Diet fermentability influences lactational performance responses to corn distillers grains: A meta-analysis

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ABSTRACT

Increasing supply of corn distillers grains (CDG) raises questions about the extent to which they can be used in diets of lactating dairy cows. A database of treatment means ($n = 44$) reported in 16 peer-reviewed journal articles published from 1985 to 2008 was developed. The database included response (within study) to a CDG diet compared with the control (no CDG) for milk yield (MY), milk fat concentration and yield, CDG content of the diet, and dietary composition of control and CDG diets (% of dietary dry matter). Additionally, corn grain fermentability was classified as high moisture ($n = 7$) or dry ($n = 37$). Data from studies with diets including more than one grain source ($n = 8$) had been eliminated from the analysis. Dietary concentrations of CDG ranged from 4.2 to 42% across studies. Dietary concentrations in diets containing CDG were $16.8 \pm 1.91\%$ (mean $\pm$ standard deviation) crude protein, $36 \pm 15.5\%$ corn silage, $23 \pm 8.8\%$ corn grain, and $28 \pm 5.8\%$ starch. Responses to CDG were 0.5 ± 2.10 kg/cow per day (mean $\pm$ standard deviation) for MY, 0.05 ± 0.178 percentage units for milk fat concentration, and 26 ± 77.6 g/cow per day for milk fat yield. Only MY response was related to increasing concentrations of CDG in diets and peaked at 1.2 kg/cow per day for 21% CDG. Diet fermentability was associated with responses. The greatest MY response to CDG was with 24% corn silage or 23% starch, and concentrations greater than 47% corn silage or 32% starch resulted in negative MY responses. Responses in MY differed by level of MY and were often more evident in higher- (>30.0 kg MY/d) than in lower-producing cows. Milk fat concentration response was not related to dietary CDG, but was correlated linearly with milk fat concentration of cows fed the control diet. Milk fat concentration greater than 3.6% for the control treatment was related to a negative milk fat concentration response to CDG, regardless of dietary concentration of CDG. Partially replacing high-moisture corn with CDG increased milk fat con-

centration by 0.16 percentage units compared with that from dry corn. When formulating diets with CDG, diet fermentability and level of MY (higher vs. lower) must be considered. Concentrations of corn silage and starch must be moderate to optimize lactational responses to CDG. Overall, lactational response to CDG in this database was dependent on diet fermentability and milk fat concentration in the control.

Key words: diet fermentability, distillers grains, lactational performance, dairy cattle

INTRODUCTION

The recent surge in ethanol production from corn grain in the United States has increased greatly the supply of corn distillers grains (CDG) available as livestock feed (Rausch and Belyea, 2006). In Michigan, dairy farmers and nutritionists often ask how much CDG can be used effectively in lactation rations. We have heard many times that more than 5 to 10% CDG in rations decreases milk yield (MY) and milk fat concentration. In contrast, as much as 20 to 30% of the ration DM (about 4.5 to 5.9 kg/cow per day) was recommended with no ill effects on MY and composition compared with that from lower dietary concentrations, if diets contain at least 50% forage (Schingoethe et al., 2009). Janicek et al. (2008) reported the greatest MY when diets contained 30% CDG. Nonetheless, greater than 30% dietary CDG decreased feed intake and MY (Schingoethe et al., 2009).

Milk fat depression (MFD) is defined as a decrease in milk fat concentration and yield without decreasing MY (Bauman and Grinari, 2003). Generally, MFD is the result of interactions of several dietary factors, including greater concentrations of unsaturated fatty acids (FA), increased fiber and grain fermentability, and type and particle length of forage (Lock, 2010). Any combination of these factors can alter ruminal metabolism, generating alternative FA (e.g., *trans*-10 *cis*-12 C_{18:2}) and lower milk fat yield by as much as 25% (Bauman and Grinari, 2003). Corn distillers grains can accentuate these dietary factors. First, FA in CDG (and in corn silage and corn grain) are predominantly unsaturated (Lock, 2010). The fat content in CDG can

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vary widely, depending on the amount of solubles or “syrup” (20% fat, dry basis) blended with the solids residue to make a particular lot of CDG (Rausch and Belyea, 2006). Second, NDF in CDG are highly digestible (Schingoethe et al., 2009). Third, NDF in CDG are not effective fiber (Clark and Armentano, 1993). Consequently, CDG can increase the risk of MFD, especially in highly fermentable diets.

Bradford and Allen (2004) detected MFD in lower-producing cows, but not in higher-producing cows, when a highly fermentable diet was fed. Higher-producing cows have a faster rate of passage, and greater rate of absorption of VFA from the rumen than do lower-producing cows. The concomitant ecological differences led to a higher and more stable ruminal pH in higher-producing cows compared with lower-producing cows (Voelker and Allen, 2003). Bradford and Allen (2004) theorized that a lower ruminal pH in lower producing than in higher producing cows fed a highly fermentable diet modified the biohydrogenative pathways in the rumen leading to MFD at the lower production level. Therefore, production level of the cows should be considered when evaluating the effects of CDG on lactational performance.

We hypothesized that 1) milk fat concentration and milk fat yield responses to increasing concentrations of CDG in diets for lactating dairy cows correlate negatively with the fermentability of the diet; and, 2) decreases in milk fat concentration and yield are greater in lower-producing than in higher-producing cows. Our objective was to evaluate by meta-analysis the effects of ration fermentability and milk production level on lactational responses when CDG were included in diets. For our analysis, changes in ration fermentability were based on the concept that ruminal fermentability increases as dietary concentrations of corn silage, starch, and grain increase. Additionally, grain fermentability is greater for high-moisture corn grain (HMC) vs. dry corn grain (DC; Oba and Allen, 2003).

MATERIALS AND METHODS

Database

The scientific literature was screened for peer-reviewed articles reporting least squares means and standard errors for lactational performance of dairy cows in feeding trials that included CDG. All treatment diets contained >4% CDG, dry basis, compared with a control diet that did not contain any CDG, but was otherwise similar to the CDG diet. Each article could potentially report more than one feeding trial, and each feeding trial could contrast more than one CDG diet to one or more control diets. Corn distillers grains could replace portions of forage, concentrates, or both.

