Ruminal Phosphorus Disappearance from Corn and Soybean Feedstuffs¹

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ABSTRACT

Byproducts of corn and soybeans have high phosphorus (P) content, but little is known about their P disappearance in the rumen of lactating dairy cows. In situ disappearance of P from corn and soybean feedstuffs was determined in 2 experiments. In the first experiment, 3 ruminally cannulated lactating dairy cows were used to estimate in situ P disappearance of 9 feed ingredients that included 3 sources of dried distillers grains with solubles (DDG; DGa, DGb, DGc), corn, corn germ, solvent-extracted soybean meal, (44% CP; SBM), expeller soybean meal (SoyPlus; SP), extruded soybeans (ES), and soyhulls (SH). Nylon bags were incubated in the rumen of each cow for 2, 6, 12, 18, 24, 36, and 48 h. The water-soluble fraction of P (A_p) was greatest in DDG (mean 82.1%) followed by corn germ (77%), with SH having the least A_p among all feedstuffs (45%). The remaining feedstuffs (SBM, SP, ES, and corn) were similar in A_p (64.2%). The slowly available fraction of P (B_p) was greatest in SH (45.6%), lowest in DDG (13.5%), and intermediate, averaging 31.4%, in SBM, ES, SP, and corn. The effective disappearance of P (ED_p) was greatest for DDG (93.5%), whereas corn germ, ES, SBM, and SP followed with an ED_p of 93.3, 88.0, 87.5, and 87.0%, respectively. The ED_p was less for corn and SH than for the other feedstuffs at 83.3 and 69.1%, respectively. Rate of P disappearance was similar for all feedstuffs (16.2%/h). In the second experiment, 3 new sources of DDG (DG1, DG2, and DG3), and one wet distillers grains with solubles (WDG) source were incubated for 3, 6, 12, 24, and 36 h on replicate days in the rumen of 2 cannulated lactating dairy cows. Fraction A_p varied from 82.7 to 90.3%, with that in WDG being the least soluble. The WDG source had a greater B_p fraction (15.8%) compared with the DDG sources (9.5%). The WDG had the lowest ED_p (88.1%), whereas the DDG varied from 89.7 to 92.7%. Corn and soybean byproducts tested, with the exception of SH,

have high ruminal P disappearance as measured with the Dacron bag technique.

Key words: ruminal phosphorus disappearance, in situ, feedstuffs, distillers grains

INTRODUCTION

Given the role of phosphorus (P) in environmental pollution and the significant cost of adding inorganic P to the dairy ration, it is critical that dietary P not exceed the requirement of the animal. High dietary P concentrations can lead to excess P consumption and high P concentrations in wastes. Excess P from confined livestock operations has become a major environmental concern because of its harmful effects on surface water. Extensive data exist on P disappearance from mineral supplements (NRC, 2001) and to some extent from forages (Emanuele and Staples, 1990; Martz et al., 1990; Flachowsky et al., 1994), but data on ruminal disappearance from concentrate sources are limited (Bravo et al., 2000; Hristov et al., 2004). There are large differences in P solubility in different feedstuffs. Ruminal P release varied from 64% for rapeseed meal to 89% for wheat (Bravo et al., 2000). Concentrates account for as much as 60% of DM and between 60 and 80% of the total P in dairy rations. Particularly, byproducts from ethanol plants, such as wet distillers grains with solubles (WDG) and dried distillers grains with solubles (DDG), are rich in P content and are increasingly used in dairy rations. Consequently, it is important to quantify their P availability to formulate rations that are sufficient but do not exceed the requirement of the animal.

Recent research in pigs demonstrated that the apparent total tract digestibility of P is greater in DDG than in corn (Pedersen et al., 2007). It has been hypothesized that the phytate phosphorus (PP) in corn undergoes hydrolysis during the fermentation process in the ethanol plant resulting in P in distillers grains that is highly soluble. If true, the nutritional value of distillers grains would be increased when it is fed to meet the P requirement of the animal, but would be detrimental to the environment if overfed.

In general, there is limited information regarding ruminal P disappearance of concentrate feedstuffs com-

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monly used in dairy cow diets. Therefore, the objective of this study was to assess ruminal P disappearance of corn and corn byproducts compared with different soybean feedstuffs.

