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Effects of monensin and protein supplementation on intake, digestion, and ruminal fermentation in beef cattle consuming low-quality forage

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ABSTRACT

Objective: The objective of this study was to evaluate the effects of monensin and protein supplementation and their interaction on intake, apparent digestion, and ruminal fermentation variables in cattle consuming low-quality forage.

Materials and Methods: Four ruminally cannulated cows (637 ± 24 kg of BW) were used in a 4 × 4 Latin square design. Treatments were arranged as a 2 × 2 factorial: (1) monensin (0 or 200 mg·cow^{-1}·d^{-1}) and (2) protein (0 or 0.64 kg·cow^{-1}·d^{-1} CP). Day 1 through 4 of each period, animals were fed only low-quality forage, d 5 through 14 allowed for treatment adaptation, and d 15 through 20 were for sample collection. Data were analyzed using the MIXED procedure of SAS 9.4 (SAS Institute Inc.).

Results and Discussion: Neither a monensin × protein interaction nor a monensin effect ($P \geq 0.30$) was observed for any intake or digestion variable measured. In contrast, protein treatment increased ($P < 0.01$) all measures of intake. Protein increased ($P < 0.01$) OM digestibility, total digestible OM intake, and total digestible NDF intake but had no effect ($P = 0.13$) on NDF digestibility. A monensin × protein interaction ($P = 0.33$) or monensin effect ($P = 0.34$) were not observed for total VFA concentration, but protein increased ($P < 0.01$) total VFA concentration. A tendency for monensin × protein interaction was observed for the acetate:propionate ratio ($P = 0.06$) and molar percentage of propionate. Monensin increased ($P < 0.01$) molar percentage of propionate but had no effect ($P = 0.21$) on acetate.

Implications and Applications: Although monensin altered ruminal VFA profiles, providing monensin to cows consuming a low-quality-forage diet provided no benefits in forage intake or digestion.

Key words: efficiency, grazing, ionophore, ruminant, supplementation

INTRODUCTION

Cattle producers across the United States depend on forages to meet the nutrient demand of cattle production. Nutritional quality of these forages varies throughout the year and, at times, can be less than optimal, which may negatively affect overall cattle production. Low-quality forage (**LQF**) is characterized as having low CP (≤7.0% CP), which tends to decrease nutrient digestibility and reduce voluntary intake, negatively affecting overall animal production and profitability. Forages deficient in CP are commonly supplemented with degradable intake protein (**DIP**; common sources include cottonseed meal, soybean meal, and dried distillers grains with solubles) to meet rumen microbial CP requirements and improve intake and digestibility (Bohnert et al., 2002); this improves productivity relative to not supplementing. Protein supplements represent a significant production cost for beef producers; the downside is that protein supplements are generally expensive.

An alternate method for improving cattle performance is the use of ionophores. Ionophores are highly lipophilic compounds toxic to many bacteria, protozoa, and fungi (Russell, 1996). Widely used with higher quality diets, ionophores improve feed efficiency by altering rumen fermentation (Russell and Strobel, 1989). However, the effectiveness of ionophores in beef cattle consuming LQF has not been thoroughly examined (Ward et al., 1990b; Neto et al., 2009). Ionophores improve effective utilization of digestible energy (Spears, 1990) and, therefore, could replace or augment protein supplementation for LQF. It

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was hypothesized that because protein supplementation improves intake and diet utilization by relieving ruminal N deficiencies, and ionophores alter end products of fermentation through microbial selection, the use of protein supplements may potentiate the ionophore effect when fed with LQF. This potential interaction between monensin and protein supplementation has not been adequately addressed. Thus, the objective of this study was to evaluate the effects of monensin and protein supplementation and their interaction on intake, apparent digestibility, and ruminal fermentation characteristics in cattle consuming LQF.

MATERIALS AND METHODS

This study was conducted at New Mexico State University, Las Cruces. The experimental protocol was approved by the Institutional Animal Care and Use Committee at New Mexico State University and included the use of anesthesia when surgical procedures were performed (IACUC Approval No. NMSU-2016-021).

Animals, Diet, and Treatments

Four ruminally cannulated Angus cross cows (637 ± 24 kg of BW; 5–6 yr old) were housed in individual pens (33.5 m^2) and used in a 4 × 4 Latin square design with treatments arranged as a 2 × 2 factorial. The first factor was level of monensin (Rumensin 90; Elanco Animal Health): 0 or 200 $mg \cdot cow^{-1} \cdot d^{-1}$. The second factor was level of protein (cottonseed meal, **CSM**): 0 or 0.64 $kg \cdot cow^{-1} \cdot d^{-1}$ CP. Animals had continuous access to fresh, clean water and *ad libitum* access to low-quality bluestem hay (Table 1). Round bales were chopped (76 × 76 mm wire mesh screen), and LQF was offered at 0600 h daily at 130% of the previous 3-d average consumption, determined d 12 to 14. A carrier supplement (0.23 $kg \cdot cow^{-1} \cdot d^{-1}$) consisting of ground hay, cracked corn, molasses, salt, dicalcium phosphate, and a commercial mineral premix (Beefmax 0510, Cargill Inc.) was provided to all animals. In addition to supplementing minerals to the animals, the carrier supplement provided a means to deliver monensin. Treatments were mixed into the carrier supplement, and the mixture was offered at 0530 h daily d 5 through 20.

