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Performance of early-lactation dairy cows as affected by dietary starch and monensin supplementation

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ABSTRACT

The objective of this study was to evaluate the effect of postpartum dietary starch content and monensin supplementation throughout the periparturient period and into early lactation on production performance of dairy cows during early lactation. Prior to parturition, primiparous (n = 21) and multiparous (n = 49) Holstein cows were fed a common controlled-energy close-up diet with a daily topdress of either 0 or 400 mg/d monensin. From d 1 to 21 postpartum, cows were fed a high-starch (HS; 26.2% starch, 34.3% NDF, 22.7% ADF, 15.5% CP) or low-starch (LS; 21.5% starch, 36.9% NDF, 25.2% ADF, 15.4% CP) total mixed ration with a daily topdress of either 0 mg/d of monensin or 450 mg/d monensin (MON), continuing with prepartum topdress treatment assignment. From d 22 through 63 postpartum, cows were fed HS and continued with their assigned daily topdress. Interactions of starch content and MON supplementation were not significant for any of the variables measured. Cows fed HS from wk 1 to 3 postpartum had higher early-lactation milk yields (starch × week interaction) compared with LS cows, but HS cows also had lower percentages of milk fat, true protein, lactose, and total solids during the same period, resulting in similar yields of energy-corrected milk (ECM) between starch treatments. Cows fed HS had higher early-lactation dry matter intake (DMI; starch × week interaction) and lost less body condition score during wk 1 to 3, contributing to improved energy balance postpartum. No effect of starch treatment was observed on apparent total-tract dry matter or starch digestibilities assessed during d 18 to 19 (±2) postpartum, although cows fed the LS diet had greater apparent total-tract NDF digestibility compared with cows fed the HS diet. Cows fed MON had higher DMI and higher milk yields during the first 9 wk of lactation. However, all cows had similar yields of ECM because of trends for lower milk fat content during early lactation. In part because of similar yields of ECM between these treatments and higher DMI for cows fed MON, ECM per DMI during the first 9 wk of lactation was not affected by MON treatment. There was no effect of MON treatment on apparent total-tract dry matter, NDF, or starch digestibilities. Overall, cows fed more propiogenic diets in early lactation (HS or MON) had increased milk yield and DMI during the immediate postpartum period, indicating that diets with greater propiogenic capacity do not have detrimental effects on early-lactation DMI.

Key words: early lactation, starch, monensin

INTRODUCTION

In the period immediately following calving, DMI is insufficient to support the high milk production of early lactation, resulting in a state of negative energy balance (**EB**) that usually begins a few days before calving and reaches the greatest deficit about 2 wk after parturition (Butler, 2000). This state of negative EB results in the increased mobilization of adipose tissue, manifested as the release of NEFA into circulation to be metabolized by the liver and other tissues and incorporated into milk fat in the mammary gland. Higher DMI postpartum generally results in lower circulating NEFA and has been associated with improved health, performance, and less severe postpartum negative EB (Ingvartsen and Andersen, 2000).

Optimizing DMI during the periparturient period is especially important to provide sufficient available energy to support milk production. Because of the increased glucose demand for milk lactose synthesis, hepatic glucose production nearly doubles within 11 d of calving compared with prepartum hepatic glucose output (Reynolds et al., 2003). Propionate that is produced via fermentation of starch in the rumen is the main precursor for hepatic glucose production (Aschenbach et al., 2010). Monensin is an ionophore that has also been shown to increase ruminal propionate production (Armentano and Young, 1983), likely from changes in the populations of gram-positive bacteria along with changes in the metabolism of gram-negative bacterial

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populations in the rumen that occur with ionophore treatment (McGuffey et al., 2001).

Allen et al. (2009) proposed that hepatic energy status is a major regulator of DMI in dairy cows. When hepatic oxidative fuel supply (propionate and NEFA) exceeds hepatic energy requirements, the brain is signaled via the vagal afferent nerve to reduce DMI (Allen et al., 2009). This hepatic oxidation theory would suggest that feeding diets that promote greater ruminal propionate production (e.g., high in fermentable starch, monensin supplementation) during early lactation could be hypophagic and thus further reduce DMI during this period of negative EB. If the hepatic oxidation theory applies to the early lactation period, then reducing dietary starch content or fermentability may increase DMI by reducing propionate production in the rumen (Allen et al., 2009). Recent work conducted using early-lactation animals has shown propionate infusion to be more hypophagic in animals with higher liver acetyl CoA concentrations (Stocks and Allen, 2012, 2013), which would occur with higher NEFA mobilization. Because liver energy requirements increase dramatically at the onset of lactation (Reynolds et al., 2003), concurrent with increased adipose mobilization (Ingvartsen and Andersen, 2000), we speculated that NEFA are most likely the predominant hepatic oxidative substrate during this period. Thus, the hypophagic effect of propionate is likely to be reduced in the immediate postpartum period because of these large increases in hepatic energy demands at the onset of lactation (Reynolds et al., 2003).

The efficacy of monensin to decrease periparturient negative EB-associated health disorders, improve energy metabolism, and enhance lactation performance has been demonstrated (Duffield et al., 2008a, b, c). However, based upon the concepts presented in the hepatic oxidation theory, it is of interest to determine whether effects of monensin on performance of postpartum cows are independent of dietary starch content, as both likely will increase supply of propionate. The objectives of the current study were to evaluate the effects of dietary starch content during the immediate postpartum period on intake and production, and to evaluate the effects of peripartal monensin supplementation in conjunction with these diets of differing starch content on DMI, production, feed efficiency, and EB. We hypothesized that increasing starch content during the immediate postpartum period and feeding monensin throughout the periparturient period and into early lactation would enhance milk production and improve energy metabolism without detrimental effects on DMI, and that the effects of monensin on performance would be independent of postpartum dietary starch content.

MATERIALS AND METHODS

Animals and Treatments

All animal procedures were approved by the Cornell University Institutional Animal Care and Use Committee and the experiment was conducted from March to October 2012. The study was a completely randomized design with randomization restricted to balance for expected calving date of primiparous and multiparous cows and previous lactation 305-d mature-equivalent milk production for multiparous cows. A 2 × 2 factorial arrangement of postpartum treatments was used with an early lactation period feeding strategy [high-starch (**HS**) vs. low-starch (**LS**) diet during the first 21 d postpartum] and postpartum monensin supplementation [0 (**CON**) or 450 mg/d (**MON**); Rumensin, Elanco Animal Health, Greenfield, IN] as the variables of interest. In addition, cows that received MON during the postpartum period were fed MON (400 mg/d) beginning on 1 d between d 21 to 28 before expected parturition (average treatment of 25 d; minimum of 14 d on treatment before actual parturition was required for inclusion in the data set). It is our experience that farms that feed monensin typically feed monensin throughout the entire transition period and into established lactation, which is why we chose to continue either monensin or control treatments throughout the entire trial period; in addition, monensin treatment was initiated during the prepartum period to allow time for ruminal adaptation before calving. The HS and LS dietary treatments reflect common feeding strategies on commercial farms and were designed specifically to evaluate whether starch content of the diet fed during the early postpartum period affected DMI and cow performance.

A total of 80 cows were enrolled in the study and the final data set included a total of 70 cows (HS + CON primiparous n = 5, multiparous n = 13; HS + MON primiparous n = 5, multiparous n = 13; LS + CON primiparous n = 6, multiparous n = 13; LS + MON primiparous n = 5, multiparous n = 10). A total of 10 cows were removed from the experiment for reasons not related to experimental treatments (6 calved before having a minimum of 2 wk on the dry period treatment, 3 calved with twins, 1 was removed from data set for being an outlier with milk production that was 3 SD below the mean). Lactating cows were dried off at least 45 d (average 53-d dry period length) before expected parturition, and moved to the experimental tiestall barn approximately 28 d before expected parturition where they began consuming the experimental close-up dry cow diet (Table 1).

Table 1. Ingredient composition of the basal diets (% of DM)

Item	Prepartum	Postpartum[1] HS	LS
Corn silage, processed	42.14	—	—
BMR corn silage[2]	—	38.50	38.50
Wheat straw	21.75	11.54	11.55
Legume silage	—	9.62	9.62
Shelled corn, finely ground	4.28	20.97	10.29
Citrus pulp	7.23	1.01	7.15
Corn germ meal	—	2.52	5.56
Soybean hulls	7.08	—	3.58
Soybean meal	5.27	5.87	3.86
Canola meal	4.63	2.73	2.08
Blood meal	1.05	1.94	1.93
Amino Plus[3]	1.78	1.70	2.34
Energy Booster 100[4]	—	0.77	0.96
Calcium carbonate	1.53	1.12	0.82
Sodium bicarbonate	—	0.86	0.85
Soy Chlor[5]	1.33	—	—
Salt	0.16	0.42	0.41
Calcium sulfate	0.73	0.17	0.17
Magnesium oxide	0.20	0.15	0.15
Magnesium sulfate, 9.9%	0.61	—	—
Selenium 0.06%	0.04	0.05	0.05
Mono dicalcium phosphate	—	0.02	0.07
Trace mineral premix[6]	0.02	0.03	0.03
Vitamin A, D, E premix[7]	0.05	0.02	0.02
Vitamin E premix[8]	0.005	—	—
Zinc sulfate	0.002	—	—
Copper sulfate	0.0004	0.001	0.001

[1]HS = high-starch diet (26.2% starch); LS = low-starch diet (21.5% starch).

[2]BMR = brown midrib corn silage.

[3]AGP Inc., Omaha, NE.

[4]Milk Specialties Global, Carpentersville, IL.

