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Nutrient demand interacts with grass particle length to affect digestion responses and chewing activity in dairy cows

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ABSTRACT

Effects of grass particle length on dry matter intake (DMI), milk production, ruminal fermentation and pool sizes, digestion and passage kinetics, and chewing activity and the relationship of these effects with preliminary DMI (pDMI) were evaluated using 15 ruminally and duodenally cannulated Holstein cows in a crossover design with a 14-d preliminary period and two 18-d treatment periods. During the preliminary period, pDMI of individual cows ranged from 22.6 to 29.8 kg/d (mean = 25.8 kg/d) and 3.5% fat-corrected milk yield ranged from 29.2 to 56.9 kg/d (mean = 41.9 kg/d). Experimental treatments were diets containing orchardgrass silage chopped to either (a) 19-mm (long) or (b) 10-mm (short) theoretical length of cut as the sole forage. Grass silages contained approximately 46% neutral detergent fiber (NDF); diets contained 50% forage, 23% forage NDF, and 28% total NDF. Preliminary DMI, an index of nutrient demand, was determined during the last 4 d of the preliminary period when cows were fed a common diet and used as a covariate. Main effects of grass particle length and their interaction with pDMI were tested by ANOVA. Grass particle length and its interaction with pDMI did not affect milk yield, milk composition, or rumen pH. Long particle length tended to decrease DMI compared with short particle length, which might have been limited by rumen fill or chewing time, or both. Passage rates of feed fractions did not differ between long and short particle lengths and were not related to level of intake. As pDMI increased, long particles decreased ruminal digestion rate of potentially digestible NDF at a faster rate than short particles. As a result, long particles decreased or tended to decrease rates of ruminal turnover for NDF, organic matter, and dry matter and increased their rumen pools compared with short particles for cows with high pDMI. Long particles increased eating time, which affected cows with high intake to the greatest extent, and total chewing time compared with short particles. As intake increased, ruminal digestion (kg/d) and digestibility (%) of starch decreased, rumen pool size of starch increased, and postruminal digestion and digestibility of starch increased quadratically. When grass silage was the only source of forage in the diet, increasing chop length from 10 to 19 mm tended to decrease DMI but did not negatively affect productivity of cows, which were fed adequate fiber.
Key words: particle size, grass silage, chewing activity, digestion kinetics

INTRODUCTION

Forage particle size affects various aspects of rumen function and digestion kinetics. Ruminal digesta passage rates decrease with increasing particle size due to greater retention time in the rumen (Dixon and Milligan, 1985) and mat formation by long forage particles, which increases digestibility of smaller particles (Grant, 1997). Greater ruminal distention caused by longer forage particles is more likely to affect passage rate and feed intake of lactating dairy cows when feed intake is limited by rumen fill. Decreasing particle size permits rapid removal of digesta from the rumen, allowing increased feed intake when intake is limited by distention, but digestibility is decreased and ruminal pH might be reduced for several reasons, including a reduction in buffer capacity of ruminal digesta mass, a decrease in rate of VFA absorption from decreased motility, and a decrease in salivary buffer secretion from decreased rumination.

Forage particle length (**FPL**) has been widely researched, but the effects of FPL on animal responses are inconsistent and inconclusive. Some of the inconsistency on responses to particle size may be due to forage type. Tafaj et al. (2007) reported that effects of forage particle size were less when corn silage was included in the TMR and greater for grass silage-based TMR. Furthermore, grasses and legumes differ in in vitro cell wall digestion rates (Smith et al., 1972; Robles et al. 1980) and anatomical structure and digestion characteristics affecting particle size reduction and passage (Allen and Mertens, 1988). These differences suggest consideration of forage family is necessary when evaluating the effects

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of particle size. Orchardgrass (**OG**; *Dactylis glomerata* L.) was selected as a representative cool-season grass for use in this experiment.

Besides dietary factors, another reason for inconsistent responses to FPL may be related to animal factors. Cows respond differently to treatments depending on their level of intake (Voelker Linton and Allen, 2008) and production (Oba and Allen, 1999). Because FPL and level of intake affect ruminal passage and digestion rates and, thus, digesta fill in the rumen, the response to effects of particle size and its relationship with intake level should be assessed to determine if responses to treatment vary among cows with a wide range in DMI. We hypothesized that responses of DMI and digesta passage rates to grass particle length are related to level of intake and shorter particle length will permit a greater increase in passage rate than longer particle length as feed intake increases.

The objectives of this experiment were to evaluate the relationships between voluntary DMI and effects of length of cut of grass silage on DMI, milk production, ruminal fermentation and pool sizes, digestion and passage kinetics, and chewing behavior in lactating dairy cows. This study had 3 unique features to improve our understanding of the role of particle size and interpret its effect on animal responses. First, it allowed effects of the interaction between FPL and preliminary DMI (**pDMI**) to be evaluated. The use of pDMI, an index of nutrient demand, allowed the evaluation of treatments on animal responses in relation to level of intake and provided an indicator to test effects of intake level independent of treatments. Second, it directly compared treatment effects of long- and short-cut OG as the sole source of forage without the confounding effects of other dietary factors. Third, ruminal passage rates of individual feed fractions, instead of entire feeds, were measured using ruminally and duodenally cannulated cows.

MATERIALS AND METHODS

Cows and Treatments

Experimental procedures were approved by the Institutional Animal Care and Use Committee at Michigan State University (East Lansing). Fifteen multiparous Holstein cows from the Michigan State University Dairy Cattle Teaching and Research Center were assigned randomly to treatment sequence in a crossover design experiment with one 14-d preliminary period and two 18-d experimental periods. The first 10 d of each period were allowed for diet adaptation and samples were collected during the final 4 d of the preliminary period and 8 d of each experimental period. Cows were 164 ± 56 (mean ± SD) DIM at the end of the preliminary period and were selected to provide a wide range and uniform distribution of pDMI and milk yield. During the final 4 d of the 14-d preliminary period, the average pDMI among cows ranged from 22.6 to 29.8 kg/d (mean = 25.8 kg/d) and 3.5% FCM yield ranged from 29.2 to 56.9 kg/d (mean = 41.9 kg/d; Table 1). Prior to calving, cows were cannulated ruminally (Bar Diamond Inc., Parma, ID) and duodenally with a gutter-type T cannula placed approximately 10 cm distal to the pylorus (Joy et al., 1997). Surgery was performed at the Department of Large Animal Clinical Science, College of Veterinary Medicine, Michigan State University.

Experimental treatments were diets containing OG silage chopped to either (a) 19 mm (long) or (b) 10 mm (short) theoretical length of cut (**TLC**) as the sole forage. These TLC were selected to provide a wide interval within the normal range of TLC to examine if animal response to FPL is affected by level of feed intake.

Orchardgrass (Baridana cultivar; Barenbrug USA, Tangent, OR) was produced at the campus farm at Michigan State University, chopped from the same field, and ensiled in Ag-Bags (Ag-Bag Systems Inc., St. Nazianz, WI). During the sample-collection periods, long- and short-cut OG contained approximately 46% NDF (DM basis; Table 2). Diets with long and short particle lengths were formulated to contain 21% forage NDF, 28% total NDF, and 18% CP. The diet fed during the preliminary period was formulated so that long- and short-cut OG each contributed 50% of forage NDF. Diets also contained dry ground corn, soybean meal (48% CP), SoyPLUS (West Central Soy Cooperative, Ralston, IA), vitamin-mineral premix, and limestone (Table 3).

Table 1. Characterization of 15 cows during the final 4 d of the 14-d preliminary period, when cows were fed a common diet

Parameter	Median	Mean	SD	Minimum	Maximum
Parity	3	3.1	1.2	2	6
BW,[1] kg	581	579	58	469	687
BCS	2.1	2.3	0.7	1.5	3.7
DIM	168	164	56	83	258
Milk, kg/d	43.1	41.5	10.6	24.2	62.2
3.5% FCM, kg/d	40.6	41.9	8.9	29.2	56.9
DMI, kg/d	25.4	25.8	2.1	22.6	29.8

[1]Empty BW (ruminal digesta removed)

Data and Sample Collection

Throughout the experiment, cows were housed in tie-stalls and fed diets as TMR once daily (1130 h) at 110% of expected intake. The amount of feed offered and refused (orts) was weighed daily for each cow. Forage samples were collected twice weekly and analyzed to adjust diets to account for DM, NDF, and CP fluctuation. Samples of all dietary ingredients (0.5 kg) and orts (12.5%) were collected daily from d 11 to 14 during the preliminary period and d 11 to 15 during each experimental period. Samples were frozen immediately after collection at −20°C and combined to 1 composite sample per period before analysis.

Cows were moved to an exercise lot twice daily (0230 and 1300 h) before milking in a parlor (0400 and 1430 h). Milk yield was measured and milk was sampled at each milking on d 11 to 14 of the preliminary period and on d 11 to 15 of the experimental periods. Rumen-empty BW was measured by weighing the cow after evacuation of ruminal digesta on d 14 of the preliminary period and d 18 of each experimental period. Body condition score was determined on the same days by 3 trained investigators blinded to treatments (Wildman et al., 1982; 5-point scale where 1 = thin and 5 = fat). Chewing activity was monitored and recorded by observation every 5 min for 24 h on d 16 of each experimental period. Activity was noted as eating, ruminating, drinking, or idle for each cow at each time.

