	Control	DDGS	DDGS-S
Ground corn	74.65	61.33	60.90	81.90	67.65	67.22
Soybean meal, 48% CP	23.00	6.00	6.00	16.00	–	–
DDGS[3]	–	30.00	30.00	–	30.00	30.00
L-Lys HCl	–	0.43	0.43	–	0.40	0.40
L-Thr	–	0.03	0.03	–	–	–
L-Trp	–	0.04	0.04	–	0.05	0.05
Dicalcium phosphate	0.85	–	–	0.90	–	–
Ground limestone	0.80	1.47	0.80	0.50	1.20	0.53
Calcium sulfate	–	–	1.10	–	–	1.10
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin–mineral premix[4]	0.30	0.30	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00	100.00	100.00

[1]Ingredient composition of experimental diets was also reported by Kim et al. (2012).

[2]Control = control diet; DDGS = diet containing 30% distillers dried grains with solubles (DDGS); DDGS-S = diet containing 30% DDGS and 1.10% $CaSO_4$.

[3]Analyzed nutrient composition of DDGS (as-is basis): CP, 25.80%; ADF, 9.98%; NDF, 32.78%; Ca, 0.02%; P, 0.68%, S, 0.30%; Arg, 1.09%; His, 0.71; Ile, 0.99%; Leu, 2.88%; Lys, 0.77%; Met, 0.49%; Phe, 1.22; Thr, 0.91; Trp, 0.18; and Val, 1.27.

[4]The vitamin–micromineral premix provided the following quantities of vitamins and microminerals per kilogram of the complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 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 as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

Table 2. Analyzed composition of experimental diets,[1] as-is basis

	Diet[2]					
	Growing period (0 to 42 d)			Finishing period (43 to 84 d)		
Item	Control	DDGS	DDGS-S	Control	DDGS	DDGS-S
GE, kcal/kg	3,769	3,997	3,784	3,784	4,024	4,007
ME, kcal/kg[3]	3,330	3,348	3,333	3,342	3,361	3,347
CP, %	17.0	16.2	16.4	13.4	14.0	13.9
Arg, %	1.08	0.70	0.74	0.84	0.54	0.56
His, %	0.48	0.41	0.43	0.40	0.35	0.36
Ile, %	0.75	0.54	0.57	0.56	0.42	0.44
Leu, %	1.57	1.54	1.64	1.28	1.34	1.43
Lys, %	0.92	0.89	0.83	0.70	0.61	0.75
Met, %	0.27	0.26	0.27	0.22	0.23	0.24
Phe, %	0.86	0.65	0.73	0.68	0.56	0.59
Thr, %	0.62	0.51	0.56	0.51	0.43	0.45
Trp, %	0.21	0.18	0.18	0.16	0.16	0.16
Val, %	0.84	0.69	0.72	0.65	0.57	0.59
Ether extract, %	2.34	4.18	4.43	2.46	4.01	4.58
NDF, %	9.34	15.85	16.89	9.67	15.99	16.70
ADF, %	2.52	4.52	4.14	2.71	4.06	4.16
Ca, %	0.58	0.76	0.67	0.54	0.65	0.51
P, %	0.49	0.40	0.40	0.48	0.39	0.37
S, %	0.17	0.19	0.38	0.14	0.16	0.37
Cu, mg/kg	11.20	12.60	14.50	15.30	14.00	13.80
Se, mg/kg	0.328	0.417	0.446	0.193	0.315	0.346

[1]All data except concentrations of Cu and Se were reported previously (Kim et al., 2012).

[2]Control = control diet; DDGS = diet containing 30% distillers dried grains with solubles (DDGS); DDGS-S = diet containing 30% DDGS and 1.10% $CaSO_4$.

[3]Values for ME were calculated from NRC (1998); all other values were analyzed.

This approach was chosen instead of using both a low-S source of DDGS and a high-S source of DDGS because if 2 different sources of DDGS were used, results might be confounded by differences other than the concentration of S between the 2 sources of DDGS.