Experimental Protocol and Sampling

The study consisted of four 20-d periods. Low-quality forage was fed without treatment d 1 through 4. Day 5 through 14 allowed for 10 d of treatment adaptation, and sample collections occurred d 15 through 20. To prevent carryover effects from feeding monensin in the previous period, 14 d were required before sampling (Bell et al., 2017b). However, to obtain optimal response from monensin, only 10 d were needed for treatment adaptation.

Hay samples were collected d 15 through 18 and composited within period. Orts were collected immediately before daily feeding d 16 through 19 and composited within animal for each period. Fecal samples were collected directly from the rectum 3 times daily beginning at 0600 h on d 16. Fecal collection from the rectum continued every 8 h for 4 d, with initial sampling time being delayed 2 h each day. Fecal samples were composited within animal and frozen at −20°C for subsequent analysis. A CSM sample was collected daily on d 15 through 18, as well as a sample of the carrier supplement.

Rumen fluid (20 mL) was collected by removing ruminal contents from 3 locations within the dorsal and ventral sacs of the rumen and filtered through 4 layers of cheesecloth 0, 2, 4, 8, 12, 16, and 20 h after feeding on d 20 for analysis of pH and VFA. A portable pH meter (Symphony; VWR International) was used to measure pH of rumen fluid at time of sampling. Following pH measurement, an 8-mL subsample of ruminal fluid was combined with 2 mL of freshly prepared metaphosphoric acid and then frozen at −20°C for later determination of VFA.

Laboratory Analyses

Intake and Digestion. Hay, ort, CSM, carrier supplement, and fecal samples were dried in a forced-air oven (96 h at 55°C) and allowed to air equilibrate to determine partial DM. Samples were ground (No. 4 Wiley Mill, Thomas Scientific) to pass through a 1-mm screen. Hay, ort, CSM, carrier supplement, and fecal samples were dried at 105°C to determine DM then combusted for 8 h at 450°C for OM determination. Analyses for NDF and ADF were performed using an ANKOM fiber analyzer (ANKOM Technology) with sodium sulfite and α-amylase omitted. Crude protein was determined by analyzing samples with an Elementar Vario Macro (Elementar); CP was calculated as N content × 6.25. Indigestible NDF was used as an internal marker and determined on hay, carrier supplement, CSM, orts, and fecal samples. Previously ground samples (1 mm) were weighed into ANKOM 57 filter bags, heat sealed, and incubated for 264 h (Casali, et al., 2008) in a ruminally cannulated *Bos taurus* steer fed *ad libitum* a diet of bermudagrass (*Cynodon dactylon*) hay. Samples were then removed from the rumen, submerged in ice water to

Table 1. Chemical composition (DM%) of forage and supplement

Item	Bluestem hay	Cottonseed meal	Carrier supplement[1]
OM	90.1	90.4	85.5
CP	4.1	44.0	0.9
NDF	62.6	16.6	47.8
ADF	43.2	14.1	32.2

[1]Ground hay, cracked corn, molasses, salt, dicalcium phosphate, and a commercial mineral premix (BeefMax, Cargill Inc.).

stop microbial activity, and subsequently rinsed with tap water until water ran clear. After washing, samples were dried at 60°C for 96 h. Neutral detergent fiber analysis was performed using an ANKOM fiber analyzer (ANKOM Technology) according to Goering and Van Soest (1975), with sodium sulfite and α-amylase omitted. Final weights were used to calculate indigestible NDF according to Valente et al. (2011).

VFA. Previously prepared rumen fluid samples were thawed and centrifuged at 39,000 × *g* for 5 min at 4°C (Vanzant and Cochran, 1994). Ruminal VFA concentrations were determined using gas chromatography [Varian Model 3800; Varian Inc.; equipped with a glass column (180 cm × 4 mm i.d.)] packed with GP 10% SP-1200/1% H_3PO_4 on 80/100 Chromosorb WAW (Supelco), and N_2 was used as a carrier gas at a flow rate of 85 mL/min^{-1}.

