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Effects of ad libitum or restricted access to total mixed ration with supplemental long hay on production, intake, and rumination

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**Effects of ad libitum or restricted access to total mixed ration with supplemental long hay on production, intake, and rumination**

**Cavallini**

**INTERPRETIVE SUMMARY**

Total mixed rations (TMR) based on dry hay are widely used in the Parmigiano Reggiano production area of Italy. In this study, mid-lactation cows were offered access to TMR for 24 or 19 h/d with or without additional free choice hay. Feed efficiency was improved with the restricted feed access, and most rumen parameters were similar. However, milk production, ruminal function, and pH stability were improved when TMR and long hay were available continuously.

42 RUNNING HEAD : AD LIBITUM OR RESTRICTED TMR  
43 **Effects of ad libitum or restricted access to total mixed ration with supplemental long hay**  
44 **on production, intake, and rumination**

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## ABSTRACT

53  
54        Limiting feeding time has been a concept used in growing and non-lactating ruminant  
55 animals with good success, especially in improving feed efficiency while maintaining normal  
56 rumen function and fiber digestibility. This study evaluated the physiological and productive  
57 responses of cows fed a total mixed ration (TMR) available for 24 or 19 h/d with or without  
58 access to additional long hay. Eight multiparous Holstein cows were used in a replicated 4 × 4  
59 Latin square design. Rations were formulated to mimic TMR used in the Parmigiano Reggiano  
60 cheese production area of Italy, consisting of all dry and non-fermented components. Intakes  
61 were reduced slightly in cows with restricted TMR access and without supplemental hay. Rumen  
62 characteristics, as well as production of milk and components, were similar for all groups. The  
63 results show that once cows adapted to diet changes, there were few differences in dry matter  
64 intake when offering TMR continuously or with limited access. In addition, the presence of long  
65 hay during the TMR restriction offered the best conditions for ruminal function and pH stability  
66 yet no effects observed on body weight change. A Latin square with 21-d periods could have a  
67 carry-over effect on energy storage and mobilization of fat reserves might be able to mask  
68 negative energy balance during restriction. This feeding system could be used as a strategy to  
69 manage feed availability according to cow production and metabolic condition, in order to  
70 maximize the use of nutrient resources, reducing the cost of milk production and improving the  
71 cows' welfare and health.

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73 **Key words:** limit feeding, lactating dairy cow, rumination

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## INTRODUCTION

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Total mixed rations (TMR) with dry hay as the only forage source are widely used in the Parmigiano Reggiano production area of Italy. Typically, little to no water is added to the TMR to avoid the risk of fermentation in the manger. In this situation, particle size of the feed must be reduced to prevent feed sorting, and therefore physically effective NDF (peNDF) is generally below what is commonly considered acceptable (Fustini et al., 2016). This may led to a reduction of rumination time and saliva secretion thereby leading to SARA (Khafipour et al., 2009). Italian hays are often of low quality and reduced nutrient value due to the climatic conditions (Palmonari et al., 2016), which often necessitates an increased amount of concentrate in the diet to satisfy the energy requirements of lactating cows.

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Adequate forage particle size in the ration is therefore critical to maintain rumen function and milk components. Furthermore, peNDF promotes chewing and salivary secretion, maintaining rumen conditions for VFA absorption, which improves pH stability in the rumen (Mertens, 1977, 1997). In a recent study, Kmicikewycz and Heinrichs (2014) concluded that supplementing rations with long hay favored the recovery of animals with SARA in early and mid-lactation. Moreover, inclusion of long hay in low proportions, particularly in diets based on finely chopped silages, has been shown to improve rumination time (Beauchemin et al., 1994).