[5]West Central, Ralston, IA.

[6]Contained 30,317 mg/kg of Cu, 136,466 mg/kg of Mn, 3,393 mg/kg of Co, 3,040 mg/kg of I, and 153,916 mg/kg of Zn.

[7]Contained 30,464 IU/kg of vitamin A, 5,862 IU/kg of vitamin D, and 93,784 IU/kg of vitamin E.

[8]Contained 510,750 IU/kg of vitamin E.

Diet Formulation, Nutrient Composition, and Feeding

Diets were balanced using the Cornell Net Carbohydrate and Protein System (CNCPS version 6.1, Cornell University, Ithaca, NY) and were fed for ad libitum intake. The HS and LS experimental diets were fed from parturition until d 21 postpartum, after which, on d 22, all cows were fed the HS diet until the end of the study at d 63 of lactation.

The ingredient composition of the diets is shown in Table 1. All formulated diets were typical of the northeast and upper Midwest regions of the United States. Prepartum all cows were fed a controlled-energy ration based on corn silage, wheat straw, and a concentrate mix. Forage compositions are presented in Table 2. Postpartum diets were formulated on the basis of a lactation diet in which brown midrib corn silage was the predominant forage, with smaller amounts of wheat straw and legume silage. The concentrate portion of the HS diet was based on corn grain (20.97% of diet DM). For the LS diet, corn grain (10.29% of diet DM) was partially replaced with citrus pulp (7.15% of diet DM) and soy hulls (3.58% of diet DM).

Mean composition (±SD) of the TMR and topdress pellets are presented in Table 3. The topdress pellets were analyzed as single samples; therefore, standard deviations are not given. The basal HS and LS diets were formulated to contain 28.0 and 21.0% starch, respectively, whereas the analyzed starch contents of the basal HS and LS diets were 26.2 and 21.5%. The calculated composition of the total diet (TMR + topdress) is presented in Table 4. The calculated starch contents, accounting for the contribution of the topdress pellets, of the HS and LS diets were 25.5 and 20.9% starch, respectively, during wk 1 to 3 postpartum. The analyzed and calculated starch content of the HS diet was lower than expected; however, the difference between the 2 diets is meaningful from an application standpoint.

Table 2. Nutrient composition of corn silage, brown midrib (BMR) corn silage, legume silage, and wheat straw (±SD)[1]

Item	Corn silage	BMR corn silage	Legume silage	Wheat straw
DM, % as fed	32.7 ± 1.9	31.3 ± 0.8	41.0 ± 4.3	93.5 ± 1.9
CP, %	8.5 ± 0.5	8.6 ± 0.3	20.4 ± 1.8	4.7 ± 1.3
ADF, %	22.7 ± 0.7	24.6 ± 0.9	32.3 ± 3.2	55.8 ± 2.7
NDF, %	38.1 ± 1.4	39.5 ± 1.1	39.2 ± 4.5	79.9 ± 1.8
30-h NDFD,[2,3] %	21.4	26.6	17.1	33.1
30-h NDFD,[2,3] % of NDF	55.4	67.3	43.3	41.2
Sugar,[2] %	1.3	1.5	3.7	2.1
Starch,[2] %	33.1	30.6	1.5	0.9
Fat,[2] %	4.4	3.6	3.4	0.5

[1]Chemcial composition was analyzed on 6 composite samples.

[2]Chemcial composition for these analyses were determined on 1 sample obtained from a subsample of the 6 composites.

[3]NDFD = NDF digestibility.

Table 3. Chemical composition of experimental diets (±SD)[1]

Item	Prepartum diet	Postpartum diet[2]		Topdress pellet[3]	
		HS	LS	CON[4]	MON[5]
DM, %	50.7 ± 2.4	48.3 ± 2.7	48.0 ± 3.2	93.2 ± 1.0	93.7 ± 1.2
CP, %	13.0 ± 0.8	15.5 ± 1.2	15.4 ± 0.8	37.5	37.0
ADF, %	28.2 ± 1.2	22.7 ± 1.2	25.2 ± 1.2	11.1	12.9
NDF, %	42.9 ± 2.0	34.3 ± 1.5	36.9 ± 1.5	22.6	21.3
30-h NDFD,[6] %	—	18.9 ± 1.2	20.7 ± 1.1	—	—
30-h NDFD,[6] % of NDF	—	55.1 ± 2.0	56.1 ± 1.4	—	—
Sugar, %	4.9 ± 0.8	3.5 ± 0.6	4.5 ± 0.4	10.6	11.3
Starch, %	17.4 ± 1.2	26.2 ± 1.2	21.5 ± 1.0	13.1	13.8
Fat, %	2.6 ± 0.2	4.0 ± 0.2	2.2 ± 0.6	2.4	2.5
Ca, %	1.28 ± 0.16	0.94 ± 0.09	1.01 ± 0.04	0.51	0.6
P, %	0.30 ± 0.02	0.34 ± 0.02	0.34 ± 0.02	0.97	0.99
Mg, %	0.41 ± 0.04	0.28 ± 0.02	0.3 ± 0.03	0.48	0.48
K, %	1.12 ± 0.13	1.12 ± 0.09	1.18 ± 0.08	1.67	1.70
S, %	0.37 ± 0.04	0.21 ± 0.09	0.22 ± 0.01	0.46	0.44
Na, %	0.12 ± 0.02	0.47 ± 0.08	0.46 ± 0.05	0.07	0.07
Cl, %	0.37 ± 0.01	0.44 ± 0.04	0.44 ± 0.03	0.07	0.09
NE_L, Mcal/kg	1.48 ± 0.03	1.64 ± 0.02	1.56 ± 0.03	1.72	1.74

[1]Chemcial composition was analyzed on 6 composite samples of the prepartum diet, 7 composite samples of the high-starch postpartum diet, and 6 composite samples of the low-starch postpartum diet.

[2]HS = high-starch diet (26.2% starch); LS = low-starch diet (21.5% starch).

[3]The composition of the topdress was 33.6% soybean meal, 33.2% wheat middlings, and 33.2% canola meal (DM basis).

[4]CON = control topdress, formulated to supplement 0 mg/d of monensin.

[5]MON = monensin topdress, formulated to supplement 400 mg/d prepartum and 450 mg/d postpartum.

[6]NDFD = NDF digestibility.

The topdress pellets consisted of 33.6% soybean meal, 33.2% wheat middlings, and 33.2% canola meal (DM basis), and were formulated to contain either 0 (CON) or 473 g/t of MON. The MON topdress fed was targeted to provide 400 mg/d prepartum and 450 mg/d postpartum and was fed as a daily topdress at rates of 0.85 kg of DM/d prepartum and 0.95 kg of DM/d postpartum. The concentration of MON in the topdress was verified by Covance Laboratories (Greenfield, IN; AOAC International, 2006; method 997.04). The mean assayed concentration of MON was 461 g/t. No MON was detected in the CON topdress (assayed concentration was below the level of detection; <1.0 g/t). Cows continued to receive assigned topdress treatments through wk 9 postpartum.

Cows were fed once daily for ad libitum intake at 0700 h. Refusals were removed daily before feeding, weighed, and recorded. All ingredients were sampled weekly for determination of DM content by drying at 55°C for 48 h and values were used weekly to adjust ration formulation. Water was available ad libitum.

Data Collection, Sampling Procedures, and Analytical Methods

Samples of all TMR and ration ingredients were obtained weekly and composited at 4-wk intervals for analysis. Samples were analyzed for chemical composition using wet chemistry techniques for CP (method 990.03; AOAC International, 2006), NDF using α-amylase and sodium sulfite (Van Soest et al., 1991), ADF (method 973.18; AOAC International, 2006), lignin (Goering and Van Soest, 1970), 30-h NDF digestibility (Goering and Van Soest, 1970), starch (Hall, 2009), sugar (Dubois et al., 1956), ether extract (method 2003.05; AOAC International, 2006), ash (method 942.05; AOAC International, 2006), neutral detergent-insoluble CP, acid detergent-insoluble CP, soluble CP (Krishnamoorthy et al., 1982), and minerals (method 985.01; AOAC International, 2006) at a commercial laboratory (Cumberland Valley Analytical Services, Hagerstown, MD). Dry matter intake was calculated from the amounts of feed offered and refused, together with the corresponding DM value for the TMR, and weekly means of daily DMI, starch, and NDF intakes were calculated for statistical analysis.

All cows were weighed once weekly and BCS were assigned for all cows weekly by 2 individuals using a 5-point system (Wildman et al., 1982). The scores were averaged before statistical analysis. Daily observations and general health records were maintained throughout the study.

All cows were milked 2 times daily for the 9-wk lactation phase of the trial and daily milk yield was measured electronically. Daily milk yield was the sum of the 2 milkings, and weekly means of daily production were calculated before statistical analysis. Milk samples were collected from 2 consecutive milkings

Table 4. Calculated diet composition during the prepartum and postpartum periods, including both TMR and topdress, for cows fed high-starch (HS) or low-starch (LS) diets during wk 1 to 3 postpartum

Item	Prepartum	Postpartum[1]	
		HS	LS
DM, %	53.6	51.1	50.9
CP, %	14.7	16.8	16.8
ADF, %	27.1	22.1	24.4
NDF, %	41.5	33.6	35.9
30-h NDFD,[2] %	—	18.9	20.7
30-h NDFD,[2] % of NDF	—	55.1	56.1
Sugar, %	5.3	4.0	4.9
Starch, %	17.1	25.5	20.9
Fat, %	2.6	3.9	2.2
Ca, %	1.23	0.91	0.98
P, %	0.35	0.38	0.38
Mg, %	0.41	0.29	0.31
K, %	1.16	1.15	1.21
S, %	0.38	0.23	0.24
Na, %	0.12	0.46	0.44
Cl, %	0.35	0.42	0.41
NE_L, Mcal/kg	1.50	1.65	1.57
ME, Mcal/kg DM[3]	2.16	2.50	2.45
Total metabolizable protein available,[3] g/d	1,150	1,660	1,548
Metabolizable protein,[3] g/kg of DM	92.74	106.41	104.59
Carbohydrate fermentability,[3] % of DM	41.9	41.1	40.7
NDF fermentability,[3] % of DM	15.5	11.5	13.6
Starch fermentability,[3] % of DM	15.2	21.9	17.1

[1]HS = 26.2% starch; LS = 21.5% starch.