MATERIALS AND METHODS

Feeds and In Situ Procedures

Experiment 1. The purpose of experiment 1 was to compare P disappearance from corn and corn byproducts to various soybean feedstuffs. The in situ procedure was conducted using 3 lactating dairy cows (averaging 235 DIM and 25 kg/d of milk) fitted with rumen cannulas. Animals were fed, for ad libitum consumption, a diet containing 50:50 forage to concentrate ratio (Table 1). Nine feedstuffs were evaluated including 3 different DDG from 3 commercial ethanol plants (DGa, DGb, and DGc), ground corn, corn germ (CG; Poet Nutrition, Sioux Falls, SD), and 4 soybean products that included solvent-extracted soybean meal (SBM; 44% CP), expeller soybean meal (SP; SoyPlus, West Central Soy, Ralston, IA), extruded soybeans (ES), and soyhulls (SH). All feed ingredients, with the exception of DDG samples, were ground to pass a 2-mm screen in a Wiley mill (Arthur H. Thomas, Philadelphia, PA). Grinding distillers grains may negate some of the physical properties that affect feed degradability in the animal such as moisture content and microbial access to the protein sources (Stern et al., 1994) and ultimately P release from feedstuffs. Five grams (as-fed basis) of each feedstuff was weighed into duplicate Dacron bags measuring 10 × 20 cm with a pore size of 53 ± 10 µm (Ankom Technology, Fairport, NY) and heat sealed. Before incubation, duplicate samples of each feedstuff were soaked in approximately 39°C water for 15 min. All sets of Dacron bags were placed in a larger, weighted mesh bag (36 × 42 cm) that was suspended below the particulate mat layer in the ventral sac of the rumen. Bags were incubated in the rumen for 2, 6, 12, 18, 24, 36, and 48 h. Bags were placed in the rumen in reverse order of sampling time so that all bags were removed from the rumen concurrently. The zero-hour bags were not placed in the rumen but was otherwise treated similarly. Blank bags in duplicate corresponding to each time point were placed in the rumen to correct for material accumulated in the bag during the incubation period. Following rumen incubation, the mesh bag containing all Dacron bags was rinsed with cold water to remove particulate matter, and the Dacron bags were removed and rinsed in a domestic washing machine under the delicate setting with warm water for approximately 5 min before draining. The cycle was repeated until effluent water remained clear.

Experiment 2. This experiment was conducted to determine if ruminal P disappearance from distillers grains varies by source. Samples used in this experiment were previously examined for protein degradability by Kleinschmit et al. (2007). Three sources of DDG (DG1, DG2, and DG3) and one source of WDG were tested for P disappearance in the rumen. Sources DG1, DG2, and DG3 in this study correspond to DG1, DG4, and DG5 in Kleinschmit et al. (2007). Samples of DG1 and DG2 were obtained from different ethanol plants, whereas DG3 and WDG originated from the same ethanol plant and were processed using similar procedures, except that DG3 was dried. Chemical

Table 1. Ingredients and chemical composition of the total mixed diet fed to cows during in situ experiments 1 and 2 (DM basis)

Ingredient	Experiment 1	Experiment 2
Corn silage	26.3	21.7
Alfalfa hay	21.4	12.2
Alfalfa haylage	—	6.63
Wet distillers grains	5.97	8.28
High moisture corn	16.2	18.7
Ground corn, shell	7.29	6.07
Soybean meal, 44% CP	—	3.23
Expellers soybean meal ¹	4.43	4.56
Fish meal	0.75	0.40
Whole cottonseed	8.96	8.90
Rumen inert fat ²	0.80	1.28
Liquid supplement ³	4.06	4.23
Calcium carbonate	—	0.97
Limestone	0.58	—
Pork meat and bone meal	1.19	0.64
Sodium bicarbonate	0.54	0.57
Salt	0.41	0.50
Mineral and vitamin premix ⁴	0.21	0.31
Yeast culture ⁵	0.19	0.21
Magnesium oxide	0.16	0.17
Feed additive ⁶	—	0.15
Urea	—	0.17
Se yeast ⁷	—	0.05
Trace mineral complex ⁸	0.05	0.05
Vitamin E premix (44,000 IU/kg)	0.02	0.02
Chemical composition		
DM, %	46.3	42.0
CP, % of DM	16.7	17.7
NDF, % of DM	29.0	30.2
ADF, % of DM	18.8	18.8
Ca, % of DM	0.80	0.92
P, % of DM	0.41	0.40

¹SoyPlus (West Central Soy, Ralston, IA).

²Megalac-R (Church & Dwight Co. Inc., Princeton, NJ).

³Energizer 4-19W (Quality Liquid Feeds, Dodgeville, WI).