Duodenal samples (900 mL), fecal samples (500 g), rumen fluid and particulate samples for microbial isolation (400 g), rumen fluid samples for pH, and

Table 2. Chemical composition, particle size distribution, and fermentation parameters of the long- (19 mm) and short-cut (10 mm) orchardgrass silage included in the treatment diets

	Orchardgrass silage	
Item	Long	Short
Chemical composition		
DM, %	26.5	31.4
OM, % DM	88.2	88.4
NDF, % DM	46.9	45.2
iNDF,[1] % DM	12.2	11.6
iNDF, % of NDF	26.1	25.7
ADF, % of DM	31.3	32.1
ADL, % of DM	4.42	4.57
CP, % DM	21.1	20.5
Starch, % DM	1.21	1.24
Particle size distribution[2]		
Wet sieving, % DM retained		
19.0 mm	30.6	27.1
9.50 mm	28.4	24.4
4.75 mm	15.5	28.1
2.36 mm	5.81	14.3
1.18 mm	3.24	4.57
0.600 mm	2.19	2.33
0.300 mm	1.09	1.41
0.150 mm	0.57	0.72
0.075 mm	0.34	0.37
0.038 mm	0.36	0.34
Mean particle size,[3] mm	15.3	11.3
Penn State Particle Separator,[4] % DM retained		
>19.0 mm	46.1	26.2
19.0 to 8.0 mm	29.0	31.7
<8.0 mm	24.9	42.1
Fermentation		
pH	4.63	4.69
Acetic acid, % DM	3.36	5.26
Propionic acid, % DM	0.12	0.49
Butyric acid, % DM	<0.01	0.09
Lactic acid, % DM	10.5	10.6
Lactic:acetic	3.14	2.01
Ethanol, % DM	0.12	0.40
Ammonia, m*M*	5.09	4.84

[1]iNDF = indigestible NDF.

[2]Particle size distributions of silages were measured each period (n = 2).

[3]Mean particle size was calculated from particle size distribution determined by wet sieving.

[4]Silages were dried to constant weight with forced air (no heat) before separation using the Penn State Particle Separator due to high moisture content.

Table 3. Ingredients and chemical composition of preliminary and treatment diets (as analyzed) containing either long- (19 mm) or short-cut (10 mm) orchardgrass silage as the sole source of forage

Diet composition	Preliminary	Long	Short
Ingredient, % DM			
Orchardgrass silage, long cut	26.0	49.8	—
Orchardgrass silage, short cut	26.0	—	49.7
Dry ground corn	36.9	38.4	37.9
Soybean meal (48% CP)	1.99	2.89	3.45
SoyPLUS[1]	3.47	3.39	3.39
Vitamin mineral mix[2]	3.97	3.97	3.97
Limestone	1.60	1.60	1.60
Chemical composition			
DM, %	41.7	40.8	46.5
OM, % DM	89.9	90.0	90.1
NDF, % DM	28.5	28.3	27.4
% Forage NDF	23.8	23.3	22.5
% NDF from forage	83.4	82.6	82.1
iNDF,[3] % DM	6.25	8.20	7.90
iNDF, % of NDF	21.9	29.0	28.8
CP, % DM	17.1	17.9	17.9
Starch, % DM	29.2	29.8	29.5

[1]West Central Soy Cooperative, Ralston, IA.

[2]Vitamin mineral mix contained (DM basis) 16.5% sodium bicarbonate, 14.2% magnesium sulfate, 7.1% salt, 5.8% dicalcium phosphate, 2.4% trace mineral premix, 0.4% vitamin A, 0.4% vitamin D, 0.2% vitamin E, and 53.1% dry ground corn as a carrier.

[3]iNDF = indigestible NDF.

concentrations of VFA, lactate, and ammonia (100 mL) were collected every 15 h from d 11 to 15 of each experimental period so that 8 samples were taken for each cow in each period, representing every 3 h of a 24-h period to account for diurnal variation. Rumen fluid and particulate matter for microbial isolation was collected from the reticulum near the reticular-omasal orifice, transported to the laboratory, and processed. Rumen fluid for pH, VFA, lactate, and ammonia was obtained by combining digesta from 5 different sites in the rumen and straining it through nylon mesh (~1 mm pore size); fluid pH was recorded immediately. Samples were stored at −20°C.

Ruminal contents were evacuated manually through the ruminal cannula 4 h after feeding at the beginning of d 17 (1530 h) and 2 h before feeding at the end of d 18 (0930) for each experimental period. Total rumen content mass and volume were determined. To ensure accurate sampling, every tenth handful of digesta (10%) was separated for a subsample throughout evacuation. This subsample was squeezed into primarily solid and liquid phases. Both phases were weighed and sampled (350 mL) for determination of nutrient pool size. All samples were stored at −20°C.

Sample Analysis and Calculations

Milk yield recorded at both milkings were summed for a daily total, which were averaged for each period. Milk samples were analyzed for fat, true protein, lactose, SNF, and MUN with infrared spectroscopy by Michigan DHIA (East Lansing). Yields of 3.5% FCM and milk components were calculated using milk yield and component concentrations for each milking, summed for a daily total, and averaged for each period.

Forage samples were combined to 1 composite sample per forage per period. Particle size distribution was determined using the Penn State Particle Separator containing 2 sieves (19 and 8 mm) and a pan (Lammers et al., 1996). Due to the high moisture content of the silages, the particles tended to cling together and remain on the top sieve during the shaking process yielding inaccurate measurements. Therefore, samples were dried to a constant weight with forced air (no added heat) before separation. In addition, samples were wet sieved manually and sequentially through screens with the following aperture sizes: 19.0, 9.50, 4.75, 2.36, 1.18, 0.600, 0.300, 0.150, 0.075, and 0.038 mm. The fraction of DM retained on the screens from wet sieving was used to calculate mean particle size.

Diet ingredients, orts, and feces were lyophilized (Tri-Philizer MP; FTS Systems Inc., Stone Ridge, NY). All dried samples were ground with a Wiley mill (1-mm screen; Arthur H. Thomas Co., Philadelphia, PA). Dried, ground fecal samples were combined on an equal DM basis into 1 sample per cow per period. Frozen duodenal samples for each cow period (n = 8) were chopped finely using a commercial food processor (84142 Food cutter; Hobart Manufacturing Co., Troy, OH) and subsampled in the frozen state to obtain rep-

resentative samples. These duodenal subsamples and the 350 mL of ruminal solid and liquid samples were lyophilized and ground as described above. Dried ruminal solid and liquid samples were recombined according to the original ratio of solid and liquid DM.

Samples were analyzed for ash, NDF, indigestible NDF (**iNDF**), ADF, ADL, CP, and starch. Ash concentration was determined after 5 h combustion at 500°C in a muffle furnace. Concentrations of NDF were determined according to Mertens (2002) and ADF and ADL according to Goering and Van Soest (1970). Indigestible NDF was estimated as NDF residue after 240-h in vitro fermentation (Goering and Van Soest, 1970); flasks were reinoculated at 120 h to ensure a viable microbial population. Ruminal fluid for the in vitro incubations was collected from a nonpregnant dry cow fed dry hay only. Fraction of potentially digestible NDF (**pdNDF**) was calculated by difference (1.00 – iNDF). Crude protein was analyzed according to Hach et al. (1987). Starch was measured by an enzymatic method (Karkalas, 1985) after samples were gelatinized with sodium hydroxide. Glucose concentration was measured using a glucose oxidase method (Glucose kit #510; Sigma Chemical Co., St. Louis, MO), and absorbance was determined with a micro-plate reader (SpectraMax 190; Molecular Devices Corp., Sunnyvale, CA). Concentrations of all nutrients except DM were expressed as percentages of DM, determined by drying at 105°C in a forced-air oven for more than 8 h.

Duodenal digesta were analyzed for purines and ammonia to estimate microbial N (**MN**) flow and nonammonia, nonmicrobial N (**NANMN**) flow to the duodenum. Purine concentration was used as a microbial marker, and purine-to-MN ratio was estimated by analysis of microbial pellets obtained by differential centrifugation of the rumen fluid and particulate samples collected near the reticulum. Rumen fluid and particulate matter was blended, strained through nylon mesh, and the liquid portion was centrifuged at 500 × *g* for 15 min. The supernatant was centrifuged at 18,000 × *g* for 15 min, and the pellet was washed with 0.9% NaCl solution and centrifuged again at 18,000 × *g* for 15 min, resuspended in water, and lyophilized. Total purines were measured by spectrophotometer (Beckman Instruments Inc., Fullerton, CA) at 260 nm according to Zinn and Owens (1986). Ammonia concentration was determined for centrifuged duodenal and rumen fluid samples according to Broderick and Kang (1980). Rumen fluid was also analyzed for concentration of major VFA and lactate by HPLC (Waters Corp., Milford, MA) according to Oba and Allen (2003a).