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Dairy cows may also be able to select in favor of longer particles if rumen pH and rumination levels are low. Maulfair et al. (2013) saw that during SARA cows were able to change their eating preferences in favor of diets with more long forage and lower contents of fermentable starch. Keunen et al. (2002) also showed that lactating cows with induced SARA increased their

96 preference for long alfalfa hay compared to alfalfa pellets. It has been suggested that under  
97 conditions of reduced ruminal pH if given an option, cows will choose feeds with more buffering  
98 capacity (DeVries et al., 2008).

99 Limit feeding has been used in ruminant animals with good success, especially in  
100 improving feed efficiency while maintaining normal rumen function and digestibility (Owens et  
101 al., 1995). Limit feeding often improves digestibility (Zanton and Heinrichs, 2008), primarily  
102 through reducing the rate of passage of material from the reticulo-rumen of animals that are fed  
103 less (Bhatti et al., 2008). However, few trials based on this concept have been conducted with  
104 cows in mid lactation.

105 The purpose of this experiment was to evaluate the physiological and productive response  
106 in cows fed a dry, finely chopped TMR administered for a 24 or 19 h/d, with or without  
107 additional free choice long hay.

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## 110 MATERIALS AND METHODS

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112 This study was conducted at the University of Bologna (Italy), and all experimental  
113 procedures involving animals were approved by the University of Bologna Animal Care and Use  
114 Committee.

### 115 *Experimental Design and Data Collection*

116 Eight multiparous Holstein cows (avg. BW  $629 \pm 49$  kg) were blocked by parity ( $2.25 \pm$   
117  $0.46$ ), milk production ( $44.9 \pm 2.5$  kg/d), and DIM ( $99 \pm 49$ ) and used in a replicated  $4 \times 4$  Latin  
118 square design study with 21-d periods (14 d adaptation and 7 d collection). Rations were  
119 formulated to mimic TMR used in the Parmigiano Reggiano cheese production area of Italy and  
120 consisted of all dry and non-fermented components. The basal diet was the same for all 4

121 treatments with or without access to additional long grass hay, which was the same hay used in  
122 the TMR (Table 1). Diets were offered in individual feed mangers divided in 2 equal parts, one  
123 for the TMR and the other for the long grass hay. Cows were offered ad libitum intake of TMR  
124 for 24 or 19 h/d; TMR (approximately 1.10× expected intake) was fed once a day at 2000 h (Zago  
125 Mixer; Padova, IT). The study was conducted during the months of September and December,  
126 and feeding was done at a time to encourage intake in the evening hours. Animals were housed in  
127 a naturally ventilated tie-stall barn and milked twice a day (0800 and 1930 h) in a double-5  
128 herringbone milking parlor. Treatments were identified by the length of TMR access as 24 h or  
129 19 h, with (F+) or without (F-) ad libitum long grass hay.

130 From d 15 to 21 of each period, we collected data and took samples. Body weight was  
131 measured daily (Afiweight scale, Afikim, Israel), and DMI was determined by recording feed  
132 offered and refused for each cow. Samples of diets and orts were collected daily and a portion of  
133 each sample was dried in a forced-air oven at 105°C for 24 h for DM determination. Milk yield  
134 was recorded daily (Afimilk Information Management System; Afikim, Israel) during d 15 to 21  
135 of each period. Milk samples from 2 consecutive milkings for each cow were collected on d 17  
136 and 18 of each period, preserved (Bronolab-W II Liquid Preservative; D & F Control Systems,  
137 Inc., Dublin, CA), and analyzed for fat, true protein, and lactose by infrared spectroscopy  
138 procedures (Associazione Provinciale Allevatori Bologna; Foss 4000, Foss Technology). Feed  
139 efficiency (kg/kg) was calculated as milk/DMI, 3.5% FCM/DMI, and solids-corrected milk/DMI  
140 during the experimental week.