⁴Contained 10% Mg; 2.6% Zn; 1.7% Mn; 4,640 mg/kg of Fe; 4,712 mg/kg of Cu; 396 mg/kg of I; 119 mg/kg of Co; 140 mg/kg of Se; 2,640,000 IU/kg of vitamin A; 528,000 IU/kg of vitamin D3; and 10,560 IU/kg of vitamin E (Land O' Lakes Inc., St. Paul, MN).

⁵Diamond V XP (Diamond V Mills Inc., Cedar Rapids, IA).

⁶MTB-100, an esterified glucomannan processed from yeast cell walls (Alltech Biotechnology, Nicholasville, KY).

⁷600 ppm Se yeast (Alltech Biotechnology).

⁸Zinpro 4-Plex contained 2.53% Zn; 1.40% Mn; 0.88% Cu; 0.18% Co; 8.31% Met; and 3.80% Lys (Zinpro Corp., Eden Prairie, MN).

Table 2. Chemical composition of dried distillers grains with solubles (DGa, DGb, and DGc), corn, corn germ (CG), soybean meal (SBM), SoyPlus (SP), extruded soybeans (ES), and soyhulls (SH)

Component	Feedstuff								
	DGa	DGb	DGc	Corn	CG	SBM	SP	ES	SH
DM, %	91.3	89.6	89.8	88.5	92.4	89.5	91.8	92.2	90.6
	% of DM								
CP	33.6	34.9	34.3	9.1	15.8	50.4	46.9	37.6	13.0
NDF	39.1	42.1	37.4	10.0	22.8	14.8	23.4	13.1	64.8
ADF	17.3	19.4	16.5	4.0	6.0	9.0	11.0	10.5	50.2
Ash	4.2	4.4	5.2	1.7	5.6	6.4	6.0	5.2	5.0
P	0.69	0.70	0.75	0.25	1.01	0.72	0.65	0.58	0.16
PP ¹	0.22	0.12	0.13	0.19	0.40	0.40	0.31	0.32	0.04
PP, % of P	31.9	17.1	17.3	76.0	39.6	55.6	47.7	55.2	25.0

¹Phytate phosphorus.

composition of the samples and the in situ procedures were described by Kleinschmit et al. (2007). Briefly, 2 ruminally cannulated lactating Holstein cows (261 and 265 DIM) producing 34 and 29 kg/d of milk were fed, for ad libitum consumption, a diet consisting of 40% forage and 60% concentrate on a DM basis (Table 1). In both experiments cows were allowed a 14-d diet adjustment period before the initiation of the in situ procedure. Samples were prepared similarly as in experiment 1. Incubation measures were completed at 3, 6, 12, 18, 24, and 36 h over 2 periods. Immediately after removal of the bags from the rumen, the mesh bag was gently agitated in tap water to remove small particles. Individual nylon bags were further rinsed with cold tap water until the water became clear.

Chemical Analysis

Original test feedstuffs were analyzed for DM, CP, and ash (AOAC, 1995), NDF (Van Soest et al., 1991), ADF (Robertson and Van Soest, 1981) using an Ankom fiber analyzer with the filter bag technique (Ankom

Technology Corp., Fairport, NY), and phytate phosphorus (Haug and Lantzsch, 1983). Phosphorus concentration was determined spectrophotometrically by the molybdo-vanadate reagent after mineralization of samples with 6 M HCl (AOAC, 1995; method 965.17) using a model DU70 Beckman spectrophotometer (Beckman Instruments Inc., Fullerton, CA). Chemical composition of the feedstuffs is presented in Table 2 (experiment 1) and Table 3 (experiment 2).

After removal from the rumen, bags were dried for 48 h at 55°C in a forced air oven, and then residues were weighed and analyzed for DM and P as described. Dry matter and P disappearance were calculated by difference of original amounts and residual amounts after ruminal incubation.

Mathematical and Statistical Analysis

In situ degradation curves of DM and P were fitted to a nonlinear model (Ørskov and McDonald (1979):

$$Y = A + B(1 - e^{-kd(t)})$$

Table 3. Chemical composition of dried distillers grains with solubles (DG1, DG2, DG3) and wet distillers grains with solubles (WDG) examined in experiment 1 (Adapted from Kleinschmit et al., 2007)

Item	Feedstuff			
	DG1	DG2	DG3	WDG
DM, %	89.6	88.2	90.7	31.6
	% of DM			
CP	31.3	33.5	30.6	32.6
NDF	37.4	29.5	35.9	38.6
ADF	20.3	14.7	14.7	15.7
Ash	4.58	5.38	4.46	3.77
P	0.84	0.74	0.71	0.56
PP ¹	0.29	0.24	0.26	0.26
PP, % of P	34.5	32.4	36.6	46.4

¹Phytate phosphorus.