Dry matter and nutrient intakes were calculated using the composition of feed offered and refused. Ruminal pool sizes (kg) of OM, NDF, iNDF, pdNDF, starch, MN, and NANMN were determined by multiplying the concentration of each component in rumen samples by the ruminal digesta DM mass (kg). Duodenal flows (kg/d) of DM, OM, total NDF, pdNDF, starch, MN, NANMN, and ammonia N were determined using iNDF as a flow marker; iNDF intake (kg/d) was multiplied by the ratio between the component and iNDF in duodenal digesta. Duodenal flow of microbial OM was determined using the ratio of purines:OM (Oba and Allen, 2003a), and true ruminally digested OM was calculated by subtracting duodenal flow of nonmicrobial OM from OM intake. Indigestible NDF was used as an internal marker to estimate nutrient digestibility in the rumen and in the total tract (Cochran et al., 1986). Turnover rate in the rumen, passage rate from the rumen, and ruminal digestion rate of each component was calculated by the following equations:

$$\text{turnover rate (\%/h)} = 100 \times (\text{intake of component/ruminal pool of component})/24;$$

$$\text{passage rate (\%/h)} = 100 \times (\text{duodenal flow of component/ruminal pool of component})/24;$$

$$\text{digestion rate (\%/h)} = \text{turnover rate in the rumen (\%/h)} - \text{passage rate from the rumen (\%/h)}.$$

Manually observed chewing activity was summarized by a logic script in Igor Pro (version 6.12; WaveMetrics Inc., Lake Oswego, OR) to generate meal and rumination bout information according to previously established criteria (Dado and Allen, 1994). Variables determined included frequency of meal bouts per day, interval between meals, frequency of ruminating bouts per day, interval between ruminating bouts, eating time per day, ruminating time per day, and total chewing time per day.

Statistical Analysis

All data were analyzed by using the fit model procedure of JMP (Version 8; SAS Institute Inc., Cary, NC). To determine differences between treatments and evaluate interactions of treatment with DMI, where pDMI (calculated as the mean of DMI values on d 11 to 14 of the 14-d preliminary period) was used as the covariate for treatment responses, data were analyzed according to the following model: $Y_{ijk} = \mu + C_i + P_j + T_k + PT_{jk} + pDMI + T_k pDMI + pDMI^2 + T_k pDMI^2 + e_{ijk}$, where Y_{ijk} is the dependent variable, μ is the overall mean, C_i is the random effect of cow (i = 1 to

15), P_j is the fixed effect of period (j = 1 to 2), T_k is the fixed effect of treatment (k = 1 to 2), PT_{jk} is the interaction of period and treatment, pDMI is the linear effect of pDMI, T_kpDMI is the interaction of treatment and pDMI (linear), $pDMI^2$ is the quadratic effect of pDMI, $T_k pDMI^2$ is the interaction of treatment and pDMI (quadratic), and e_{ijk} is the residual error. Statistical significance for T_kpDMI and $T_k pDMI^2$ indicated treatment differences were related to pDMI. Covariate and interaction terms were removed stepwise from the model if $P > 0.20$. Treatment effects and their interaction (linear and quadratic relationships) were declared significant at $P \leq 0.05$ and $P \leq 0.10$, respectively. Tendencies for treatment effects and their interactions were declared at $P \leq 0.10$ and $P \leq 0.15$, respectively.

Sixteen cows started the experiment; however, 1 cow went off feed during the second experimental period 2 d before the start of sample collection and was removed. Thus, data from 15 cows were statistically analyzed.

RESULTS AND DISCUSSION

Comparison of Forages and Diets

Physical characteristics of OG are listed in Table 2. Forages chopped to a TLC of 19 and 10 mm had mean particle sizes of 15.3 and 11.3 mm, respectively. The proportion of particles >19 mm was 20 percentage points higher (46 vs. 26%) and the proportion of particles <8 mm was 17 percentage points lower (25 vs. 42%) for long- than short-cut OG, respectively. The particle size distribution of short-cut OG was similar to the guidelines recommended by Heinrichs (1996) that the portion of haylage retained on the 19-mm sieve, the 8-mm sieve, and the bottom pan of the Penn State Particle Separator should be 15 to 25%, 30 to 40%, and 40 to 50%, respectively.

Chemical analyses (Table 2) showed that OG with different lengths of cut had similar concentrations of OM, total NDF, pdNDF, iNDF, ADF, ADL, CP, and starch. Both silages were wetter than expected and long-cut OG had lower DM concentration than short-cut OG due to the shorter wilting time for long-cut OG, as the silages were sequentially harvested and long-cut OG was mowed, chopped, and ensiled first. Both OG silages underwent favorable fermentation and were well preserved based on the low pH and high lactic acid concentrations. However, the concentrations of acetic acid were higher than that typical for grass silages, which is likely due to the high moisture content of both OG (Kung and Shaver, 2001).

Diet ingredients and chemical composition are shown in Table 3. The preliminary diet contained similar proportions of forage NDF from long- and short-cut OG. Both treatment diets had a 50:50 forage:concentrate ratio, contained 23% forage NDF, and had similar chemical composition, which was calculated according to the proportion of each feed ingredient in the diet and its respective analytical values. The calculated percent forage NDF in the diet was slightly higher than the formulated target but was similar for both long and short particles and above NRC (2001) minimum require-

Table 4. Milk production and composition, feed intake, and BW change of cows fed treatment diets containing either long- (19 mm) or short-cut (10 mm) orchardgrass silage as the sole source of forage

	Treatment LSM			*P*-value[1]					
Item	Long	Short	SE	Trt	Trt × period	pDMI	Trt × pDMI	pDMI × pDMI	Trt × pDMI × pDMI
Yield, kg/d									
Milk	39.9	40.0	2.3	0.80	NS[2]	<0.001	0.59	0.71	0.15
FCM (3.5%)	39.8	39.5	1.5	0.62	NS	<0.001	NS	NS	NS
Milk fat	1.40	1.40	0.05	0.99	NS	0.004	NS	NS	NS
Milk protein	1.17	1.18	0.06	0.57	NS	0.006	0.71	0.93	0.18
Milk lactose	1.88	1.89	0.12	0.77	NS	<0.001	0.42	0.68	0.18
SNF	2.26	2.27	0.14	0.73	NS	<0.001	0.41	0.68	0.16
Milk composition, %									
Fat	3.61	3.68	0.12	0.22	NS	0.03	NS	NS	NS
Protein	3.04	3.06	0.06	0.44	NS	0.001	NS	NS	NS
Lactose	4.68	4.67	0.07	0.75	NS	0.11	NS	NS	NS
SNF	5.62	5.61	0.08	0.74	NS	0.16	NS	NS	NS
MUN, mg/dL	12.3	11.2	0.3	<0.001	NS	0.07	NS	NS	NS
DMI, kg/d	21.8	22.7	0.9	0.06	NS	0.02	NS	0.20	NS
3.5% FCM/DMI	1.64	1.60	0.06	0.39	NS	0.01	0.42	0.21	0.09
BW change, kg/18 d	6.88	2.57	3.91	0.54	NS	0.88	0.02	0.46	0.16
BCS change/18 d	−0.08	−0.06	0.05	0.84	NS	NS	NS	NS	NS

[1]*P*-values for treatment (Trt), Trt by period interaction (Trt × period), preliminary DMI (pDMI), Trt by preliminary DMI interaction (Trt × pDMI), quadratic effect of preliminary DMI (pDMI × pDMI), and Trt by quadratic effect of preliminary DMI (Trt × pDMI × pDMI).
[2]Nonsignificant, with $P > 0.20$; term was removed from the statistical model.

ments. In both diets, forage NDF provided over 82% of the total diet NDF. Differences in DM concentration in diets were because of the different DM concentrations of the forages.

Effects of Grass FPL and pDMI

Forage particle length and its interaction with pDMI did not affect yields of milk or milk components or milk composition (Table 4). Long particles increased MUN concentrations ($P < 0.001$; Table 4) compared with short particles. This is consistent with higher ruminal ammonia concentration and flux of ammonia N to the duodenum ($P < 0.01$; Table 5) for long than short particles. Although long-cut OG silage was wetter, similar ammonia concentrations (Table 2) were measured in both silages and, therefore, long-cut OG silage was not the source for increased ammonia observed in cows fed long particles.

Long particles tended to increase starch ruminal rate of digestion (19.0 vs.14.9%/h, $P = 0.07$; Table 6) and true ruminal digestibility (60.3 vs. 49.8%, $P = 0.09$; Table 7) and tended to decrease starch flux from the rumen to the duodenum (2.84 vs. 3.51 kg/d, $P = 0.09$; Table 7) compared with short particles. The mechanism for increased starch digestion rate is unclear but one explanation is that longer forage particles may promote greater numbers or activity of starch-digesting bacteria in the rumens of cows consuming long particles. Some starch-digesting bacteria in the rumen (e.g., *Streptococcus bovis*) also have high proteolytic activity (Russell et al., 1981), resulting in deamination of amino acids and production of ammonia, which could contribute to the increased ammonia concentration for long particle-fed cows.

