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Evaluation of Various Sources of Corn Dried Distillers Grains Plus Solubles for Lactating Dairy Cattle[1]

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ABSTRACT

The objectives of this study were to evaluate the effects of feeding dried distillers grains plus solubles (DDGS) from different sources on milk production and composition in dairy cows. Eight multiparous and 4 primiparous Holstein cows were used in a replicated 4 × 4 Latin square design with 28-d periods. Treatments consisted of total mixed diets containing no DDGS (CON), or DDGS from source 1 (DDGS-1), source 2 (DDGS-2), or source 3 (DDGS-3) at 20% of diet dry matter. The processing of DDGS-2 and DDGS-3 was intended to decrease heat damage and improve nutritional quality. The DDGS in the diets replaced a portion of the ground corn and soybean meal, allowing them to be isonitrogenous at 16% crude protein. All diets had a forage-to-concentrate ratio of 55:45. Dry matter intake (21.4 kg/d) did not differ among diets, but cows fed diets containing DDGS had greater yields of milk (34.6 vs. 31.2 kg/d), 4% fat-corrected milk (32.7 vs. 29.6 kg/d), and energy-corrected milk (35.4 vs. 32.3) compared with cows fed the CON diet. Feed efficiency was greater in cows fed DDGS compared with CON (1.78 vs. 1.63). Milk fat yield was greater in cows fed DDGS compared with those fed CON (1.26 vs. 1.14 kg/d). Milk protein percentages (3.28, 3.13, 3.19, and 3.17% for CON, DDGS-1, DDGS-2, and DDGS-3, respectively) were greater for CON vs. DDGS and tended to be lower for DDGS-1 than for DDGS-2 and DDGS-3. Milk protein yields tended to be greater for cows fed DDGS than for those fed CON (1.09 vs. 1.02 kg/d). Concentrations of milk urea nitrogen were lower in cows fed DDGS compared with CON (9.36 vs. 10.6 mg/dL). Feeding DDGS decreased arterial plasma concentrations of Arg, Ile, Lys, and Thr and increased His and Leu compared with CON. Arterial plasma from cows fed DDGS-2 and DDGS-3 had greater concentrations of Ile, Trp, and Val compared with DDGS-1. In all diets, Lys, Met, and Phe were the first 3 limiting amino acids for protein synthesis with Lys being first limiting in DDGS-1 and DDGS-3 and Met being first limiting for CON and DDGS-2. Inclusion of DDGS did not affect the molar proportions of ruminal acetate or propionate compared with CON. Ruminal proportions of butyrate were lower in CON compared with DDGS. Total concentrations of VFA were greater in CON compared with DDGS. The concentrations of rumen ammonia were greater in CON (7.2 mg/dL) compared with DDGS (4.5 mg/dL). Overall, the source of DDGS used in this study did not affect lactation performance.
Key words: dried distillers grains plus solubles, dairy cattle, amino acids

INTRODUCTION

The rapid growth of the ethanol industry in the Midwest has generated large quantities of dried distillers grains plus solubles (**DDGS**) that are available for feeding to dairy cattle. This coproduct is an excellent source of RUP (Firkins et al., 1984; Powers et al., 1995). It is a source of highly digestible fiber (Al-Suwaiegh et al., 2002), and because of its low concentration of starch, DDGS incorporated into a dairy ration in lieu of corn can reduce the occurrence of acidosis (Larson et al., 1993) that may accompany a feeding program targeted at high-producing dairy cows. Furthermore, DDGS contains a fairly high concentration of fat, making it a high-energy feedstuff.

The manufacturing process of DDGS may damage a portion of the protein due to excessive heat during the drying that accompanies this process, thus making it unavailable to the animal. In particular, Lys is the first-limiting AA in corn byproducts and is also most susceptible to heat damage because the ε-amino group easily binds with reducing sugars in a Maillard reaction (Schwab, 1995). Nichols et al. (1998) found Lys to be the first-limiting AA in milk protein synthesis when diets contained 20% DDGS. The status of this AA was improved and milk protein content and yield were increased by feeding ruminally protected Lys and Met. In contrast, Liu et al. (2000) found that feeding additional Lys was not beneficial.

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Manufacturing practices may vary among ethanol plants; therefore, the DDGS produced in one may differ considerably from that produced in another (Spiehs et al., 2002). Significant nutrient variation has also been shown to occur within ethanol plants themselves (Belyea et al., 2004). As a result, one source of DDGS may not sustain the same level of milk production reached when feeding another source. For example, in a study conducted by Powers et al. (1995), replacing soybean meal with 2 sources of DDGS increased the milk yield, but a third source had no effect. In addition, feeding 1 source of DDGS increased the concentration of milk protein compared with the other 2 sources. Modifications in processing DDGS, such as fine grinding (Maisch, 2003), germ (Singh and Eckhoff 1996, 1997) and germ-fiber removal (Singh et al. 1999; Wahjudi et al., 2000), enzymatic milling processes (Singh et al., 2005), and dilute-acid pretreatment (Tucker et al., 2004) to improve ethanol yields or controlled drying conditions to minimize protein denaturation that occur during excessive drying (Nakamura et al., 1994b) have been adopted since that study was conducted.

A lactation study evaluating the effect of DDGS processed using more current practices on milk production and composition or efficiency of AA utilization for milk protein synthesis has not been conducted to date. Therefore, the objectives of this study were to evaluate the performance of lactating cows and the efficiency of AA utilization for milk protein synthesis when fed DDGS from various sources.

MATERIALS AND METHODS

All procedures for this study were conducted under approval of the South Dakota State University Animal Care and Use Committee. Eight multiparous (123 ± 15 DIM) and 4 primiparous Holstein cows (104 ± 27 DIM) were used in a replicated 4 × 4 Latin square design with 28-d periods. Weeks 1 and 2 of each period were used for adjustment to diets; wk 3 and 4 were used for data collection. Dietary treatments (Table 1) consisted of no DDGS (**CON**) or DDGS from 3 different sources at 20% of diet DM (**DDGS-1**, **DDGS-2**, or **DDGS-3**). The 3 sources were manufactured using proprietary methods but details of the processes were not disclosed to the authors. We considered DDGS-1 to be representative of most commercially available DDGS; DDGS-2 and DDGS-3 were both supplied by the same company but were likely prepared by 2 different methods. Dried distillers grains plus solubles replaced a portion of the ground corn and soybean meal in the CON diet. The diets were formulated to contain 16% CP and have a negative balance of MP for a 613-kg Holstein cow producing 40.9 kg of milk/d with 3.70% fat and 3.10% true protein (NRC, 2001) to evaluate protein quality. Milk yield was a known parameter prior to the study and all others were estimated. When evaluating protein quality among feed sources, providing adequate MP may negate a possible production or blood AA response because the diet already may provide the adequate amounts of essential AA to the animal from other feedstuffs to meet its genetic potential. Cows were housed in a free-stall barn and individually were fed diets as a TMR for ad libitum consumption once daily (0800 h) using Calan Broadbent feeder doors (American Calan, Inc., Northwood, NH). Feed intakes were recorded daily.