Energy and all nutrients, including vitamins and minerals, were included in the diets to meet or exceed estimated nutrient requirements (NRC, 1998) of pigs during the growing and finishing phases. The same quantity of the vitamin–micromineral premix was added to all diets so any differences among diets in concentrations of S, Se, and Cu was a result of different inclusion rates of corn, soybean meal, DDGS, and $CaSO_4$. All diets within each phase provided similar concentrations of ME, CP, and digestible P. Pigs had ad libitum access to feed and water during the entire experiment.

Carcass Evaluation, Sample Collection, and Chemical Analyses

At the conclusion of the experiment, the pig in each pen that had a BW that was closest to the mean BW of the 4 pigs in the pen was transported to the Meat Science Laboratory at the University of Illinois (Urbana, IL). After an overnight fast, the live BW of each pig was recorded and pigs were slaughtered following the procedure described by Carr et al. (2005). Hair samples were collected along the dorsal midline of the shoulder before slaughter. Blood samples were collected during exanguination and urine samples were collected directly from the bladder. The liver, kidney, heart, and spleen of each pig were collected, patted dry, and weighed. Approximately 30 cm of the distal ileum was collected just cranial to the ileocecal junction and rinsed with water to remove digesta. All samples were placed in a plastic bag and stored at –20°C until analyzed.

The HCW was recorded before carcasses were placed in a cooler at –4°C. At 24 h postmortem, the carcass length, 10th-rib fat depth, and 10th-rib loin area were measured following the procedures described by the National Pork Producers Council (2000). Carcass fat-free lean and percentage of carcass fat-free lean relative to HCW was calculated according to the National Pork Producers Council (2000). The pH of each loin was measured at the 10th rib by a SFK star probe (SFK Technologies Inc., Cedar Rapids, IA) 24 h postmortem. The objective loin color for L*, a*, and b* were measured using a Minolta chromameter (Minolta Camera Co., Osaka, Japan). Subjective color on a scale from 1 to 6 (1 = pale pinkish gray to white and 6 = dark purplish red), marbling on a scale from 1 to 10 (1 = devoid and 10 = abundant), and firmness on a scale from 1 to 5 (1 = very soft and watery and 5 = very firm and dry) were determined as described by the National Pork Producers Council (2000). A 2.5-cm loin chop at the 10th rib was collected, placed in a plastic Whirl-Pak bag (Uline, Pleasant Prairie, WI), and suspended from a fish hook for 24 h. Drip loss was then calculated by the difference between initial and final weight of the loin chop.

Diets were analyzed for GE using an adiabatic bomb calorimeter (model 6300; Parr Instruments, Moline, IL), CP (method 930.15; Hortwitz and Latimer, 2007), AA by an AA analyzer (model L8800; Hitachi High Technologies America, Inc., Pleasanton, CA; method 982.30 E; Hortwitz and Latimer, 2007), ether extract (method 2003.16; Hortwitz and Latimer, 2007), NDF (Holst, 1973), ADF (method 973.18; Hortwitz and Latimer, 2007), Ca (method 968.08; Hortwitz and Latimer, 2007), and P (method 975.03; Hortwitz and Latimer, 2007). All collected tissue samples and loin chops were ground using a food processor, lyophilized, and ground again in a coffee grinder. Concentrations of S in diet, tissue, hair, urine, and loin samples were analyzed using a thermal combustion method (Kerr et al., 2008). Concentrations of Se in diet, tissue, hair, and loin samples were measured by inductively coupled plasma spectroscopic tech-

nology according to Mahan et al. (2005). Diet and liver samples were also analyzed for Cu by atomic absorption spectroscopy (Shaw et al., 2002). The tissues that were analyzed for Se are the tissues that are most likely to have elevated concentrations of Se if increased quantities of Se are available (Mahan et al., 2005). In contrast, the liver is the tissue with the greatest storage of Cu (Turnlund, 1998), which is the reason liver samples were used for Cu analysis.