[2]NDFD = NDF digestibility.

[3]Values predicted in CNCPS (v 6.1) using actual feed intakes of 12.4 kg/d of DMI for dry cows, 15.6 kg/d of DMI for cows fed HS, and 14.8 kg/d of DMI for cows fed LS.

obtained over a 24-h period once per week. Individual milk samples were sent to a commercial laboratory for analysis of milk composition (Dairy One, Ithaca, NY). Samples were analyzed for contents of fat, true protein, lactose, TS, MUN using midinfrared analysis (AOAC International, 2006; method 972.160), and SCC by an optical fluorescent method (AOAC International, 2006; method 978.26); SCS was calculated as SCS = $\log_2(\text{SCC}/100) + 3$. Weekly yields of milk components were calculated, as well as yields of 3.5% FCM = [0.432 × milk (kg)] + [16.216 × fat (kg)] (Dairy Records Management Systems, 2014), and ECM = [0.327 × milk (kg)] + [12.95 × fat (kg)] + [7.65 × true protein (kg)] as described by Tyrrell and Reid (1965).

Prepartum and postpartum energy balance calculations were determined according to NRC (2001) equations. Weekly values for prepartum calculated energy balance were determined as follows:

$$\text{Prepartum NE}_L \text{ (Mcal/d) balance} = \text{energy intake (Mcal of NE}_L\text{/d)} - [\text{maintenance requirement (Mcal of NE}_L\text{/d)} + \text{pregnancy requirement (Mcal of NE}_L\text{/d)}],$$

where energy intake (Mcal/d) = weekly DMI average (kg/d) × diet NE_L (Mcal/kg of DM); maintenance requirement (Mcal) = weekly metabolic BW (**MBW**; $kg^{0.75}$) × 0.08 (Mcal/$kg^{0.75}$ per day); and pregnancy requirement (Mcal) = (0.00318 × d of gestation − 0.0352) × (1/0.218).

Weekly values for postpartum calculated energy balance were determined as follows:

$$\text{Postpartum NE}_L \text{ (Mcal/d) balance} = \text{energy intake (Mcal of NE}_L\text{/d)} - [\text{maintenance requirement (Mcal of NE}_L\text{/d)} + \text{lactation requirement (Mcal of NE}_L\text{/d)}],$$

where energy intake (Mcal/d) = weekly DMI average (kg/d) × diet NE_L (Mcal/kg of DM); maintenance requirement (Mcal/d) = weekly MBW ($kg^{0.75}$) × 0.08 (Mcal/ $kg^{0.75}$ per day); and lactation requirement (Mcal/d) = milk yield (kg/d) × [(0.0929 × fat percentage) + (0.0563 × true protein percentage) + (0.0395 × lactose percentage)].

Total-tract nutrient digestibilities of DM, NDF, and starch were determined using 240-h undigestible NDF as an internal marker and nutrient concentrations in the orts-adjusted diet and feces. Two fecal grab samples were collected from a subset of cows (primiparous n = 14, multiparous n = 33) at 24-h intervals on 2 consecutive days between d 18 and 19 (±2) postpartum. Daily orts samples were collected for each cow and daily treatment TMR samples were collected during the fecal sampling period. Treatment TMR, fecal, and ort samples were composited by the 2-d sampling period (TMR samples) or cow (orts and fecal samples) and the composite samples were analyzed for DM, NDF, starch, and 240-h undigestible NDF (Goering and Van Soest, 1970) at a commercial laboratory (Cumberland Valley Analytical Services).

Statistical Analysis

Statistical analyses were performed using SAS software (version 9.2; SAS Institute Inc., Cary, NC). Prepartum and postpartum data were analyzed separately. Postpartum data were analyzed as a completely randomized design with a 2 × 2 factorial arrangement of treatments. Fixed effects included starch content, MON treatment, parity, time (week), and all 2-way interactions. A prepartum covariate (data collected week before enrollment on prepartum topdress assignment) was used for all DMI, starch and NDF intakes, BW, BCS, and EB analyses. The random effect was cow nested within starch and MON treatment. Postpartum data were analyzed separately as wk 1 to 3 (dietary treatment period) and wk 1 to 9 (duration of experiment). Data measured over time were subjected to ANOVA using the REPEATED statement in the MIXED procedure of SAS (Littell et al., 1996). For variables with measurements repeated over time, 4 covariance structures were tested: compound symmetry, heterogeneous compound symmetry, first-order autoregressive, and heterogeneous first-order autoregressive; the covariance structure that resulted in the smallest Akaike's information criterion was used (Littell et al., 1996). Data not analyzed over time were subjected to ANOVA using the MIXED procedure of SAS (Littell et al., 1996). Fixed effects included starch content, MON treatment, parity, and all 2-way interactions. The random effect was cow nested within starch and MON treatment. Degrees of freedom were estimated by using the Kenward-Roger option in the model statement.

RESULTS

Prepartum DMI, BW, BCS, and EB

Effects of MON treatment during the prepartum period on prepartum weekly DMI, BW, BCS, and EB are shown in Table 5. No effect of prepartum MON treatment was noted for DMI (average 12.5 ± 0.2 kg/d), BW (679 ± 4 kg), or BCS (3.55 ± 0.03). Overall, cows maintained similar DMI as a percent of BW prepartum; however, as parturition approached, cows fed MON had slightly lower DMI as a percent of BW compared with CON cows (MON × week interaction; $P = 0.002$). Primiparous cows fed MON gained 8 kg less precalving than primiparous cows fed CON (MON × parity interaction; $P < 0.001$). Cows fed MON tended to have a greater decrease in BCS prepartum compared with CON ($P = 0.07$), and had generally decreasing EB as parturition approached, expressed as both megacalories per day and as a percentage of requirement, whereas changes were less in CON cows (MON × week interaction; $P = 0.009$ and $P = 0.006$ respectively).

Milk Production and Composition

Milk production and composition results are reported in Table 6. Interactions of starch content in the early postpartum diet and MON treatment were not significant for any of the variables measured; therefore,

Table 5. Prepartum DMI, BW, and BCS as affected by monensin supplementation beginning during the prepartum period

	Prepartum diet[1]			*P*-value					
Item	CON[2]	MON[3]	SEM	MON	Parity	Week	MON × week	MON × parity	Parity × week
DMI, kg/d	12.3	12.6	0.2	0.37	<0.001	<0.001	0.39	0.87	0.08
DMI, % of BW	1.76	1.79	0.05	0.65	<0.001	<0.001	0.002	0.99	0.20
BW, kg	680	678	4	0.71	0.18	<0.001	0.56	0.76	0.42
BW change,[4] kg	21	21	13	0.84	<0.001	—	—	<0.001	—
BCS	3.56	3.53	0.03	0.40	0.003	0.001	0.78	0.34	0.07
BCS change[4]	−0.02	−0.12	0.04	0.07	0.13	—	—	0.11	—
Energy balance, Mcal/d	5.00	5.11	0.54	0.88	<0.001	<0.001	0.009	0.18	0.35
Energy balance, %	140.44	140.62	4.60	0.98	<0.001	<0.001	0.006	0.16	0.20

[1]CON = control topdress; MON = monensin topdress.

[2]Formulated to supplement 0 mg/d of monensin.

[3]Formulated to supplement 400 mg/d prepartum and 450 mg/d postpartum.

[4]Body weight and BCS change were calculated as the difference between BW (or BCS) at the initiation of monensin treatment and wk −1 prepartum.