Statistical Analysis

Intake and digestion were analyzed using the MIXED procedure of SAS 9.4 (SAS Institute Inc.). Fixed effects in the model included monensin, protein, and monensin × protein with animal and period as random effects. Ruminal fermentation variables were analyzed using the MIXED procedure. Fixed effects in the model included monensin, protein, hour, and all their interactions; random effects included animal, period, and protein × monensin × period × animal. The repeated measures term was hour, with animal × monensin × protein as the subject. Because hour represented a repeated measures effect, nonindependence is possible. We modeled the following variance-covariance structures to account for nonindependence: first-order autoregression, compound symmetry, Toeplitz and their heteroscedastic forms; variance-components; unstructured; and first-order autoregressive moving average. The Akaike information criteria, second order, were used to select the most appropriate structure. Normality of residuals was assessed with the Shapiro-Wilk test (Shapiro and Wilk, 1965). When residuals were skewed, we applied a version of the Box-Cox transformation (Box and Cox, 1964), with exponents for a power transformation ranging from −2 to 2 (by increments of 0.5) and including a log-transformation; the objective was to maximize the Shapiro-Wilk test statistic. All inferential statistics are based on transformed data (when needed); we present back-transformed means ± SE (Sokal and Rohlf, 2012). When analyzing data, $P \leq 0.05$ was considered significant, and $P > 0.05$ and ≤ 0.10 was considered a tendency.

RESULTS AND DISCUSSION

VFA

No monensin × protein × hour after feeding, monensin × hour after feeding, or protein × hour after feeding interactions were observed for any ruminal fermentation variable measured ($P \geq 0.17$). Treatment means are reported averaged over sampling times.

Total VFA. A monensin × protein interaction was not observed ($P = 0.33$; Table 2) for total VFA concentration. For this reason, effects of protein supplementation and monensin are discussed individually.

Protein supplementation increased ($P < 0.01$) total VFA concentration by 20.0% (from 54.72 to 65.67 m*M*). Increased total VFA concentration in protein-supplemented cows could be, in part, a result of increased microbial fermentation of the LQF but also could be a direct result of microbial fermentation of the CSM supplement (Owens and Goetsch, 1988). This increase in total VFA concentration in response to protein supplementation of the cows consuming LQF was expected and is similar to previous work. Wickersham et al. (2008) reported total VFA concentration increased (25.1%) as level of DIP supplementation increased (from 52.2 to 63.9 m*M*). Similarly, Köster et al. (1996) reported a 28.8% increase in total ruminal VFA concentration in supplemented groups (casein) compared with unsupplemented groups; total concentration increased linearly with increasing DIP level (180, 360, 540, and 720 g/d). The DIP source in the studies by both Wickersham et al. (2008) and Köster et al. (1996) was casein. Köster et al. (1996) observed enhanced ruminal ammonia N concentrations with increasing DIP supplementation. This reflects provision of a readily available N source; protein supplementation increased ruminal ammonia N levels, thus improving rumen microbial fermentation of the forage, as is evidenced by the increase in total VFA.

In contrast to providing casein directly to the rumen, Hannah et al. (1991) supplemented steers with soybean meal and observed greater (62.3%) total VFA concentration for groups supplemented with soybean meal than for control groups; the highest production occurred with the highest level of protein (1.8 kg, 43% soybean meal, 57% grain sorghum supplement). Although the additional ruminally available nitrogen from the soybean meal potentially increased microbial fermentation of the LQF, the increased VFA concentration response observed by Hannah et al. (1991) is likely also due to the direct effect of microbial fermentation of the soybean meal, which may be similar to a direct result of microbial fermentation of the CSM supplement observed in the present study.

Monensin had no effect ($P = 0.34$) on total VFA concentration. Similar to intake and digestion, effects of monensin on total VFA and individual VFA vary among studies, particularly among forage-based studies. Several have reported no effect of monensin on total VFA concentration in cattle consuming forage-based diets (Turner et al., 1977; Davenport et al., 1989; Ward et al., 1990a,b; Linneen et al., 2015). In contrast, Vagnoni et al. (1995) reported a 4.4% decrease in total VFA concentration (85 vs. 81.3 m*M*, for control vs. monensin, respectively). In agreement with the majority of studies, monensin had no effect on total concentration of VFA in the present study.

Acetate and Propionate. Because monensin did not alter total VFA concentration, an interaction between monensin and supplemental protein was not expected.