#### 141 ***Rumen Characteristics***

142 Cows were monitored for rumination activity from d 15 to 20 of each period using the Hi-  
143 Tag rumination monitoring system (SCR Engineers Ltd., Netanya, Israel). Data Flow software  
144 analyzed rumination time with a resolution of 2 h (Schirmann et al., 2009) and calculated the



145 rumination time during the last 24 h. To continuously monitor rumen pH, all cows received an  
146 indwelling wireless pH-transmitting unit (SmaXtec Animal Care Sales GmbH, Graz, Austria),  
147 which has been validated with rumen-cannulated dairy cows (Klevenhusen et al., 2014). These  
148 units (3.5 cm i.d., 12 cm long, and weighing 210 g) were manually inserted into the reticulorumen  
149 via the esophagus on d 14 of the first period. Prior to this, the units were calibrated following the  
150 company's instruction protocol. The units measured pH and temperature every 10 min and  
151 transmitted the data in real time to a basestation using the ISM band (433 MHz). Both data of pH  
152 and temperature were collected using an analog-to-digital converter and stored in an external  
153 memory chip. Data of pH from d 15 to 21 of each period were analyzed as daily mean pH and  
154 time (min/d) below specific cut-off points (5.5 and 5.8). Because wireless sensors were located in  
155 the ventral reticulorumen (Gasteiner et al., 2009) and few differences were observed between pH  
156 measured by wireless units and in the ventral rumen sac (Klevenhusen et al., 2014), the term  
157 "reticuloruminal pH" will be used.

158 On day 5 and 6 of experimental week, rumen fluid was collected via esophageal probe at  
159 12h (0800) and 24h (2000) after feeding. Volatile fatty acid (VFA) concentrations were  
160 determined by gas chromatography (Goetsch and Galyeen, 1983), while ammonia was evaluated  
161 via commercial kit (Urea/BUN – color, BioSystems S.A. Barcelona, Spain) according to the  
162 producer procedure.

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#### 164 *Chemical Analysis*

165 Individual feed ingredients were collected weekly and dried in a forced-air oven at 55°C  
166 for 48 h for DM. During the experimental week of each period, diets were sampled daily and  
167 analyzed for chemical composition according the following methods: CP, amylase-treated, ash-  
168 corrected NDF (aNDFom), and ADF according to Mertens (2002) and AOAC 973.18. Starch was

169 determined according to AOAC 996.11 and ether extract according to AOAC 920.390020.  
170 Forage and diet composite samples were used to determine particle size distribution on an as-fed  
171 basis using the Penn State Particle Separator (Lammers et al., 1996), physical effectiveness factor  
172 (pef) using a RoTap Separator (W.S. Tyler, Mentor, OH). Diet peNDF was calculated as the  
173 product of the total diet NDF content and its pef (Mertens, 1997). In vitro digestibility (24, 48,  
174 and 240 h) of aNDFom of forage composite and diet composite samples (1-mm grind; Wiley  
175 mill; Arthur H. Thomas, Philadelphia, PA) were determined using an in vitro fermentation (Tilly  
176 and Terry, 1963) in buffered media containing ruminal fluid (Goering and Van Soest, 1970).  
177 Ingredients and diets also were analyzed for in vitro aNDFom digestibility at 24 h and 240 h  
178 according to the procedure described by Palmonari et al. (2017). Briefly, in vitro aNDFom  
179 digestibility at 24 h and 240 h (**IVNDFD24h** and **IVNDFD240h**) was performed using the Tilley  
180 and Terry modified technique (Tilley and Terry, 1963; Van Soest et al., 1991).

### 181 *Statistical Analysis*

182 Data for DMI, milk yield and composition, feed efficiency, microbial protein supply, and  
183 BW, and were analyzed as a replicated Latin square design with model effects for diet, period,  
184 and replicate using the MIXED procedure of SAS (version 9.1, Statistical Analysis Systems  
185 Institute Inc., Cary, NC) using cow within replicate as a random effect. Repeated measurements  
186 on performance data (i.e. DMI, milk yield, etc.) were reduced to period means for each cow  
187 before statistical analysis. Data for ruminal pH, NH<sub>3</sub>-N, and VFA were analyzed with repeated  
188 measures using the MIXED procedure of SAS. The model included effects of diet, period, time,  
189 and the interaction of diet and time, with cow as a random effect. Least squares means were  
190 separated using PDIFF option with Tukey's adjusted *P*-values when a significant *F*-test (*P* ≤  
191 0.05) was detected.