Long particles tended to decrease DMI (21.8 vs. 22.7 kg/d, $P = 0.06$; Table 4) compared with short particles. We expected long particles to be more filling than short particles, causing greater rumen distention and potentially limiting DMI, particularly in cows with high DMI for which ruminal distention is more likely to limit feed intake (Allen, 1996). Oba and Allen (1999) and Voelker et al. (2002) found DMI responses varied by production level, which is generally correlated with DMI (NRC, 2001), where DMI was increasingly limited by high-fill diets compared with low-fill diets as milk yield increased. Although we expected the long-particle diet to slow rates of ruminal passage, FPL and its in-

Table 5. Nitrogen metabolism of cows fed treatment diets containing either long- (19 mm) or short-cut (10 mm) orchardgrass silage as the sole source of forage

	Treatment LSM			*P*-value[1]					
Item	Long	Short	SE	Trt	Trt × period	pDMI	Trt × pDMI	pDMI × pDMI	Trt × pDMI × pDMI
N intake, g/d	620	650	25	0.02	NS[2]	0.05	NS	0.15	NS
Ruminal ammonia, mg/dL	8.11	6.47	0.26	<0.001	NS	0.002	NS	0.15	NS
Flow to duodenum									
Ammonia N, g/d	12.5	10.7	0.8	0.004	NS	0.05	NS	0.16	NS
NAN									
g/d	523	514	40	0.64	NS	0.06	NS	0.18	NS
% of N intake	80.3	75.6	3.0	0.14	NS	0.19	NS	NS	NS
NANMN[3]									
g/d	296	269	27	0.18	NS	0.10	0.23	0.09	0.18
% of N intake	45.2	42.3	3.1	0.24	NS	0.20	NS	0.13	NS
% of duodenal NAN	52.0	51.6	1.9	0.83	NS	NS	NS	NS	NS
Microbial N									
g/d	230	230	15	0.98	NS	0.11	NS	NS	NS
% of duodenal NAN	48.0	48.4	1.9	0.83	NS	NS	NS	NS	NS
g/kg of TRDOM[4]	19.7	18.8	1.3	0.55	NS	NS	NS	NS	NS
NAN apparent postruminal digestion									
g/d	302	295	29	0.69	NS	0.05	NS	0.11	NS
% of N intake	47.8	45.0	3.2	0.37	NS	0.07	NS	0.10	NS
% of duodenal passage	57.2	56.8	2.1	0.87	NS	0.12	NS	0.05	NS
N apparent total-tract digestion									
g/d	399	431	15	0.008	NS	0.03	0.12	0.06	NS
%	63.9	65.8	1.3	0.24	NS	NS	NS	NS	NS

[1]*P*-values for treatment (Trt), Trt by period interaction (Trt × period), preliminary DMI (pDMI), Trt by preliminary DMI interaction (Trt × pDMI), quadratic effect of preliminary DMI (pDMI × pDMI), and Trt by quadratic effect of preliminary DMI (Trt × pDMI × pDMI).

[2]Nonsignificant, with $P > 0.20$; term was removed from the statistical model.

[3]NANMN = nonammonia, nonmicrobial nitrogen.

[4]TRDOM = true ruminally digested OM.

Table 6. Rumen kinetics of cows fed treatment diets containing either long- (19 mm) or short-cut (10 mm) orchardgrass silage as the sole source of forage

	Treatment LSM			*P*-value[1]					
Item	Long	Short	SE	Trt	Trt × period	pDMI	Trt × pDMI	pDMI × pDMI	Trt × pDMI × pDMI
Ruminal turnover rate, %/h									
DM	7.55	7.93	0.37	0.29	NS[2]	0.34	0.11	NS	NS
OM	7.62	8.03	0.39	0.27	NS	0.34	0.08	NS	NS
NDF	4.40	4.44	0.22	0.83	NS	0.18	0.07	NS	NS
pdNDF[3]	7.31	7.04	0.36	0.48	NS	0.35	0.11	NS	NS
Starch	32.9	31.0	2.6	0.49	NS	0.16	0.89	0.46	0.09
Ruminal turnover time, h									
DM	13.6	13.0	0.6	0.32	NS	0.29	0.07	NS	NS
OM	13.5	12.9	0.6	0.31	NS	0.28	0.05	NS	NS
NDF	23.6	23.3	1.1	0.83	NS	0.14	0.05	NS	NS
pdNDF	14.1	14.8	0.7	0.37	NS	0.28	0.13	NS	NS
iNDF[4]	48.2	45.2	2.6	0.38	NS	0.08	0.09	NS	NS
Starch	3.12	3.43	0.25	0.21	NS	0.29	0.85	0.48	0.06
Ruminal passage rate, %/h									
pdNDF	0.89	0.75	0.22	0.53	NS	0.12	0.45	0.45	0.19
iNDF	2.23	2.29	0.13	0.70	NS	0.14	NS	NS	NS
Starch	14.3	15.8	1.9	0.41	NS	0.50	NS	0.13	NS
Ruminal digestion rate, %/h									
pdNDF	6.63	6.28	0.29	0.38	NS	0.04	0.08	NS	NS
Starch	19.0	14.9	1.8	0.07	NS	0.01	0.34	0.01	0.02

[1]*P*-values for treatment (Trt), Trt by period interaction (Trt × period), preliminary DMI (pDMI), Trt by preliminary DMI interaction (Trt × pDMI), quadratic effect of preliminary DMI (pDMI × pDMI), and Trt by quadratic effect of preliminary DMI (Trt × pDMI × pDMI).

[2]Nonsignificant, with $P > 0.20$; term was removed from the statistical model.

[3]pdNDF = potentially digestible NDF.

[4]iNDF = indigestible NDF.

teraction with pDMI did not affect the rates of pdNDF, iNDF, or starch passed from the rumen (Table 6). However, the rate of ruminal digestion of pdNDF was related to pDMI, which decreased at a faster rate for long particles than short particles as pDMI increased (interaction $P = 0.08$; Figure 1A). As a result, long particles decreased or tended to decrease rates of ruminal turnover of pdNDF, NDF (interaction $P = 0.07$; Figure 1B), OM, and DM (Table 6) and increased rumen pools of NDF (interaction $P = 0.04$; Figure 1C), OM, and

Table 7. Starch digestion of cows fed treatment diets containing either long- (19 mm) or short-cut (10 mm) orchardgrass silage as the sole source of forage

	Treatment LSM			*P*-value[1]					
Starch	Long	Short	SE	Trt	Trt × period	pDMI	Trt × pDMI	pDMI × pDMI	Trt × pDMI × pDMI
Intake, kg/d	6.49	6.62	0.22	0.41	NS[2]	0.02	NS	NS	NS
Apparent ruminal digestion									
kg/d	3.91	3.31	0.34	0.19	NS	0.80	0.23	0.10	0.15
%	58.9	48.4	4.9	0.09	NS	0.10	0.30	0.02	0.14
True ruminal digestion									
kg/d	4.01	3.40	0.34	0.19	NS	0.75	0.22	0.10	0.14
%	60.3	49.8	4.8	0.09	NS	0.10	0.30	0.02	0.13
Passage to duodenum, kg/d	2.84	3.51	0.35	0.09	NS	0.03	0.34	0.02	0.13
Apparent postruminal digestion									
kg/d	2.53	3.19	0.34	0.11	NS	0.03	0.43	0.02	0.16
% of intake	36.5	47.0	4.8	0.11	NS	0.10	0.40	0.02	0.17
% of duodenal passage	89.2	89.9	1.3	0.63	NS	0.39	NS	0.02	NS
Apparent total-tract digestion									
kg/d	6.19	6.32	0.20	0.38	NS	0.02	NS	NS	NS
%	95.4	95.5	0.4	0.76	NS	0.54	0.15	NS	NS

[1]*P*-values for treatment (Trt), Trt by period interaction (Trt × period), preliminary DMI (pDMI), Trt by preliminary DMI interaction (Trt × pDMI), quadratic effect of preliminary DMI (pDMI × pDMI), and Trt by quadratic effect of preliminary DMI (Trt × pDMI × pDMI).

[2]Nonignificant, with $P > 0.20$; term was removed from the statistical model.

DM (Table 8) compared with short particles for cows with high pDMI, but effect of treatment on DMI was not related to pDMI. Although the treatment by pDMI interaction was not significant (interaction $P > 0.40$), a visual examination of a graph with pDMI and DMI (Figure 1D) illustrated the difference in DMI between long and short particles was small for cows with low pDMI but the difference became greater as pDMI increased, with the greatest divergence for cows with high pDMI. Therefore, rumen fill as a constraint limiting DMI for cows with high intake fed long particles compared with short particles is possible but results did not provide conclusive evidence.

Chewing activity results (Table 9) suggest that DMI for the long-particle diet was possibly limited by chewing time. Long particles increased meal length (39.1 vs. 33.0 min/bout, $P = 0.008$) and meal size (2.52 vs. 2.28 kg of DM/meal, $P = 0.05$), resulting in greater eating time (16.5 vs. 15.1 min/kg of DMI, $P = 0.02$) and ruminating time (25.4 vs. 23.2 min/kg of DMI, $P = 0.05$) and, thus, increased total chewing time (42.0 vs. 38.3 min/kg of DMI and 867 vs. 827 min/d, $P = 0.02$) compared with short particles. Long particles increased total time spent chewing to reduce particle size compared with short particles, but the effect of FPL on eating time was related to pDMI. Long particles increased and short particles decreased eating time [expressed as minutes per kilogram of DMI, minutes per kilogram of NDF intake (interaction $P = 0.006$, Figure 1E), and min per kilogram of forage NDF intake] as pDMI increased. Long particles increased eating time (expressed as min/d) with increasing pDMI compared with short particles, which remained constant for short particle-fed cows across the range of pDMI (interaction $P = 0.004$; Figure 1F). Because the total amount of time spent chewing per day is likely limited (Van Soest, 1994), cows with high intake consuming long particles might have reached the upper limit for time spent chewing. In this study, long particle-fed cows had greater time chewing (mean = 867 min/d,) compared with the mean chewing time (694 min/d) across 72 treatments and 19 experiments (Tafaj et al., 2007), and total chewing time for individual cows ranged from 735 to 1,055 min/d. Cows consuming long particles spent 42 min/kg of DM and 152 min/kg of NDF, which approached the maximum chewing time per unit of DM and NDF consumed (47 and 160 min, respectively) reported by Tafaj et al. (2007).