Samples of corn silage, alfalfa hay, concentrate mixes, DDGS, and TMR were collected on 3 consecutive days at the end of each period and stored at –20°C until analysis. Samples were composited by period and dried at 55°C in a Despatch oven (style V-23; Despatch Oven Co., Minneapolis, MN) for 48 h. Composites were ground through a 4-mm screen of a Wiley mill (model 3; Arthur H. Thomas Co., Philadelphia, PA), then reground through a 1-mm screen of an ultracentrifuge mill (Brinkman Instruments Co., Westbury, NY). Composites were analyzed for NDF with sodium sulfite and α-amylase (Van Soest et al., 1991), ADF (Robertson and Van Soest, 1981), and acid detergent lignin (Lowry et al., 1994) sequentially with an ANKOM fiber analyzer (ANKOM Technology Corp., Fairport, NY). Crude protein, ether extract, ash, Ca, P, and Mg were analyzed according to AOAC procedures (AOAC, 2000). The neutral detergent insoluble nitrogen (**NDIN**) and ADIN fractions were quantified in the DDGS as described by Licitra et al. (1996).

Feed fatty acids for TMR and DDGS were prepared as butyl esters for analysis in an adapted method described by Sukhija and Palmquist (1988) using gas chromatography (model 6890, Hewlett-Packard, Palo Alto, CA). Using an adaptation of methods described by Loor et al. (2005), samples were analyzed using a flame-ionization detector. The injector port was at 230°C with a split ratio of 50:1. The column was 100 m in length, with an inside diameter of 0.25 mm (Varian, CP-Sil 88, Lake Forest, CA). Flow rate was 2.0 mL/min of helium. Initial temperature was 50°C held for 1 min then increased to 145°C at a rate of 5°C/min and held for 30 min. Temperature was then increased 10°C/min to 190°C and held for 30 min. Finally, the temperature was increased 5°C/min to 210°C and held for 35 min. The total run per sample was 123.5 min. Samples were corrected to 100% DM basis by drying an aliquot of the composites at 105°C for 24 h. Particle size distribution and mean particle size was determined on the DDGS samples using a Rototap shaker sieve (model RX-29, W. S. Tyler, Mentor, OH). Color score was determined

Table 1. Ingredient content of diets containing either soybean meal or 20% dried distillers grains plus solubles (DDGS) from 3 different sources as the primary protein source

	Diet[1]			
Ingredient, % of DM	CON	DDGS-1	DDGS-2	DDGS-3
Corn silage	38.50	38.50	38.50	38.50
Alfalfa hay	16.50	16.50	16.50	16.50
Ground corn, shelled	29.28	20.10	20.10	20.10
Soybean meal, 44% CP	13.60	2.90	2.90	2.90
DDGS-1	—	20.00	—	—
DDGS-2	—	—	20.00	—
DDGS-3	—	—	—	20.00
Salt	0.70	0.70	0.70	0.70
Magnesium oxide	0.20	0.20	0.20	0.20
Dairy Micro premix[2]	0.24	0.24	0.24	0.24
Dicalcium phosphate	0.28	—	—	—
Limestone	0.65	0.81	0.81	0.81
Vitamin E premix (44,000 IU/kg)	0.05	0.05	0.05	0.05

[1]CON = No DDGS (control); DDGS-1, DDGS-2, and DDGS-3 = DDGS from source 1, source 2, and source 3, respectively.

[2]10% Mg; 2.6% Zn; 1.7 ppm Mn; 4,640 ppm Fe; 4,712 ppm Cu; 396 ppm I; 119 ppm Co; 140 ppm Se; 2,640,000 IU/kg vitamin A; 528,000 IU/kg vitamin D_3; and 10,560 IU/kg vitamin E.

on DDGS samples using a LabScan XE spectrocolorimeter (Hunter Associates Laboratory, Reston, VA) with the L, a, and b opposable color scales (Hunter Associates Laboratory, 2002).

Cows were milked at 0600, 1400, and 2100 h and yields were recorded. Milk samples were collected at the end of each period for each milking on 3 consecutive days. Milk samples were mixed by gentle inversion and composited in volumes corresponding to the respective milking for each cow on the sampling day. Samples were analyzed by Heart of America DHIA Laboratory (Manhattan, KS) according to approved procedures of AOAC (1997). Milk true protein, fat, and lactose were determined by near infrared spectroscopy (Bentley 2000 Infrared Milk Analyzer, Bentley Instruments, Chaska, MN). Concentration of MUN was determined using chemical methodology based on a modified Berthelot reaction (ChemSpec 150 Analyzer, Bentley Instruments) and somatic cells were counted using a flow cytometer laser (Somacount 500, Bentley Instruments).

Cows were weighed and scored for body condition on a scale of 1 to 5 (Wildman et al., 1982) approximately 3 h after feeding on 3 consecutive days at the end of each period. Blood was collected at the end of each period from the coccygeal artery into heparin Vacutainer tubes (Becton Dickinson and Co., Franklin Lakes, NJ). Plasma was obtained by centrifuging at $500 \times g$ and stored at –20°C until analyzed for AA via HPLC (model 1100, Agilent Technologies, Inc., Palo Alto, CA) with a PCX 5200 postcolumn derivatizer (Pickering Laboratories Inc., Mountain View, CA) as described by Mondina et al. (1972), Pickering (1989), and Grunau and Swiader (1992). Amino acid transfer efficiency, {AA output in milk (g/d) × 100/[arterial AA concentration (g/L) × mammary blood flow (L/d)]}, was calculated using estimates of mammary blood flow (Kronfeld et al., 1968) and AA output in milk (Jacobson et al., 1970) to evaluate the limiting AA of each diet. After discarding the first 150 mL to minimize saliva contamination, approximately 250 mL of ruminal fluid was collected 3 h after feeding by applying vacuum pressure to an esophageal tube fitted with a suction strainer on 2 consecutive days at the end of each period. A 10-mL aliquot was mixed with 2 mL of 25% (wt/vol) metaphosphoric acid and frozen at –20°C until centrifugation at $30,000 \times g$ and analyzed for concentrations of ammonia-N (Weatherburn, 1967) and VFA. Concentrations of VFA were measured using a 6890 gas chromatograph (Hewlett-Packard) equipped with a 0.25 mm i.d. × 15 m column (Nukol, 17926-01C, Supelco, Inc., Bellefonte, PA). The split ratio in the injector port (250°C) was 100:1 with a flow of 1.3 mL/min of He. Column and detector temperature were maintained at 130 and 225°C, respectively.