192

## RESULTS AND DISCUSSION

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194       The TMR fed was adequate in terms of nutrient composition (NRC, 2001) but smaller in  
195 particle size (peNDF =  $14.14 \pm 1.30\%$ ) than what is often recommended (Heinrichs, 2013,  
196 Kmicikewycz et al., 2015; Table 1). This level of dietary particle size minimized the risk of cows  
197 sorting (Fustini et al., 2016). When cows were offered TMR 24 vs 19 h/d, TMR DMI increased  
198 (25.98 vs 23.49 kg, SEM = 1.66,  $P = 0.04$ , Table 2). Supplemental hay intake was similar  
199 between diets. Consequently, total DMI tended to be greater for cows with 24-h TMR access  
200 (26.21 vs 23.85 kg, SEM = 1.70,  $P = 0.06$ , Table 2) compared to cows offered TMR 19 h/d. Diets  
201 including hay tended to increase total NDF intake (8.26 vs 7.55 kg/d, SEM = 0.54,  $P = 0.07$ ,  
202 Table 2). When hay was offered in addition to TMR, cows consumed relatively little hay (< 1  
203 kg/d) and tended to consume more hay when TMR was offered for 19 vs 24 h/d. However, this  
204 hay intake was not equal to the reduction in TMR intake, likely due to feed palatability or  
205 preference for the TMR over the hay alone. A change in eating behavior may have occurred and  
206 may fall into the category of slug feeding once cows had adapted to this feeding (19 vs 24 h)  
207 change (Fustini et al., 2016). According to other authors (Albright, 1993; Maulfair et al., 2013),  
208 animals modified their eating behavior after adaptation to a different feeding regimen. It was  
209 thought that when dairy cows had a limited amount of TMR, it would result in faster eating rates,  
210 which could lead to substantial diurnal changes in VFA production and increase the risk of  
211 SARA (Van Soest, 1994). Previous work (Kmicikewycz and Heinrichs, 2014) demonstrated that  
212 long hay availability with no TMR offered could decrease risk of SARA in lactating dairy cows.  
213 This hay availability should also limit the chance of a higher amount of feed being consumed in  
214 the first meal after TMR delivery the following day. This condition is often called “slug feeding,”  
215 and is characterized by a long period of time in which cows remain out of feed, after which they  
216 rapidly consume an amount of fermentable carbohydrate able to induce a drop in ruminal pH

217 (Krause and Oetzel, 2006). Cows with TMR available for 19 h/d consumed 37.1% of their hay  
218 intake in the 5 h after TMR was removed, while cows with TMR continuously available had  
219 14.4% of their hay intake in the same period of time. Due to the quality of this hay, cows that had  
220 it available had higher intakes of NDF and unavailable NDF intake. Results of fiber digestibility  
221 (total tract digestibility > 75% in all the treatments; Table 4) appeared to be comparable to values  
222 obtained in other experiments and, confirm digestibility shown by Fustini et. al. (2017), given the  
223 quality of forage used in the dry diets of the Parmigiano Reggiano cheese production area of Italy  
224 (Palmonari et al., 2016) (total tract digestibility higher than 75% in all the treatments; Table 3).