Table 4. Rumen dry matter degradation parameters for dried distillers grains with solubles (DGa, DGb, DGc), corn, corn germ (CG), soybean meal (SBM), SoyPlus (SP), extruded soybeans (ES), and soyhulls (SH)

Parameter ¹	Feedstuff								SEM	
	DGa	DGb	DGc	Corn	CG	SBM	SP	ES		SH
A _{DM} , %	34.9 ^d	42.2 ^c	47.9 ^a	37.3 ^d	44.1 ^{abc}	43.7 ^{bc}	43.0 ^{bc}	46.4 ^{ab}	30.5 ^e	2.34
B _{DM} , %	58.9 ^{bc}	55.5 ^{bc}	41.9 ^{cd}	58.5 ^{bc}	53.2 ^{bc}	54.3 ^{bc}	54.4 ^{bc}	47.4 ^c	69.5 ^a	3.58
K _{dDM} , %/h	4.64 ^{ab}	2.86 ^c	5.00 ^{ab}	5.89 ^{ab}	6.84 ^{ab}	7.47 ^a	5.00 ^{ab}	6.85 ^{ab}	4.12 ^{ab}	0.01
ED _{DM} , %	60.7 ^c	59.5 ^c	65.1 ^{bc}	66.0 ^{bc}	72.2 ^a	73.3 ^a	66.8 ^{abc}	71.4 ^a	58.6 ^d	2.45

^{a-e}Within the same row, means with different superscripts differ significantly ($P < 0.05$).

¹A_{DM} = rapidly degradable fraction of DM; B_{DM} = potentially degradable fraction of DM; K_{dDM} = rate of degradation of fraction B_{DM}; and ED_{DM} = effective degradation of DM.

where A = rapidly degradable DM (A_{DM}) or soluble P (A_P) that disappeared at 0 h after the rinsing procedure; B = potentially degradable DM (B_{DM}) or releasable P (B_P); K_d = constant rate of DM degradation (K_{dDM}) or P disappearance of the fraction B (K_{dP}); and t = time of incubation, h. The unreleasable fraction (C_P) was calculated as $100 - A_P - B_P$. Effective DM degradability and P disappearance were determined assuming a passage rate from the rumen of 6%/h by the equation:

$$ED = A + B [K_d / (K_d + K_p)],$$

where K_p is the passage rate from the rumen (%/h), and A, B, and K_d are the degradation constants described previously (Ørskov and McDonald, 1979).

Degradation or disappearance constants of DM or P described above were estimated using the NLIN procedure of SAS (SAS Institute, 2001). Phosphorus disappearance at each time point was analyzed using the MIXED procedure of SAS (SAS Institute, 2001) with cow as a random variable. The model for experiment 1 included the fixed effects of treatment, time, and treatment $\times$ time. The model for experiment 2 included fixed effects of treatment, time, period, and treatment $\times$ time. In situ disappearance constants and effective disappearance were analyzed using the MIXED procedure of SAS (SAS Institute, 2001) for each feed ingredient with cow as a random variable. The model used for experiment 1 included treatment as a fixed effect and the model for experiment 2 included fixed effects of treatment and period. Mean comparisons were performed by using the Tukey test with $P < 0.05$ as the significant level.

RESULTS

Experiment 1

Phosphorus concentrations in corn and soybean feedstuffs ranged from 0.16 for SH to 1.01% DM for CG,

whereas PP ranged from 0.04 for SH to 0.40% for SBM and CG (Table 2). Concentrations of PP were twice as high in DGa compared with DGb and DGc. Distillers grains sources contained less PP compared with soybean products with the exception of SH.

Dry matter A fraction was significantly different among feedstuffs and ranged from 30.5 to 47.9% (Table 4). Source DGc had the greatest A_{DM} fraction, whereas SH contained the lowest A_{DM} fraction. As a result, the SH showed greater B_{DM} fraction ($P < 0.05$) and DGc had the least B_{DM} among feedstuffs. The rate of DM disappearance was different among feedstuffs ($P < 0.05$). Of the feeds tested, SBM had significantly the greatest DM degradation rate, whereas DGb had the lowest K_{dDM}. The remaining feedstuffs (DGa, DGc, corn, CG, SP, ES, and SH) had comparable K_{dDM} averaging 5.47 (SD $\pm$ 1.0) /h. Effective disappearance of DM varied from 73.3 to 58.6% and was high for SBM, CG, and ES [72.3 (SD $\pm$ 0.90) %], intermediate for SP, CG, and DGc [66.0 (SD $\pm$ 0.85) %] and low for DGa, DGb, and SH [59.6 (SD $\pm$ 1.05) %].