Diets in the selected studies were similar to typical US Midwestern dairy cow rations in that forage sources were exclusively corn silage, alfalfa hay, and haylage. All distillers grains originated from corn. Only treatment means from experiments that met these criteria were included in the database. A discrete variable was assigned to corn grain fermentability, which was “high” when diets contained HMC, “medium” when diets contained DC and small grains, or “low” when DC or hominy represented the grain source.

Descriptors of Diets and Response Variables

All dietary variables, other than DM concentration, were based on a dry basis. Independent variables included the dietary concentrations of DM, CDG, forage, corn silage, grain (including DC, HMC, barley, and hominy), NDF, NDF from forage (**ForNDF**; as % of DM), and ether extract (**EE**) of the control and CDG diets (Table 1). If dietary FA concentration was reported, EE was computed according to Allen (2000) using the following equation: $[EE] = [FA] + 1$. Starch concentrations of diets were calculated from book values (NRC, 2001): barley, 60.6%; corn gluten meal, 20.5%; corn silage, 39.4%; ground dry corn, 76.1%; high-moisture ear corn, 72.3%; high-moisture shell corn, 79.0%; and hominy, 31.0%. We assumed that CDG contained no starch. Forage NDF was only calculated in studies that provided NDF analysis of forages. Difference (Δ) in concentration of each individual nutrient was calculated by subtraction of the nutrient concentration in the control diet from that of the CDG diet. Thus, for example, a negative value for Δ -starch indicates a lower starch concentration in the CDG diet compared with that in the control diet (Table 1).

Lactational response variables for the control and CDG diets included MY, 4% FCM yield (**FCMY**), milk fat concentration and yield, and DMI. If FCMY was not reported, it was calculated as: $MY \times [0.4 + 15 \times \text{milk fat (\%)} / 100]$. Change in responses to dietary CDG was calculated as the difference in response of cows fed the control diet and the CDG diet (Allen, 2000).

Lactational responses to inclusion of CDG in diets with “medium” grain fermentability were not intermediate to responses to diets of high or low grain fermentability (results not shown). This may have resulted from the wide variety of small grains and their concentration in the total DM in these diets, a small number of treatment means ($n = 8$), or both. Thus, treatment means with medium grain fermentability were removed from the database ($n = 8$ treatment means). Consequently, corn grain represented greater than 85% (DM basis) of the grain source, as opposed to small grains, for all

Table 1. Descriptive statistics of fermentability in control diets (Ctrl), corn distillers grains (CDG) treatment diets, and the change in fermentability (Δ ; CDG minus Ctrl) in experiments included in the statistical analyses of CDG on lactational performance¹

Variable	Diet	n	Mean	SD	Minimum	Maximum
DM, %		26	59.4	9.49	39.4	72.5
Corn distillers grains	CDG	44	17.4	8.40	4.2	41.6
Corn silage	Ctrl	44	35.4	15.13	0.0	56.0
	CDG	44	34.9	15.47	0.0	56.0
	Δ^2	44	-0.54	1.693	-6.2	1.41
Starch ³	Ctrl	44	33.2	5.59	22.0	43.3
	CDG	44	27.8	5.77	16.8	39.3
	Δ	44	-5.37	3.707	-15.3	1.9
Grain	Ctrl	44	30.4	7.85	16.3	48.0
	CDG	44	22.7	8.80	5.9	38.4
	Δ	44	-7.74	5.320	-21.8	2.7
Forage	Ctrl	44	48.8	6.36	29.6	57.9
	CDG	44	48.1	7.41	29.6	57.8
	Δ	44	-0.73	2.38	-9.3	2.1
NDF	Ctrl	35	30.2	3.86	19.7	35.7
	CDG	35	34.8	5.23	23.5	42.9
	Δ	35	4.65	3.28	0.1	14.6
Forage-NDF	CDG	23	20.4	4.69	12.0	27.9
Ether extract ⁴	Ctrl	32	4.1	1.10	2.2	6.0
	CDG	32	5.2	0.80	3.7	6.5
	Δ	32	1.05	0.83	-0.3	2.9

¹Results are reported as g/100 g of DM, unless indicated otherwise.

²Change in an independent variable to dietary inclusion of CDG. A positive value represents an increase in response to CDG and a negative value a decrease.

³Calculated from book values (NRC, 2001).

⁴Conversion of dietary fat content: ether extract [%] = dietary fat [%] + 1 (Allen, 2000).

treatment means in our analysis. Another study ($n = 3$ treatment means) was eliminated from the database because the control diet contained 13.9% CP and was likely CP-deficient. Thus, the final database included 44 treatment means from 18 trials reported in 16 peer-reviewed publications (Van Horn et al., 1985; Johnson and Huber, 1987; Voss et al., 1988; Broderick et al., 1990; Scott et al., 1991; Clark and Armentano, 1993, 1997; Powers et al., 1995; Zhu et al., 1997; Nichols et al., 1998; Schingoethe et al., 1999; Leonardi et al., 2005; Anderson et al., 2006; Kleinschmit et al., 2006; Janicek et al., 2008; Sasikala-Appukuttan et al., 2008), all published in the Journal of Dairy Science, although we did not limit data acquisition to this journal or time span. In all cases, CDG replaced solely or predominantly concentrate feedstuffs of the control diet. Corn distillers grains replaced as much as 9.3 percentage units of the forage portion of the control diet (Table 1) in one study but very little forage in all other studies. Composition of control diets and CDG diets, and Δ -compositions related to diet fermentability are shown in Table 1. Monensin was not reported to be supplemented in any of the diets in our analysis.

Statistical Analysis

Treatment means were weighted by their reported SEM (St-Pierre, 2001). However, several studies in the

database did not account for the random effect of cow in Latin square designs. Thus, reported SE were smaller than the corrected SE. These studies were not weighted in the current analyses (N. R. St-Pierre, personal communication, 2008). For calculated FCMY means, the SEM of the respective MY was used. We were unable to analyze the publication bias by use of a funnel plot (Egger et al., 1997) because of variation of designs used (e.g., crossover vs. randomized complete block designs) and because of differences in types of models used (e.g., fixed vs. random effects).