225         There were no differences in milk production between the 24 and 19 h feed groups;  
226 however, there was a tendency for increased milk yield by cows that consumed supplemental  
227 forage (38.03 vs 35.95 kg, for F+ and F- respectively, SEM = 1.63,  $P = 0.09$ , Table 4). Cows with  
228 TMR access for 19 h/d had greater feed efficiency (Table 3) on both a milk volume (milk kg/DMI  
229 kg,  $P = 0.03$ ) and component (ECM kg/DMI kg,  $P = 0.05$ ) basis compared to the 24 h group. This  
230 improved efficiency is likely a result of the design of the study with relatively short periods  
231 where body reserves could be used to support production. However BW of cows did not change  
232 over the study. There were no differences in milk protein, fat, and urea content; however, somatic  
233 cells tended to be higher for 19 h/d TMR diets, in particular when hay was not offered (Table 3).  
234 Lactose tended to be higher in milk from cows with 24-h TMR access, likely because of the  
235 lower SCC (Table 3).

236         Rumination times were much higher than values considered as a minimum threshold to  
237 ensure rumen functionality (> 390 min/d; Zebeli et al., 2007, 2009). An interaction was observed  
238 between TMR availability and provision of supplemental hay for rumination time (Table 5).  
239 Cows with 19 h of TMR access ruminated less when hay was offered ( $P < 0.01$ ). In contrast, hay  
240 had no effect on rumination time in cows with 24-h TMR access. Rumination time, average

241 reticuloruminal pH values, and time when pH was below pH 5.8 and 5.5 are shown in Table 5.  
242 The results obtained are reflective of the high fiber diets used in this study. Time in which the pH  
243 fell below 5.5, the minimum critical threshold, was negligible. Average pH values were lower ( $P$   
244  $< .05$ ) in the diets where long hay was offered, but for no obvious reason. Overall pH of cows  
245 was not affected by diet treatment. This was likely a result of the cows' preference for TMR and  
246 their ability to somewhat compensate for total TMR DMI once adapted to the restricted hours of  
247 availability (Maulfair et al., 2013) while the group having no access to feed for 5 h ate less..

248         There were no differences regarding average ammonia and ruminal VFA levels, as shown  
249 in Table 6. At 12 h after feeding (0800 h) there was a tendency for lower ammonia for the cows  
250 with 19-h TMR access. This could be explained by the lower DMI for the restricted diets that  
251 release a higher amount of fermentable carbohydrates allowing bacteria to consume more  
252 nitrogen during the part of the day when feed was available. Conversely, when looking the values  
253 obtained 24 h after feed distribution (2000 h), acetate, propionate, and total VFA tended to be  
254 lower in cows with 19 h of TMR access, and butyrate was significantly lower. This condition is  
255 likely due to the absence of new feed that could have reduced VFA production in the rumen. All  
256 other rumen parameters measured were similar. Restricting TMR comprised of dry forages while  
257 offering additional long hay appears to be consistent with previous research using silage-based  
258 diets (Kmicikewycz and Heinrichs, 2014). In the same research, once cows adapted to the  
259 restricted feeding period, the lack of hay made little change to their feed intake and digestion.

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## CONCLUSIONS

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266           The results obtained in this study show that once cows adapted to diet changes, there were  
267 few differences when offering TMR continuously 24 h/d or limited to 19 h/d. In addition, the  
268 presence of long hay during the TMR restriction offered the best conditions for ruminal function  
269 and pH stability and tended to improve milk production. It was noted that a restriction of TMR  
270 availability for 5 h/d can potentially increase feed efficiency, as has been shown in other classes  
271 of ruminants. These results need to be confirmed by longer duration experiments using mid-  
272 lactation dairy cows. Due to the design of the experiment, milk production results need to be  
273 considered with caution. A Latin square with 21-d periods could have a carry-over effect on  
274 energy storage and mobilization of fat reserves might be able to mask negative energy balance  
275 during restriction. However, in our experiment we did not see any BW variation. This feeding  
276 system could be used as a strategy to manage feed availability according to cow production and  
277 metabolic condition, in order to maximize the use of nutrient resources, reducing the cost of milk  
278 production and improving the cows' welfare and health.