Statistical Analysis

Data were analyzed as a randomized complete block design using the Proc Mixed procedure of SAS (SAS Inst. Inc., Cary, NC). The model included dietary treatment as the fixed effect and replicate as the random effect. The LSMEANS procedure was used to calculate mean values for all treatments. Least squares means were reported along with the SEM for all measurements. When treatment effect was significant, least squares means among treatments were compared in a pairwise manner using the probability of differences (PDIFF) option with a Tukey adjustment of SAS. The differences were converted to letter superscripts using the PDMIX800 macro in SAS (Saxton, 1998). The pig was the experimental unit. For carcass length, 10th-rib fat depth, and loin area, data were calculated both without and with HCW as a covariate in the model. An α-value of 0.05 was used to assess significance among means.

RESULTS

Carcass Characteristics and LM Quality

The slaughter weight and HCW was less ($P < 0.05$) for pigs fed the DDGS diet or the DDGS-S diet than for pigs fed the control diet (Table 3). Carcass length was less ($P < 0.05$) for pigs fed the DDGS diet than for pigs fed the control diet, but pigs fed the DDGS-S diet had carcass length that was not different from that of pigs fed the control diet or the DDGS diet. However, values for carcass length that were adjusted by using HCW as a covariate were not affected by dietary treatments. Carcass fat-free lean was greatest ($P < 0.05$) for pigs fed the control diet, but least ($P < 0.05$) for pigs fed the DDGS diet. There were, however, no differences in carcass characteristics between pigs fed the DDGS diet and pigs fed the DDGS-S diet.

For loin quality, 24-h pH, drip loss, and subjective scores for color, marbling, and firmness, no differences among treatments were observed (Table 4). Redness value was greater ($P < 0.05$) for pigs fed the control diet than for pigs fed the DDGS-S diet, but the value for pigs fed the DDGS diet was not different from the values for pigs fed the other diets. Lightness and b* values were not affected by dietary treatments.

Table 3. Carcass characteristics of pigs fed experimental diets[1]

	Diet[2]				
Item	Control	DDGS	DDGS-S	SEM	*P*-value
Carcass characteristics					
Slaughter wt, kg	116.8[a]	107.8[b]	108.6[b]	2.0	<0.01
HCW, kg	87.9[a]	80.7[b]	80.9[b]	1.7	<0.01
Dressing percentage, %	75.2	74.8	74.5	0.4	0.31
Carcass length, cm	85.5[a]	82.8[b]	83.0[ab]	0.8	<0.01
10th-rib fat depth, cm	28.7	30.2	26.7	1.6	0.30
LM area, cm^2	38.9	36.4	37.8	0.9	0.14
Adjusted carcass length,[3] cm	84.7	83.2	83.4	0.8	0.44
Adjusted 10th-rib fat depth,[3] cm	27.4	30.9	27.3	1.7	0.22
Adjusted LM area,[3] cm^2	38.2	36.8	38.2	0.9	0.43
Carcass fat-free lean, kg	41.8[a]	37.3[b]	39.1[ab]	1.0	<0.01
Carcass fat-free lean, % of HCW	47.6	46.2	48.3	0.9	0.22

[a,b]Means within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Data are least squares means of 10 pigs per treatment.

[2]Control = control diet; DDGS = diet containing 30% distillers dried grains with solubles (DDGS); DDGS-S = diet containing 30% DDGS and 1.10% $CaSO_4$.

[3]Adjusted values are calculated using HCW as a covariate.

Organ Weights and Tissue Mineral Concentrations

The weight of the liver and kidney was less ($P < 0.05$) for pigs fed the DDGS diet than for pigs fed the control diet, but values for pigs fed the DDGS-S diet were not different from values for pigs fed the other diets (Table 5). Percentage weight of the liver, kidney, heart, and spleen relative to BW or empty BW did not differ among treatments.

Concentrations of S in liver, kidney, heart, spleen, loin, hair, and blood were not affected by dietary treatments, but the concentration of S in intestinal tissue collected from the distal ileum was less ($P < 0.05$) in pigs fed the DDGS-S diet than in pigs fed the control diet (Table 6). In contrast, urinary S concentration was greater ($P < 0.05$) for pigs fed the DDGS-S diet than for pigs fed the control diet or the DDGS diet.