Analysis of variance was conducted (SAS Version 9.1.3, SAS Institute, 2005) using multiple general linear models. Lactational responses were characterized by one or more independent (fixed) variables. Respective lactational response datum from the control diet served as a covariate. Significance was declared at $P < 0.05$ and trends at $0.05 < P < 0.10$ for single variables. Interactions were excluded from the model at $P > 0.15$. The normality of data distribution was evaluated using the Shapiro-Wilk test in the Univariate procedure of the SAS Institute (2005). If data were not normally distributed ($P < 0.05$), they were transformed to achieve normal distribution as indicated in the results section for specific variables. Individual treatment means were evaluated for their influence on the result with Cook's distance (Cook, 1979) and removed, if they changed the overall outcome; however, not more than one outlier was

Table 2. Descriptive statistics of lactational performance in control diets (Ctrl) and corn distillers grains (CDG) treatment diets, and the resulting responses to CDG inclusion (Δ ; CDG minus Ctrl) in experiments included in the meta-analysis (n = 44)

Variable	Diet	Mean	SD	Minimum	Maximum
DMI, kg/cow per day	Ctrl	23.1	2.12	19.4	29.4
	CDG	23.1	2.56	17.6	31.7
	Δ^1	0.02	1.194	-2.6	2.6
Milk yield, kg/cow per day	Ctrl	31.6	5.83	24.3	44.6
	CDG	32.0	6.49	23.3	46.4
	Δ	0.45	2.099	-5.7	3.8
4% FCM yield, ² kg/cow per day	Ctrl	28.7	5.06	21.6	40.5
	CDG	29.2	5.68	20.6	41.7
	Δ	0.60	1.858	-3.6	4.4
Milk fat, %	Ctrl	3.42	0.245	2.75	3.90
	CDG	3.47	0.229	2.87	3.85
	Δ^3	0.049	0.1780	-0.21	0.46
Milk fat yield, g/cow per day	Ctrl	1,074	182	860	1,490
	CDG	1,100	200	830	1,530
	Δ	26	77.6	-200	160

¹Change in response of dependent variable to dietary inclusion of CDG. A positive value represents an increase in response to CDG.

²Conversion for 4% FCM yield is: milk yield $\times$ [0.4 + (15 $\times$ milk fat %)/100].

³Change in milk fat in percentage units.

removed from any analysis. The database was divided into higher- and lower-producing cows using a least squares means in the control of 30.0 kg/cow per day as the breakpoint to evaluate the responses to CDG based on the differing effect of diet fermentability in higher- and lower-producing cows. The database was tested for a balanced distribution of means when 2 independent variables were used in the model. If the distribution was not balanced, the database was restricted by either variable to achieve a more balanced distribution, and the analysis was repeated.

RESULTS

Descriptive statistics of the lactational performance of cows fed control diets (no CDG) and CDG diets, and the resulting responses to dietary CDG are listed in Table 2. Prediction equations for the instances where lactational responses to CDG differed by the binominal category of milk production level in the control diet (30.0 kg/cow per day; higher- vs. lower-producing cows) are presented in Table 3. Some data were not well-balanced among 2 independent variables because the range of values for a variable (variable A) did not coincide with the range of values of a second independent variable (variable B). This potentially could have resulted in erroneous conclusions without further evaluation. In these cases, we analyzed 2 restricted databases that were balanced for either variable A or variable B. Thus, means from experiments that did not fall within the limitations for one of the variables were excluded from the respective restricted database. Outcomes from restricted databases are summarized in Table 4.

Milk Fat Concentration Response

Milk fat concentration response in all experiments was not related to dietary concentration of CDG (Figure 1A). However, the database was not well-balanced regarding milk fat concentration in the control treatment and CDG concentration in the CDG diet. Milk fat concentration did not respond to concentration of CDG, when experimental treatment diets had less than 21% CDG ($P_{\text{model}} = 0.11$; n = 32; Figure 1B). When milk fat concentration was greater than 3.30% in control diets, a tendency for a quadratic response in milk fat concentration to CDG addition was observed ($R^2 = 0.18$; $P_{\text{model}} = 0.08$; n = 29; Figure 1C). Response was least with 24% CDG ($P_{\text{quadratic}} = 0.03$).

Response in milk fat concentration to CDG was related negatively with milk fat concentration of cows fed the control diets (Figure 2). When milk fat concentration of control cows was greater than 3.58%, adding CDG decreased milk fat concentration. However, when milk fat was less than 3.58% for cows fed control diets, the milk fat concentration response to CDG addition was positive. Ten of the 44 control diet means in the database for milk fat concentration were greater than 3.58%. This observation was more pronounced in experiments with lower-producing cows ($R^2 = 0.26$; $P_{\text{model}} < 0.001$; n = 21) than with higher-producing cows ($R^2 = 0.14$; $P_{\text{model}} = 0.08$; n = 23; Table 3).

Fermentability Factor: Dietary Corn Source.

Milk fat concentration of cows fed control diets was less in experiments when HMC versus DC was fed as the grain source (HMC: $3.17 \pm 0.33\%$, mean $\pm$ SD, n = 7; DC: $3.47 \pm 0.20\%$, n = 37). Addition of CDG

Table 3. Lactational responses to dietary corn distillers grains (CDG) in the full database compared with the databases divided by milk production level (higher: >30.0 kg/cow per day; lower: <30.0 kg/cow per day)