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**Table 1.** Composition of the TMR diet and the hay (mean  $\pm$  SD)

Item	TMR <sup>1</sup>	Hay
DM, %	87.66 $\pm$ 0.72	88.54 $\pm$ 2.93
Ether extract, % DM	2.53 $\pm$ 0.38	1.64 $\pm$ 0.20
Ash, % DM	9.76 $\pm$ 0.37	8.93 $\pm$ 0.63
aNDFom <sup>2</sup> , % DM	31.44 $\pm$ 5.45	58.46 $\pm$ 3.45
ADF, % DM	20.77 $\pm$ 4.18	42.61 $\pm$ 1.62
ADL, % DM	2.94 $\pm$ 0.64	6.62 $\pm$ 0.80
IVNDFD <sup>3</sup> 24h, % aNDFom	77.33 $\pm$ 6.95	67.02 $\pm$ 3.21
d-NDF 24h, % aNDFom	45.51 $\pm$ 3.44	44.74 $\pm$ 5.27
uNDF <sub>240</sub> <sup>4</sup> , % DM	6.40 $\pm$ 1.98	17.82 $\pm$ 5.40
Starch, % DM	23.55 $\pm$ 4.78	1.98 $\pm$ 2.12
Sugar, % DM	6.96 $\pm$ 0.56	4.79 $\pm$ 0.66
CP, % DM	14.28 $\pm$ 0.90	8.76 $\pm$ 1.10
Soluble protein, % DM	3.91 $\pm$ 0.44	3.55 $\pm$ 0.37
NDIP <sup>5</sup> , % DM	3.00 $\pm$ 0.28	4.92 $\pm$ 0.65
ADIP <sup>6</sup> , % DM	1.01 $\pm$ 0.07	1.55 $\pm$ 0.15
PSPS <sup>7</sup>		
19 mm %	0.39 $\pm$ 0.79	
8 mm %	15.18 $\pm$ 5.10	
4 mm %	18.73 $\pm$ 1.92	
Bottom %	65.69 $\pm$ 5.60	
Ro-Tap % >1.18 mm	46.24 $\pm$ 3.90	
peNDF <sup>8</sup> % DM	14.14 $\pm$ 1.30	

<sup>1</sup>TMR Ingredients: 34.5% grass hay, 19.2% steam flaked corn, 3.9% cane-beet molasses blend, and 42.4% grain mix [29.6% wheat bran, 29.4% sorghum grain, 21.6% soybean meal, 14.7% flaked soybean, 2.2% calcium carbonate, 1% sodium chloride, 0.4% magnesium oxide, 0.9% sodium bentonite, and 0.3% vitamin and mineral premix (provided 40,000 IU vitamin A, 4,000 IU vitamin D3, 30 mg vitamin E 92%  $\alpha$ -tocopherol, 5 mg vitamin B1, 3 mg vitamin B2, 1.5 mg vitamin B6, 0.06 mg vitamin B12, 5 mg vitamin K, 5 mg vitamin H1 (para-aminobenzoic acid), 150 mg vitamin PP (niacin), 50 mg choline chloride, 100 mg Fe, 1 mg Co, 5 mg I, 120 mg Mn, 10 mg Cu, and 130 mg Zn)].

<sup>2</sup>Amylase- and sodium sulfite-treated NDF with ash correction.

<sup>3</sup>In vitro NDF digestibility, in % aNDFom.

<sup>4</sup>Unavailable NDF estimated via 240-h in vitro fermentation.

<sup>5</sup>Neutral detergent insoluble protein (Neutral detergent insoluble nitrogen\*6.25).

<sup>6</sup>Acid detergent insoluble protein (Acid detergent insoluble nitrogen\*6.25).

<sup>7</sup>Penn State Particle Separator, % sample retained on each sieve (Lammers et al., 1996).

<sup>8</sup>Physically effective NDF (aNDFom\*pef), calculated using the Ro-Tap system (Mertens, 1997).