Means of DMI and milk yield during wk 3 and 4 and means of milk composition and arterial plasma AA concentrations during wk 4 of each period were used for statistical analysis. Analysis of variance was conducted using the MIXED procedure (Littell et al., 1996) of SAS (SAS Institute, 1999). Cow served as the experimental unit. The model was Y = treatment + parity + period + treatment × parity + treatment × period + parity × period + treatment × parity × period, with cow(parity) designated as a random variable. Treatment × parity × period was not significant and was removed from the model. Orthogonal contrasts were designed to test for differences between soybean meal vs. DDGS (CON vs. DDGS-1, DDGS-2, and DDGS-3), between ethanol com-

Table 2. Chemical composition of concentrate mixes, corn silage, alfalfa hay, and dried distillers grains plus solubles (DDGS)

	Concentrate mix[1]						DDGS		
Nutrient	CON	DDGS-1	DDGS-2	DDGS-3	Corn silage	Alfalfa hay	DDGS-1	DDGS-2	DDGS-3
DM, %	87.2	89.2	88.7	88.6	34.0	90.2	91.3	88.4	89.2
	(% of DM)								
CP	19.2	20.1	19.9	21.4	8.15	20.7	30.3	29.9	31.4
NDIN[2]	ND[3]	ND	ND	ND	ND	ND	2.22	2.25	2.60
ADIN	ND	ND	ND	ND	ND	ND	1.12	0.44	0.52
Ether extract	1.92	6.02	8.40	7.21	2.45	2.25	10.8	10.6	10.5
Fatty acids	ND	ND	ND	ND	ND	ND	9.79	9.55	9.95
NDF[4]	12.1	24.5	19.3	22.5	44.3	44.5	44.0	39.8	39.1
ADF	5.8	12.4	9.7	9.8	27.1	37.2	16.0	13.1	12.3
Lignin	1.29	2.73	2.00	2.10	3.34	9.10	4.86	3.04	2.98
Ash	7.82	7.60	8.06	7.73	5.14	10.0	4.58	5.16	5.48
Ca	0.74	0.65	0.86	0.67	0.26	1.26	0.08	0.05	0.10
P	0.47	0.53	0.54	0.57	0.26	0.27	0.79	0.90	0.88
Mg	0.58	0.55	0.57	0.61	0.25	0.36	0.32	0.37	0.37

[1]CON = No DDGS (control); DGGS-1, DDGS-2, and DDGS-3 = DDGS from source 1, source 2, and source 3, respectively.

[2]NDIN = Neutral detergent insoluble N.

[3]ND = Not determined.

[4]NDF for DDGS was 51.3, 45.7, and 46.4% for DDGS-1, DDGS-2, and DDGS-3, respectively, when sodium sulfite was not used.

panies (DDGS-1 vs. DDGS-2 and DDGS-3), and between processing practices within an ethanol company (DDGS-2 vs. DDGS-3). Significance was declared at $P < 0.05$ and tendencies were noted at $P < 0.10$.

RESULTS AND DISCUSSION

The chemical composition of the ingredients used in this study is shown in Table 2. The sources of DDGS used in this study had similar concentrations of CP. Distillers grains from source 1 had a greater percentage of the CP recovered as NDIN (45.8%) and ADIN (23.1%) compared with sources 2 (47.1 and 9.4% for NDIN and ADIN, respectively) and 3 (51.7 and 10.3% for NDIN and ADIN, respectively). Sodium sulfite was excluded from the analysis of NDIN as described by Licitra et al. (1996). Without the addition of sodium sulfite, the NDF of the sources of DDGS used in this study were 51.3, 45.7, and 46.4% for DDGS-1, DDGS-2, and DDGS-3, respectively. The greater percentage of ADIN in source 1 indicated that DDGS-1 might have been dried under more extreme conditions, which may increase the amount of potentially unavailable protein to the animal. It has been well established that there is a strong negative relationship between ADIN and N digestibility in forages (Goering et al., 1972; Yu and Thomas, 1976). When N is fractionated, the ADIN is assumed to be completely unavailable to the animal (Licitra et al., 1996). However, past animal studies have found ADIN to be a poor indicator of protein digestibility (Weiss et al., 1989; Nakamura et al., 1994a). Nakamura et al. (1994a) found the digestibility of various sources of DDGS to be similar in N digestibility, but the ADIN was highly variable among the DDGS sources (7.8 to 27.9% of N). There was also a weak relationship between ADIN and N digestibility ($R^2 = 0.24$). Van Soest (1989) stated that feeds generally contain 3 to 15% of the N as ADIN, and values within this range may not be high enough to pose negative effects. In a 3-yr study, Spiehs et al. (2002) observed variation in the nutrient content of DDGS among 10 ethanol plants in South Dakota and Minnesota. In that study, CP content ranged from 28.7 to 31.6% (CV = 6.4%), fat content from 10.2 to 11.7% (CV = 7.8%), NDF content from 36.7 to 49.1% (CV = 14.3%), and Lys content from 0.72 to 1.02% (CV = 17.3). The major sources of variation in DDGS originate from processing factors such as temperature and duration of drying, starch extraction efficiency, and amount of solubles added back to distillers grains. It also has been suggested that the chemical composition of the corn used may impact the nutrient content of DDGS; however, Belyea et al. (2004) found that there was a poor relationship between the chemical composition of corn and that of the DDGS produced.

The color scores of the DDGS are shown in Table 3. The color of DDGS-3 (41.7) was much lighter compared with DDGS-1 (33.8) and DDGS-2 (32.0). Cromwell et al. (1993) found that decreasing color score and greater ADIN concentrations in DDGS were highly correlated ($r = 0.79$). In contrast, Harty et al. (1998) found this relationship to be weak. Generally, the ADIN content of the DDGS used in the first study were greater (aver-

Table 3. Color score of dried distillers grains plus solubles (DDGS) used in this experiment

DDGS[2]	Hunter lab color score[1]		
	L	a	b
DDGS-1	33.8	8.48	14.9
DDGS-2	32.0	10.0	14.9
DDGS-3	41.7	11.0	19.5

[1]L = Lightness of sample, 0 = black, 100 = white; the greater the value of a and b, the greater degree of redness and yellowness, respectively.

[2]DDGS-1, DDGS-2, and DDGS-3 = DDGS from source 1, source 2, and source 3, respectively.

age of 22.4% of N) than that used in the second (average of 8.0% of N). However, Harty et al. (1998) found the darkness and ADIN of DDGS to be strongly correlated (r = 0.80) when analysis included DDGS with an ADIN greater than 13% of N. Overall, using color as an indicator of DDGS quality may be appropriate only when the feed contains a high concentration of ADIN. The results in this experiment agree with that observed by Harty et al. (1998), such that there was little difference in color score between DDGS-1 and DDGS-2, but DDGS-2 contained much less N bound as ADIN. Furthermore, DDGS-3 was scored much lighter that DDGS-2, but DDGS-2 had a slightly lower concentration of ADIN. The particle size distribution and mean particle diameter of DDGS is shown in Table 4. Overall, DDGS-2 (1.177 mm) had the greatest mean particle size, followed by DDGS-1 (0.735 mm) and DDGS-3 (0.512 mm).

The chemical composition of the diets fed in this study is shown in Table 5. Diet CON provided adequate RDP, unlike diets containing DDGS, because soybean meal is a source of highly degradable protein in the rumen. The diets containing the 3 sources of DDGS failed to meet estimated RDP requirements of the animals and were found to differ in a companion in situ study (22.0, 32.2, and 36.4% of CP for DDGS-1, DDGS-2, and DDGS-3, respectively; Kleinschmit et al., 2005). As a result, it was estimated that the diet containing DDGS-1 did not meet the MP requirement of the animals as sufficiently as DDGS-2 and DDGS-3. The RDP values in these sources of DDGS were quite low compared with what is commonly used to formulate diets (46 to 53% of the CP; Firkins et al., 1984). However, these values are similar to what has been observed by Brouk (1994; 12.8 to 46.8% of CP) and Harty et al. (1998; 37.4 to 52.2% of CP).