Lactational response ¹	Descriptor variable ²	Database	Term ³	R ²	P-value	n
Δ [milk fat]	A: [milk fat]	All	$-0.38 \times A + 1.34$	0.26	0.001	43
		>30 kg/d	$-0.24 \times A + 0.85$	0.14	0.081	23
		<30 kg/d	$-0.60 \times A + 2.12$	0.32	0.001	21
Δ milk yield	A: [CDG]	All	$-0.164 \times A^2 + 6.99 \times A - 48.80^4$	0.15	0.036	44
		>30 kg/d	$-82.3 \times A^2 + 3,338 \times A - 19,516^5$	0.48	0.002	23
		<30 kg/d			NS ⁶	21
Δ milk yield	A: [CS]	All	$-0.0035 \times A^2 + 0.17 \times A - 0.52$	0.32	0.001	44
		>30 kg/d	$-0.0042 \times A^2 + 0.018 \times A - 0.48$	0.36	0.012	23
		<30 kg/d	$-363 \times A + 17,684^5$	0.30	0.010	21
Δ milk yield	A: [starch]	All	$-0.018 \times A^2 + 0.84 \times A - 8.38$	0.34	0.001	44
		>30 kg/d	$-0.035 \times A^2 + 1.75 \times A - 19.99$	0.40	0.006	23
		<30 kg/d	$-0.156 \times A + 4.36$	0.38	0.003	21
Δ milk yield	A: [CS] B: [grain]	All	$-0.014 \times A^2 + 0.94 \times A + 0.32 \times B + 0.00031 \times A^2B - 0.024 \times AB - 11.44$	0.48	0.001	44
		>30 kg/d	$-0.0036 \times A^2 + 0.13 \times A - 0.087 \times B + 2.71$	0.39	0.021	23
		<30 kg/d	$-0.091 \times A - 0.082 \times B + 5.51$	0.42	0.007	21
Δ milk yield	A: Δ -[grain]	All	$-0.514 \times A^2 - 9.34 \times A - 15.23^4$	0.22	0.006	44
		>30 kg/d	$-0.047 \times A^2 - 0.93 \times A - 2.20$	0.50	0.001	23
		<30 kg/d			NS	21
Δ milk yield	A: Δ -[starch]	All	$-1.144 \times A^2 - 14.98 \times A - 19.95^4$	0.26	0.002	44
		>30 kg/d	$-0.095 \times A^2 - 1.31 \times A - 2.12$	0.51	0.001	23
		<30 kg/d			NS	21
Δ DMI	A: [starch]	All	$-0.10 \times A + 2.86$	0.25	0.001	44
		>30 kg/d			NS	23
		<30 kg/d	$-0.12 \times A + 3.54$	0.63	0.001	21

¹Lactational response (Δ response) = CDG diet mean minus control diet mean. Milk yield and DMI responses are in kg/cow per day.²[milk fat] = milk fat concentration of the control diet; [CDG], [CS], [starch], and [grain] = respective concentration in CDG diet in %; Δ = difference of respective concentration in percentage units, CDG minus control diet; CS = corn silage.³A = first descriptor variable; B = second descriptor variable.⁴Response variable transformed: $(X + 10)^2 - 100$.⁵Response variable transformed: $(X + 10)^4 - 10,000$.⁶Nonsignificant ($P > 0.10$).

Table 4. Lactational responses to dietary corn distillers grains (CDG) in the full database and restricted, but balanced databases

Lactational response ¹	Descriptor variable ²	Restricted		Term ³	R ²	P-value	n
		Variable	Limit ⁴				
Δ [milk fat]	A: [CDG]	NA ⁵	NA	$-0.00062 \times A^2 + 0.024 \times A + 0.83^7$	0.18	NS ⁶	44
		[CDG]	<21%			NS	32
		[milk fat]	>3.30%			0.078	29
Δ [milk fat]	A: Δ-[starch]	NA	NA	$0.0028 \times A^2 + 0.031 \times A + 0.010 \times B + 0.168 \times C - 0.27$	0.32	0.004	44
	B: [starch]	[starch]	>28.0%	$0.0028 \times A^2 + 0.030 \times A + 0.017 \times B + 0.169 \times C - 0.53$	0.32	0.004	38
	C: grain ferm	Δ [starch]	>−7.5	$0.011 \times B + 0.150 \times C - 0.34$	0.21	0.024	34
Δ milk yield	A: [CDG]	NA	NA	$-0.164 \times A^2 + 6.99 \times A - 48.8^8$	0.15	0.036	44
		[CDG]	<21%	$4.44 \times A - 43.2^8$	0.31	0.001	32
		milk yield	<35.0	$161 \times A^2 - 3,325 \times A + 16,227^9$	0.51	NS	34
		[CDG]	<21%				
		milk yield	<35.0			0.002	22
Δ 4% FCM yield	A: [CDG]	NA	NA	$0.135 \times A - 1.00$	0.13	NS	44
		[CDG]	<21%			0.04	32
		FCMY	<32.0			NS	32

¹Lactational response (Δ response) = CDG diet mean minus control diet mean. Milk yield and FCM yield are in kg/cow per day.

²[CDG], [starch] = respective concentration in CDG diet; Δ = difference of respective concentration in percentage units, CDG minus control diet; grain ferm = grain fermentability [0 = dry corn, 1 = high-moisture corn].

³A = first descriptor variable; B = second descriptor variable; C = third descriptor variable.

⁴Milk yield in kg/cow per day.

⁵Not available, full database.

⁶Nonsignificant ($P > 0.10$).

⁷Response variable transformed: $1/(X + 1)$.

⁸Response variable transformed: $(X + 10)^2 - 100$.

⁹Response variable transformed: $(X + 10)^4 - 10,000$.

Figure 1. Response in milk fat concentration [corn distillers grains (CDG) diet mean minus control diet mean within experiment] related to CDG for all treatment means (A; no consistent response); for treatment means based on CDG concentration less than 21%, dry basis (B; no consistent response); and for treatment means based on more than 3.30% milk fat in the control diet (C; $P_{\text{model}} = 0.08$; $P_{\text{quadratic}} = 0.03$).

increased milk fat concentration 0.16 percentage units more with HMC compared with DC ($R^2 = 0.11$; $P = 0.03$), consistent with the positive response in milk fat concentration of cows fed CDG when milk fat concentration of cows in the control diet was low.

Fermentability Factor: Dietary Starch. Corn distillers grains replaced, on average, 5.4 percentage units of dietary starch (Table 1). Thus, the CDG concentration of diets correlated negatively with the Δ -starch concentration ($r = -0.66$, $P < 0.001$), because CDG replaced starch sources in most CDG diets. Response in milk fat concentration to CDG was related to Δ -starch concentration, starch concentration in the control diet, and grain fermentability (Table 4). Response (change) in milk fat concentration reached a minimum of 0.01 percentage units ($P_{\text{quadratic}} = 0.03$), when Δ -starch was -5.1 percentage units. Furthermore, each additional percentage unit of dietary starch in the control diet was associated with an increased milk fat concentration response of 0.01 percentage units ($P = 0.02$). Additionally, greater grain fermentability (HMC inclusion) in CDG diets increased milk fat concentration response by 0.17 percentage units ($P = 0.01$) compared with less grain fermentability (DC). Response was not different by milk production level.