A greater proportion of P disappeared compared with DM. The proportion of P determined to be immediately released (A_P) differed ($P < 0.05$) among feedstuffs (Table 5). Sources DGc and DGb contained the greatest A_P fraction among all feedstuffs, whereas SH contained the least amount of P in the A_P fraction. As a result, greater potentially releasable P remained in SH ($P < 0.05$) compared with other feedstuffs. Fraction B_P for SBM, SP, and ES was 32.9 (SD $\pm$ 2.20) %; ground corn and CG followed with a B_P fraction estimated at 24.2 (SD $\pm$ 2.96) %. Dried distillers grains had the least B_P fraction among the feedstuffs, averaging 13.5 (SD $\pm$ 5.80) % and did not differ across source indicating a rapid disappearance of P in the rumen. The unavailable fraction, C_P, was similar in all feedstuffs, ranging from 1.6% for CG to 9.4% for SH. The rate of ruminal phosphorus disappearance, K_{dP}, was similar for all feedstuffs (16.2 $\pm$ 3.54%/h). Effective disappearance of P was greater for DDG (91.3 $\pm$ 2.37%), CG, and soy-

Table 5. Rumen phosphorus disappearance parameters for DGa dried distillers grains with solubles (DGa, DGb, DGc), corn, corn germ (CG), soybean meal (SBM), SoyPlus (SP), extruded soybeans (ES), and soyhulls (SH)

Parameter ¹	Feedstuff									SEM
	DGa	DGb	DGc	Corn	CG	SBM	SP	ES	SH	
A _P , %	74.5 ^b	84.4 ^a	87.5 ^a	65.4 ^c	77.0 ^b	62.1 ^c	62.9 ^c	66.6 ^c	45.0 ^d	1.44
B _P , %	20.2 ^d	10.7 ^d	9.7 ^d	27.0 ^{cd}	21.4 ^{cd}	35.1 ^{bc}	33.0 ^{bc}	30.7 ^{bc}	45.6 ^a	3.25
C _P , %	5.3	4.9	2.8	8.0	1.6	2.8	4.1	2.8	9.4	2.8
K _{dP} , %/h	24.6	15.5	14.1	11.7	14.9	16.1	16.7	17.0	14.9	7.32
ED _P , %	88.8 ^{ab}	91.7 ^a	93.5 ^a	83.6 ^b	93.3 ^a	87.5 ^{ab}	87.0 ^{ab}	88.0 ^{ab}	69.0 ^c	2.88

^{a-d}Within the same row, means with different superscripts differ significantly ($P < 0.05$).

¹A_P = rapidly soluble fraction of P; B_P = potentially releasable fraction of P; C_P = unavailable fraction of P; K_{dP} = rate of P disappearance of fraction B_P; and ED_P = effective disappearance of P.

bean products ($87.5 \pm 0.50\%$) with the exception of SH in which the ED_P was the lowest among tested feedstuffs.

In the first 2 h of ruminal incubation, SH had the fastest P release among all feedstuffs where it increased from 41.9 to 59.7% between 0 and 2 h (Table 6). Corn byproducts and SP had a relatively fast rate of ruminal disappearance of P, whereas SBM and ES had the lowest extent of P disappearance in the first 2 h of ruminal incubation. The extent of P disappearance was greater for SBM than for corn byproducts during the first 12 h of ruminal incubation. The percentage of P disappearance increased from 66.2 and 92.9% for SBM from 2 to 12 h, whereas in DDG, P disappearance only slightly increased from 87.6 to 90%. The extent of P disappearance tended to be similar for all feedstuffs after 12 h of incubation, as the extent of P release reached its maximum between 18 and 48 h depending on the feedstuff.

Experiment 2

Concentrations of P for DDG (Table 3) ranged from 0.71 to 0.84% of DM and in average were greater than WDG (0.56%). These values are similar to reported concentrations (Belyea et al., 2006). Concentrations of

PP were similar in all distillers grains samples (0.26%). However, PP as a percentage of P was greater in WDG (46.4%) compared with DDG (34.5%). Nutrient composition of the different distillers grains was similar in CP (32.0%) and NDF (35.4%).