Diets containing DDGS also had greater concentrations of ether extract, fatty acids, and NDF compared with CON.

Table 4. Particle size distribution and mean particle size of dried distillers grains plus solubles (DDGS) used in this experiment

US sieve size (mm)	DDGS[1]		
	DDGS-1	DDGS-2	DDGS-3
2.28	6.01	11.43	2.69
1.68	8.14	19.40	4.64
1.19	17.18	31.70	10.32
0.841	20.24	25.05	13.89
0.595	20.11	15.64	5.88
0.42	8.22	6.97	11.75
0.297	7.47	0.77	12.07
0.210	4.17	1.07	12.30
0.149	2.03	0.63	10.84
0.105	4.42	0.30	4.13
0.074	1.92	0.02	0.16
0.053	0.10	0.00	0.00
Geometric mean diameter (mm)	0.735	1.177	0.512

[1]DDGS-1, DDGS-2, and DDGS-3 = DDGS from source 1, source 2, and source 3, respectively.

Table 5. Chemical composition of diets containing either soybean or 20% dried distillers grains plus solubles (DDGS) from 3 different sources as the primary protein source[1]

Nutrient	Diet[2]			
	CON	DDGS-1	DDGS-2	DDGS-3
DM, %	67.2	68.1	67.9	67.8
CP, % of DM	15.2	15.6	15.5	16.2
RDP, % of CP	68.7	50.3	55.1	55.9
Balance,[3] g/d	208	–451	–316	–246
RUP, % of CP	31.3	49.7	44.9	44.1
Balance, g/d	–545	–697	–457	–371
MP Balance, g/d	–464	–480	–358	–297
Ether extract, % of DM	2.18	4.02	5.09	4.56
Fatty acids, % of DM	1.90	3.01	3.24	3.15
NDF, % of DM	30.0	35.4	33.1	34.6
NDICP,[4] % of DM	3.0	2.9	2.3	3.5
ADF, % of DM	20.4	22.2	20.9	21.0
Lignin, % of DM	3.37	4.02	3.65	3.73
NFC,[5] % of DM	48.5	40.8	41.4	41.6
Ash, % of DM	7.15	7.05	7.26	7.11
Ca, % of DM	0.64	0.60	0.70	0.61
P, % of DM	0.36	0.34	0.37	0.38
Mg, % of DM	0.39	0.39	0.40	0.40
NE_L, Mcal/kg[6]	1.54	1.58	1.58	1.58

[1]Calculated based upon chemistry of individual feedstuffs, RUP and RDP values of DDGS and soybean meal (Kleinschmit et al., 2005), and NRC (2001) values.

[2]CON = No DDGS (control); DDGS-1, DDGS-2, and DDGS-3 = DDGS from source 1, source 2, and source 3, respectively.

[3]Based on requirements for a 613-kg Holstein cow producing 40.9 kg of milk/d with 3.70% fat and 3.10% true protein with milk yield being a known parameter and all others being estimated.

[4]NDICP = Neutral detergent insoluble CP.

[5]NFC = 100 – (CP + ether extract + (NDF – NDICP) + ash).

[6]Estimated from NRC (2001).

DMI, Milk Yield, and Milk Composition

In this study, DMI (21.4 kg/d; Table 6) and CP intake (3.34 kg/d) did not differ among treatments. In general, past studies have also found feeding DDGS at levels similar to this study (approximately 20% of DM) did

Table 6. Dry matter intake, milk yield, milk composition, and feed efficiency of cows fed diets containing soybean meal or 20% dried distillers grains plus solubles (DDGS) from 3 different sources as the primary protein source

	Diet[1]					Contrast[2] (*P*-value)		
	CON	DDGS-1	DDGS-2	DDGS-3	SE	1	2	3
DMI, kg/d	21.7	21.2	21.5	21.1	1.7	0.54	0.83	0.57
CP intake, kg/d	3.28	3.30	3.34	3.43	0.27	0.44	0.44	0.41
Milk, kg/d	31.2	35.0	34.3	34.6	1.9	0.007	0.67	0.85
4% FCM, kg/d	29.6	32.8	32.0	33.2	2.3	0.008	0.87	0.32
ECM,[3] kg/d	32.3	35.5	34.8	35.9	2.2	0.01	0.89	0.42
Feed efficiency[4]	1.63	1.77	1.72	1.86	0.14	0.03	0.77	0.10
Fat								
%	3.69	3.60	3.53	3.67	0.19	0.25	0.96	0.10
kg/d	1.14	1.26	1.22	1.29	0.11	0.02	0.98	0.16
Protein								
%	3.28	3.13	3.19	3.17	0.10	<0.001	0.10	0.51
kg/d	1.02	1.09	1.09	1.09	0.05	0.10	0.92	0.97
MUN, mg/dL	10.6	9.04	9.47	9.58	0.38	<0.001	0.16	0.77
Nitrogen efficiency[5]	0.338	0.352	0.352	0.355	0.032	0.29	0.92	0.89
Lactose								
%	4.90	4.96	4.92	4.93	0.05	0.15	0.25	0.74
kg/d	1.53	1.73	1.69	1.72	0.10	0.006	0.64	0.69
SCC, $\times 10^3$/mL	59.6	41.7	79.2	65.4	27.0	0.90	0.18	0.58

[1]CON = No DDGS; DDGS-1 = DDGS from source 1; DDGS-2 = DDGS from source 2; DDGS-3 = DDGS from source 3.

[2]Contrast: 1 = CON vs. DDGS-1, DDGS-2, and DDGS-3; 2 = DDGS-1 vs. DDGS-2 and DDGS-3; 3 = DDGS-2 vs. DDGS-3.

[3]ECM: [0.3246 × milk yield (kg) + 12.86 × fat yield (kg) + 7.04 × protein yield (kg); Orth, 1992].

[4]Feed efficiency: (ECM/DMI).

[5]Nitrogen efficiency: [milk protein (kg/d)/CP intake (kg/d)].

not affect DMI (Powers et al., 1995; Liu et al., 2000, Hippen et al., 2003). Cows fed diets containing DDGS had greater yields of milk (average of 34.6 vs. 31.2 kg/d; $P = 0.007$), 4% FCM (average of 32.7 vs. 29.6 kg/d; $P = 0.008$), and ECM (average of 35.4 vs. 32.3; $P = 0.01$) compared with CON. As a result, feed efficiency was greater ($P = 0.03$) in cows fed DDGS compared with CON (1.78 vs. 1.63 kg of ECM/kg of DMI). There was also a tendency for feed efficiency to be greater ($P = 0.10$) when cows were fed DDGS-3 compared with DDGS-2 (1.86 vs. 1.72 kg of ECM/kg of DMI). Previous studies found that replacing soybean meal with DDGS increased yields of milk (Powers et al., 1995; Nichols et al., 1998) and ECM (Nichols et al., 1998); however, the changes in those experiments were moderate compared with what was observed in this study. The increased milk yield of cows fed DDGS may have been due to the fact that about one-third of the corn in CON diet was replaced with DDGS. This byproduct generally contains about 10 to 12% fat, and incorporating DDGS in place of corn may increase the energy density of the diet. Birkelo et al. (2004) found that wet distillers grains contained more energy than corn when fed to lactating dairy cattle.