Table 2. Effect of monensin and protein on VFA and pH in ruminal fluid of cows consuming bluestem hay

	Treatment[1]				*P*-value[2]		
Item	No monensin, no protein	Monensin, no protein	No monensin, protein	Monensin, protein	Monensin × protein	Monensin	Protein
Total VFA,[3] m*M*	57.78 (4.43)	50.34 (4.30)	65.79 (4.30)	65.88 (4.33)	0.33	0.34	<0.01
Acetate:propionate[4,5]	5.35 (5.17, 5.53)	4.41 (4.20, 4.62)	5.13 (4.95, 5.31)	4.89 (4.70, 5.08)	0.06	<0.01	0.55
Molar percentage, %							
Acetate[4,5]	78.41 (77.29, 79.52)	76.05 (74.96, 77.13)	76.01 (74.92, 77.09)	75.81 (74.70, 76.92)	0.28	0.21	0.19
Propionate[4,6]	14.66 (14.24, 15.11)	17.41 (16.76, 18.13)	15.23 (14.78, 15.71)	15.88 (15.38, 16.43)	0.06	<0.01	0.53
Butyrate[4,7]	6.29 (5.89, 6.75)	5.33 (5.05, 5.64)	6.27 (5.88, 6.71)	6.17 (5.79, 6.59)	0.40	0.22	0.10
Isobutyrate[8]	0.21 (0.06)	0.26 (0.06)	0.22 (0.06)	0.24 (0.06)	0.47	0.63	0.72
Valerate[4,9]	0.10 (0.06, 0.16)	0.01 (0.0008, 0.03)	0..20 (0.14, 0.28)	0.20 (0.14, 0.27)	0.19	0.16	<0.01
Isovalerate[8]	0.16 (0.10)	0.15 (0.10)	0.30 (0.10)	0.30 (0.10)	0.92	0.91	0.12
pH[10]	6.71 (0.13)	6.75 (0.13)	6.22 (0.13)	6.47 (0.13)	0.43	0.29	0.01

[1]No monensin = 0 mg·cow^{-1}·d^{-1} monensin; monensin = 200 mg·cow^{-1}·d^{-1} monensin; no protein = 0 kg·cow^{-1}·d^{-1} supplemental CP; protein = 0.64 kg·cow^{-1}·d^{-1} supplemental CP.

[2]Monensin × protein = monensin × protein interaction; monensin × protein × hour after feeding interactions, $P \geq 0.08$, protein × hour, $P \geq 0.25$, monensin × hour, $P \geq 0.05$. *P*-values are from analyses on the transformed scale (when used).

[3]Data were not transformed; the SE is in parentheses.

[4]Response variables were transformed to improve normality. Data are presented as back-transformed means; it is not appropriate to back-transform SE. Shown in parentheses are back-transformed values of mean − SEM and mean + SEM (Sokal and Rohlf, 2012).

[5]Analysis based on acetate^{2} and acetate:propionate^{2}.

[6]Analysis based on propionate^{-2}.

[7]Analysis based on butyrate^{-1}.

[8]Response variables were not transformed, but most appropriate variance-covariance structures yielded treatment-specific SE, rounded to 2 decimals.

[9]Analysis based on valerate$^{0.5}$.

[10]Response variable was not transformed; variances were homogeneous. The SE is in parentheses.

Although an effect of monensin on total VFA was not expected, it was hypothesized, based on previous studies, that both supplemental protein (Köster et al., 1996; Mathis et al., 2000) and monensin (Linneen et al., 2015; Bell et al., 2017a) would alter the acetate:propionate ratio and therefore may result in an interaction between supplemental protein and monensin.

As hypothesized, a tendency for a monensin × protein interaction was observed for the acetate:propionate ratio ($P = 0.06$; Figure 1) with protein reducing the ratio when no monensin was present and increasing the ratio when monensin was present. Protein supplementation or monensin individually had no effect on molar percentage of acetate ($P \geq 0.19$). A tendency for a monensin × protein interaction was observed for molar percentage of propionate ($P = 0.06$; Figure 2) with protein increasing the molar percentage of propionate when no monensin was present and reducing molar percentage of propionate when monensin was present.

Monensin is known to shift the acetate:propionate ratio (Linneen et al., 2015; Bell et al., 2017a); propionate molar percentage increases at the expense of acetate. Propionate is a more gluconeogenic VFA; thus, monensin increases propionate availability for glucose production. Monensin decreased the molar percentage of acetate, increased the molar percentage of propionate, and reduced the acetate:propionate ratio in a study by Bell et al. (2017a). Linneen et al. (2015) reported similar results with acetate:

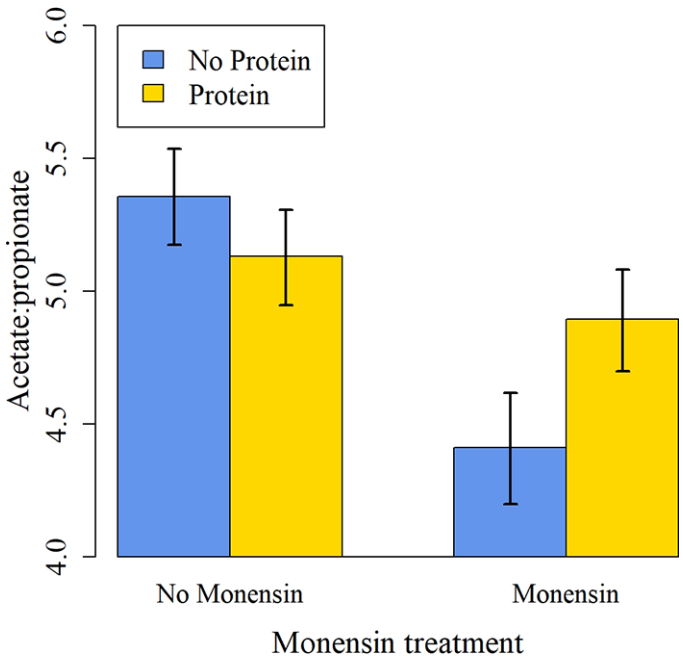

Figure 1. Effects of monensin and protein on acetate:propionate ratio in the ruminal fluid of cows consuming low-quality bluestem hay. No monensin = 0 mg·head^{-1}·d^{-1} monensin; monensin = 200 mg·head^{-1}·d^{-1} monensin (Rumensin 90; Elanco Animal Health); no protein = 0 kg·head^{-1}·d^{-1} supplemental CP; protein = 0.64 kg·head^{-1}·d^{-1} supplemental CP. Effect of hour after feeding (P = 0.77). The error bars represent 1 SE.

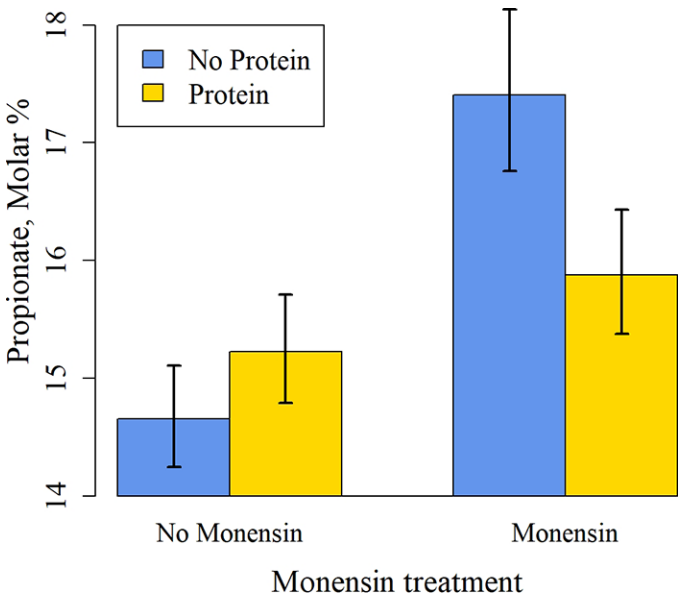

Figure 2. Effects of monensin and protein on molar percentage of propionate in the ruminal fluid of cows consuming low-quality bluestem hay. No monensin = 0 mg·head^{-1}·d^{-1} monensin; monensin = 200 mg·head^{-1}·d^{-1} monensin (Rumensin 90; Elanco Animal Health); no protein = 0 kg·head^{-1}·d^{-1} supplemental CP; protein = 0.64 kg·head^{-1}·d^{-1} supplemental CP. Effect of hour after feeding (P = 0.82). The error bars represent 1 SE.

propionate ratio decreasing for steers consuming monensin compared with steers fed control diets. Turner et al. (1977) observed a similar increase in propionate and decrease in acetate when monensin was fed. Propionate was increased from 19.2% in control cattle to 26.9% in monensin-fed cattle (Potter et al., 1976). Vagnoni et al. (1995) reported a decrease in acetate and butyrate but an increase in propionate production.

Butyrate and the Minor VFA. A monensin × protein interaction was not observed ($P \geq 0.19$) for butyrate or the minor VFA (isobutyrate, valerate, and isovalerate). For this reason, effects of protein supplementation and monensin are discussed individually.

Protein supplementation had no effect ($P \geq 0.12$) on molar percentage of isobutyrate or isovalerate but increased ($P < 0.01$) molar percentage of valerate and had a tendency to increase ($P = 0.10$) the molar percentage of butyrate. Olson et al. (1999) found that supplemented and control steers had similar ruminal proportions of butyrate, but supplemented steers had greater molar percentages of the minor VFA than control steers. Similarly, Köster et al. (1996) reported that the minor VFA increased linearly as supplemental DIP increased; however, butyrate was not affected. Mathis et al. (2000) observed an increase in molar percentage of all 3 minor VFA, whereas butyrate was unaffected by protein supplementation.

Monensin had no effect ($P \geq 0.16$) on molar percentage of butyrate or the minor VFA. Similarly, Lemenager et al. (1978b) and Ward et al. (1990a) observed no effect of monensin on butyrate in cattle consuming forage diets.