Table 6. Milk yield and composition for cows fed either high- or low-starch diets during the first 3 wk postpartum and control or monensin treatments throughout the periparturient period and into early lactation

	Diet[1]			Topdress[2]			*P*-value[5]							
Item	HS	LS	SEM	CON[3]	MON[4]	SEM	S	M	P	S × M	S × week	M × week	S × P	M × P
Milk yield, kg/d														
wk 1 to 3	31.0	29.8	0.9	29.8	31.0	0.9	0.35	0.32	<0.001	0.45	0.002	0.07	0.57	0.63
wk 1 to 9	36.3	36.0	0.8	35.1	37.3	0.8	0.81	0.05	<0.001	0.43	<0.001	0.19	0.33	0.71
3.5% FCM, kg/d														
wk 1 to 3	34.7	36.3	1.2	35.9	35.1	1.3	0.36	0.64	<0.001	0.93	0.04	0.98	0.58	0.77
wk 1 to 9	37.1	37.8	1.0	37.0	38.0	1.0	0.61	0.52	<0.001	0.63	0.22	0.44	0.37	0.74
ECM, kg/d														
wk 1 to 3	34.7	36.7	1.2	35.9	35.4	1.2	0.24	0.80	<0.001	0.97	0.01	0.93	0.45	0.93
wk 1 to 9	36.9	37.6	1.0	36.8	37.8	1.0	0.59	0.47	<0.001	0.51	0.19	0.48	0.44	0.55
Fat, %														
wk 1 to 3	4.38	5.01	0.17	4.90	4.48	0.18	0.01	0.10	0.03	0.74	0.46	0.42	0.55	0.98
wk 1 to 9	3.76	3.97	0.09	3.96	3.77	0.09	0.11	0.13	0.002	0.52	0.16	0.69	0.97	0.52
Fat, kg														
wk 1 to 3	1.32	1.44	0.06	1.41	1.34	0.06	0.14	0.34	<0.001	0.91	0.11	0.97	0.67	0.86
wk 1 to 9	1.33	1.37	0.04	1.35	1.35	0.05	0.48	0.93	<0.001	0.95	0.20	0.61	0.56	0.96
True protein, %														
wk 1 to 3	3.31	3.84	0.20	3.59	3.57	0.20	0.05	0.94	0.58	0.33	0.17	0.74	0.98	0.95
wk 1 to 9	2.92	3.10	0.09	3.01	3.01	0.09	0.12	0.96	0.29	0.32	0.22	0.90	0.47	0.75
True protein, kg														
wk 1 to 3	0.99	1.07	0.05	1.02	1.04	0.05	0.25	0.85	<0.001	0.79	0.09	0.44	0.35	0.81
wk 1 to 9	1.03	1.06	0.03	1.02	1.06	0.04	0.53	0.33	<0.001	0.76	0.15	0.64	0.62	0.33
Lactose, %														
wk 1 to 3	4.60	4.83	0.08	4.81	4.62	0.09	0.05	0.09	0.51	0.79	0.30	0.20	0.46	0.81
wk 1 to 9	4.82	4.93	0.04	4.93	4.82	0.04	0.03	0.03	<0.001	0.88	0.08	0.69	0.03	0.69
Lactose, kg														
wk 1 to 3	1.43	1.44	0.05	1.42	1.44	0.05	0.89	0.77	<0.001	0.58	0.04	0.06	0.23	0.90
wk 1 to 9	1.75	1.78	0.04	1.73	1.79	0.04	0.62	0.32	<0.001	0.35	0.09	0.36	0.08	0.70
TS, %														
wk 1 to 3	13.31	14.76	0.40	14.35	13.71	0.40	0.009	0.24	0.13	0.96	0.16	0.59	0.18	0.66
wk 1 to 9	12.42	12.97	0.17	12.88	12.52	0.18	0.03	0.13	0.002	0.76	0.08	0.88	0.46	0.86
TS, kg														
wk 1 to 3	4.04	4.27	0.15	4.17	4.13	0.15	0.26	0.84	<0.001	0.90	0.02	0.69	0.39	0.94
wk 1 to 9	4.44	4.55	0.11	4.44	4.55	0.12	0.49	0.51	<0.001	0.44	0.21	0.63	0.26	0.49
MUN, mg/dL														
wk 1 to 3	11.6	10.9	0.4	10.5	11.9	0.4	0.16	0.007	0.05	0.86	0.44	0.46	0.89	0.59
wk 1 to 9	11.7	11.5	0.4	11.0	12.2	0.4	0.59	0.02	0.23	0.42	0.21	0.37	0.98	0.49
SCS														
wk 1 to 3	3.38	3.28	0.30	3.55	3.11	0.31	0.81	0.30	0.72	0.45	0.04	0.34	0.60	0.89
wk 1 to 9	2.41	2.36	0.29	2.50	2.27	0.30	0.91	0.58	0.07	0.86	0.05	0.28	0.40	0.75

[1]Postpartum diets: HS = high-starch diet (26.2% starch); LS = low-starch diet (21.5% starch).

[2]CON = control topdress; MON = monensin topdress.

[3]Formulated to supplement 0 mg/d of monensin.

[4]Formulated to supplement 400 mg/d prepartum and 450 mg/d postpartum.

[5]S = starch, M = monensin, and P = parity.

results are presented and discussed as the main effects of starch and MON. Overall effects of starch content on milk yield during early lactation were not significant during wk 1 to 3 or 1 to 9; however, treatment × week interactions existed during both periods because cows fed the HS diet had increased milk production in early lactation (Figure 1A; $P < 0.001$). Further evaluation of the patterns of milk yield during wk 1 to 3 for cows fed different starch content using daily milk yield data rather than weekly means suggest that cows fed the HS diet tended to have higher overall milk yield (31.1 vs. 29.2 kg/d; $P = 0.10$; data not shown).

Cows fed HS postpartum diets had lower percentages of milk fat ($P = 0.01$) and true protein ($P = 0.05$) than cows fed LS during wk 1 to 3 postpartum (Table 6); however, these effects were not significant when evaluated over the 9-wk postpartum period. Percentages of lactose ($P = 0.05$) and TS ($P = 0.009$) were also decreased during wk 1 to 3 in cows fed HS postpartum diets compared with those fed LS; these effects were also significant when evaluated over the 9-wk postpartum period ($P = 0.03$ for both variables). A starch × parity interaction ($P = 0.03$) for lactose percentage during wk 1 to 9 suggested that these decreases were more

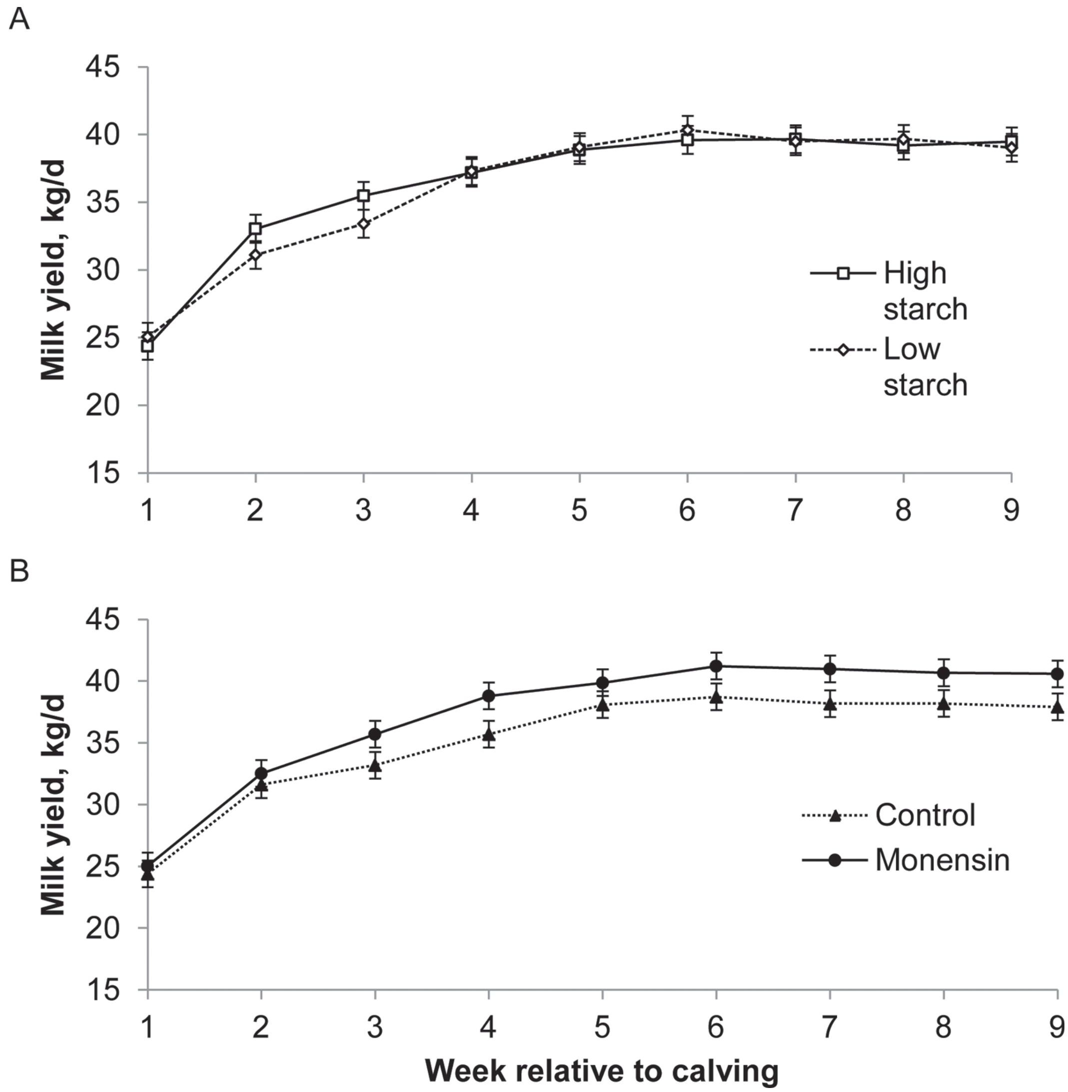

Figure 1. Least squares means (± SEM) for milk yield (kg/d) for cows fed different starch content in the postpartum diet and monensin throughout the periparturient period. Postpartum data was analyzed separately as wk 1 to 3 (dietary treatment period) and wk 1 to 9 (duration of experiment). (A) Effects of high- (26.2%) versus low-starch (21.5%) fed during wk 1 to 9. The P-values for the overall effects of starch content were 0.35 during wk 1 to 3 and 0.81 during wk 1 to 9. The P-values for the interaction of starch content × week were 0.002 for wk 1 to 3 and <0.001 for wk 1 to 9. (B) Effects of monensin supplementation (0 vs. 400 mg/d prepartum and 450 mg/d postpartum). The P-values for the overall effect of monensin were 0.32 for wk 1 to 3 and 0.05 for wk 1 to 9. The P-values for the interaction of monensin × week were 0.07 for wk 1 to 3 and 0.19 for wk 1 to 9.

pronounced in primiparous cows fed HS than multiparous cows (5.08% lactose for primiparous cows fed LS vs. 4.78% for primiparous cows fed HS). There was no difference in lactose yields during wk 1 to 9 for primiparous cows, although lactose yields tended to be higher in multiparous cows fed HS compared with LS (starch × parity interaction; $P = 0.08$; 2.06 kg/d of lactose for multiparous cows fed HS vs. 1.52 kg/d of lactose for multiparous cows fed LS). Overall, concentrations of MUN and SCS were not affected by treatment during either postpartum period evaluated; however, starch × week interactions existed during both wk 1 to 3 ($P = 0.04$) and 1 to 9 ($P = 0.05$) for SCS, although differences appeared to be slight in both cases.