Feeding DDGS did not decrease the concentration of milk fat compared with CON, which has been a general perception in the field. In addition, there was a tendency ($P = 0.10$) for milk fat percentage to be greater in cows fed DDGS-3 compared with DDGS-2. The CON diet had a relatively high concentration of NFC, but this diet did not appear to affect the milk fat content; cows fed this diet produced milk containing 3.69% fat. Past studies have found that feeding DDGS to dairy cattle at concentrations similar to that fed in this study did not affect milk fat content when the control diet did not have added fat (Powers et al., 1995; Nichols et al., 1998, Liu et al., 2000). Other studies that provided added fat in the control diet, as would commonly be found in an applied setting, found that feeding DDGS (Hippen et al., 2004) or wet distillers grains plus solubles (Hippen et al., 2003) at concentrations similar to that fed in this study did not affect milk fat content. In contrast, Leonardi et al. (2005) found that feeding DDGS at an increasing concentration decreased milk fat content linearly (3.38, 3.35, 3.33, and 3.24% fat for 0, 5, 10, and 15% DDGS) with the only significant change occurring between 10 and 15% DDGS. However, that change was probably not biologically significant. Milk fat yield was

greater ($P = 0.02$) in cows fed DDGS compared with CON (1.26 vs. 1.14 kg/d) and was a result of the increased milk yield.

Milk protein percentages were greater ($P < 0.001$) for CON vs. DDGS. A similar finding was observed when wet distillers grains (Schingoethe et al., 1999) and DDGS (Owens and Larson, 1991) replaced soybean meal. This small decrease in milk protein percentage typically occurs when diets contain additional fat (Schingoethe et al., 1999), as was the case with DDGS diets. It has also been observed that Lys is the first-limiting AA for milk protein synthesis in diets containing DDGS (Nichols et al., 1998). As previously noted, the MP requirement of the animals was more adequately met with DDGS-2 and DDGS-3 compared with CON, which indicated that more AA were available to the mammary gland for milk protein synthesis. Schingoethe (1996) reported that the milk protein score (i.e., the AA content of the most limiting AA in a protein supplement or diet relative to that AA in milk) of DDGS was 0.32 compared with 0.46 for soybean meal. Furthermore, according to NRC (2001) estimates, RDP was limiting in diets containing DDGS but not in CON, thus depriving the cows fed DDGS of some high quality microbial protein that has a milk protein score of 0.78. More of the CP in DDGS-1 was recovered as ADIN compared with the other 2 sources, which may have resulted in poorer CP digestibility and a tendency ($P = 0.10$) for milk protein content to be less. Milk protein yields tended ($P = 0.10$) to be greater for cows fed DDGS than for those fed CON (1.09 vs. 1.02 kg/d), which was a function of increased milk yield in DDGS diets. Concentrations of MUN were lower ($P < 0.001$) in cows fed DDGS compared with CON (9.36 vs. 10.6 mg/dl). The lower values in the cows fed DDGS were possibly because of the lower RDP of those diets. The concentrations of MUN in this study were relatively low because of the low concentrations of dietary CP.

Nitrogen efficiency [milk protein output (kg/d)/CP intake (kg/d)] was not affected by feeding DDGS. Based on this measure, it was assumed that N excretion was probably similar between CON and DDGS. Compared with CON, more of the excreted N from DDGS was most likely via the feces. This assumption was validated by the lower concentrations of MUN in milk from cows fed DDGS (Kauffman and St-Pierre, 2001) and by the observation that the protein digestibility of DDGS (68.8, 84.2, and 83.9% for DDGS-1, DDGS-2, and DDGS-3, respectively) was estimated to be less that of than soybean meal (94.9%; Kleinschmit et al., 2005). The concentration of lactose was similar among treatments; however, DDGS diets had increased ($P < 0.01$) yields of this component compared with CON, which was in agreement with increased milk yields. Body weight of the cows was not different among treatments (average of 641 kg) and cows had an average BCS of 3.00.

Amino Acids

Arterial concentrations of Arg, Ile, Lys, and Thr were decreased and concentrations of His and Leu increased when DDGS replaced soybean meal in the diet (Table 7). There was a tendency for arterial concentrations of Phe and Trp to increase when DDGS was fed. Previous research showed a tendency for arterial Lys concentrations to decrease when DDGS replaced soybean meal (Nichols et al., 1998) or a blend of various protein sources (Liu et al., 2000). The concentrations of Ile, Trp, and Val were less when DDGS-1 was fed compared with DDGS-2 and DDGS-3, and there was a tendency for cows fed DDGS-1 to have lower concentrations of arterial plasma Leu and Lys compared with those fed DDGS-2 and DDGS-3. The decrease in the concentrations of certain AA in DDGS-1 compared with DDGS-2 and DDGS-3 was most likely the cause of the slight depression in milk protein content. Even though cows fed DDGS-2 and DDGS-3 had greater concentrations of specific individual essential AA than those fed DDGS-1, concentrations of total essential AA did not differ by treatment. Overall, the concentrations of nonessential AA did not differ by treatment, though there was a tendency for Glu to be greater ($P = 0.10$) in cows fed CON than DDGS diets and Ser to be greater ($P = 0.07$) in cows fed DDGS-3 than DDGS-2.

The AA transfer efficiencies (Table 8) of His, Leu, Phe, Trp, and Tyr were less and that of Lys was greater ($P = 0.004$) in cows fed DDGS diets compared with CON. There was also a tendency for the transfer efficiencies of Arg and Ile to be lower for CON than for DDGS. Compared with DDGS-1, sources 2 and 3 decreased ($P = 0.04$) the AA transfer efficiency of Ile, and DDGS-2 had a greater transfer efficiency of Tyr compared with DDGS-3. Methionine was the first-limiting AA for milk protein synthesis for CON and DDGS-2, and Lys was the first-limiting AA for DDGS-1 and DDGS-3. The Lys requirement may have been better met in DDGS-2 compared with DDGS-1 and DDGS-3 because Kleinschmit et al. (2005) found more dietary Lys available to the small intestine with DDGS-2 compared with the other sources. More of the protein in DDGS-1 may have been unavailable to the animal, which may have been caused by excessive heating of the product. In particular, Lys is the first AA that is susceptible to Maillard reactions (Schwab, 1995). In contrast to this finding, the protein in DDGS-3 was found to be more ruminally available than DDGS-2 in a companion in situ study (Kleinschmit et al., 2005). Total protein digestibility did not differ

Table 7. Amino acid concentrations in coccygeal arterial plasma from cows fed diets containing soybean meal or 20% distillers dried grains plus solubles (DDGS) from 3 different sources as the primary protein source