Other Factors Related to Fermentability. We developed a database of means from experiments in which we were able to calculate ForNDF concentrations (Table 1); data were not used from individual studies that did not report ForNDF concentrations. Response in milk fat concentration to added CDG tended to decrease as concentration of ForNDF increased ($R^2 = 0.15$; $P_{\text{model}} = 0.07$; $n = 23$). Forage NDF concentration was not correlated with milk fat percentage in the control diets and dietary concentrations of forage or, specifically, corn silage did not relate with a consistent response in milk fat concentration to dietary CDG in the full database.

Milk Yield Response

Milk yield response was quadratic ($P_{\text{quadratic}} = 0.02$) to increasing CDG concentration ($R^2 = 0.15$; $P_{\text{model}} = 0.04$; Figure 3A) with a maximum response of 1.2 kg/cow per day at 21% CDG, dry basis. This response was pronounced in experiments with higher-producing cows, but did not occur in experiments with lower-producing cows (Table 3). However, the database was not well-balanced with regard to dietary CDG concentration and MY of the control. Milk yield response related positively to dietary CDG within the range of 4 to 21% in the treatment diets in a restricted database (Figure 3B). Concentration of CDG did not consistently affect MY response in a database restricted to less than

Figure 2. Milk fat concentration response [corn distillers grains (CDG) diet mean minus control diet mean within experiment] to dietary CDG related to milk fat concentration in the control diet ($R^2 = 0.26$; $P < 0.001$; $n = 43$).

35.0 kg of MY/d in the control diet (Figure 3C). The intersection of responses in the 2 restricted databases represents the quadrant where inclusion of CDG was less than 21% and MY of cows in control diets was less than 35.0 kg/cow per day. In this restricted database, response in MY to dietary CDG was quadratic ($R^2 = 0.51$; $P < 0.01$; $n = 22$; Figure 3D) with the greatest response at the greatest concentration of CDG (21%).

Fermentability Factor: Dietary Starch. In our analysis, 3 independent variables contributing appreciable dietary starch were evaluated: corn silage, total dietary starch, and grain. Response in MY to CDG was quadratic to increasing concentrations of corn silage ($R^2 = 0.32$; $P_{\text{model}} < 0.001$) and starch ($R^2 = 0.34$; $P_{\text{model}} < 0.001$; Table 3). Dietary inclusions of 24% corn silage ($P_{\text{quadratic}} = 0.02$) and 23% starch ($P_{\text{quadratic}} = 0.01$) were related to the greatest MY response (1.6 and 1.3 kg/d, respectively). However, MY response was negative when CDG diets contained more than 47% corn silage or more than 32% starch. Milk yield response was not associated with grain (when the grain fraction was comprised of more than 85% corn grain and less than 15% small grains) concentration in the CDG diet. Yet, grain and corn silage concentrations accounted for more variation in MY response ($R^2 =$

0.48; $P_{\text{model}} < 0.001$; Figure 4) than did corn silage concentration alone. Grain and corn silage concentrations were not correlated ($P > 0.05$) in the database. Milk yield response to CDG as related to concentrations of corn silage, grain, or starch in CDG diets in experiments with higher-producing cows (>30.0 kg/cow per day in the control) was similar to those of the full database (Table 3). However, for experiments with lower-producing cows (<30.0 kg/cow per day in the control diet), MY response to CDG decreased linearly with increasing concentrations of corn silage and grain, or starch (Table 3).

Differences in dietary concentrations of grain and starch between CDG and control diets may predict the response in MY to CDG diets more accurately than the respective concentrations of grain and starch in the CDG diets. Response in MY was positive when Δ -grain was between -16.4 to -2.8 percentage units or when Δ -starch was between -11.5 to -1.5 percentage units; beyond these ranges MY response to CDG was negative (Table 3). These MY responses to CDG were significant in higher-, but not lower-producing cows. Concentration of corn silage was similar in control and CDG diets in most experiments; thus, we did not evaluate MY response to Δ -corn silage.

Figure 3. Response in milk yield [MY; corn distillers grains (CDG) diet mean minus control diet mean within experiment] to feeding varying dietary concentrations of CDG to dairy cows. Response in MY to CDG for all treatment means (A; $P_{\text{model}} = 0.04$); for treatment means based on CDG concentration less than 21%, dry basis (B; $P_{\text{model}} < 0.001$); for treatment means based on less than 35.0 kg of MY/cow per day in the control diet (C; no response); and for treatment means based on 1) CDG concentration less than 21%, dry basis; and 2) less than 35 kg of MY/cow per day (D; $P_{\text{model}} = 0.002$). A, B, and C: $[\text{response in MY (kg/cow per day)} + 10]^4 - 100$; D: $[\text{response in MY (kg/cow per day)} + 10]^4 - 10,000$.

Fermentability Factor: Dietary Corn Source.

Corn fermentability (HMC vs. DC) did not affect MY response to CDG. However, an interaction of corn fermentability and dietary corn silage concentration on MY response to CDG was found ($R^2 = 0.55$; $P_{\text{model}} < 0.001$; $P_{\text{interaction}} < 0.01$; Figure 5). The CDG diets with only DC contained 19 to 56% corn silage, dry basis ($n = 37$). Milk yield response to CDG was negative in DC-containing diets when 50% or more corn silage was in the CDG diets. However, MY response was positive with less than 50% corn silage in DC-containing diets.

In contrast to DC, HMC was only fed in 7 of the 44 CDG diets. In 5 of those diets, corn silage was less than 12% of the DM; thus, corn silage concentration

in the CDG diets was different between diets containing either HMC or DC. Milk yield response of cows fed HMC-containing diets did not deviate from 0 kg/cow per day (Figure 5). Extending the previous model based on corn silage concentration and grain fermentability to include grain concentration in the CDG diet improved the accuracy ($R^2 = 0.60$; $P_{\text{model}} < 0.001$; Eq. [1], where A is the response in MY to dietary CDG; B is the dietary corn silage concentration of the CDG diet; C is a binomial variable for grain fermentability [$0 = \text{DC}$, $1 = \text{HMC}$]; and D is the dietary grain concentration of the CDG diet). Grain concentration related weakly to MY response to CDG ($P = 0.08$), regardless of dietary grain fermentability (HMC vs. DC) or corn silage concentration.