Despite the differences in milk component percentages during wk 1 to 3 for cows fed diets of different starch content, effects of starch content on overall yields of milk fat, true protein, lactose, and TS were not significant during either wk 1 to 3 or 1 to 9 (Table 6). Although overall yields of milk and milk components were not affected by starch content, interactions or trends for interactions of starch content × week existed during wk 1 to 3 for yields of milk and milk components (true protein yield, lactose yield, TS yield, 3.5% FCM, and ECM) such that component yields were lower during the early postpartum period for cows fed the HS diet. Whereas trends for interactions of starch content × week existed for yields of lactose and TS over the 9-wk postpartum period, these effects were small and similar to those detected during wk 1 to 3.

Even though the overall effects of MON administration on milk yield during wk 1 to 3 were not significant, when evaluated from wk 1 to 9 postpartum cows fed MON produced 2.2 kg/d more milk than CON (Figure 1B; $P = 0.05$). Trends for MON × week interactions during wk 1 to 3 for both milk yield ($P = 0.07$) and lactose yield ($P = 0.06$) suggested that yields of each increased more as lactation progressed for cows fed MON compared with those fed CON. Cows fed MON tended to have lower percentages of fat ($P = 0.10$) and lactose ($P = 0.09$) during wk 1 to 3 postpartum; however, effects of MON treatment on percentages of true protein and TS, as well as yields of fat, true protein, lactose, TS, 3.5% FCM, and ECM during wk 1 to 3 were not significant. During wk 1 to 9, cows fed MON had lower percentages of lactose in milk ($P = 0.03$); however, percentages of other components, yields of milk components, and 3.5% FCM and ECM were not affected by treatment. Cows fed MON had higher MUN during wk 1 to 3 and 1 to 9 ($P = 0.007$ and $P = 0.02$, respectively). There was no difference between MON treatments for SCS.

Postpartum DMI, BW, BCS, Milk Production Efficiency, and EB

Postpartum DMI, BW, BCS, milk production efficiency, and EB for cows fed varying content of starch and MON are presented in Table 7. All cows had similar overall DMI, expressed as kilograms per day, during the early lactation period (Figure 2A); however, interactions of starch content × week for DMI (expressed either as kilograms per day or as a percentage of BW) suggested that cows fed HS had a faster increase in DMI during wk 1 to 3 [$P = 0.04$ (kg/d) and $P = 0.01$ (% of BW)]; this difference resulted in a similar interaction from wk 1 to 9 when expressed as a percent of BW (Figure 3A; $P < 0.001$). A starch × week interaction was noted for both wk 1 to 3 ($P < 0.001$) and 1 to 9 ($P < 0.001$) for starch intake, and cows fed HS diets had higher early-lactation starch intakes. Cows fed HS tended to have increased NDF intake during wk 1 to 3 compared with cows fed LS ($P = 0.08$) and a starch × week interaction ($P = 0.004$) was observed for wk 1 to 9, suggesting that HS cows had greater early-lactation NDF intake likely because HS cows had greater early-lactation DMI compared with cows fed LS. There was no effect of dietary starch content on postpartum BW, BW change, or BCS.

Primiparous cows fed the HS postpartum diet lost less BCS compared with those fed LS during the first 3 wk postpartum (−0.37 for LS primiparous cows vs. −0.01 for HS primiparous cows; starch × parity interaction; $P = 0.01$). Milk production efficiency during both wk 1 to 3 and 1 to 9, calculated either as milk yield per unit of DMI ($P = 0.04$ for both time periods) or ECM yield per unit of DMI ($P = 0.002$ and 0.006, respectively), was increased in cows fed the LS diets. This increased calculated milk production efficiency is likely because cows fed the LS diet had decreased DMI postpartum and likely were mobilizing more adipose tissue during wk 1 to 3 rather than reflecting a true increase in feed efficiency for cows fed the LS diet. Cows fed HS diets postpartum had less severe negative EB compared with LS cows ($P < 0.001$). There was an interaction of starch × week during wk 1 to 9 for EB, and cows fed LS had a greater degree of negative EB postpartum compared with cows fed HS when expressed as either megacalories per day (Figure 4A; $P < 0.001$) or as a percentage of requirements ($P < 0.001$).

Overall cows fed MON had a 1.8-kg/d higher DMI than CON cows during wk 1 to 3 and a 1.1-kg/d higher DMI during wk 1 to 9. This increase in DMI was driven by an interaction of MON × week for both wk 1 to 3 ($P = 0.009$) and 1 to 9 (Figure 2B; $P < 0.001$) such that cows fed MON had a faster increase in DMI during early lactation. There was a MON × week interaction ($P = 0.04$) for starch intake during wk 1 to 3, and cows fed MON had greater starch intake compared with CON cows as lactation progressed, likely from the increased DMI observed in MON cows. There was also a MON × week interaction ($P = 0.05$) for NDF intake during wk 1 to 3, and cows fed MON had greater NDF intake compared with CON cows as lactation progressed, again likely from increased DMI in MON cows. Cows fed MON tended to have greater BW change during wk 1 to 3 (−36 vs. −24 kg; $P = 0.08$). Whereas no overall effect of MON treatment was observed on DMI as a percent of BW or BCS during the postpartum period, an interaction of MON × parity ($P = 0.006$) for BCS change existed during wk 1 to 9 and primiparous cows fed MON lost slightly less BCS (−0.57 for CON vs. −0.31 for MON) and multiparous cows fed MON lost slightly more BCS (−0.34 for CON cows vs. −0.52 for MON cows).

An interaction of MON × parity and a trend for this interaction were evident for milk per DMI ($P = 0.04$) and ECM per DMI ($P = 0.07$), such that primipa-

Table 7. Postpartum DMI, BW, BCS, efficiency, and energy balance for cows fed either high- or low-starch diets during the first 3 wk postpartum and control or monensin treatments throughout the periparturient period and into early lactation

	Diet[1]			Topdress[2]			P-value[5]							
Item	HS	LS	SEM	CON[3]	MON[4]	SEM	S	M	P	S × M	S × week	M × week	S × P	M × P
DMI, kg/d														
wk 1 to 3	15.6	14.8	0.4	14.3	16.1	0.4	0.21	0.004	<0.001	0.77	0.04	0.009	0.24	0.74
wk 1 to 9	19.8	19.1	0.3	18.9	20.0	0.3	0.13	0.02	<0.001	0.66	0.32	<0.001	0.99	0.67
DMI, % of BW														
wk 1 to 3	2.67	2.41	0.06	2.48	2.60	0.06	0.006	0.20	<0.001	0.71	0.01	0.29	0.84	0.25
wk 1 to 9	3.37	3.22	0.05	3.24	3.35	0.05	0.03	0.11	<0.001	0.47	<0.001	0.66	0.98	0.99
Starch intake, kg/d														
wk 1 to 3	3.90	3.22	0.12	3.51	3.62	0.11	0.001	0.49	<0.001	0.45	<0.001	0.04	0.51	0.44
wk 1 to 9	5.29	5.03	0.12	5.13	5.19	0.12	0.10	0.73	0.005	0.21	<0.001	0.39	0.96	0.69
NDF intake, kg/d														
wk 1 to 3	5.61	5.21	0.16	5.34	5.49	0.16	0.08	0.50	<0.001	0.42	0.26	0.05	0.93	0.47
wk 1 to 9	7.03	6.77	0.16	6.88	6.92	0.16	0.25	0.86	0.001	0.25	0.004	0.33	0.72	0.63
BW, kg														
wk 1 to 3	614	605	4	609	609	4	0.12	0.93	0.07	0.32	0.85	0.99	0.36	0.49
wk 1 to 9	602	595	4	597	600	4	0.21	0.55	0.02	0.47	0.85	0.85	0.21	0.60
BW change,[6] kg														
wk 1 to 3	−27	−33	5	−24	−36	6	0.37	0.08	0.34	0.30	–	–	0.99	0.29
wk 1 to 9	−21	−29	7	−19	−31	7	0.39	0.20	0.48	0.80	–	–	0.58	0.15
BCS														
wk 1 to 3	3.19	3.18	0.04	3.20	3.17	0.04	0.98	0.50	<0.001	0.32	0.90	0.64	0.99	0.70
wk 1 to 9	3.01	3.02	0.04	3.03	3.01	0.04	0.86	0.75	<0.001	0.56	0.96	0.66	0.67	0.67
BCS change[6]														
wk 1 to 3	−0.21	−0.33	0.04	−0.30	−0.24	0.04	0.04	0.29	0.23	0.32	–	–	0.01	0.16
wk 1 to 9	−0.39	−0.48	0.05	−0.46	−0.42	0.05	0.23	0.59	0.91	0.76	–	–	0.33	0.006
Milk/DMI														
wk 1 to 3	1.95	2.10	0.05	2.05	2.03	0.06	0.04	0.59	0.84	0.48	0.51	0.95	0.30	0.04
wk 1 to 9	1.84	1.95	0.03	1.88	1.90	0.03	0.04	0.67	0.97	0.17	0.53	0.95	0.28	0.21
ECM/DMI														
wk 1 to 3	2.20	2.50	0.07	2.45	2.26	0.07	0.002	0.05	0.47	0.98	0.66	0.76	0.45	0.07
wk 1 to 9	1.90	2.05	0.04	1.99	1.97	0.04	0.006	0.69	0.14	0.26	0.13	0.58	0.28	0.65
Energy balance, Mcal/d														
wk 1 to 3	−6.76	−11.83	0.84	−10.06	−8.53	0.83	<0.001	0.19	0.74	0.89	0.27	0.52	0.73	0.32
wk 1 to 9	−2.05	−4.50	0.46	−3.46	−3.08	0.46	<0.001	0.55	<0.001	0.20	<0.001	0.65	0.39	0.92
Energy balance, %														
wk 1 to 3	79.97	65.68	1.95	70.09	75.55	1.93	<0.001	0.05	0.003	0.98	0.12	0.57	0.41	0.06
wk 1 to 9	94.35	87.00	1.13	89.76	91.59	1.15	<0.001	0.25	<0.001	0.22	<0.001	0.68	0.15	0.36