	Diet[1]					Contrast[2] (*P*-value)		
AA	CON	DDGS-1	DDGS-2	DDGS-3	SE	1	2	3
	(μmol/dL)							
EAA[3]								
Arg	8.07	7.06	7.14	7.08	0.33	0.01	0.91	0.90
His	4.42	5.17	5.18	4.94	0.30	0.02	0.71	0.49
Ile	12.2	9.60	11.5	11.7	0.53	0.05	0.003	0.81
Leu	16.4	18.4	20.1	21.3	1.1	0.009	0.10	0.46
Lys	8.28	5.88	7.10	6.51	0.51	0.005	0.10	0.36
Met	2.12	2.09	2.11	2.07	0.10	0.79	0.98	0.73
Phe	4.15	4.42	4.68	4.82	0.26	0.10	0.30	0.71
Thr	10.1	8.76	8.40	8.52	0.73	0.02	0.67	0.88
Trp	2.78	2.91	3.45	3.58	0.28	0.07	0.05	0.70
Val	26.3	22.4	26.1	26.7	1.2	0.39	0.01	0.69
Total EAA	95.0	89.2	95.9	97.3	3.8	0.84	0.12	0.78
NEAA[4]								
Ala	23.6	23.9	23.8	23.1	1.3	0.97	0.72	0.56
Asp	1.40	1.22	1.28	1.42	0.11	0.43	0.28	0.33
Asn	3.12	2.54	3.51	2.58	0.35	0.51	0.23	0.05
Glu	9.92	8.82	8.46	8.73	0.71	0.10	0.78	0.77
Gln	22.0	20.2	21.6	20.2	1.1	0.21	0.51	0.32
Gly	23.0	27.5	25.9	24.1	1.9	0.13	0.20	0.40
Pro	8.06	8.41	8.97	9.56	0.58	0.13	0.18	0.42
Ser	7.95	8.15	6.81	7.03	0.59	0.31	0.07	0.77
Tyr	5.28	5.58	5.45	6.18	0.39	0.29	0.61	0.17
Total NEAA	104.7	108.7	105.2	101.6	4.5	0.90	0.20	0.46

[1]CON = No DDGS; DDGS-1 = DDGS from source 1; DDGS-2 = DDGS from source 2; DDGS-3 = DDGS from source 3.

[2]Contrasts: 1 = CON vs. DDGS-1, DDGS-2, and DDGS-3; 2 = DDGS-1 vs. DDGS-2 and DDGS-3; 3 = DDGS-2 vs. DDGS-3.

[3]Essential AA.

[4]Nonessential AA.

Table 8. Amino acid transfer efficiency[1] of essential amino acids from cows fed diets containing soybean meal or 20% distillers dried grains plus solubles (DDGS) from 3 different sources as the primary protein source

	Diet[2]					Contrast[3] (*P*-value)		
AA	CON	DDGS-1	DDGS-2	DDGS-3	SE	1	2	3
	(μmol/dL)							
Arg	12.6 (8)[4]	14.0 (8)	13.6 (8)	14.3 (8)	0.7	0.09	0.90	0.43
His	19.8 (6)	16.9 (7)	17.3 (7)	17.3 (7)	1.1	0.05	0.78	0.98
Ile	18.4 (7)	21.7 (5)	20.0 (5)	19.1 (5)	1.0	0.06	0.04	0.45
Leu	23.6 (4)	18.8 (6)	18.8 (6)	17.6 (6)	1.3	<0.001	0.69	0.46
Lys	33.4 (3)	44.0 (1)	40.6 (2)	43.3 (1)	2.8	0.004	0.50	0.44
Met	42.4 (1)	40.2 (2)	42.1 (1)	42.0 (2)	2.4	0.66	0.42	0.97
Phe	37.3 (2)	32.3 (3)	32.6 (3)	30.6 (3)	2.3	0.03	0.79	0.49
Thr	20.7 (5)	24.4 (4)	24.2 (4)	23.6 (4)	2.2	0.16	0.87	0.83
Trp	11.9 (9)	10.2 (10)	10.4 (9)	9.5 (10)	0.8	0.03	0.78	0.36
Val	10.0 (10)	10.9 (9)	10.3 (10)	9.9 (9)	0.6	0.53	0.18	0.56
Tyr[5]	28.7 [4]	24.1 [5]	26.1 [4]	22.6 [5]	1.5	0.006	0.87	0.05

[1]Transfer efficiency = AA output in milk (g/d; Jacobson et al., 1970) × 100/[arterial AA concentration (g/L) × mammary blood flow (L/d; Kronfeld et al., 1968)].

[2]CON = No DDGS; DDGS-1 = DDGS from source 1; DDGS-2 = DDGS from source 2; DDGS-3 = DDGS from source 3.

[3]Contrasts: 1 = CON vs. DDGS-1, DDGS-2, and DDGS-3; 2 = DDGS-1 vs. DDGS-2 and DDGS-3; 3 = DDGS-2 vs. DDGS-3.

[4]Numbers in parentheses indicate the apparent order of limiting AA.

[5]Numbers in brackets are ranking of Tyr if it were considered an essential AA.

Table 9. Ruminal VFA and ammonia from cows fed diets containing soybean meal or 20% distillers dried grains plus solubles (DDGS) from 3 different sources as the primary protein source

	Diet[1]					Contrast[2] (*P*-value)		
Measurement	CON	DDGS-1	DDGS-2	DDGS-3	SE	1	2	3
VFA, %								
Acetate (A)	63.5	61.9	63.2	63.2	1.3	0.55	0.29	0.97
Propionate (P)	22.6	24.0	22.6	21.3	1.0	0.95	0.04	0.23
Isobutyrate	1.40	1.18	1.19	1.25	0.06	0.008	0.55	0.51
Butyrate	9.2	10.5	10.5	11.0	0.4	0.004	0.67	0.42
Isovalerate	1.61	1.32	1.33	1.57	0.12	0.09	0.32	0.11
Valerate	1.42	1.48	1.37	1.38	0.92	0.90	0.28	0.93
Total, m*M*/L	65.6	55.1	50.3	56.1	3.7	0.03	0.52	0.10
A:P	2.92	2.74	3.00	2.98	0.19	0.96	0.18	0.95
Ammonia, mg/dL	7.20	3.78	4.82	4.90	0.71	<0.001	0.17	0.93

[1]CON = No DDGS; DDGS-1 = DDGS from source 1; DDGS-2 = DDGS from source 2; DDGS-3 = DDGS from source 3.

[2]Contrasts: 1 = CON vs. DDGS-1, DDGS-2, and DDGS-3; 2 = DDGS-1 vs. DDGS-2 and DDGS-3; 3 = DDGS-2 vs. DDGS-3.

between these 2 sources, thereby suggesting that a greater proportion of the AA, in particular Lys, escaped ruminal degradation and was available to the animal. In this study, Lys, Met, and Phe were the 3 most limiting AA in all diets. This finding has also been observed in past research (Nichols et al., 1998; Liu et al., 2000).