Forage particle length and its interaction with pDMI did not affect ruminal pH (Table 10). We expected long particles to potentially increase ruminal pH through greater chewing and salivary buffer flow (Allen, 1997), but this was not observed. This might be because no main effects of treatment existed on rumen pool sizes (Table 8), total rumination time (Table 9), or OM truly digested in the rumen (Table 11). Differences were detected for concentrations of VFA (Table 10), but these differences were quite small and likely not biologically significant.

Long particles decreased rumen empty BW for cows with pDMI <26 kg/d but increased BW for cows with pDMI >26 kg/d compared with short particles (interaction $P = 0.02$; Table 4). The BW gain for long particle-fed cows with high pDMI occurred despite digesting less DM in total tract than short particle-fed cows (interaction $P = 0.04$; Table 11). The reason for the BW changes observed in relation to FPL and pDMI is not clear.

Direct comparisons of animal responses across individual studies evaluating the effects of FPL should be interpreted with caution. Multiple reasons exist for this, which may help explain why results from particular experiments may or may not be in agreement. A wide range of FPL (2 to 32 mm) has been reported for studies from 1997 to 2005 (Tafaj et al., 2007) and differences between FPL compared within studies (6 vs. 8 mm, Yang and Beauchemin, 2004; 24 vs. 170 mm, Randby et al., 2008). Furthermore, the lack of a consistent method of measuring and reporting physical characteristics complicates interpretation because similar TLC and physically effective NDF do not necessarily yield the same particle size distribution (Beauchemin and Rode, 1998). Responses to FPL vary depending on forage source, with greater differences reported for grass-based TMR compared with corn silage-based TMR (Tafaj et al., 2007). Additionally, feeding conditions differ, from offering forage and concentrate separately and limit fed (Zebeli et al., 2007) to numerous studies where cows are fed TMR ad libitum. Studies often evaluate the effect of FPL in combination with other dietary factors including, but not limited to, forage:concentrate ratio (Soita et al., 2000; Einarson et al., 2004), grain processing (Yang et al., 2001), grain fermentability (Krause and Combs, 2003), nonforage fiber sources (Mooney and Allen, 1997), and supplemental fat (Onetti et al., 2003).

Effects of pDMI on Ruminal Passage Rates

Experimental data on rates of passage from the rumen, particularly for individual feed fractions, are scarce. Given the effect of passage on ruminal digestion and microbial growth, quantitative knowledge on rates of nutrient passage from the rumen are needed to better understand nutrient availability in ruminants and improve nutrition models. Furthermore, because passage rates from the rumen generally increase with increased intake, measurements of ruminal passage rates

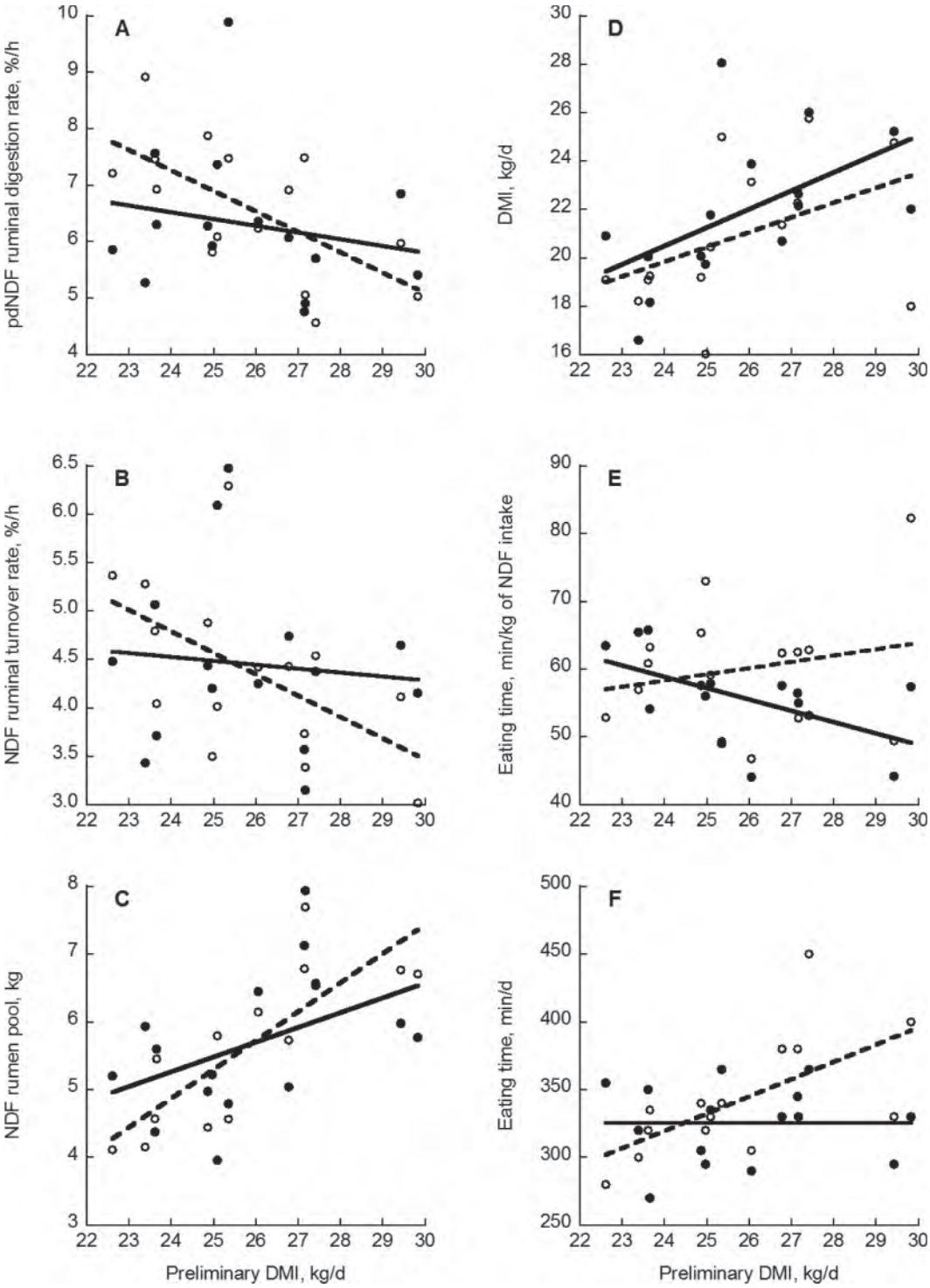

Figure 1. Interaction of long (19 mm; open circles, dashed line) and short (10 mm; closed circles, solid line) orchardgrass particle length with preliminary DMI for (A) potentially digestible NDF (pdNDF) ruminal digestion rate ($P = 0.08$), (B) NDF ruminal turnover rate ($P = 0.07$), (C) NDF rumen pool ($P = 0.04$), (D) DMI (interaction not significant), (E) eating time (min/kg of NDF intake; $P = 0.006$), and (F) eating time (min/d; $P = 0.004$). The preliminary DMI on the x-axis are the mean DMI of individual cows during the final 4 d of the preliminary period when all cows were fed a common diet.

Table 8. Rumen pools of cows fed treatment diets containing either long- (19 mm) or short-cut (10 mm) orchardgrass silage as the sole source of forage

	Treatment LSM			*P*-value[1]					
Item	Long	Short	SE	Trt	Trt × period	pDMI	Trt × pDMI	pDMI × pDMI	Trt × pDMI × pDMI
Wet weight, kg	94.3	92.5	3.4	0.47	0.17	0.18	NS[2]	NS	NS
Volume, L	108	114	5	0.11	0.19	0.09	0.09	0.47	0.07
Density, kg/L	0.87	0.84	0.02	0.30	NS	NS	NS	NS	NS
Rumen pool, kg									
DM	12.4	12.3	0.6	0.89	0.13	0.03	0.09	0.17	NS
OM	11.1	11.0	0.5	0.83	0.14	0.03	0.05	0.17	NS
NDF	5.64	5.67	0.22	0.89	NS	0.004	0.04	NS	NS
pdNDF[3]	2.43	2.58	0.12	0.32	NS	0.02	NS	NS	NS
iNDF[4]	3.22	3.10	0.14	0.48	0.17	0.03	0.12	NS	NS
Starch	0.87	0.97	0.06	0.17	NS	0.008	0.84	0.14	0.11

[1]*P*-values for treatment (Trt), Trt by period interaction (Trt × period), preliminary DMI (pDMI), Trt by preliminary DMI interaction (Trt × pDMI), quadratic effect of preliminary DMI (pDMI × pDMI), and Trt by quadratic effect of preliminary DMI (Trt × pDMI × pDMI).