[1]Postpartum diets: HS = high-starch diet (26.2% starch); LS = low-starch diet (21.5% starch).

[2]CON = control topdress; MON = monensin topdress.

[3]Formulated to supplement 0 mg/d of monensin.

[4]Formulated to supplement 400 mg/d prepartum and 450 mg/d postpartum.

[5]S = starch, M = monensin, and P = parity.

[6]Body weight and BCS change were calculated as the difference between BW (or BCS) in wk 1 postpartum and either wk 3 or wk 9 postpartum.

rous cows fed MON had slightly lower feed efficiency than CON, whereas efficiencies were similar between treatments for multiparous cows (data not shown). The higher DMI and trends for lower milk fat content for primiparous cows fed MON likely contributed to this effect. Primiparous cows fed MON tended to have less negative EB in early lactation compared with primiparous CON cows, as they met a higher percentage of energy requirements in wk 1 to 3 than CON primiparous cows (MON × parity; $P = 0.06$; 73.9 vs. 63. 4% of requirement); however, differences between treatments for multiparous cows were not significant (average 77.0% of requirement).

Apparent Total-Tract Digestibility

Results for the apparent total-tract digestibilities for DM, NDF, and starch measured from d 18 and 19 (±2) postpartum for cows fed the different treatments are presented in Table 8. There was no effect of starch content on apparent total-tract digestibility for digestibility of either DM or starch. Cows fed LS had higher apparent total-tract digestibility of NDF compared with cows fed HS diet ($P < 0.001$). This is likely because of the increased inclusion of high-NDF by-product feeds that typically have high NDF digestibility in the LS diet. There was no effect of peripartal

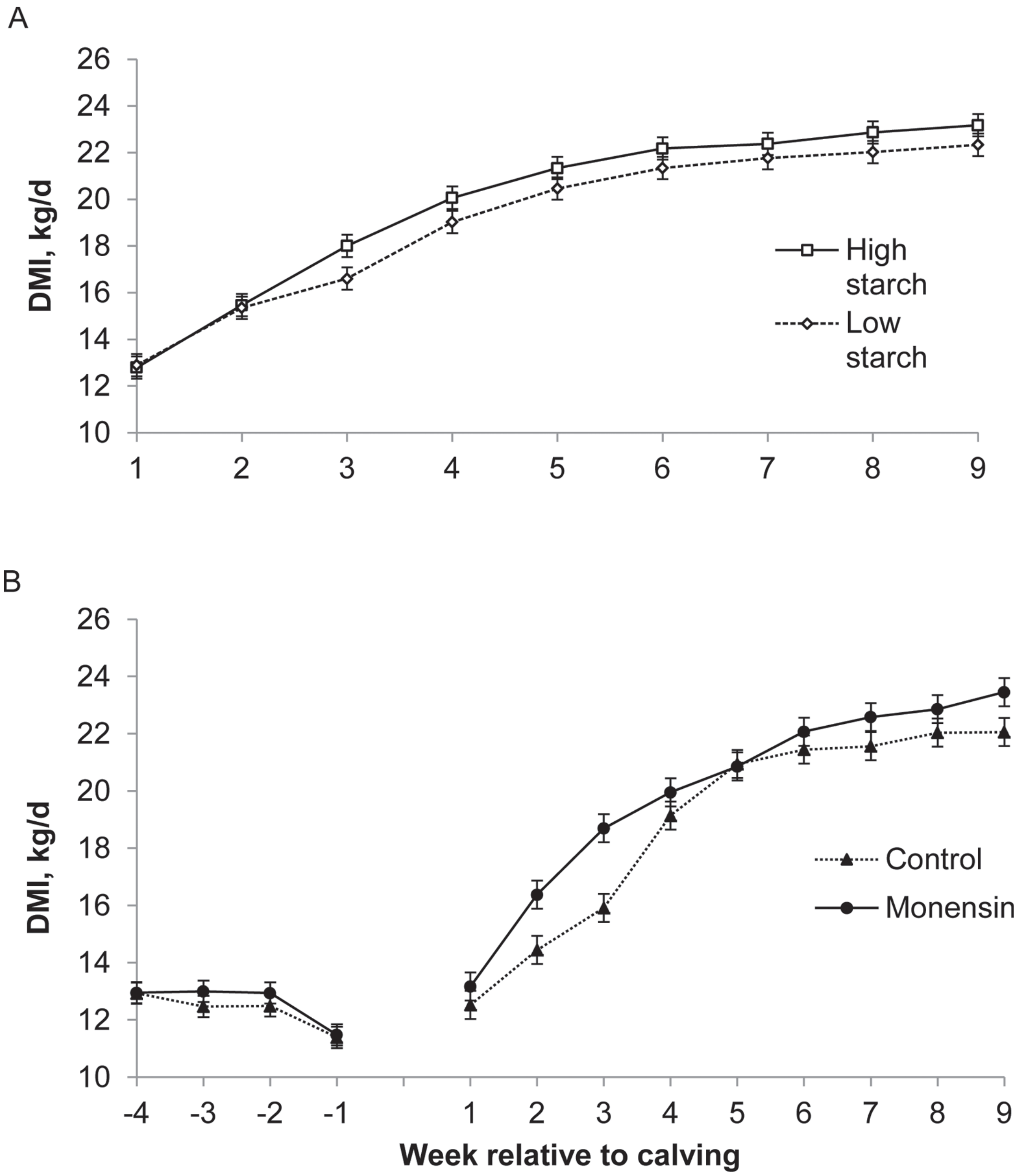

Figure 2. Least squares means (± SEM) for DMI (kg/d) for cows fed different starch content in the postpartum diet and monensin throughout the periparturient period. Postpartum data was analyzed separately as wk 1 to 3 (dietary treatment period) and wk 1 to 9 (duration of experiment). (A) Effects of high- (26.2%) versus low-starch (21.5%) fed during wk 1 to 9. The *P*-values for the overall effects of starch content were 0.21 for wk 1 to 3 and 0.13 for wk 1 to 9. The *P*-values for the interaction of starch content × week were 0.04 for wk 1 to 3 and 0.32 for wk 1 to 9. (B) Effects of monensin supplementation (0 vs. 400 mg/d prepartum and 450 mg/d postpartum). Pre- and postpartum effects of monensin were analyzed separately. The *P*-value for the overall effect of monensin during the prepartum period was 0.37. The *P*-value for the interaction of monensin × week prepartum was 0.39. The *P*-values for the overall effect of monensin postpartum were 0.004 for wk 1 to 3 and 0.02 for wk 1 to 9. The *P*-values for the interaction of monensin × week postpartum were 0.009 for wk 1 to 3 and <0.001 for wk 1 to 9.

MON treatment on measures of apparent total tract digestibility for DM, NDF, or starch.

DISCUSSION

Our overall hypothesis was that feeding diets with greater propiogenic potential during early lactation would increase milk yield because of increased gluconeogenic capacity. We also hypothesized that these more propiogenic diets would not have hypophagic effects on DMI because of the increased demand for glucose after calving. Postpartum, the estimated glucose requirements of the lactating mammary gland more than doubles compared with glucose requirements of