Ruminal Components

The VFA and ammonia composition of ruminal samples is shown in Table 9. The molar percentage of ruminal acetate (63.0%) was similar among treatments. Inclusion of DDGS did not affect the molar percentage of propionate (22.6%) compared with CON; however, DDGS-1 (24.0%) had a greater ($P = 0.04$) molar percentage of this VFA compared with DDGS-2 (22.6%) and DDGS-3 (21.3%). There was also a parity × treatment interaction for this acid in that the concentration of propionate in multiparous cows was similar across all treatments. Primiparous cows had a greater concentration ($P = 0.02$) of this acid than multiparous cows. Primiparous cows consumed less feed in this study, and this may have decreased the ruminal passage rate of feed particles in these animals. As a result, the greater residence time of the feed in primiparous cows may have allowed more complete fermentation compared with the multiparous animals. Among the primiparous cows, feeding DDGS-1 increased the concentration of propionate compared with CON and DDGS-3. Reasons for these findings are unknown. Concentrations of isobutyrate were greater ($P = 0.008$), and the concentrations of butyrate were less in CON ($P < 0.004$) compared with diets containing DDGS. Cows fed the CON diet tended ($P = 0.09$) to have a greater concentration of isovalerate compared with diets containing DDGS. The ruminal concentrations of valerate were similar among diets. Cows fed CON had greater ($P = 0.03$) concentrations of VFA compared with those fed DDGS (65.6 vs. 53.8 m*M*/L), and those fed DDGS-2 tended ($P = 0.10$) to have lower concentrations of VFA compared with those fed DDGS-3. The greater concentrations of VFA from cows fed CON compared with DDGS may have been caused by the presence of more nonstructural carbohydrates, which allowed more fermentation to occur. The method for obtaining rumen fluid in this study was not ideal due to the unavailability of cannulated cows, and salivary contamination by the sample may have diluted total concentrations of VFA; however, such contamination affects primarily pH (which was not measured) and does not affect molar proportions of various VFA. The findings observed within this study agree with what has been observed in previous studies feeding wet distillers grains plus solubles (Schingoethe et al., 1999) and DDGS (Nichols et al., 1998). Primiparous cows had greater concentrations of ruminal VFA compared with multiparous cows, which was probably due to a lower passage rate caused by less DMI. The acetate to propionate ratio was similar among all treatments. Cows fed diets containing DDGS had lower ($P < 0.001$) concentrations of rumen ammonia compared with CON (4.50 vs. 7.20 mg/dL), which coincided with lower concentrations of MUN in cows fed DDGS. As previously mentioned, salivary contamination may have diluted rumen ammonia concentrations; however, soybean meal is highly ruminally degradable, which explains the greater concentration of ammonia in cows fed CON compared with those fed DDGS. The rumen ammonia values observed within this study are comparable to concentrations normally found within the rumen (Satter and Slyter, 1974). The low concentrations of rumen ammonia combined with lower concentrations of nonstructural carbohydrates from DDGS may have limited

rumen microbial synthesis, thus further explaining the decline in milk protein content in animals fed DDGS.

CONCLUSIONS

Replacing the majority of the soybean meal in a protein-deficient dairy ration with DDGS significantly increased the yields of milk, 4% FCM, and ECM. Yields of milk protein tended to increase; however, milk protein percentage was decreased. This decrease may have been the result of lower concentrations of Lys available to synthesize milk protein in animals fed DDGS. Replacing soybean meal with DDGS decreased the concentrations of MUN. Feeding cows DDGS decreased total concentrations of VFA. Overall, the source of DDGS did not have a significant effect on the lactation performance. Decreasing the ADIN content in DDGS, as in DDGS-2 and DDSG-3, may have contributed to improved protein quality, which increased concentrations of specific individual essential AA needed to synthesize milk protein.

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REFERENCES

Al-Suwaiegh, S., K. C. Fanning, R. J. Grant, C. T. Miton, and T. J. Klopfenstein. 2002. Utilization of distillers grains from the fermentation of sorghum or corn in diets for finishing beef and lactating dairy cattle. J. Anim. Sci. 80:1105–1111.

AOAC. 1997. Official Methods of Analysis. 16th ed. Association of Official Analytical Chemists, Gaithersburg, MD.

AOAC. 2000. Official Methods of Analysis. 17th ed. Association of Official Analytical Chemists, Gaithersburg, MD.

Belyea, R. L., K. D. Rausch, and M. E. Tumbleson. 2004. Composition of corn and distillers dried grains with solubles from dry grind ethanol processing. Bioresour. Technol. 94:293–298.

Birkelo, C. P., M. J. Brouk, and D. J. Schingoethe. 2004. The energy content of wet corn distillers grains for lactating dairy cows. J. Dairy Sci. 87:1815–1819.

Brouk, M. J. 1994. Net energy for lactation and ruminal degradability of wet corn distillers grains. PhD Thesis, South Dakota State University, Brookings.

Cromwell, G. L., K. L. Herkelman, and T. S. Stahly. 1993. Physical, chemical, and nutritional characteristics of distillers dried grains with solubles for chicks and pigs. J. Anim. Sci. 71:679–686.

Firkins, J. L., L. L. Berger, G. C. Fahey, Jr., and N. R. Merchen. 1984. Ruminal nitrogen degradability and escape of wet and dry distillers grains and wet and dry corn gluten feeds. J. Dairy Sci. 67:1936–1944.

Goering, H. K., C. H. Gordon, R. W. Hemken, D. R. Waldo, P. J. Van Soest, and L. W. Smith. 1972. Analytical estimates of nitrogen digestibility in heat damaged forages. J. Dairy Sci. 55:1275–1280.

Grunau, J. A., and J. M. Swiader. 1992. Chromatography of 99 amino acids and other ninhydrin-reactive compounds in the Pickering lithium gradient system. J. Chromatogr. 594:165–171.

Harty, S. R., J. M. Akayezu, J. G. Linn, and J. M. Cassady. 1998. Nutrient composition of distillers grains with added solubles. J. Dairy Sci. 81:1201. (Abstr.)

Hippen, A. R., K. F. Kalscheur, D. J. Schingoethe, and A. D. Garcia. 2004. Increasing inclusion of dried corn distillers grains in diary cow diets. J. Dairy Sci. 87(Suppl. 1):1965. (Abstr.)

Hippen, A. R., K. N. Linke, K. F. Kalscheur, D. J. Schingoethe, and A. D. Garcia. 2003. Increased concentrations of wet distillers in dairy cow diets. J. Dairy Sci. 86(Suppl. 1):340. (Abstr.)

Hunter Associates Laboratory. 2002. Universal Software User's Manual, Version 2.5. Hunter Associates Laboratory, Reston, VA.

Jacobson, D. R., H. H. Van Horn, and C. J. Sniffen. 1970. Lactating ruminants. Fed. Proc. 29:35–40.

Kauffman, A. J., and N. R. St-Pierre. 2001. The relationship of milk urea nitrogen to urine nitrogen excretion in Holstein and Jersey cows. J. Dairy Sci. 84:2284–2294.

Kleinschmit, D. H., J. L. Anderson, D. J. Schingoethe, K. F. Kalscheur, and A. R. Hippen. 2005. Ruminal and intestinal digestibility of distillers grains with solubles varies by source. J. Dairy Sci. 88(Suppl. 1):186. (Abstr.)

Kronfeld, D. S., F. Raggi, and C. F. Ramberg, Jr. 1968. Mammary blood flow and ketone body metabolism in normal, fasted, and ketotic cows. Am. J. Physiol. 215:281–227.

Larson, E. M., R. A. Stock, T. J. Klopfenstein, M. H. Sindt, and R. P. Huffman. 1993. Feeding value of wet distillers byproducts for finishing ruminants. J. Anim. Sci. 71:2228–2236.

Leonardi, C., S. Bertics, and L. E. Armentano. 2005. Effect of increasing oil from distillers grains or corn oil on lactation performance. J. Dairy Sci. 88:2820–2827.