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**Table 2.** Effect of feed restriction and supplemental hay<sup>1</sup> on DMI and fiber fraction intake

Item	Feed availability				SEM	<i>P</i> value	
	24 h		19 h			24 vs 19	F+ vs F-
	F+	F-	F+	F-			
TMR DMI, kg	27.36	24.60	23.27	23.71	1.66	0.04	0.31
Hay DMI, kg	0.55	-	0.70	-	0.09	0.09	-
DMI, kg	27.85	24.56	24.05	23.65	1.70	0.06	0.13
BW, kg	637.93	637.86	646.56	631.67	20.99	0.76	0.08
aNDFom <sup>2</sup> , kg/d	8.79	7.66	7.73	7.44	0.54	0.10	0.07
aNDFom <sup>2</sup> , % BW	9.39	9.48	9.31	9.51	0.34	0.83	0.24
uNDF <sup>3</sup> , kg/d	1.89	1.60	1.70	1.57	0.12	0.17	0.02
uNDF <sup>3</sup> , % BW	0.30	0.26	0.26	0.25	0.02	0.25	0.19

<sup>1</sup>F+ = supplemental hay; F- = no supplemental hay.

<sup>2</sup>Amylase- and sodium sulfite-treated NDF with ash correction.

<sup>3</sup>Unavailable NDF estimated via 240-h in vitro fermentation.

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**Table 3.** Effect of feed restriction and supplemental hay<sup>1</sup> on fecal fiber content and total tract fiber digestibility

Item	Feed availability				SEM	<i>P</i> value	
	24 h		19 h			24 vs 19	F+ vs F-
	F+	F-	F+	F-			
Fecal aNDFom <sup>2</sup> , % DM	60.42	60.15	60.14	60.38	0.48	0.92	0.95
Fecal uNDFom <sup>3</sup> , % DM	32.21	31.99	32.48	31.69	0.83	0.97	0.21
Fecal pdNDF <sup>4</sup> , % DM	28.20	28.17	27.66	28.69	1.03	0.98	0.34
aNDFom TTD <sup>5</sup> , %	59.64	60.21	59.54	59.76	1.08	0.58	0.42
pdNDF TTD <sup>5</sup> , %	75.90	76.30	76.10	75.69	1.37	0.76	0.99

<sup>1</sup>F+ = supplemental hay; F- = no supplemental hay.

<sup>2</sup>Amylase- and sodium sulfite-treated NDF with ash correction.

<sup>3</sup>Unavailable NDF estimated via 240-h in vitro fermentation.

<sup>4</sup>Potentially digestible NDF.

<sup>5</sup>Total tract fiber digestibility.

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**Table 4.** Effect of feed restriction and supplemental hay<sup>1</sup> on milk production and quality

Item	Feed availability				SEM	P value	
	24 h		19 h			24 vs 19	F+ vs F-
	F+	F-	F+	F-			
Milk, kg/d	37.87	36.56	38.19	35.33	1.63	0.71	0.09
ECM, kg/d	40.26	38.23	39.13	36.84	1.33	0.13	0.01
Milk kg/DMI kg	1.40	1.54	1.91	1.64	0.18	0.03	0.64
ECM kg/DMI kg	1.48	1.60	1.92	1.68	0.17	0.05	0.63
Fat, %	3.82	3.62	3.58	3.60	0.18	0.31	0.46
Fat yield, kg/d	1.27	1.32	1.35	1.33	0.16	0.71	0.91
Protein, %	3.38	3.38	3.42	3.31	0.11	0.74	0.34
Protein yield, kg/d	1.13	1.26	1.28	1.20	0.10	0.65	0.83
Lactose, %	4.88	4.88	4.80	4.79	0.05	0.04	0.94
Lactose yield, kg/d	1.65	1.83	1.86	1.75	0.15	0.68	0.85
Urea, %	14.68	15.42	15.30	15.53	1.36	0.72	0.65
SCC, log cfu/mL	2.39	3.49	3.38	4.00	0.80	0.07	0.04
BW variation, kg	0.52	-3.48	17.63	17.47	9.60	0.08	0.85

<sup>1</sup>F+ = supplemental hay; F- = no supplemental hay.