Concentrations of Se in liver, loin, and hair were greater ($P < 0.05$) for pigs fed the DDGS diet or the DDGS-S diet than for pigs fed the control diet, but values did not differ between pigs fed the DDGS diet and pigs fed the DDGS-S diet. Concentration of Se in the heart was greatest ($P < 0.05$) for pigs fed the DDGS-S diet, and pigs fed the DDGS diet also had a greater ($P < 0.05$) concentration of Se in the heart than pigs fed the control diet. The concentration of Cu in the liver was not affected by dietary treatments.

Table 4. The LM quality of pigs fed experimental diets[1]

Item	Diet[2]			SEM	*P*-value
	Control	DDGS	DDGS-S		
24-h pH	5.48	5.49	5.53	0.02	0.37
Drip loss, %	4.74	5.41	3.39	0.80	0.21
Minolta color score					
L*	51.29	51.82	49.31	1.10	0.25
a*	8.62[a]	7.51[ab]	7.39[b]	0.37	0.04
b*	5.53	5.17	4.72	0.37	0.32
Subjective score[3]					
Color	2.40	2.70	2.70	0.18	0.40
Marbling	1.70	2.30	2.50	0.26	0.10
Firmness	2.10	2.40	2.90	0.27	0.13

[a,b]Means within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Data are least squares means of 10 pigs per treatment.

[2]Control = control diet; DDGS = diet containing 30% distillers dried grains with solubles (DDGS); DDGS-S = diet containing 30% DDGS and 1.10% $CaSO_4$.

[3]Color (1 = pale pinkish gray to white and 6 = dark purplish red), marbling (1 = 1.0% intramuscular fat and 10 = 10% intramuscular fat), and firmness (1 = soft and 6 = very firm).

Table 5. Organ weights of pigs fed experimental diets[1]

Item	Diet[2]			SEM	*P*-value
	Control	DDGS	DDGS-S		
Organ wt, kg					
Liver	1.86[a]	1.66[b]	1.77[ab]	0.06	<0.05
Kidney	0.37[a]	0.33[b]	0.35[ab]	0.01	0.03
Heart	0.47	0.43	0.45	0.02	0.26
Spleen	0.22	0.19	0.20	0.01	0.17
Organ wt, % of BW					
Liver	1.60	1.55	1.62	0.06	0.63
Kidney	0.32	0.31	0.32	0.01	0.31
Heart	0.40	0.40	0.42	0.01	0.45
Spleen	0.19	0.18	0.19	0.01	0.74
Organ wt, % of empty BW					
Liver	2.13	2.07	2.18	0.08	0.63
Kidney	0.42	0.41	0.44	0.01	0.29
Heart	0.53	0.53	0.56	0.02	0.34
Spleen	0.25	0.24	0.25	0.01	0.74

[a,b]Means within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Data are least squares means of 10 pigs per treatment.

[2]Control = control diet; DDGS = diet containing 30% distillers dried grains with solubles (DDGS); DDGS-S = diet containing 30% DDGS and 1.10% $CaSO_4$.

DISCUSSION

Carcass Characteristics and LM Quality

The decrease in slaughter weight and HCW for pigs fed the DDGS diet or the DDGS-S diet is a consequence of decreased final BW for these pigs compared with pigs fed the control diet. Pigs fed both DDGS-containing diets had a reduced ADG compared with pigs fed the control diet, which is the reason for the reduced final BW (Kim et al., 2012). This observation is in agreement with data from Whitney et al. (2006), who reported that feeding 30% DDGS to growing and finishing pigs decreased final BW and, therefore, decreased slaughter weight and HCW. The reduced carcass length and carcass fat-free lean weight for pigs fed the DDGS-containing diets compared with pigs fed the control diet was also a result of the reduced HCW, which is the reason no differences in carcass length were observed if HCW was used as a covariant in the calculations.

These observations indicate that it is the reduced weight at harvest rather than dietary DDGS that influences carcass length of pigs at harvest. The fact that carcass leanness and backfat were not influenced by dietary treatments is in agreement with results of most previous experiments (Stein and Shurson, 2009). Results of this experiment, however, also indicate that the concentration of dietary S has no impact on carcass characteristics. The observation that measures of LM quality were not influenced by the inclusion of DDGS in the diets is in agreement with data from Whitney et al. (2006) and Xu et al. (2010a), whereas Xu et al. (2010b) reported that pigs fed diets containing 30% DDGS had decreased subjective loin marbling and firmness scores.