[2]Nonsignificant, with $P > 0.20$; term was removed from the statistical model.

[3]pdNDF = potentially digestible NDF.

[4]iNDF = indigestible NDF.

Table 9. Chewing activity of cows fed treatment diets containing either long- (19 mm) or short-cut (10 mm) orchardgrass silage as the sole source of forage

	Treatment LSM			*P*-value[1]					
Item	Long	Short	SE	Trt	Trt × period	pDMI	Trt × pDMI	pDMI × pDMI	Trt × pDMI × pDMI
Meals									
Bouts/d	9.28	10.2	0.67	0.13	NS[2]	0.46	0.49	0.61	0.08
Length, min/bout	39.1	33.0	2.3	0.008	NS	0.85	0.007	0.98	0.03
Interval, min	138	123	10	0.14	NS	0.67	0.38	0.95	0.09
Meal size, kg									
DM	2.52	2.28	0.24	0.05	NS	0.52	0.58	0.69	0.01
OM	2.26	2.06	0.21	0.05	NS	0.51	0.58	0.70	0.01
NDF	0.70	0.62	0.06	0.02	NS	0.57	0.50	0.65	0.01
pdNDF[3]	0.50	0.44	0.04	0.02	NS	0.55	0.62	0.64	0.01
iNDF[4]	0.20	0.17	0.02	0.04	NS	0.61	0.38	0.67	0.03
Starch	0.78	0.69	0.07	0.03	NS	0.41	0.75	0.72	0.02
Eating time									
Min/d	342	326	8	0.08	NS	0.08	0.004	NS	NS
Min/kg of DMI	16.5	15.1	0.5	0.02	NS	0.47	0.006	NS	NS
Min/kg of NDF intake	59.9	55.9	2.0	0.06	NS	0.67	0.006	NS	NS
Min/kg of forage NDF intake	70.9	67.2	2.4	0.13	NS	0.39	0.005	NS	NS
Rumination									
Bouts/d	14.5	14.1	0.9	0.44	NS	0.45	0.04	0.51	0.05
Length, min/bout	36.8	34.3	1.4	0.06	NS	NS	NS	NS	NS
Interval, min	55.1	57.3	3.6	0.43	NS	0.19	0.41	0.74	0.13
Ruminating time									
Min/d	525	502	13	0.17	NS	NS	NS	NS	NS
Min/kg of DMI	25.4	23.2	0.8	0.05	NS	0.07	NS	NS	NS
Min/kg of NDF intake	92.0	86.1	3.1	0.12	NS	0.15	NS	NS	NS
Min/kg of forage NDF intake	109	103	4	0.23	NS	0.06	NS	NS	NS
Total chewing time									
Min/d	867	827	16	0.02	NS	0.16	NS	NS	NS
Min/kg of DMI	42.0	38.3	1.2	0.02	NS	0.13	NS	NS	NS
Min/kg of NDF intake	152	142	5	0.04	NS	NS	NS	NS	NS
Min/kg of forage NDF intake	180	170	5	0.12	NS	0.10	NS	NS	NS

[1]*P*-values for treatment (Trt), Trt by period interaction (Trt × period), preliminary DMI (pDMI), Trt by preliminary DMI interaction (Trt × pDMI), quadratic effect of preliminary DMI (pDMI × pDMI), and Trt by quadratic effect of preliminary DMI (Trt × pDMI × pDMI).

[2]Nonsignificant, with $P > 0.20$; term was removed from the statistical model.

[3]pdNDF = potentially digestible NDF.

[4]iNDF = indigestible NDF.

Table 10. Ruminal VFA concentrations and pH of cows fed treatment diets containing either long- (19 mm) or short-cut (10 mm) orchardgrass silage as the sole source of forage

	Treatment LSM			*P*-value[1]					
Item	Long	Short	SE	Trt	Trt × period	pDMI	Trt × pDMI	pDMI × pDMI	Trt × pDMI × pDMI
Total VFA, m*M*	152	151	2	0.62	NS[2]	NS	NS	NS	NS
Acetate	91.8	91.3	0.9	0.52	NS	0.02	NS	NS	NS
Propionate	35.3	33.7	1.0	0.11	NS	NS	NS	NS	NS
Butyrate	18.5	19.9	0.8	0.002	NS	0.92	NS	0.15	NS
Lactate	0.18	0.34	0.18	0.42	NS	0.10	0.04	0.12	NS
Isobutyrate	1.26	1.18	0.05	0.08	NS	0.55	0.11	0.79	0.18
Valerate	1.87	1.91	0.07	0.32	NS	0.54	NS	0.19	NS
Isovalerate	2.15	1.98	0.09	0.02	NS	0.36	0.78	0.39	0.07
Branched-chain VFA	3.42	3.16	0.13	0.01	NS	0.41	0.32	0.51	0.05
Acetate:propionate	2.62	2.74	0.06	0.09	NS	0.03	0.15	NS	NS
Ruminal pH	5.84	5.84	0.03	0.88	NS	NS	NS	NS	NS

[1]*P*-values for treatment (Trt), Trt by period interaction (Trt × period), preliminary DMI (pDMI), Trt by preliminary DMI interaction (Trt × pDMI), quadratic effect of preliminary DMI (pDMI × pDMI), and Trt by quadratic effect of preliminary DMI (Trt × pDMI × pDMI).
[2]Nonsignificant, with $P > 0.20$; term was removed from the statistical model.

of nutrients over a wide range of DMI are necessary. We measured the effects of DMI on rates of passage of nutrients from the rumen using the pool and flux method (Robinson et al, 1987).

Although we expected ruminal passage rates to increase with pDMI, passage rates of pdNDF, iNDF, and starch were not related to level of intake independent of or dependent upon treatment (Table 6). However, rate of starch digestion decreased quadratically (interaction $P = 0.02$; Figure 2A) and true ruminal digestibility of starch tended to decrease quadratically (interaction $P = 0.13$; Figure 2B) as pDMI increased. Two cows with high pDMI (>29 kg of DM/d) amplified the quadratic effects. The decreases in starch rate of digestion and digestibility are consistent with increased starch rumen pool (interaction $P = 0.11$; Figure 2C) and likely related to the increased liquid dilution rate associated with increased intake (not measured), decreasing popu-

Table 11. Dry matter and OM digestion of cows fed treatment diets containing either long- (19 mm) or short-cut (10 mm) orchardgrass silage as the sole source of forage

	Treatment LSM			*P*-value[1]					
Item	Long	Short	SE	Trt	Trt × period	pDMI	Trt × pDMI	pDMI × pDMI	Trt × pDMI × pDMI
DM									
Intake, kg/d	21.8	22.7	0.9	0.06	NS[2]	0.02	NS	0.20	NS
Apparent total-tract digestion									
kg/d	15.5	16.4	0.6	0.02	NS	0.009	0.04	0.07	NS
%	70.6	71.6	0.9	0.42	NS	0.98	0.09	NS	NS
OM									
Intake, kg/d	19.6	20.4	0.8	0.06	NS	0.02	NS	0.20	NS
Apparent ruminal digestion									
kg/d	9.45	10.2	0.41	0.25	NS	0.20	0.16	NS	NS
%	47.4	48.5	2.7	0.64	NS	0.17	0.16	0.06	NS
True ruminal digestion									
kg/d	11.7	12.4	0.4	0.22	NS	0.08	0.15	NS	NS
%	59.2	59.9	2.4	0.71	NS	0.19	0.12	0.04	NS
Passage to duodenum, kg/d	10.4	10.6	0.8	0.74	NS	0.06	0.16	0.08	NS
Apparent postruminal digestion									
kg/d	5.06	5.09	0.55	0.95	NS	0.04	NS	0.02	NS
% of intake	25.4	25.0	2.4	0.87	NS	0.08	NS	0.009	NS
Apparent total-tract digestion									
kg/d	14.2	14.9	0.5	0.03	NS	0.009	0.04	0.07	NS
%	72.0	72.6	0.9	0.56	NS	0.87	0.08	NS	NS

[1]*P*-values for treatment (Trt), Trt by period interaction (Trt × period), preliminary DMI (pDMI), Trt by preliminary DMI interaction (Trt × pDMI), quadratic effect of preliminary DMI (pDMI × pDMI), and Trt by quadratic effect of preliminary DMI (Trt × pDMI × pDMI).
[2]Nonsignificant, with $P > 0.20$; term was removed from the statistical model.