Rumen pH

No monensin × protein × hour, protein × hour, or monensin × hour interactions were observed for ruminal pH ($P \geq 0.51$). There was an effect of hour after feeding ($P = 0.04$) on ruminal pH, with a decrease observed after feeding until h 16 and then an increase at h 20 (Figure 3).

No monensin × protein interaction ($P \geq 0.43$) was observed for pH. Because no monensin × protein interaction was observed, effects of protein supplementation and monensin inclusion are discussed independently.

Effect of Protein on Rumen pH. Protein supplementation reduced ($P < 0.01$) rumen pH from 6.73 to 6.34. A decline in ruminal pH, with increasing levels of DIP, reflects an increase in ruminal fermentation (Köster et al., 1996). A decline in ruminal pH may be associated with increased ruminal fermentation and the subsequent increase in VFA production. Accordingly, total VFA concentration was increased in the present study resulting in a 6.1% reduction in pH. Wickersham et al. (2008) reported ruminal pH to be reduced by 1.2% when a high level of DIP (720 g/d of casein) was supplemented. Likewise, ruminal pH was reduced by 5.78% with infusion of supplemental DIP (casein; Köster et al., 1996).

Effect of Monensin on Rumen pH. Monensin had no effect ($P = 0.29$) on ruminal pH. Others (Davenport et al., 1989; Cochran et al., 1990; Fredrickson et al., 1993)

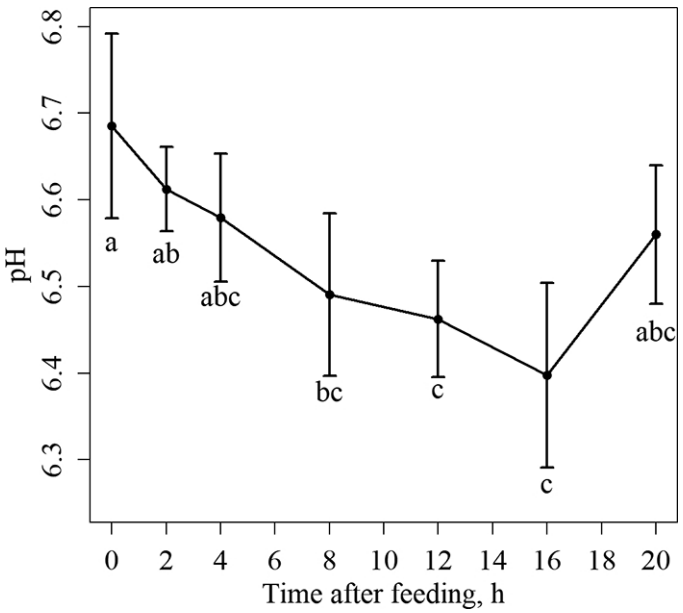

Figure 3. Effect of hour after feeding on pH in the ruminal fluid of cows consuming low-quality bluestem hay. Effect of hour after feeding ($P = 0.04$). Means followed by the same lowercase letter (a–c) are not significantly different ($P > 0.05$, protected LSD test). The error bars represent 1 SE.

have also found that monensin had little effect on ruminal pH in cows consuming forage.

When ruminant animals are fed high starch diets, ruminal pH is reduced as a result of increased lactate and VFA produced during starch fermentation (Bell et al., 2015). Monensin inhibits most lactate-producing bacteria, increasing ruminal pH. However, when ruminant animals consume forage diets, fiber degradation does not result in increased lactate or VFA as it does with starch. Thus, ruminal pH remains relatively unchanged.

Intake

No monensin × protein interactions ($P \geq 0.30$; Table 2) were observed for any intake variable measured. Because no monensin × protein interactions were observed, effects of protein supplementation and monensin inclusion are discussed independently.

Effect of Protein on Intake. Protein supplementation increased ($P < 0.01$) forage OM intake by 56.7% (from 5.80 to 9.09 g/kg of BW) and total OM intake by 88.3% (from 6.08 to 11.45 g/kg of BW). When total OM intake and OM digestibility were evaluated together as total digestible OM intake, protein supplementation increased ($P < 0.01$) total digestible OM intake by 112% (from 3.5 to 7.42 g/kg of BW). Protein supplementation increased ($P < 0.01$) forage NDF intake by 54.9% (from 5.73 to 8.88 g/kg of BW) and total NDF intake by 61.6% (from 5.93 to 9.58 g/kg of BW). When total NDF intake and NDF digestibility were evaluated together as total digestible NDF intake, protein supplementation increased ($P < 0.01$) total digestible NDF intake by 70.9% (from 2.75 to 4.70 g/kg of BW).