The fact that loin L* values were not influenced by DDGS in the diets agrees with previous experiments (Whitney et al., 2006; Xu et al., 2010a,b); however, Xu et al. (2010b) and Widmer et al. (2008) reported a decrease in loin b* value for pigs fed diets containing 20 or 30% DDGS, but in the present experiment, no differences in b* values were observed. These differences among experiments may be a result of differences in the quality among sources of DDGS, feeding duration of DDGS, and methodologies used to measure loin quality. The reduced loin a* value that was obtained for pigs fed the diet containing 30% DDGS and additional S, but not for pigs fed the diet with 30% DDGS and no additional S, could potentially reflect an increased percentage of white fibers (Type IIb) relative to intermediate fibers (Type IIa) or decreased amounts of oxymyoglobin in the muscle (Carr et al., 2005). However, to our knowledge, there is no evidence that high concentration of S in the diet influences muscle fiber composition and oxygen-binding capacity of myoglobin. Therefore, the reason for the decreased loin a* value as 30% DDGS and additional S were included in diets fed to pigs is not clear. The fact that no differences in carcass characteristics and loin quality were observed between pigs fed the DDGS diet and pigs fed the DDGS-S diet indicates that additional S has no negative impact on carcass characteristics and loin quality.

Organ Weight and Tissue Mineral Concentrations

The reduced weight of the liver and kidneys for pigs fed the DDGS diet compared with pigs fed the con-

Table 6. Tissue mineral concentrations in pigs fed experimental diets[1,2]

Item	Diet[3]			SEM	*P*-value
	Control	DDGS	DDGS-S		
S, mg/g					
Liver	2.24	2.20	2.16	0.05	0.48
Kidney	1.44	1.52	1.43	0.03	0.08
Heart	1.56	1.58	1.56	0.03	0.86
Spleen	1.60	1.56	1.61	0.03	0.49
Loin	1.95	1.95	1.97	0.03	0.85
Distal ileum	1.15[a]	1.14[a]	1.09[b]	0.02	0.04
Hair	40.2	40.0	40.5	0.50	0.42
Blood	1.06	1.04	1.02	0.02	0.29
Urine	0.60[b]	0.63[b]	1.07[a]	0.12	0.02
Se, μg/g					
Liver	0.55[b]	0.69[a]	0.67[a]	0.02	<0.01
Kidney	1.66	1.72	1.68	0.05	0.59
Heart	0.19[c]	0.30[b]	0.33[a]	0.01	<0.01
Loin	0.14[b]	0.29[a]	0.24[a]	0.02	<0.01
Hair	0.55[b]	0.65[a]	0.70[a]	0.03	<0.01
Cu, μg/g					
Liver	7.35	7.14	6.34	0.68	0.55

[a–c]Means within a row lacking a common superscript letter are different ($P < 0.05$).

[1]Data are least squares means of 10 pigs per treatment.

[2]Mineral concentrations are on the basis of fresh samples.

[3]Control = control diet; DDGS = diet containing 30% distillers dried grains with solubles (DDGS); DDGS-S = diet containing 30% DDGS and 1.10% $CaSO_4$.

trol diet was likely a result of the decreased final BW (Kim et al., 2012) and slaughter weight for these pigs. If finishing pigs fed 30% DDGS have similar final BW and slaughter weight as pigs fed a control diet without DDGS, no differences in the weights of the liver, kidney, heart, and spleen are observed (Gutierrez, 2009). The fact that no differences in percentage weight of body organs relative to slaughter weight or empty BW was observed further indicates that DDGS per se does not influence organ weights of pigs. Therefore, the reduced dressing percentage of pigs fed diets containing DDGS that has sometimes been reported (Stein and Shurson, 2009) appears not to be a result of differences in organ weights of pigs fed diets containing DDGS. There was also no effect on organ weights of feeding the DDGS-S diets to pigs, which indicates that additional S in diets does not alter organ growth and development in pigs.