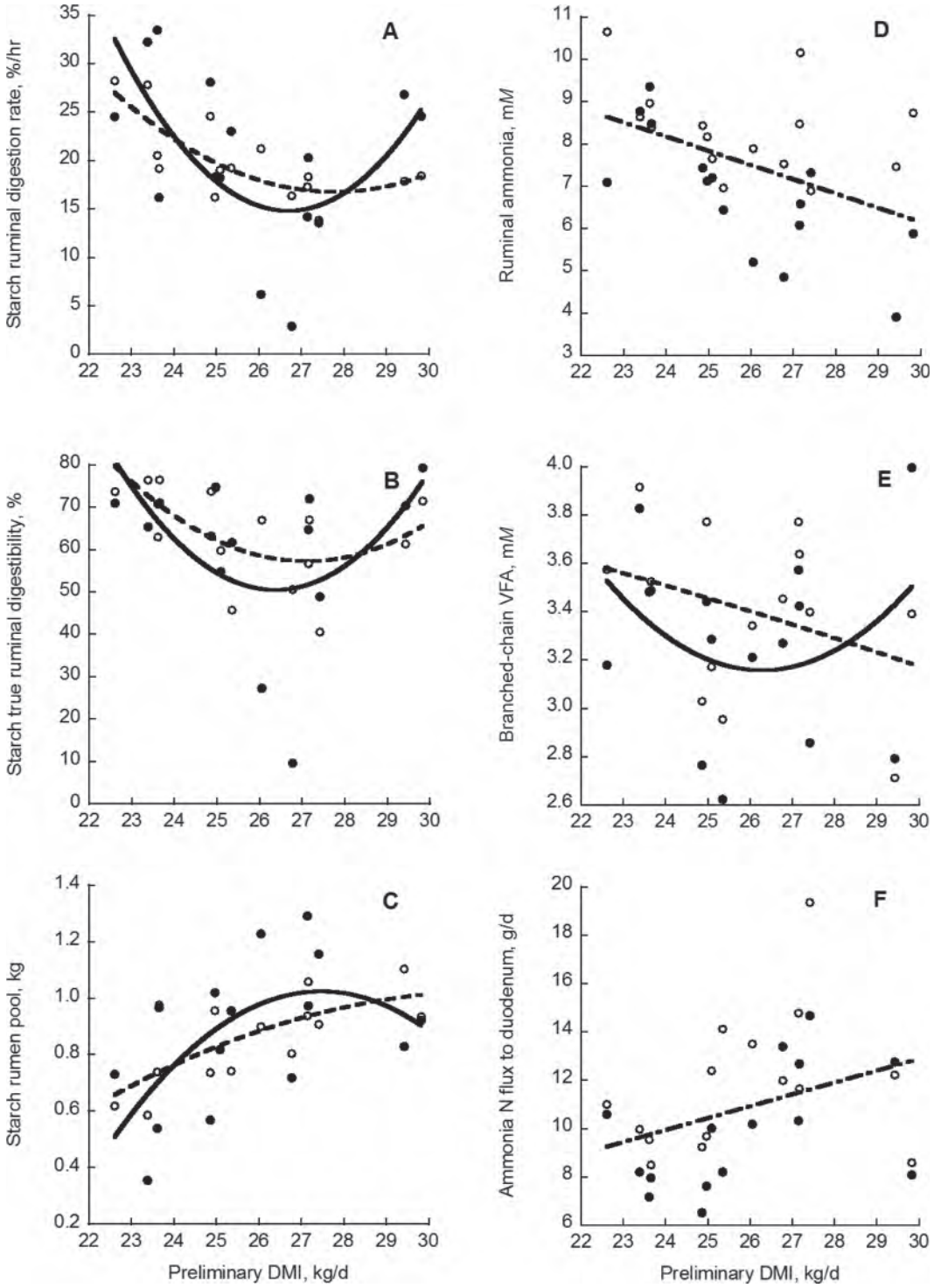

Figure 2. Relationship of long (19 mm; open circles, dashed line) and short (10 mm; closed circles, solid line) orchardgrass particle length with preliminary DMI for (A) starch ruminal digestion rate (interaction $P = 0.02$), (B) starch true ruminal digestibility (interaction $P = 0.13$), (C) starch rumen pool (interaction $P = 0.11$), (D) ruminal ammonia concentration ($P = 0.002$), (E) branched-chain VFA concentration (interaction $P = 0.05$), and (F) ammonia N flux to duodenum ($P = 0.05$). The preliminary DMI on the x-axis are the mean DMI of individual cows during the final 4 d of the preliminary period when all cows were fed a common diet.

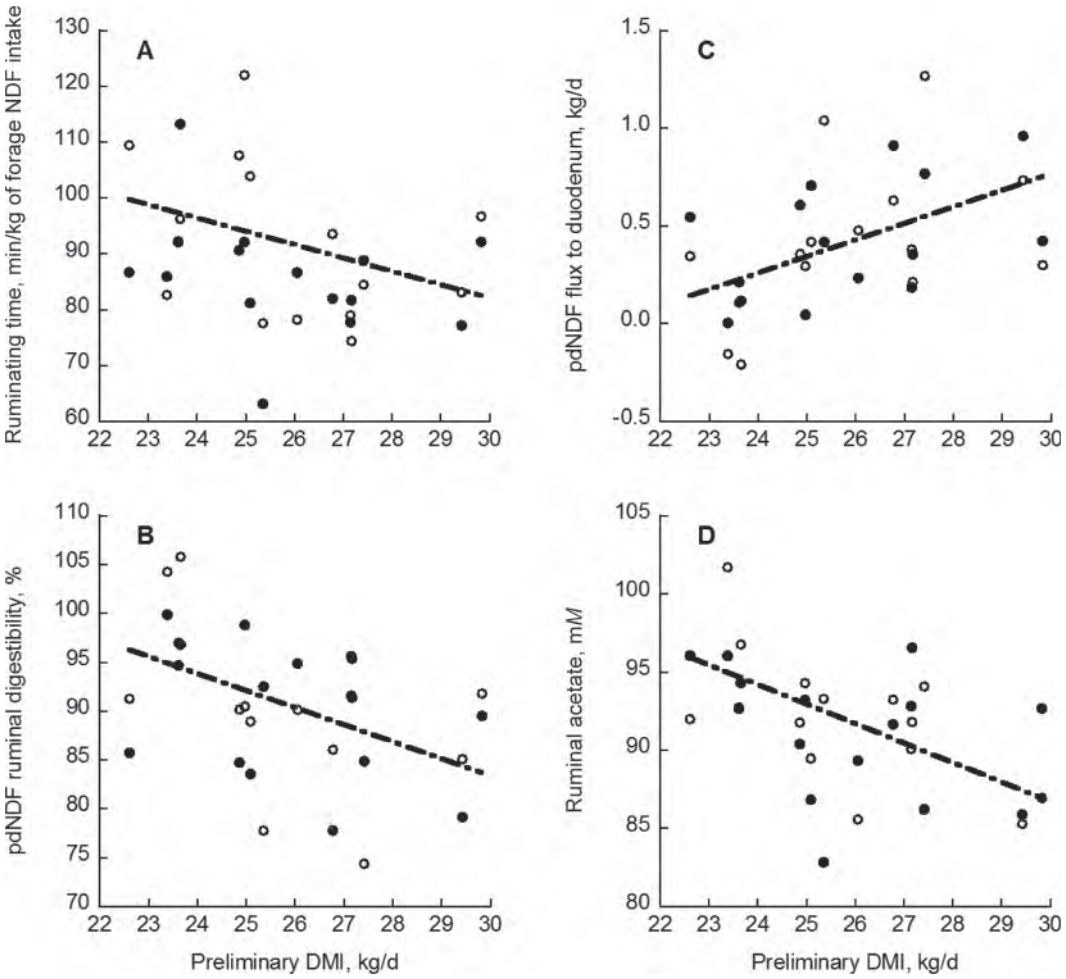

Figure 3. Relationship of long (19 mm; open circles) and short (10 mm; closed circles) orchardgrass particle length with preliminary DMI for (A) ruminating time per unit of forage NDF ($P = 0.06$), (B) potentially digestible NDF (pdNDF) ruminal digestibility ($P = 0.07$), (C) pdNDF flux to duodenum ($P = 0.05$), and (D) ruminal acetate concentration ($P = 0.02$). The preliminary DMI on the x-axis are the mean DMI of individual cows during the final 4 d of the preliminary period when all cows were fed a common diet.

lations of starch-digesting microbes. Concentrations of ruminal ammonia ($P = 0.002$; Figure 2D) and branch-chained VFA (interaction $P = 0.05$; Figure 2E), which are derived from degradation of branched-chain amino acids, also decreased with increased pDMI and are consistent with less proteolytic activity in the rumen due to greater removal of ruminal microbes through passage and lysis. As pDMI increased, ammonia N flux to the duodenum ($P = 0.05$; Figure 2F) increased and MUN concentration ($P = 0.07$; Table 4) tended to increase.