Phosphorus disappearance kinetics in different distillers grains samples is presented in Table 7. The percentage of P immediately released, A_P, differed among the DDG sources ($P < 0.05$). Source DG3 had the greatest A_P fraction followed in order by DG2, DG1, and WDG. The range of fraction B_P (representing the slowly released P) was 8.9 (DG1) to 15.8% (WDG). The DDG samples averaged 9.5 (SD $\pm$ 0.60) %. The unavailable fraction of P, C_P, was greater ($P < 0.05$) in DG1, intermediate in DG2 and WDG, and smallest in DG3. Disappearance rate, K_{dP}, did not differ among the different sources of distillers grains. The ED_P ranged from 88.1 to 92.8% ($P < 0.05$). The DG1 and DG3 had the greatest ED_P among the different sources, followed by DG2 and WDG. During the first 12 h of ruminal incubation, the extent of P disappearance was faster in DG1 compared with the other sources because of rapid release within 3 h of rumen incubation (Table 8). In the intermediate incubation phase (12 to 24 h), P release from DG1 was negligible, probably because most of the available P disappeared within the first 12 h, whereas

Table 6. Phosphorus disappearance after ruminal incubation for dried distillers grains with solubles (DGa, DGb, and DGc), corn, corn germ (CG), soybean meal (SBM), SoyPlus (SP), extruded soybeans (ES), and soyhulls (SH)

Incubation time, h	Phosphorus disappearance, %									SEM
	DGa	DGb	DGc	Corn	CG	SBM	SP	ES	SH	
0	73.9 ^b	83.3 ^a	85.6 ^a	66.8 ^c	78.0 ^b	65.1 ^c	62.4 ^c	69.2 ^c	41.9 ^d	1.44
2	83.1 ^a	90.0 ^a	89.6 ^a	71.0 ^a	82.9 ^a	66.2 ^b	72.9 ^a	70.2 ^a	59.7 ^b	3.67
6	85.1 ^a	88.6 ^a	93.2 ^a	80.7 ^{ab}	91.2 ^a	85.6 ^a	84.4 ^a	85.1 ^a	65.1 ^a	3.77
12	89.2 ^a	92.1 ^a	94.0 ^a	87.5 ^a	96.4 ^a	92.9 ^a	90.4 ^a	92.1 ^a	68.5 ^b	3.96
18	91.4 ^a	93.5 ^a	95.3 ^a	88.9 ^a	98.1 ^a	96.1 ^a	93.3 ^a	94.6 ^a	72.1 ^b	3.56
24	93.4 ^a	94.9 ^a	95.1 ^a	89.2 ^a	97.4 ^a	96.4 ^a	94.8 ^a	95.4 ^a	77.1 ^b	3.29
36	94.1 ^a	94.5 ^a	95.6 ^a	95.0 ^a	100.0 ^a	95.7 ^a	96.5 ^a	97.8 ^a	77.7 ^b	3.25
48	95.4 ^a	95.4 ^a	96.2 ^a	95.8 ^a	100.0 ^a	100.0 ^a	98.2 ^a	96.7 ^a	88.4 ^b	2.66

^{a-d}Within the same row, means with different superscripts differ significantly ($P < 0.05$).

Table 7. Rumen phosphorus disappearance parameters from dried distillers grains with solubles (DG1, DG2, DG3), and wet distillers grains with solubles (WDG)

Parameter ¹	Feedstuff				SEM
	DG1	DG2	DG3	WDG	
A _P , %	84.1 ^c	86.4 ^b	90.3 ^a	82.7 ^d	0.21
B _P , %	8.9 ^b	10.1 ^b	9.6 ^b	15.8 ^a	1.31
C _P , %	7.0 ^a	3.4 ^b	0.1 ^c	1.5 ^b	1.85
K _{dP} , %/h	7.0	5.0	2.2	4.1	0.80
ED _P , %	92.1 ^a	89.8 ^b	92.8 ^a	88.1 ^b	0.45

^{a-d}Within the same row, means with different superscripts differ significantly ($P < 0.05$).

¹A_P = rapidly soluble fraction of P; B_P = potentially releasable fraction of P; C_P = unavailable fraction of P; K_{dP} = rate of P disappearance of fraction B_P; and ED_P = effective disappearance of P.

in WDG, the extent of P release increased from 86.9 to 91.2%. The extent of P disappearance during the last 12 h of incubation was low and comparable in all distillers grains sources indicating that P disappearance tended to attain its maximum, averaging 94.2% at 36 h of ruminal incubation.