Protein is vital to cattle diets because rumen microorganisms require the nitrogen in protein for growth and to degrade feedstuffs in the rumen. McCollum and Galyean (1985) and Köster et al. (1996) reported that forage intake, digestion, and rate of passage were positively associated with protein supplementation and improved usage of LQF. Results from this study are similar to earlier findings (McCollum and Galyean, 1985; Stokes et al., 1988; Köster et al., 1996) where total OM intake, forage OM intake, total NDF intake, and forage NDF intake were increased in response to providing a high-DIP protein supplement to cattle consuming LQF. McCollum and Galyean (1985) reported a 27.5% increase in voluntary intake (DM) of low-quality prairie hay (6.1% CP) when CSM (37.9% CP) was supplemented. Stokes et al. (1988) observed a 57% increase in total OM intake compared with control when soybean meal (48.4% CP) was provided to cows consuming prairie hay (4.81% CP); however, forage OM intake was not affected. In a concurrent experiment to the present study (Solis et al., 2017), protein supplementation increased rate of DM degradation (from 1.87 to 4.76%/h), thus explaining the observed increase in forage intake.

Effect of Monensin on Intake. Monensin had no effect ($P \geq 0.29$) on forage OM intake or total OM intake. When total OM intake and OM digestibility were evaluated together as total digestible OM intake, no response to monensin was observed ($P = 0.45$). Similarly, monensin had no effect ($P \geq 0.33$) on forage NDF intake or total NDF intake. When total NDF intake and NDF digestibility were evaluated together as total digestible NDF intake, no response to monensin was observed ($P = 0.49$).

Monensin has been reported to have inconsistent effects on intake when provided to cattle consuming forage-based diets. In the present study, monensin did not significantly alter any of the intake variables measured, despite forage OM and NDF intakes being numerically (15 to 16%) lower when cows not supplemented with protein were fed monensin. Similarly, Cochran et al. (1990) reported that monensin (provided via monensin ruminal delivery device; 100 mg·cow^{-1}·d^{-1}) had no effect on OM intake (30 vs. 29 g/kg of BW) when cattle were consuming immature bluestem (12% CP). Likewise, forage intake (OM intake) and ruminal passage rates were not different between control and monensin-fed (monensin ruminal delivery device; 68 mg·cow^{-1}·d^{-1}) groups (15.4 vs. 14.4 g/kg of BW) for cows grazing native forage (7.08% CP; Fredrickson et al., 1993). Davenport et al. (1989) observed similar results for intake in steers consuming wheat forage (14.7% CP; 22.5 vs. 21.2 g/kg of BW). Forage DMI was not different for control versus monensin-fed groups in steers consuming low-quality prairie hay (Linneen et al., 2015). Similar results were reported by Bell et al. (2017a) who observed no effect of monensin on forage OM intake, total OM intake, or NDF intake in steers consuming bermudagrass hay (13.7% CP).

Table 3. Effect of monensin and protein on intake of cows consuming low-quality bluestem hay

	Treatment[1]					*P*-value[2]		
Item	No monensin, no protein	Monensin, no protein	No monensin, protein	Monensin, protein	SEM	Monensin × protein	Monensin	Protein
OM intake, g/kg of BW								
Forage	6.31	5.29	9.13	9.06	0.66	0.35	0.29	<0.01
Total	6.59	5.57	11.49	11.42	0.68	0.35	0.30	<0.01
Digestible	3.80	3.19	7.41	7.42	0.45	0.43	0.45	<0.01
NDFI,[3] g/kg of BW								
Forage	6.21	5.24	8.90	8.86	0.64	0.37	0.33	<0.01
Total	6.41	5.44	9.60	9.55	0.66	0.37	0.33	<0.01
Digestible	2.97	2.53	4.65	4.74	0.30	0.30	0.49	<0.01

[1]No monensin = 0 mg·cow^{-1}·d^{-1} monensin; monensin = 200 mg·cow^{-1}·d^{-1} monensin; no protein = 0 kg·cow^{-1}·d^{-1} supplemental CP; protein = 0.64 kg·cow^{-1}·d^{-1} supplemental CP.

[2]Monensin × protein = monensin × protein interaction.

[3]NDFI = NDF intake.

Others (Lemenager et al., 1978a; Ellis et al., 1983) have reported a reduction in intake due to monensin inclusion. Lemenager et al. (1978a) reported that cows grazing native range and consuming monensin (200 mg·cow^{-1}·d^{-1}) had a reduced (23.4 vs. 18.9 g/kg of BW) forage intake (DMI). Although not statistically significant, cows in the present study that were not supplemented with protein had 15 to 16% lower forage OM and NDF intakes when fed monensin versus no monensin, which is consistent with the findings of Lemenager et al. (1978a). A review by Ellis et al. (1983) reported that monensin decreased intake of low-quality wheat pasture when there was ≤45% OM digestibility. A review by Spears (1990) concluded high variability in digestible OM intake with monensin supplementation of forage diets; monensin increased apparent digestibility by an average of 2.0%.