Licitra, G., T. M. Hernandez, and P. J. Van Soest. 1996. Standardization of procedures for nitrogen fractionation of ruminant feeds. Anim. Feed Sci. Technol. 57:347–358.

Littell, G. C., G. A. Milliken, S. W. Walter, and R. D. Wolfinger. 1996. SAS Systems for Mixed Models. SAS Institute, Inc., Cary, NC.

Liu, C., D. J. Schingoethe, and G. A. Stegeman. 2000. Corn distillers grains versus a blend of protein supplements with or without ruminally protected amino acids for lactating cows. J. Dairy Sci. 83:2075–2084.

Loor, J. J., A. Ferlay, A. Ollier, K. Ueda, M. Doreou, and Y. Chilliard. 2005. High concentrate diet and polyunsaturated oils alter *trans* and conjugated isomer in bovine rumen, blood and milk. J. Dairy Sci. 88:3986–3999.

Lowry, J. B., L. L. Conlan, A. A. Schlink, and C. S. McSweeney. 1994. Acid detergent dispersible lignin in tropical grasses. J. Food Agric. 65:41–50.

Maisch, W. F. 2003. Fermentation processes and products. Pages 695–721 in Corn Chemistry and Technology. 2nd ed. American Association of Cereal Chemists, Inc., St. Paul, MN.

Mondina, A., G. Bongiovanni, S. Fumero, and L. Rossi. 1972. An improved method of plasma deproteination with sulphosalicylic acid for determining amino acids and related compounds. J. Chromatogr. 74:255–263.

Nakamura, T., T. J. Klopfenstein, and R. A. Britton. 1994a. Evaluation of acid detergent insoluble nitrogen as an indicator of protein quality in nonforage proteins. J. Anim. Sci. 72:1043–1048.

Nakamura, T., T. J. Klopfenstein, D. J. Gibb, and R. A. Britton. 1994b. Growth efficiency and digestibility of heated proteins fed to growing ruminants. J. Anim. Sci. 72:774–782.

National Research Council. 2001. Nutrient Requirements of Dairy Cattle. 7th rev. ed. Natl. Acad. Sci., Washington, DC.

Nichols, J. R., D. J. Schingoethe, H. A. Maiga, M. J. Brouk, and M. S. Piepenbrink. 1998. Evaluation of corn distillers grains and ruminally protected lysine and methionine for lactating dairy cows. J. Dairy Sci. 81:482–491.

Orth, R. 1992. Sample day and lactation report. DHIA 200 Fact Sheet A-2. Midstates DRPC, Ames, IA.

Owens, F. G., and L. L. Larson. 1991. Corn distillers dried grains versus soybean meal in lactation diets. J. Dairy Sci. 74:972–979.

Pickering, M. 1989. Ion-exchange chromatography of free amino acids. LC GC. 7:484–490.

Powers, W. J., H. H. Van Horn, B. Harris, Jr., and C. J. Wilcox. 1995. Effects of variable sources of distillers dried grains plus solubles on milk yield and composition. J. Dairy Sci. 78:388–396.

Robertson, J. B., and P. J. Van Soest. 1981. The detergent system of analysis and its application to human foods. Pages 123–158 in The Analysis of Dietary Fiber in Food. W. P. T. James and O. Theander, ed. Marcel Dekker Inc., New York, NY.

SAS Institute. 1999. SAS User's Guide. Statistics, Version 8.01 ed. SAS Institute, Inc., Cary, NC.

Satter, L. D., and L. L. Slyter. 1974. Effect of ammonia concentration on rumen microbial protein production in vitro. Br. J. Nutr. 32:199–208.

Schingoethe, D. J. 1996. Balancing the amino acid needs of the dairy cow. Anim. Feed Sci. Technol. 60:153–160.

Schingoethe, D. J., M. J. Brouk, and C. P. Birkelo. 1999. Milk production and composition from cows fed wet corn distillers grains. J. Dairy Sci. 82:574–580.

Schwab, C. G. 1995. Protected proteins and amino acids for ruminants. Pages 115–141 in Biotechnology in Animal Feeds and Animal Feeding. R. J. Wallace and A. Chesson, ed. V. C. H. Press, Weinheim, Germany.

Singh, V., and S. R. Eckhoff. 1996. Effect of soak time, soak temperature, and lactic acid on germ recovery parameters. Cereal Chem. 73:716–720.

Singh, V., and S. R. Eckhoff. 1997. Economics of germ preparation for dry-grind ethanol facilities. Cereal Chem. 74:462–466.

Singh, V., D. B. Johnston, K. Naidu, K. D. Rausch, R. L. Belyea, and M. E. Tumbleson. 2005. Comparison of modified dry-grind corn processes for fermentation characteristics and DDGS composition. Cereal Chem. 82:187–190.

Singh, V., R. A. Moreau, L. W. Doner, S. R. Eckhoff, and K. B. Hicks. 1999. Recovery of fiber in the corn dry-grind ethanol process: A feedstock for valuable coproducts. Cereal Chem. 76:868–872.

Spiehs, M. J., M. H. Whiteny, and G. C. Shurson. 2002. Nutrient database for distiller's dried grains with solubles produced from new ethanol plants in Minnesota and South Dakota. J. Anim. Sci. 80:2639–2645.

Sukhija, P. S., and D. L. Palmquist. 1988. A rapid method for determination of total fatty acid content and composition of feedstuffs and feces. J. Agric. Food Chem. 36:1202–1206.

Tucker, M. P., N. J. Nagle, E. W. Jennings, K. N. Ibsen, A. Aden, Q. A. Nguyen, K. H. Kim, and S. L. Noll. 2004. Conversion of distiller's grain into fuel alcohol and a higher-value animal feed by dilute-acid pretreatment. Appl. Biochem. Biotechnol. 115:1139–1159.

Van Soest, P. J. 1989. On the digestibility of bound N in distillers grains: A reanalysis. Pages 127–135 in Proc. Cornell Nutr. Conf. Feed Manuf. Cornell University, Ithaca, NY.

Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74:3583–3597.

Wahjudi, J., L. Xu, P. Wang, V. Singh, P. Buriak, K. D. Rausch, A. J. McAloo, M. E. Tumbleson, and S. R. Eckhoff. 2000. Quick fiber process: Effect of mash temperature, dry solids, and residual germ on fiber yield and purity. Cereal Chem. 77:640–644.

Weatherburn, M. W. 1967. Phenol-hypochlorite reaction for determinations of ammonia. Anal. Chem. 39:971–974.

Weiss, W. P., D. O. Erickson, G. M. Erickson, and G. R. Fisher. 1989. Barley distillers grains as a protein supplement for dairy cows. J. Dairy Sci. 72:980–987.

Wildman, E. E., G. M. Jones, P. E. Wagner, R. L. Bowman, H. F. Troutt, Jr., and T. N. Lesch. 1982. A dairy cow body condition scoring system and relationship to selected production characteristics. J. Dairy Sci. 65:495–501.

Yu, Y., and J. W. Thomas. 1976. Estimation of the extent of heat damage in alfalfa haylage by laboratory measurements. J. Anim. Sci. 42:766–774.