DISCUSSION

A good understanding of P digestion and metabolism in ruminants is critical to improve the efficiency of P utilization and minimize the pollution risk associated with overfeeding P. Utilization of P is a function of 2 processes that combine the disappearance of the element from feedstuffs and the animal absorption capacity of the fraction released in the rumen. Field (1981) stated that mineral absorption as well as utilization depends largely on solubility in the rumen. Therefore, P disappearance is an important precondition of its utilization in animals.

Experiment 1

Few estimates of DM degradation in soybean products and DDG are available for comparison. Dry matter A fractions for the different DDG samples were similar to

those in the report of Batajoo and Shaver (1998; 40.2%). Dry matter A fraction for SBM was greater than the value reported by Batajoo and Shaver (1998; 35.4%) and Ganesh and Grieve (1990; 21.3%) but similar to the value reported by Armentano et al. (1986; 44.0%). Dry matter disappearance rate varied by source of DDG ranging from 2.86 to 5.00%/h. Similar values have been reported by Batajoo and Shaver (1998) and DePeters et al. (1997). Effective disappearance of DM was similar to reported values for DDG and greater for SBM (Batajoo and Shaver, 1998). Differences in DM kinetics between our study and others may be explained by several factors such as feed particle size (Nocek, 1985; Cerneau and Michalet-Doreau, 1991), bag surface area ratio (Mehrez and Ørskov, 1977), sample size, origin of grains, bag material and pore size, diet fed during the measurement (Weakley et al., 1983; Nocek, 1985), and washing procedures (Cherney et al., 1990).

Phytate phosphorus averaged between 17 and 76% of the total P for the feedstuffs tested in this study. Phosphorus release depends upon hydrolysis of the phytate molecule. In ruminants, the inherent phytase activity of rumen microbes digests nearly all the PP into inorganic P (Reid et al., 1947; Raun et al., 1956; Soares, 1995). In theory, P should reach the same extent of release in different feedstuffs if allowed sufficient

Table 8. Phosphorus disappearance after ruminal incubation from dried distillers grains with solubles (DG1, DG2, DG3), and wet distillers grains with solubles (WDG)

Incubation time, h	Phosphorus disappearance, %				SEM
	DG1	DG2	DG3	WDG	
0	84.1 ^c	86.4 ^b	90.3 ^a	82.7 ^d	0.21
3	91.2 ^a	87.1 ^b	90.7 ^a	85.3 ^c	0.51
6	92.3 ^a	88.9 ^b	91.5 ^a	85.7 ^c	0.77
12	92.5 ^a	89.8 ^{ab}	92.3 ^a	86.9 ^c	1.00
18	92.3 ^a	90.5 ^a	93.2 ^a	88.2 ^b	0.93
24	93.1 ^a	91.2 ^b	93.8 ^a	91.2 ^b	0.90
36	94.3	93.5	95.7	93.2	0.46

^{a-d}Within the same row, means with different superscripts differ significantly ($P < 0.05$).

incubation in the rumen. However, in high-producing dairy cows this may not be true as rumen dilution rates are high, resulting in PP that escapes the rumen in undigested grains (Clark et al., 1986).

The readily soluble fraction of P (A_P) in SBM from this experiment was greater than the value reported by Bravo et al. (2000; 49.0%). However, the effective disappearance of P was similar. Differences may be explained by experimental procedures, genetic variation, and processing variations. Regarding DDG, the ED_P was noticeably greater in the current experiment (91.3%) compared with the ED_P reported by Bravo et al. (2000; 66.4%). The corn distillers tested in that study originated from a corn in which the germ was completely removed. Phosphorus in that product (0.08%) was probably integrated as a structural part and therefore not easily released in the rumen. Similar to our results, the disappearance of P in phytate from SBM and DDG followed the same patterns when assessed using an *in vitro* method (Morse et al., 1992). Phosphorus in phytate was rapidly degraded in DDG compared with SBM (71.3 vs. 36.3%) after 1 h of *in vitro* incubation and maximal P disappearance from SBM required longer incubation time compared with DDG (Morse et al., 1992).

Soybean products, with the exception of SH, tend to have greater CP and PP concentrations compared with DDG. Phytate molecules form stable complexes with protein (Thomas et al., 1946) and it becomes less available to the animal when protein concentration increases (Fontaine et al., 1946). Chemical bonds formed between protein and PP must be broken before inorganic P can be released from the phytate molecules (Fontaine et al., 1946). This may explain the greater disappearance rate of P in DDG compared with soybean products during the first 2 h of rumen incubation. On the other hand, the greater ruminal disappearance of P in DDG may be attributable to fermentation during ethanol production in which a considerable portion of PP in the corn is hydrolyzed. This hydrolysis of PP yields inorganic P that is readily available to the animal (Cromwell, 1979). Phosphorus disappearance kinetics was affected by the source of DDG. The DGa source contained more P as PP and resulted in a lower A_P ($P < 0.05$) and a numerical decrease in ED_P compared with other sources of DDG. Processing methods and heat treatment applied to the different samples may contribute to these differences. These results suggest that the DGa sample may have been subjected to moderate heat damage during processing.