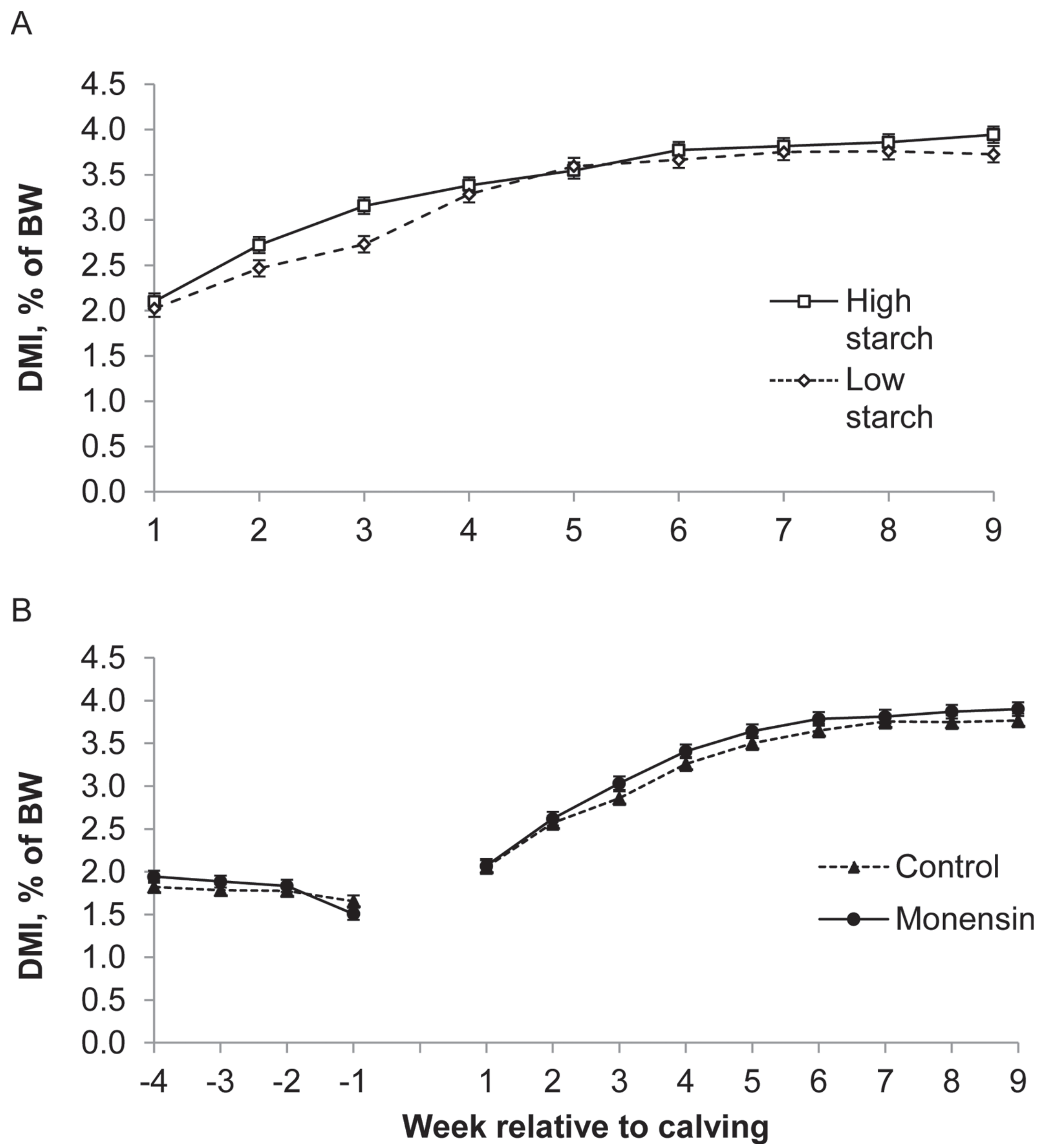

Figure 3. Least squares means (± SEM) for DMI expressed as a percentage of BW for cows fed different starch content in the postpartum diet and monensin throughout the periparturient period. Postpartum data was analyzed separately as wk 1 to 3 (dietary treatment period) and wk 1 to 9 (duration of experiment). (A) Effects of high- (26.2%) versus low-starch (21.5%) fed during wk 1 to 9. The P-values for the overall effects of starch content were 0.006 for wk 1 to 3 and 0.03 for wk 1 to 9. The P-values for the interaction of starch content × week were 0.01 for wk 1 to 3 and <0.001 for wk 1 to 9. (B) Effects of monensin supplementation (0 vs. 400 mg/d prepartum and 450 mg/d postpartum). Pre- and postpartum effects of monensin were analyzed separately. The P-value for the overall effect of monensin during the prepartum period was 0.65. The P-value for the interaction of monensin × week prepartum was 0.002. The P-values for the overall effect of monensin postpartum were 0.20 for wk 1 to 3 and 0.11 for wk 1 to 9. The P-values for the interaction of monensin × week were 0.29 for wk 1 to 3 and 0.66 for wk 1 to 9.

the gravid uterus prepartum (Bell, 1995). These adaptations in glucose demand occur while DMI is generally decreased in the weeks before calving (Ingvartsen and Andersen, 2000; Hayirli et al., 2002) and results in a state of negative EB postpartum. Ruminal propionate is the largest contributor to liver glucose output (Reynolds et al., 2003). Therefore, by increasing ruminal propiogenic substrate supply via dietary feeding strategies (e.g., feeding higher-starch diets or monensin), the amount of propionate that is available to the liver is increased (Armentano and Young, 1983; Rabelo et al., 2003). An increase in hepatic glucose output increases the energy that is available to the cow postpartum. In the current study, increasing dietary starch content and the addition of monensin to the diet were the strategies employed to increase hepatic propionate supply after parturition. When the diets were analyzed in the CNCPS software using actual intakes and forage analy-

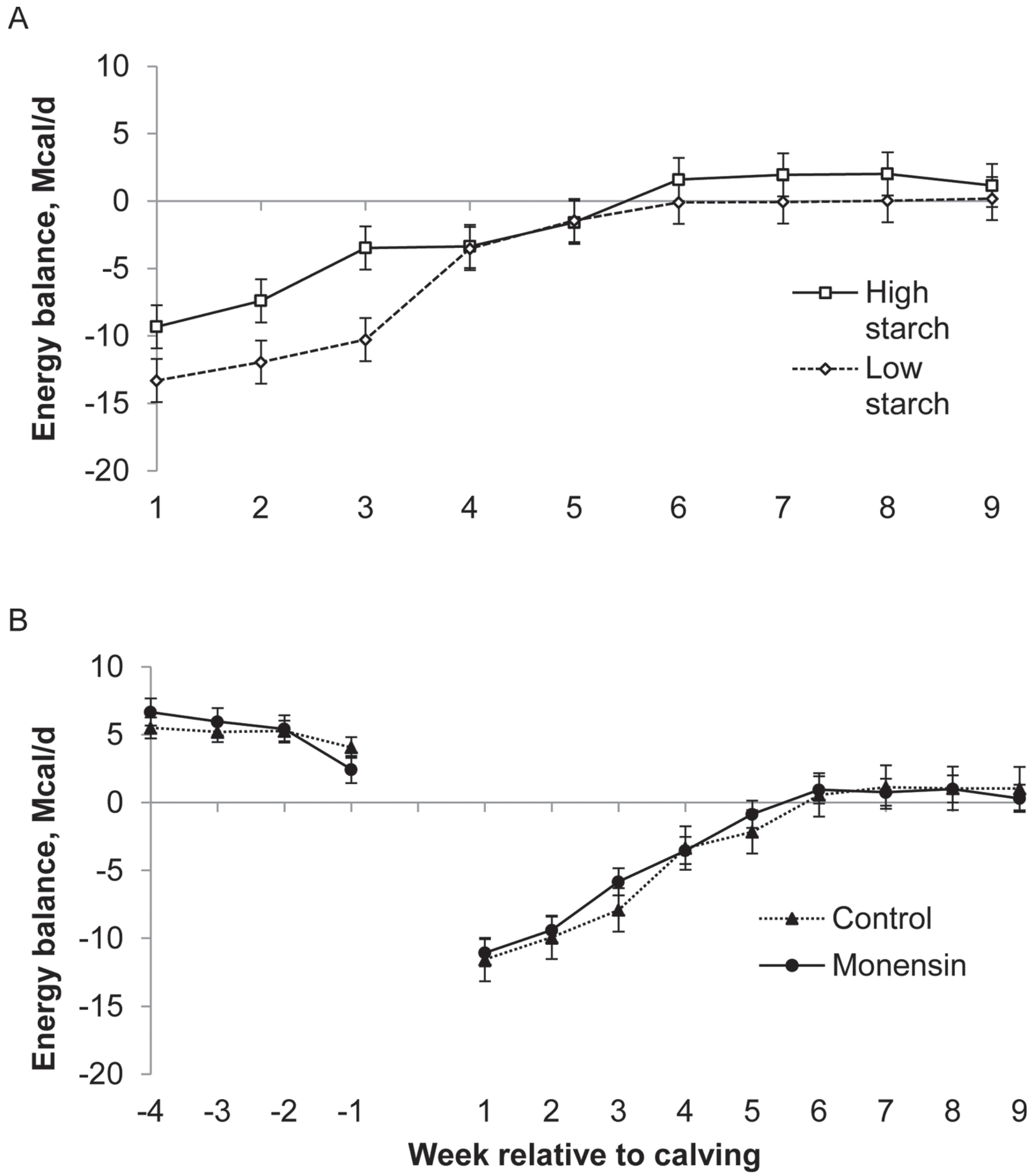

Figure 4. Least squares means (± SEM) for energy balance (Mcal/d) for cows fed different starch content in the postpartum diet and monensin throughout the periparturient period. Postpartum data was analyzed separately as wk 1 to 3 (dietary treatment period) and wk 1 to 9 (duration of experiment). (A) Effects of high- (26.2%) versus low-starch (21.5%) fed during wk 1 to 9. The *P*-value for the overall effects of starch content was <0.001 for both wk 1 to 3 and wk 1 to 9. The *P*-values for the interaction of starch content × week were 0.27 for wk 1 to 3 and <0.001 for wk 1 to 9. (B) Effects of monensin supplementation (0 vs. 400 mg/d prepartum and 450 mg/d postpartum). Pre- and postpartum effects of monensin were analyzed separately. The *P*-value for the overall effect of monensin during the prepartum period was 0.88. The *P*-value for the interaction of monensin × week prepartum was 0.009. The *P*-values for the overall effect of monensin postpartum were 0.19 for wk 1 to 3 and 0.55 for wk 1 to 9. The *P*-values for the interaction of monensin × week were 0.52 for wk 1 to 3 and 0.65 for wk 1 to 9.

ses (Table 4), the LS diet had a lower starch fermentability compared with the HS diet (17.1% vs. 21.9% of DM); however, overall carbohydrate fermentability was very similar between the 2 diets (40.7% vs. 41.1% of DM). It is likely that the decreased starch fermentability in the LS diet slightly reduced the predicted ME and metabolizable protein compared with the HS diet.