Figure 4. Response in milk yield [MY; corn distillers grains (CDG) diet mean minus control diet mean within experiment] to dietary CDG related to dietary concentrations of corn silage (CS) and grain in CDG diets. CDG diets contained 0 to 56% corn silage; 6 to 38% grain (>85% corn grain); and 4 to 42% CDG, dry basis. The concentration of CDG was not a significant variable in this model and, consequently, was removed. Different shading of surface response corresponds to each 2-kg/d increment in MY response to CDG.

$$\begin{aligned}
 A &= 0.749 (\pm 0.265) \times B - 0.011 (\pm 0.003) \times B^2 \\
 &+ 0.1145 (\pm 4.60) \times C - 0.984 (\pm 0.298) \times BC \\
 &+ 0.017 (\pm 0.005) \times B^2C - 0.055 (\pm 0.030) \\
 &\times D - 8.47 (\pm 4.79). \quad [1]
 \end{aligned}$$

Other Factors Related to Fermentability. Forage NDF concentration in control diets averaged 20.4% (Table 1) in a restricted database with mean MY response of + 1.6 kg/cow per day (SD = ± 1.37). Milk yield response was related to ForNDF ($R^2 = 0.29$; $P_{\text{model}} < 0.01$). Each percentage unit of ForNDF in the control diet corresponded to + 0.16 kg/cow per day in MY to CDG. Dietary concentrations of NDF or forage (Table 1) in control diets were not related to the MY response. Nonetheless, the concentration of ForNDF may serve as a better predictor of MY response than does dietary NDF, because of the confounding factor of non-forage NDF in CDG (Clark and Armentano, 1993).

Increasing the concentration of EE in the control diet was related to an increased MY response to CDG ($R^2 = 0.34$; $P_{\text{model}} < 0.001$). Moreover, Δ -EE concentration (1.0 ± 0.82 percentage units, mean $\pm$ SD) tended to influence MY response ($R^2 = 0.11$; $P_{\text{model}} = 0.06$). Increasing dietary EE concentration in the CDG diet coincided with increased MY response to CDG. This

may be the result of EE concentration in the control diets correlating negatively with Δ -EE ($r = -0.69$; $P < 0.001$).

Figure 5. Response in milk yield [MY; corn distillers grains (CDG) diet mean minus control diet mean within experiment] to CDG as related to dietary concentration of corn silage (CS) and fermentability of corn grain (high-moisture vs. dry corn) in CDG diets. Fermentability of corn grain [high moisture corn (dotted line) vs. dry corn (solid line)] interacted with CS concentration ($R^2 = 0.55$; $P_{\text{model}} < 0.001$; $P_{\text{interaction}} < 0.01$). Response in MY: [Response in milk yield (kg/cow per d) + 10]² - 100.

Figure 6. Response in milk yield [MY; corn distillers grains (CDG) diet mean minus control diet mean within experiment] to CDG as related to the interaction ($P < 0.01$) of dietary corn silage (CS) concentration and DMI in control diets. Control diets contained 0 to 56% corn silage and 4 to 42% CDG, dry basis. Dry matter intake ranged from 19.4 to 29.4 kg/cow per day. The concentration of CDG was not a significant variable in this model and, consequently, was removed. Different shading of surface response corresponds to each 2-kg/d increment in MY response to CDG.

Dry matter intake and dietary corn silage concentration in control diets accounted for 60% of the variability in MY response to CDG ($P_{\text{model}} < 0.001$; $n = 43$; Figure 6). Although MY response was positive for most combinations of DMI and dietary corn silage concentration, DMI less than 22 kg/cow per day in combination with either high or low concentrations of corn silage (e.g., more than 40% or less than 20%, dry basis) was related to a negative MY response ($P_{\text{interaction}} < 0.01$).

Milk Fat Yield Response

Milk fat yield response was not associated with dietary concentration of CDG. Moreover, fat yield of cows fed control diets was not associated with milk fat yield response to CDG. This is in contrast to results for response in milk fat concentration, in which low milk fat concentrations in control diets were related to a greater magnitude of response in milk fat concentration for cows fed CDG diets.

Dietary corn silage concentration influenced milk fat yield response to CDG ($R^2 = 0.23$; $P_{\text{model}} < 0.01$). Response in milk fat yield was maximum with about 21% corn silage, but negative with a corn silage concentration greater than 47% ($P_{\text{quadratic}} = 0.04$). When DMI of the control diet was included to explain milk fat yield response, prediction improved ($R^2 = 0.44$; P_{model}

< 0.001). Corn silage concentration interacted with DMI of the control diets ($P_{\text{interaction}} = 0.04$). Milk fat yield response was positive over a wide range of corn silage concentrations and DMI. However, greater than 40% corn silage and low DMI (e.g., less than 22 kg/cow per day) of the control diets resulted in decreased milk fat yield response. This surface response had a similar pattern as the MY response to CDG (Figure 6). Other dietary predictor variables, such as concentrations of grain, starch, forage type, or NDF, as well as their respective Δ did not relate to milk fat yield response.

4% FCMY Response

Response in 4% FCMY was not associated with dietary inclusion of CDG overall. The concentration of CDG tended to affect FCMY response in experiments with higher-producing cows (>30.0 -kg MY/cow per day in control diets; $R^2 = 0.27$; $P = 0.06$; $n = 21$) with maximum response of +2.2 kg of FCMY/cow per day with 20% dietary CDG, dry basis, but CDG did not affect FCMY response of lower-producing cows (<30.0 kg of MY/cow per day). When means from experiments feeding more than 21% CDG were excluded to better balance the database, response in FCMY increased linearly with increasing CDG concentration (Table 4).

Responses in 4% FCMY to CDG were similar to those for MY when evaluating influences of concentrations of corn silage, grain, or starch of control diets. However, these models explained less variation for the FCMY response than the respective MY response to CDG. And, the interaction of dietary corn silage concentration and grain concentration to predict response was not significant ($P > 0.10$) for FCMY.