In the present study, adding monensin to the diet of animals consuming LQF had no significant effect on any intake variable measured. The lack of intake response to monensin was anticipated as it is in agreement with the majority of previous work in cattle consuming LQF diets. Because of the lack of intake response, an interaction between monensin and protein were not expected.

Digestion

No monensin × protein interactions ($P \geq 0.74$; Table 3) were observed for any digestion variable measured. Because no monensin × protein interactions were observed, effects of protein supplementation and monensin inclusion are discussed independently for digestion.

Effects of Protein on Digestion. Protein supplementation increased ($P < 0.01$) OM digestibility by 10.7% (from 58.36 to 64.63%) but had no effect (56.85 vs. 59.01 for cows that received 0 vs. 0.64 kg·cow^{-1}·d^{-1} CP, respectively; $P = 0.13$) on NDF digestibility (Table 4).

Wickersham et al. (2008) found that total OM digestibility and NDF digestibility increased linearly in DIP supplemented (casein) steers compared with control groups when consuming tallgrass prairie hay (4.9% CP). Mathis et al. (2000) observed linear increases in OM digestibility and NDF digestibility with increasing levels of DIP

Table 4. Effect of monensin and protein on digestion of cows consuming low-quality bluestem hay

	Treatment[1]					*P*-value[2]		
Total-tract digestion, %	No monensin, no protein	Monensin, no protein	No monensin, protein	Monensin, protein	SEM	Monensin × protein	Monensin	Protein
OM	58.58	58.13	64.37	64.89	2.68	0.74	0.98	<0.01
NDF	56.32	57.38	58.35	59.66	2.92	0.92	0.38	0.13

[1]No monensin = 0 mg·cow^{-1}·d^{-1} monensin; monensin = 200 mg·cow^{-1}·d^{-1} monensin; no protein = 0 kg·cow^{-1}·d^{-1} supplemental CP; protein = 0.64 kg·cow^{-1}·d^{-1} supplemental CP.

[2]Monensin × protein = monensin × protein interaction.

(sodium caseinate) compared with unsupplemented steers consuming low-quality forage sorghum (4.1% CP). In the present study, the increase in total-tract OM digestibility may not have been solely a LQF digestibility response to the supplemental CP, but also may be a response to the digestibility of OM in the overall diet. Specifically, the digestibility of OM in CSM is greater than the digestibility of OM in LQF. Thus, supplementing CSM will increase overall OM digestibility of the combined CSM and LQF diet. This conclusion is supported by the lack of increase in NDF digestibility with protein supplementation. A significant portion of OM in the LQF is represented by NDF, whereas CSM contains less NDF. Although supplementing CSM added a more digestible source of OM to the diet, a numerical increase (4%) in NDF digestibility with protein supplementation indicates that the CSM may have also increased forage NDF and OM digestibility.

Effect of Monensin on Digestion. Monensin did not affect ($P \geq 0.38$) OM digestibility or NDF digestibility in the present study. When fed across a variety of forage types with low to moderate CP concentration, monensin often has limited direct effects on digestibility. Cochran et al. (1990) reported that monensin had no effect on OM digestibility in cattle grazing rangeland forage (12% CP). Similarly, Fredrickson et al. (1993) observed that OM digestibility was not altered by monensin fed to cows grazing native forage (7.1% CP). Furthermore, Ward et al. (1990b) reported forage OM digestibility to be similar for control and monensin-fed steers (57.3 vs. 57.5%) grazing winter range (6.6% CP). A study by Bell et al. (2017a) reported that monensin had no effect on OM digestibility or NDF digestibility in steers consuming bermudagrass hay (13.7% CP). Neutral detergent fiber digestion was not different for control- and monensin-fed steers consuming low-quality prairie hay (5.0% CP) in a study by Linneen et al. (2015).

Previous work observing the effects of monensin on digestion have been inconsistent. In contrast to our findings, and those of others who report no effect of monensin on digestion, others (Lemenager et al., 1978b; Ellis et al., 1983) have observed an increase in digestion. A review by Ellis et al. (1983) reported an average 4% increase in OM digestibility by cattle receiving monensin and suggested that a decreased rate of passage might explain the increase in digestion. In accordance with Ellis et al. (1983), Lemenager et al. (1978b) and Linneen et al. (2015) found monensin to decrease rate of passage in forage-based diets. The apparent effects of monensin on digestibility may be a result of the tendency of monensin to reduce intake, thus reducing passage rate and increasing residence time and, therefore, extent of digestion.

APPLICATIONS

Our results suggest that both intake and digestibility of LQF are improved with protein supplementation but that neither was affected by the addition of monensin. Although an interaction between monensin and protein was observed on the acetate:propionate ratio, these data suggest that adding monensin to a protein supplement for cattle consuming LQF will not provide any added improvement to intake or digestion compared with protein alone. Therefore, producers should prioritize the protein requirement to maximize forage intake and digestion of LQF.

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