Soybean meal, SP, and ES are soybean byproducts that differ considerably in protein degradability in the rumen. Konishi et al. (1999) reported that treatments that lower protein degradability in the rumen, such

as temperature, might decrease the rate and extent of phytate degradation. However, in this experiment SBM, SP, and ES showed similar P disappearance kinetics. Phosphorus release was distinctly low in SH. The high NDF concentration in SH (49% of DM) may partially explain the low ED_P . Emanuele and Staples (1990) reported that high NDF concentrations negatively affected ruminal P release in forages. Furthermore, P in SH may be integrated as a structural part of the cell walls and it may require longer incubation time in the rumen to be released. Finally, P was readily soluble in CG compared with ground corn. More than 90% of the phytate in corn is found in the germ portion of the kernel (Ravindran et al., 1995) and when germ is extracted from the grain, P is also extracted because corn P is concentrated in the germ (Pointillart, 1994). Thus, the peripheral parts of corn need to be digested first in order for the P to be released, whereas in CG, such structural parts do not exist, allowing for fast access of phytase by microbes in the rumen.

Experiment 2

Variations in P concentrations among the DDG sources were most likely due to differences in processing techniques and conditions among ethanol plants. Dried distillers grains with solubles are made by blending condensed distillers solubles (also referred to as syrup) with wet grains. Condensed distillers solubles contain high concentrations of P (1.52%), whereas wet grains contain approximately 0.54% (Belyea et al., 2006). Consequently, considerable differences in P concentrations among distillers grains are likely to occur because of variable amounts of condensed distillers solubles added back to wet grains to make the final product.

Dried distillers grains contained more P in the A_P fraction and less in the B_P fraction compared with WDG resulting in a greater ED_P in DDG. The greater concentration of PP as percentage of total P in WDG compared with DDG (46.5 vs. 34.4%, respectively) could explain these differences. Although it is unknown how much condensed distillers solubles was added back to create each distillers grains feedstuff, the lower P concentration in WDG implies that less syrup may have been included in this WDG sample. Consequently, a greater proportion of the total P in the WDG was PP compared with the other DDG feedstuffs. Phosphorus contained in the phytate molecule requires longer fermentation before it can be released.

In this study, differences existed among the DDG samples; DG3 showed greater A_P fraction and ED_P compared with other samples, whereas DG1 had the lowest A_P fraction among the DDG and the greatest C_P

fraction (7.0%). Kleinschmit et al. (2007) reported that geometric mean diameters for DG1, DG2, and DG3 were 0.74, 1.01, and 0.46 mm, respectively, making loss of particles from the bag an unlikely explanation for the high soluble fraction of P (A_p) for the distillers grains samples. In addition, Kleinschmit et al. (2007) reported ruminally effective degradability of CP (RDP) to be 28.3, 32.5, 39.7, and 46.4% for DG1, DG2, DG3, and WDG, respectively, demonstrating that although P disappearance of DDG in the rumen is quite high, CP disappearance is not.

The DG1 had a much greater proportion of CP in the unavailable fraction and less in the soluble fraction compared with other sources, suggesting that DG1 may have been excessively heated. On the contrary, the extent of P release in DG1 was not depressed indicating that drying temperature in processing DG1 was not enough to adversely affect the disappearance of P. Heating treatment, however, is not likely the only factor that may affect ruminal P disappearance. Other factors such as genetic variations or other technological procedures likely contributed to differences between samples. A wide range of distillers grains from different processing plants is needed to assess the effect that heating, processing, and other factors have on P disappearance in the rumen.

CONCLUSIONS

In situ results from both experiments confirmed that distillers grains, corn germ, and soybean products have high ruminal disappearance of P (>88.0%). The extent of P disappearance was similar for all sources of DDG in spite of differences in the readily soluble P in the rumen. Wet distillers grains had less effective disappearance of P in the rumen compared with DDG. The high P disappearance from DDG in the rumen of dairy cows suggests that the need of supplementing inorganic P would become unnecessary when diets contain adequate amounts of DDG.

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