Similar to the MY response, Δ -grain or Δ -starch explained some of the variation in FCMY response to CDG and grain fermentability (DC vs. HMC) interacted with dietary concentration of corn silage to affect FCMY response ($R^2 = 0.43$; $P_{\text{model}} < 0.001$; $P_{\text{interaction}} = 0.01$). Furthermore, DMI interacted with the concentration of corn silage ($R^2 = 0.51$; $P_{\text{model}} < 0.001$; $P_{\text{interaction}} = 0.02$; $n = 43$), similar to results for MY response, but DMI of the control diet did not affect FCMY response to CDG.

The ForNDF concentration of the control diet was not associated with the FCMY response, unlike the MY response. Moreover, the dietary concentration of forage ($n = 44$) or NDF ($n = 35$) did not influence FCMY response to CDG.

The response of FCMY to CDG was $+1.36$ kg/cow per day (SD: ± 1.342 ; $n = 32$) in experiments reporting EE concentration. Ether extract concentration in the control diet affected FCMY response to CDG ($R^2 = 0.33$; $P_{\text{model}} < 0.01$). The effect was quadratic ($P_{\text{quadratic}} = 0.04$); however, the prediction of FCMY response was similar to the linear prediction of MY response for EE concentrations in diets with less than 5.5% EE.

DMI Response

Dietary inclusion of CDG was not associated with a response in DMI to CDG. Likewise, DMI of cows fed control diets was not associated with a DMI response to CDG. However, DMI response related linearly to starch concentration in the control diet ($R^2 = 0.19$; $P_{\text{model}} = 0.003$) and the CDG diet ($R^2 = 0.25$; $P_{\text{model}} < 0.001$). The response in DMI was negative if the control diets or CDG diets contained more than 34 or 28% starch, respectively. These responses in DMI were evident in lower-producing cows, but not in higher-producing cows (Table 3).

Forage concentration influenced DMI response to CDG ($R^2 = 0.18$; $P_{\text{model}} < 0.01$). Each additional percentage unit of forage was associated with a decrease in DMI response of 0.079 (± 0.026) kg/cow per day. Forage concentration less than 49% was related to a positive DMI response to CDG. In addition, a linear relationship between corn silage concentration and DMI response to CDG existed ($R^2 = 0.09$; $P_{\text{model}} = 0.04$; $n = 44$). Response was positive for diets containing

less than 37% corn silage, but negative for diets with greater corn silage concentrations.

Response in DMI to CDG was associated with concentrations of EE in the control diets ($R^2 = 0.37$; $P_{\text{model}} < 0.001$; $n = 32$) and in CDG diets ($R^2 = 0.26$; $P_{\text{model}} < 0.01$; $n = 32$). Dry matter intakes of cows increased 0.68 (± 0.162) and 0.73 (± 0.225) kg/cow per day in control and CDG diets, respectively, per percentage unit of dietary EE. Concentrations above 3.8 and 4.8% EE in control and CDG diets, respectively, were related to a positive DMI response; yet, Δ -EE was not related to DMI response.

DISCUSSION

We hypothesized, based on observations from the field, that dietary inclusion of CDG is a risk factor for MFD and risk is greater when CDG is included in highly fermentable diets. Based on the results of this meta-analysis, we can neither accept nor reject our hypothesis. Overall, inclusion of CDG or concentration of CDG in treatment diets did not consistently affect milk fat concentration response. Yet, milk fat concentration response to CDG was negative when milk fat concentration in control diets was greater than 3.6%. Milk fat concentration was less than 3.6% in more than three-quarters of the treatment means in the database and dietary inclusion of CDG was related to a positive response in milk fat concentration, when milk fat concentration of the control diet within the experiment was below 3.6%. However, milk fat concentration in commercial herds is often greater than 3.6% before CDG is introduced into rations. Therefore, the observed negative effect of CDG on milk fat test in the field likely occurs more typically when basal milk fat concentrations are greater than 3.6%.

Coincidentally with the low milk fat concentration, estimated starch concentration in many of the control diets in the database exceeded the commonly recommended 23 to 30% of ration DM for higher-producing cows (Grant, 2005). Starch concentration in the control diets correlated negatively with milk fat concentration ($r = -0.36$; $P < 0.001$) in the current meta-analysis database. Moreover, milk fat concentration responded more favorably when CDG replaced HMC compared with DC. Starch from HMC is more degradable in the rumen than that from DC and may cause MFD (Oba and Allen, 2003). Presumably, substituting CDG for portions of the corn grain alleviated the potential milk fat-depressing effects of a higher dietary concentration of corn starch (Emery, 1988), especially when HMC was fed. This may, in part, explain the positive milk fat concentration response in trials with less than 3.6% milk fat when cows were fed the control diets.

The low mean milk fat concentration in cows fed control diets (3.42%) may restrict the applicability of this meta-analysis in commercial settings. The cows in experiments in the current database were on average 142 DIM ($SD \pm 48$) at the time of sampling across all experiments. Thus, the negative correlation of milk fat concentration in control and milk fat concentration response to CDG is unlikely a result of diluted milk fat concentration in early lactation. More likely, the excessive starch or grain concentration in control diets led to the low mean milk fat concentration in control.

Increased dietary concentration of linoleic acid presents an additional risk factor for MFD by increasing substrate for biohydrogenation (Lock, 2010). Corn distillers grains contain approximately 5% linoleic acid, dry basis (Schingoethe et al., 1999; Leonardi et al., 2005; Anderson et al., 2006; Sasikala-Appukuttan et al., 2008). Thus, supplementation of CDG to cows can alter ruminal biohydrogenation of FA and may increase outflow of *trans*-10 *cis*-12 $C_{18:2}$ from the rumen, especially in combination with other dietary risk factors for MFD, such as a highly fermentable diet. This may cause MFD by decreasing de novo synthesis of FA in the mammary gland. The proportion of milk FA shorter than 18 carbon atoms was less in CDG treatments than that in control treatments in several experiments (Schingoethe et al., 1999; Leonardi et al., 2005; Anderson et al., 2006; Sasikala-Appukuttan et al., 2008), and concentration of *trans*-10 *cis*-12 $C_{18:2}$ or *trans*-10 $C_{18:1}$ in milk fat was increased in 2 of 3 CDG diets (Leonardi et al., 2005; Anderson et al., 2006; Sasikala-Appukuttan et al., 2008).