Over the first 9 wk of lactation overall milk yields were similar between cows fed HS and LS diets, although the cows fed the HS diet had increased milk yields in the immediate postpartum period. In the study of Andersen et al. (2003), cows fed a higher-energy propiogenic diet (26.7% starch) had higher milk yields (38.8 kg/d vs. 30.5 kg/d) in the first 8 wk of

Table 8. Apparent total-tract digestibility of DM, NDF, and starch during early lactation (d 18 and 19 ± 2) for cows fed either high- or low-starch diets during the first 3 wk postpartum and control or monensin treatments throughout the periparturient period and into early lactation

	Diet[1]			Topdress[2]			*P*-value[5]					
Item	HS	LS	SEM	CON[3]	MON[4]	SEM	S	M	P	S × M	S × P	M × P
DM digestibility, %	61.3	63.9	1.2	63.3	61.9	1.2	0.13	0.38	0.23	0.43	0.66	0.42
NDF digestibility, %	37.0	47.8	1.5	43.9	41.0	1.4	<0.001	0.15	0.87	0.81	0.33	0.27
Starch digestibility, %	95.4	96.3	0.5	95.9	95.8	0.5	0.15	0.87	0.07	0.45	0.51	0.52

[1]Postpartum diets: HS = high-starch diet (26.2% starch); LS = low-starch diet (21.5% starch).

[2]CON = control topdress; MON = monensin topdress.

[3]Formulated to supplement 0 mg/d of monensin.

[4]Formulated to supplement 400 mg/d prepartum and 450 mg/d postpartum.

[5]S = starch, M = monensin, and P = parity.

lactation compared with cows fed a low-energy diet (17.8% starch). Similarly, Rabelo et al. (2003) observed that cows fed a higher-energy propiogenic postpartum diet (47.2% NFC) had a faster increase in milk yield compared with cows fed a lower-energy diet postpartum (41.1% NFC). The increase in milk yield in early lactation seen across these studies is likely a result of greater gluconeogenic precursor supply to the liver that is provided by the higher-energy propiogenic diets (with greater concentrate inclusion). In a recent study, cows that were precision fed to maintain a 5-Mcal/d positive EB in early lactation (via increased percent of concentrate offered) had sustained increases in milk yield that extended beyond the period in which the precision-fed cows were consuming a more energy-dense diet than control cows, suggesting that higher-energy propiogenic diets offered in early lactation have benefits to milk production over the longer term (Maltz et al., 2013).

In the current study, cows fed HS had lower milk component percentages than those fed LS, although milk component yields were not affected. Rabelo et al. (2003) observed that cows fed a high-energy diet postpartum tended to have lower milk protein percentages, although other component percentages and yields were not affected by diet, whereas Andersen et al. (2003) determined that cows fed the high-energy density diet had a lower fat percentage, a higher protein percentage, and higher milk lactose content. The effects of a higher-energy diet on early-lactation milk components have not been consistent across studies; however, in the case of the current study, the lower milk component percentages from HS cows are likely the result of these cows being in less negative EB and mobilizing less BCS during the immediate postpartum period than cows fed LS.

Allen et al. (2009) proposed that liver energy status may serve to regulate DMI and that increased propionate supply to the liver during the early postpartum period would likely decrease DMI. Increased propionate and FA supply to the liver may reduce DMI through increased hepatic oxidation (Allen et al., 2009; Allen and Piantoni, 2013). However, we proposed that the modulation of DMI by propionate during early lactation is less than at other stages of lactation because NEFA likely are the predominant oxidative substrate for liver during this period as they are in such abundant supply (Reynolds et al., 2003), and any hypophagic effect of propionate would depend upon NEFA supply to the liver (Stocks and Allen, 2012, 2013). However, feeding higher-energy propiogenic diets in early lactation have been reported to have positive effects on DMI, likely driving the increases in milk yield (Andersen et al., 2003; Rabelo et al., 2003) and improved measures of energy metabolism (Andersen et al., 2004; Rabelo et al., 2005) observed in cows fed those diets. In the current study, cows fed HS had faster increases in DMI, as well as starch and NDF intakes during early lactation than cows fed LS. Cows fed the HS diet had lower feed efficiency expressed as milk per DMI and ECM per DMI compared with cows fed LS. However, because both DMI and EB were higher in HS cows immediately postpartum, this decreased feed efficiency is likely a reflection of increased DMI and less BCS mobilization postpartum rather than true reflections of decreased feed efficiency. In the current study cows fed HS had reached positive EB by wk 6 postpartum, whereas cows fed LS remained at zero EB from wk 6 through the end of the trial period. Rabelo et al. (2003) reported that cows fed a higher-energy diet had greater ruminal propionate concentrations, and both Andersen et al. (2004) and Rabelo et al. (2005) observed increased plasma concentrations of glucose and insulin and decreased BHBA for cows fed higher levels of starch and NFC, respectively, indicating improved EB concurrent with increased propionate supply for gluconeogenesis.

We hypothesized that we would not see any difference in apparent total-tract starch digestibility because starch sources were the same in both diets. Cows fed the LS diet had higher apparent total-tract NDF digestibility than those fed HS, which concurs with previous observations that cows fed diets containing higher concentrations of digestible NDF by-products have increased apparent total-tract NDF digestibility (Gencoglu et al., 2010; McCarthy et al., 2013).

Monensin treatment has been shown to increase ruminal propionate production (Armentano and Young, 1983). However, based upon the concepts presented in the hepatic oxidation theory (Allen et al., 2009), one could speculate that responses to monensin may vary depending upon dietary starch content, as both likely will increase supply of propionate. However, in the current study no interaction between starch and monensin was observed for any of the production variables measured. The effects of monensin were not dependent on early-lactation dietary starch content in our study; as such, feeding monensin during the periparturient period and into early lactation would result in these responses regardless of if they are fed as part of a high- or low-starch diet during the early lactation period. Conversely, the effects of feeding a high- or low-starch diet results in these responses regardless of if monensin is included in the diet or not. Interestingly, this lack of interaction between starch and monensin treatments on production performance variables has also recently been observed in mid-lactation cows (Akins et al., 2014).

In the current study, cows fed MON during the periparturient period had faster increases in milk yield compared with CON and averaged 2.2 kg/d higher milk yield. When a controlled-release capsule of monensin (335 mg/d) was administered in conjunction with a high-energy postpartum diet, weekly milk yield was higher in monensin-treated cows compared with controls (Arieli et al., 2008). Using data from cows in all stages of lactation, monensin treatment resulted in a 2.3% increase in milk yield (Duffield et al., 2008b), although no effect of monensin treatment on early-lactation milk production has also been observed (Erasmus et al., 2005; Mullins et al., 2012).

In the meta-analysis of Duffield et al. (2008b), monensin treatment resulted in an overall 2.3% decrease in DMI using data from cows in all stages of lactation. Supplementation of monensin during the periparturient period has been shown to either have no effect on early-lactation intake (Van der Werf et al., 1998; Phipps et al., 2000; Chung et al., 2007) or decrease intermeal interval (Mullins et al., 2012), whereas in the current study cows fed MON had increased DMI during both wk 1 to 3 and 1 to 9 compared with CON. Regardless, monensin treatment in early lactation does not appear to have a hypophagic effect on DMI likely because of the increased need for propionate to support gluconeogenesis during this time period.

Arieli et al. (2008) observed no differences in milk component percentages between treatments, although monensin-treated cows had increased component yields. In the current study, cows fed MON had lower percentages of milk fat and lactose, although no effect of monensin treatment on component yields was noted. The effects of monensin on milk components have been variable across studies (Arieli et al., 2008; Duffield et al.; 2008b; Mullins et al., 2012); however, in the current study the decreased milk component percentages for cows fed MON are likely the result of these cows mobilizing less adipose tissue due to increased DMI in the immediate postpartum period.

Cows fed monensin in the current study had lower calculated early lactation feed efficiency (ECM/DMI), which is likely a reflection of higher DMI rather than biological differences in feed efficiency. Data from cows at all stages of lactation show small increases in BCS and BW with monensin treatment (Duffield et al., 2008b), and monensin supplementation has been shown to improve energy metabolism (Duffield et al., 2008a) and reduce incidence of energy-related diseases (Duffield et al., 2008c). This is likely because monensin increases ruminal propionate supply to the liver resulting in increased hepatic glucose production and improvements in EB of the cow. In the current study we observed improvements in EB as a percentage of requirements during wk 1 to 3 for cows fed MON, indicating improvements in EB during very early lactation with MON treatment.

CONCLUSIONS

In conclusion, cows fed more propiogenic diets in early lactation via increased starch content or monensin inclusion had increased milk yield and DMI during the immediate postpartum period. Cows fed high-starch diets had lower fat, true protein, and lactose percentages, and cows fed monensin had lower fat and lactose percentages in early lactation, although no differences were observed among treatments in overall milk component yields. Cows fed high-starch diets or monensin had less negative EB during the immediate postpartum period. Overall, feeding more propiogenic diets via higher starch content and monensin inclusion favorably affected postpartum production outcomes, increased feed intake, and improved energy balance during the postpartum period.

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