Dietary S is readily absorbed from the gastrointestinal tracts of animals (Krijgsheld et al., 1979) and humans (Florin et al., 1991). Sulfur is stored in all body cells, especially as keratin presented in the skin, hair, and nails (Parcel, 2002). However, the lack of a detectable change in the concentration of S in tissues in the body for pigs fed the high-S diet indicates that increased absorption does not result in increased deposition of S. Instead, excess absorbed S is excreted via the urine, which is the reason for the increased concentration of S in urine that was observed for pigs fed the DDGS-S diets. Therefore, S homeostasis is apparently regulated at the renal level. We are not aware of other data investigating S homeostasis in pigs, but a similar observation has been reported for Ca homeostasis (Stein et al., 2006).

The reason for the decreased concentration of S in intestinal tissue from the distal ileum is not clear, but intake of S in excess of the requirement may promote intestinal S excretion in the form of mucin possibly due to irritation of the intestinal mucosa caused by increased synthesis of H_2S (Florin et al., 1991; Kerr et al., 2011). An increased expression of inflammatory cytokines in the small intestine of pigs fed high-S diets has also been demonstrated (Kerr et al., 2011). Therefore, the reduced concentration of S in the intestinal tissue from the ileum is possibly a result of excess endogenous secretion of S, but more research is needed to verify this hypothesis.

Although the diets containing DDGS contained more Se than diets without DDGS, the analyzed concentration of Se in these diets were less than the toxic levels for pigs (Mahan et al., 2005; Mahan, 2008) and it is, therefore, not expected that these levels will result in any toxicity symptoms in pigs. However, the increased concentrations of Se in liver, heart, loin, and hair of pigs fed DDGS-containing diets compared with pigs fed the control diets are likely a consequence of the greater concentrations of Se in the DDGS diets and the DDGS-S diets than in the control diets. This observation is in agreement with results of experiments indicating that dietary Se concentrations directly influence tissue Se concentrations in pigs (Ku et al., 1972; Mahan et al., 1999, 2005), but we are not aware of previous data that have demonstrated that feeding of DDGS results in increased deposition of Se in pig tissues.

The reason the concentration of Cu in the liver was not affected by inclusion of 30% DDGS in the diet may be that the concentration of Cu in the diets containing DDGS, which ranged from 12.6 to 14.5 mg/kg, was adequate but not excessive, and hence additional storage in the liver did not occur. Baker and Ammerman (1995) reported that hepatic Cu concentrations in pigs linearly increased with more than 150 mg/kg DM of Cu in diets, whereas no change was observed if diets contained less than 80 mg/kg DM of Cu. Results of this experiment are, therefore, in agreement with the data by Baker and Ammerman (1995).

Dietary S may decrease the absorption of Se in rats (Halverson et al., 1962; Ardüser et al., 1985) and of Se and Cu in ruminant animals (Pope et al., 1979; Suttle, 1991; Ivancic and Weiss, 2001) because of competition for a common transport mechanism in the intestinal tract. It is also possible that S and Se or Cu will form an unabsorbable complex in the intestinal tract, but such effects

have not been demonstrated in pigs. The observation in this experiment that there were no differences in tissue concentrations of Se and Cu between pigs fed the DDGS and the DDGS-S diets indicates that dietary concentrations of S of approximately 0.38% have no adverse effect on absorption and utilization of dietary Se and Cu in pigs and it appears that pigs have greater tolerance for S than ruminants and rats.

Conclusions

Results of this experiment indicated that diets fed to growing–finishing pigs that contain 30% DDGS and approximately 0.38% S had no negative effects on loin quality or organ weight expressed as percentage of BW. Likewise, with the exception of the concentration of S in tissue collected from the distal ileum, dietary S did not influence tissue concentrations of S, Se, or Cu. Pigs fed S in excess of the requirement excreted the excess in the urine and S homeostasis appears to be regulated at the renal level. Inclusion of DDGS, which may contain 3 to 4 times as much Se as corn and soybean meal, in diets fed to growing–finishing pigs increased the concentration of Se in hair and body tissues, but DDGS had no effect on hepatic Cu concentration. The concentration of S in diets containing DDGS did not affect the concentrations of Se and Cu in body tissues of pigs and there was no evidence that S had a depressive effect on absorption of Se and Cu when fed to pigs.