In the current meta-analysis, milk fat yield was decreased when CDG was included in diets of cows with low DMI and dietary corn silage concentration less than 20% or more than 40% of dietary DM. Milk fat yield response was more correlated with MY response ($r = 0.73$; $P < 0.001$) than with milk fat concentration response ($r = 0.32$; $P = 0.03$), and MY response was correlated negatively with milk fat concentration response. Apparently, MY responses offset or were not synchronal with milk fat concentration responses to the CDG diet. The net result was less variation accounted for in the milk fat yield response compared with that of milk fat concentration or MY.

Milk yield response to CDG peaked at approximately 20% CDG (of total dietary DM) but response was influenced by diet composition. Inclusion of CDG decreased MY when diet fermentability was high (e.g., when dietary concentrations of corn silage or starch were greater than 47 or 32%, respectively). Nonetheless, it was surprising that factors characterizing diet fermentability (e.g., increasing concentrations of corn silage, starch, or grain; or, grain fermentability), gener-

ally implicated in potential MFD, better described the MY response in the current study. Dietary concentrations of corn silage, corn grain, starch, and CDG are inseparably confounded with the protein quality of the diet. Diets with high concentrations of CP from corn sources may be limited in one or more essential AA (NRC, 2001). This limitation may be exacerbated when CDG replaces non-corn sources of CP. The MY response, therefore, may be related to dietary CP quality based on the concentration of CP originating from corn sources in the diet. The associations of dietary protein quality with lactational responses to CDG are characterized in the companion paper (Hollmann et al., 2011).

Schingoethe et al. (2009) suggested that sufficient dietary forage (e.g., 50% of dietary DM) prevents the decrease in milk fat percentage in response to feeding CDG. Based on our current analysis, dietary starch concentration was associated with milk fat concentration response to the CDG diet, but the response was not necessarily related to forage concentration. In general, compositional differences in treatment diets (e.g., addition of CDG, forages, and other feedstuffs) lead to poor repeatability of milk fat percentage responses to dietary treatments (Clark and Armentano, 1997; Firkins, 1997). The increase in milk fat concentration with CDG diet reported by Clark and Armentano (1997) was not likely a result of an increased chewing activity because non-forage fiber sources have little effect on chewing activity (Allen, 1997) and can increase milk fat concentration without affecting chewing activity (Clark and Armentano, 1997). However, ForNDF concentration is correlated positively with chewing time and milk fat percentage (Armentano and Pereira, 1997). And, in our analysis, ForNDF concentration of control and CDG diets correlated negatively to milk fat concentration response, but positively to MY response. Dietary forage and EE concentrations were confounded within this database ($r = -0.76$; $P < 0.001$), as concentrates, such as grains, proteins, and feed byproducts, presumably contained more EE than forages. Therefore, results of this analysis on the basis of EE concentrations must be viewed cautiously.

Lower-producing cows are more prone to MFD than higher-producing cows, when fed the same, highly fermentable diet (Bradford and Allen, 2004). Similarly, a stronger and more significantly negative correlation occurred between milk fat concentration in the control and milk fat concentration response in lower- than in higher-producing cows in the present study. In contrast, some variables of diet fermentability explained MY response to CDG more consistently in higher- than in lower-producing cows. A significant portion of lactating dairy cows are likely lower-producing cows based on

the breakpoint of 30.0 kg/cow per day. The level of milk production should be included in determining how much CDG to feed, because responses in milk fat concentration and DMI were more affected in lower- than in higher-producing cows, whereas MY response was more affected in higher-producing cows.

The contradicting responses in MY and milk fat concentration led to factors explaining less variability in FCMY response than in MY response, and, consequentially offsetting effects on milk fat yield. Indeed, MY response correlated negatively to milk fat concentration response ($r = -0.37$; $P = 0.01$) in the current analysis. In addition, response in FCMY to CDG was correlated strongly with response in MY ($r = 0.89$; $P < 0.001$), but not with response in milk fat concentration ($P > 0.20$).

Efficiency of converting corn starch into ethanol has improved with new technologies implemented in the distilling process, thus, changing the composition of CDG over time (Rausch and Belyea, 2006). Furthermore, nutrient composition of CDG varies significantly among batches from plants, among plants, by processing method, and as technology and know-how have improved over the past 25 yr (Rausch and Belyea, 2006). We were unable to differentiate between different types of CDG, because of lack of research results in the literature [e.g., wet ($n = 4$) vs. dry ($n = 40$) CDG]. Furthermore, for our analysis, we assumed no residual starch in CDG post-distillation. Interestingly, CDG depressed MY at least 2.0 kg/cow per day for all experiments published between 1985 and 1989. However, since 1989 MY was increased by CDG in some experiments and the greatest depression in MY was 0.9 kg/cow per day. Indeed, MY response to CDG across the whole database (1985 through 2008) increased 0.20 kg/cow per day ($R^2 = 0.66$; $P < 0.001$; $n = 43$) annually. In addition to changes in composition of CDG, a better understanding of ration formulation and feeding of CDG likely led to better research studies on CDG. Finally, as with any meta-analysis, the possibility of reporting bias can be a general concern (Egger et al., 1997). There is always the question if some studies with unfavorable outcomes are not reported in the scientific literature; for example, perhaps studies with CDG diets that caused MFD may not have been published. Additionally, the majority of control diets in our database had dietary starch concentrations greater than 30% and milk fat concentration less than 3.6%; these results may not necessarily represent those typical in the field.

CONCLUSIONS

Lactational responses to dietary CDG in dairy cows were related to measures of dietary fermentability and

level of milk production and milk fat concentration. Milk fat concentration response to CDG was negatively related to milk fat concentration in the control. Presumably, substituting concentrates with CDG alleviated the adverse effect of a highly fermentable diet, such as diets with HMC. However, dietary CDG inclusion was related to a negative milk fat concentration response when milk fat concentration was greater than 3.6% in the control diet. Milk yield response was associated with dietary concentrations of corn silage, starch, and grain. Moreover, MY response was associated with the difference in starch concentration replaced by CDG compared with the control. Supplying too much or too little corn silage or starch was related to a decreased MY response to CDG. Furthermore, responses to CDG based on dietary fermentability factors differed by level of MY. Corn distillers grains influenced milk fat concentration and DMI more in lower-producing cows and MY in higher-producing cows. Therefore, diet fermentability and production level must be considered when including CDG in dairy cow rations.

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