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**Table 5.** Effect of feed restriction and supplemental hay<sup>1</sup> on rumination time and reticuloruminal pH

Item	Feed availability				SEM	<i>P</i> value	
	24 h		19 h			24vs19	F+ vs F-
	F+	F-	F+	F-			
Rumination, min/d	424.98 <sup>a</sup>	443.10 <sup>a</sup>	446.26 <sup>a</sup>	412.22 <sup>b</sup>	30.49	0.62	0.41
Daily average pH	6.10	6.11	6.09	6.12	0.09	0.88	0.04
Time pH < 5.8, min/d	18.79	19.06	22.02	18.44	11.78	0.32	0.21
Time pH < 5.5, min/d	0.79	0.25	0.10	1.74	0.84	0.51	0.36

<sup>1</sup>F+ = supplemental hay; F- = no supplemental hay.

<sup>ab</sup> Means with different superscripts differ at  $P < 0.05$ . (Significant interaction between effects of feed availability and provision of supplemental hay.)

**Table 6.** Effect of feed restriction and supplemental hay<sup>1</sup> on ruminal VFA and ammonia content

Item	Feed availability				SEM	<i>P</i> value	
	24 h		19 h			24 vs 19	F+ vs F-
	F+	F-	F+	F-			
Average, mmol/L							
NH <sub>3</sub>	3.95	4.00	3.33	3.56	0.49	0.24	0.75
Acetic	45.46	50.76	47.54	42.95	3.19	0.37	0.91
Propionic	18.94	21.92	20.26	18.29	1.86	0.48	0.76
Butyric	9.14	9.61	9.48	8.98	0.82	0.49	0.76
Isobutyric	0.47	0.56	0.49	0.45	0.08	0.83	0.98
Valerianic	0.91	1.07	1.06	0.95	0.09	0.88	0.84
Isovalerianic	0.92	1.02	1.10	0.98	0.13	0.50	0.96
Total VFA	75.84	84.94	79.93	72.60	5.14	0.45	0.87
12 h after feeding, mmol/L							
NH <sub>3</sub>	4.23	4.70	3.54	3.24	0.57	0.07	0.88
Acetic	39.77	48.38	47.03	42.78	4.37	0.86	0.63
Propionic	15.11	19.63	20.13	17.71	2.09	0.46	0.62
Butyric	7.77	8.96	9.95	9.22	1.11	0.24	0.82
Isobutyric	0.42	0.61	0.45	0.40	0.09	0.34	0.42
Valerianic	0.79	0.99	1.05	0.95	0.12	0.37	0.70
Isovalerianic	0.76	1.03	0.97	0.96	0.15	0.56	0.30
Total VFA	64.62	79.59	79.59	72.03	7.18	0.62	0.62
24 h after feeding, mmol/L							
NH <sub>3</sub>	3.66	3.31	3.11	3.87	0.51	0.99	0.68
Acetic	51.17	53.17	47.99	42.61	3.86	0.10	0.69
Propionic	22.76	24.20	20.42	19.07	2.45	0.10	0.96
Butyric	10.53	10.28	8.97	8.40	0.82	0.03	0.56
Isobutyric	0.53	0.51	0.53	0.48	0.08	0.81	0.59
Valerianic	1.04	1.14	1.07	0.92	0.11	0.44	0.89
Isovalerianic	1.07	1.01	1.21	0.92	0.14	0.79	0.16
Total VFA	87.08	90.30	80.22	72.75	6.35	0.09	0.77

<sup>1</sup>F+ = supplemental hay; F- = no supplemental hay.