Additionally, the rate of pdNDF digestion decreased as pDMI increased and had a greater effect on long than short particles (interaction $P = 0.08$; Figure 1A), as previously mentioned. The decrease in pdNDF digestion rate is likely related to differences in mechanical processing (TLC) and mastication, which reduce particle size and increase the surface area available for microbial attachment and enzymatic attack (Bowman and Firkins, 1993). The proportion of large particles in the rumen increases with higher DMI (Okine and Mathison, 1991) because ruminating time per unit of DM consumed decreases as DMI increases (Welch and Smith, 1969). In this experiment, cows tended to decrease amount of time spent ruminating per unit of forage NDF consumed as level of intake increased ($P = 0.06$; Figure 3A). As a result of the decrease in pdNDF digestion rate, cows tended to decrease ruminal pdNDF digestibility (%, $P = 0.07$; Figure 3B) and increased pdNDF flux from the rumen to the duodenum ($P = 0.05$; Figure 3C) as pDMI increased (Table 12). Furthermore, ruminal acetate concentration decreased as pDMI increased ($P = 0.02$; Figure 3D), which is con-

Table 12. NDF digestion of cows fed treatment diets containing either long- (19 mm) or short-cut (10 mm) orchardgrass silage as the sole source of forage

	Treatment LSM			*P*-value[1]					
Item	Long	Short	SE	Trt	Trt × period	pDMI	Trt × pDMI	pDMI × pDMI	Trt × pDMI × pDMI
NDF									
Intake, kg/d	6.02	6.12	0.24	0.39	NS[2]	0.03	NS	0.16	NS
Ruminal digestion									
kg/d	3.85	3.91	0.14	0.63	NS	0.18	NS	0.19	NS
%	63.3	64.9	1.8	0.37	NS	0.07	0.16	0.49	0.16
Passage to duodenum, kg/d	2.25	2.14	0.16	0.33	NS	0.03	0.20	0.28	0.08
Postruminal digestion									
kg/d	0.04	−0.04	0.12	0.60	NS	0.11	NS	0.07	NS
% of intake	0.63	−0.23	2.06	0.70	NS	0.10	NS	0.04	NS
Total-tract digestion									
kg/d	3.89	3.87	0.13	0.87	NS	0.01	0.14	0.01	NS
%	64.8	63.8	1.5	0.56	NS	0.99	NS	0.04	NS
Potentially digestible NDF									
Intake, kg/d	4.32	4.41	0.16	0.29	NS	0.03	NS	0.14	NS
Ruminal digestion									
kg/d	3.85	3.91	0.14	0.63	NS	0.18	NS	0.19	NS
%	90.7	89.9	1.8	0.69	NS	0.07	NS	NS	NS
Passage to duodenum, kg/d	0.52	0.44	0.12	0.47	NS	0.05	0.23	0.44	0.19
Postruminal digestion									
kg/d	0.04	−0.04	0.12	0.60	NS	0.11	NS	0.07	NS
% of intake	0.91	−0.21	2.89	0.73	NS	0.08	NS	0.04	NS
Total-tract digestion									
kg/d	3.89	3.87	0.13	0.87	NS	0.01	0.14	0.01	NS
%	90.6	88.7	2.0	0.44	NS	0.97	NS	0.03	NS
Indigestible NDF									
Intake, kg/d	1.64	1.65	0.06	0.80	NS	0.12	NS	NS	NS

[1]*P*-values for treatment (Trt), Trt by period interaction (Trt × period), preliminary DMI (pDMI), Trt by preliminary DMI interaction (Trt × pDMI), quadratic effect of preliminary DMI (pDMI × pDMI), and Trt by quadratic effect of preliminary DMI (Trt × pDMI × pDMI).
[2]Nonsignificant, with $P > 0.20$; term was removed from the statistical model.

sistent with lower ruminal pdNDF digestibility because acetate is the predominant VFA produced from fiber digestion.

Effects of pDMI on N Flux and Microbial Efficiency

Fluxes of NAN and NANMN from the rumen to the duodenum tended to increase as pDMI increased, which increased or tended to increase postruminal NAN digestion (g/d) and digestibility (%) with increased pDMI ($P \leq 0.10$; Table 5). Microbial N flux and efficiency (gram of MN produced per kilogram of true ruminally digested OM) were not related to level of intake (Table 5) or quantity of OM truly digested in the rumen (not shown). However, a positive relationship was observed between microbial efficiency and ruminal passage rates of starch ($P < 0.001$, $R^2 = 0.44$; Figure 4A) and pdNDF ($P < 0.001$, $R^2 = 0.52$; Figure 4B). This indicated that energy from ruminal fermentation was more efficiently utilized for microbial growth as passage rates for starch and pdNDF increased, and the greater passage rates possibly decreased microbial lysis and turnover in the rumen because many microbial organisms flow from the rumen attached to fibrous particles.

Microbial N flux and efficiency are low for both treatments in the present experiment. This is unlikely associated with the method used because this same method was used in other experiments that reported higher MN flux and efficiency (Oba and Allen, 2003b; Taylor and Allen, 2005). Microbial N flux has not been consistent among studies comparing orchardgrass and alfalfa with MN flux ranging from low (Voelker Linton and Allen, 2009) to high (K. L. Kammes and M. S. Allen, unpublished data). This indicates low microbial yield is not specific to OG. The reason for low MN production in this study is not clear but appears to be related to the treatments.

CONCLUSIONS

Grass particle length and its interaction with pDMI did not affect milk yield, milk composition, or rumen pH. Increasing grass particle length tended to decrease DMI, which might be limited by rumen fill or chewing time, or both. Passage rates of feed fractions did not differ between long and short particles and were not related to level of intake. As pDMI increased, long particles decreased ruminal digestion rate of pdNDF

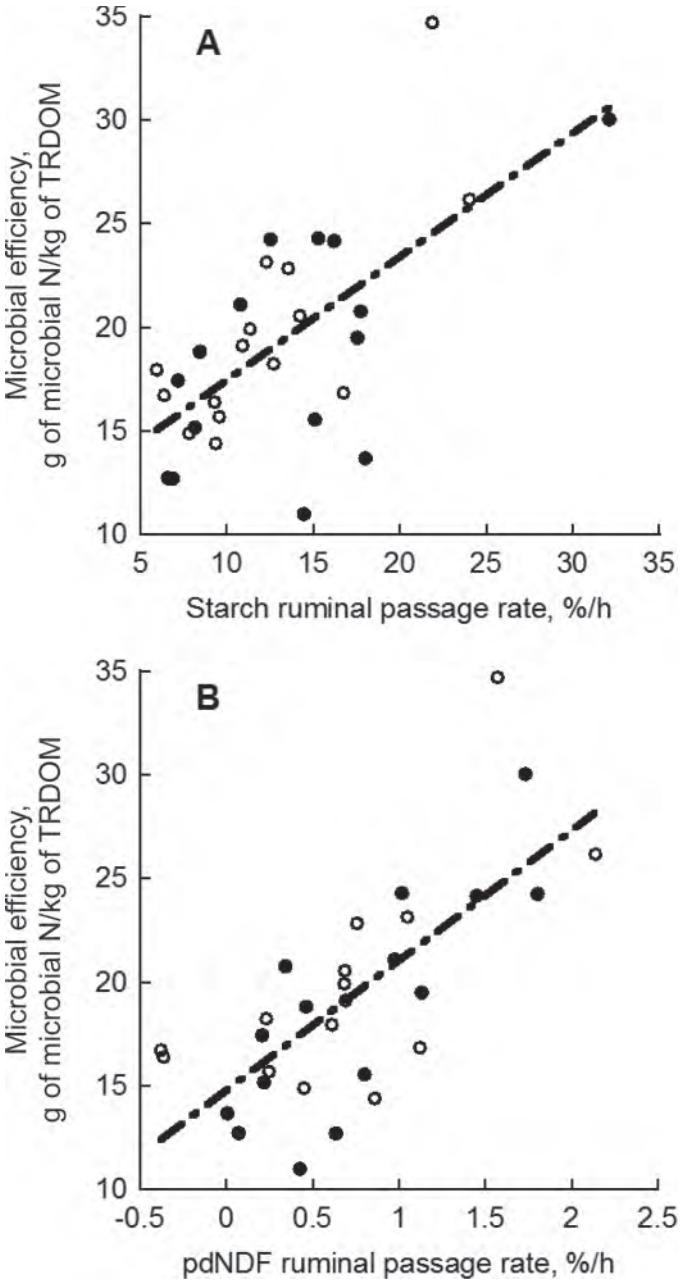

Figure 4. (A) Relationship between starch ruminal passage rate and microbial efficiency. Microbial efficiency [g of microbial N/kg of true ruminally digested OM (TRDOM)] = 11.5 + 0.595 × starch ruminal passage rate (%/h; $P < 0.001$, $R^2 = 0.44$). (B) Relationship between potentially digestible NDF (pdNDF) ruminal passage rate and microbial efficiency. Microbial efficiency (g of microbial N/kg of TRDOM) = 14.8 + 6.26 × pdNDF ruminal passage rate (%/h; $P < 0.001$, $R^2 = 0.52$). Open circles denote long (19 mm) and closed circles denote short (10 mm) orchardgrass particle length. Starch and pdNDF ruminal passage rates were also positively correlated ($P < 0.001$, $R^2 = 0.43$, not shown).

at a faster rate than did short particles. As a result, long particles decreased or tended to decrease rates of ruminal turnover for NDF, OM, and DM and increased their rumen pools compared with short particles for cows with high pDMI. Long particles increased eating time, which affected cows with high intake to the greatest extent, and total chewing time compared with short particles. Ruminal starch digestibility decreased, starch rumen pool increased, and postruminal starch digestibility increased quadratically as feed intake increased. Sorting of feed particles was minimal in this experiment due to the wet forages and individual feeding of cows, but sorting would likely increase for cows fed diets using drier forages or group fed. When grass silage was the only source of forage in the diet, increasing chop length from 10 to 19 mm tended to decrease DMI but did not negatively affect productivity of cows, which were fed adequate fiber.

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