LITERATURE CITED

Ardüser, F., S. Wolffram, and E. Scharrer. 1985. Active absorption of selenite by rat ileum. J. Nutr. 115:1203–1208.

Baker, D. H., and C. B. Ammerman. 1995. Copper bioavailability. In: C. B. Ammerman, D. H. Baker, and A. J. Lewis, editors, Bioavailability of nutrients for animals. Academic Press, San Diego, CA. p. 127–156.

Carr, S. N., D. J. Ivers, D. B. Anderson, D. J. Jones, D. H. Mowrey, M. B. England, J. Killefer, P. J. Rincker, and F. K. McKeith. 2005. The effects of ractopamine hydrochloride on lean carcass yields and pork quality characteristics. J. Anim. Sci. 83:2886–2893.

Florin, T., G. Neale, G. R. Gibson, S. U. Christl, and J. H. Cummings. 1991. Metabolism of dietary sulphate: Absorption and excretion in humans. Gut 32:766–773.

Gutierrez, N. A. 2009. Energy and nutrient digestibility of corn distillers co-products fed to growing and finishing pigs. MS Thesis. Univ. of Illinois, Urbana.

Halverson, A. W., P. L. Guss, and O. E. Olsen. 1962. Effect of sulfur salts on selenium poisoning in the rat. J. Nutr. 77:459–464.

Holst, D. O. 1973. Holst filtration apparatus for Van Soest detergent fiber analysis. J. Assoc. Off. Anal. Chem. 56:1352–1356.

Hortwitz, W., and G. W. Latimer Jr., editors. 2007. Official methods of analysis of AOAC Int. 18th ed. Rev. 2. AOAC Int., Gaithersburg, MD.

Ivancic, J., Jr., and W. P. Weiss. 2001. Effect of dietary sulfur and selenium concentrations on selenium balance of lactating Holstein cows. J. Dairy Sci. 84:225–232.

Kerr, B. J., T. E. Weber, C. J. Ziemer, C. Spence, M. A. Cotta, and T. R. Whitehead. 2011. Effect of dietary inorganic sulfur level on growth performance, fecal composition, and measures of inflammation and sulfate-reducing bacteria in the intestine of growing pigs. J. Anim. Sci. 89:426–437.

Kerr, B. J., C. J. Ziemer, T. E. Weber, S. L. Trabue, B. L. Bearson, G. C. Shurson, and M. H. Whitney. 2008. Comparative sulfur analysis using thermal combustion or inductively coupled plasma methodology and mineral composition of common livestock feedstuffs. J. Anim. Sci. 86:2377–2384.

Kim, B. G., and M. D. Lindemann. 2007. A new spreadsheet method for the experimental animal allotment. J. Anim. Sci. 85(Suppl. 2):218 (Abstr.).

Kim, B. G., Y. Zhang, and H. H. Stein. 2012. Sulfur concentration in diets containing corn, soybean meal, and distillers dried grains with solubles does not affect feed preference or growth performance of weanling or growing finishing pigs. J. Anim. Sci. 90:272–281.

Krijgsheld, K. R., H. Frankena, E. Scholtens, J. Zweens, and G. L. Mulder. 1979. Absorption, serum levels and urinary excretion of inorganic sulfate after oral administration of sodium sulfate in the conscious rat. Biochim. Biophys. Acta 586:492–500.

Ku, P. K., W. T. Ely, A. W. Groce, and D. E. Ullrey. 1972. Natural dietary selenium, alpha-tocopherol and effect on tissue selenium. J. Anim. Sci. 34:208–211.

Mahan, D. C. 2008. Selenium toxicity in the Western United States' pork industry. Pork checkoff.

Mahan, D. C., J. H. Brendemuhl, S. D. Carter, L. I. Chiba, T. D. Crenshaw, G. L. Cromwell, C. R. Dove, A. F. Harper, G. M. Hill, G. R. Hollis, S. W. Kim, M. D. Lindemann, C. V. Maxwell, P. S. Miller, J. L. Nelssen, B. T. Richert, L. L. Southern, T. S. Stahly, H. H. Stein, E. van Heugten, and J. T. Yen. 2005. Comparison of dietary selenium fed to grower-finisher pigs from various regions of the United States on resulting tissue Se and loin mineral concentrations. J. Anim. Sci. 83:852–857.

Mahan, D. C., T. R. Cline, and B. Richert. 1999. Effects of dietary levels of selenium-enriched yeast and sodium selenite as selenium sources fed to grower-finisher pigs on resulting performance, tissue selenium, serum glutathione peroxidase activity, carcass characteristics, and loin quality. J. Anim. Sci. 77:2172–2179.

National Pork Producers Council. 2000. Pork composition and quality assessment procedures. National Pork Producers Council, Des Moines, IA.

NRC. 1996. Nutrient requirements of beef cattle. 7th ed. National Academy Press, Washington, DC.

NRC. 1998. Nutrient requirements of swine. 10th ed. National Academy Press, Washington, DC.

NRC. 2012. Nutrient requirements of swine. 11th ed. National Academy Press, Washington, DC.

Parcel, S. W. 2002. Sulfur in human nutrition and applications in medicine. Altern. Med. Rev. 7:22–44.

Pope, A. L., R. J. Moir, M. Somers, E. J. Underwood, and C. L. White. 1979. The effect of sulphur on 75Se absorption and retention in sheep. J. Nutr. 109:1448–1455.

Saxton, A. M. 1998. A macro for converting mean separation output to letter groupings in Proc Mixed. In: Proc. 23rd SAS Users Group Int., Nashville, TN. SAS Inst. Inc., Cary, NC. p. 1243–1246.

Shaw, D. T., D. W. Rozeboom, G. M. Hill, A. M. Booren, and J. E. Link. 2002. Impact of vitamin and mineral supplement withdrawal and wheat middling inclusion on finishing pig growth performance, fecal mineral concentration, carcass characteristics, and the nutritional content and oxidative stability of pork. J. Anim. Sci. 80:2920–2930.

Stein, H. H., M. G. Boersma, and C. Pedersen. 2006. Apparent and true total tract digestibility of phosphorus in field peas (*Pisum sativum* L.) by growing pigs. Can. J. Anim. Sci. 86:523–525.

Stein, H. H., and G. C. Shurson. 2009. The use and application of distillers dried grains with solubles in swine diets. J. Anim. Sci. 87:1292–1303.

Suttle, N. F. 1991. The interactions between copper, molybdenum, and sulphur in ruminant nutrition. Annu. Rev. Nutr. 11:121–140.

Turnlund, J. R. 1998. Human whole-body copper metabolism. Am. J. Clin. Nutr. 67:960S–964S.

Whitney, M. H., G. C. Shurson, L. J. Johnson, D. M. Wulf, and B. C. Shanks. 2006. Growth performance and carcass characteristics of grower-finisher pigs fed high-quality corn distillers dried grain with solubles originating from a modern Midwestern ethanol plant. J. Anim. Sci. 84:3356–3363.

Widmer, M. R., L. M. McGinnis, D. M. Wulf, and H. H. Stein. 2008. Effects of feeding distillers dried grains with solubles, high-protein distillers dried grains, and corn germ to growing-finishing pigs on pig performance, carcass quality, and the palatability of pork. J. Anim. Sci. 86:1819–1831.

Xu, G., S. K. Baidoo, L. J. Johnston, D. Bibus, J. E. Cannon, and G. C. Shurson. 2010a. The effects of feeding diets containing corn distillers dried grains with solubles, and withdrawal period of distillers dried grains with solubles, on growth performance and pork quality in grower-finisher pigs. J. Anim. Sci. 88:1388–1397.

Xu, G., S. K. Baidoo, L. J. Johnston, D. Bibus, J. E. Cannon, and G. C. Shurson. 2010b. Effects of feeding diets containing increasing content of corn distillers dried grains with solubles to grower-finisher pigs on growth performance, carcass composition, and pork fat quality. J. Anim. Sci. 88:1398–1410.