Corn Silage Management: Effects of Hybrid, Maturity, Chop Length, and Mechanical Processing on Rate and Extent of Digestion

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ABSTRACT

Five experiments were conducted to evaluate the effects of hybrid, chop length, maturity, and mechanical processing of corn silage on dry matter and nutrient disappearance in the rumen. Corn silage that had not been dried or ground was incubated in macro in situ bags (30 × 35 cm) for 8, 16, 24, 48, and 96 h. Experiments 1a and 2 evaluated the effects of maturity and mechanical processing for two corn silage hybrids harvested at two theoretical lengths-of-cut. Experiments 3 through 5 evaluated the effects of chop length and mechanical processing for two corn silage hybrids harvested at two-thirds milkline. The hybrid with low neutral fiber (NDF) concentrations had greater dry matter and starch disappearance than the hybrid with high NDF concentrations. The effect of chop length on nutrient disappearance was variable across experiments 3 through 5. Processing improved dry matter disappearance in experiments 1a, 2 (two-thirds milkline and blackline), 3, 4, and 5 at the majority of ruminal incubation timepoints. Starch disappearance was greater for unprocessed corn silage in experiment 1a (hard dough and two-thirds milkline) and was greater for processed corn silage in experiments 2 and 5. However, there was no consistent trend in starch disappearance between processed and unprocessed corn silage in experiments 3 and 4. This can be partially explained by the high disappearance of starch (experiment 3, ≥98% and experiment 4, ≥94%) by 24 h of ruminal incubation. Minimal differences were detected in NDF disappearance between processed and unprocessed corn silage across maturities. In experiments 2 and 5, crude protein disap-

pearance was improved due to processing at some incubation timepoints. Rate of dry matter, starch (one-third milkline and two-thirds milkline), and NDF disappearance tended to increase when corn silage was mechanically processed in experiment 2. Dry matter, starch, and crude protein disappearance tended to be greater for corn silage harvested at the early maturity (one-third milkline) in experiment 2 compared with advanced maturities (two-thirds milkline and blackline). Disappearance of NDF was greater at early maturities compared with advanced maturities in experiments 1a and 2. Rate of dry matter (hybrid 3845), starch, and NDF (hybrid 3845) disappearance tended to decrease as maturity advanced from one-third milkline to blackline in experiment 2. These results suggest that the macro in situ method can be used to evaluate nutrient disappearance in the rumen.

(Key words: chop length, corn silage hybrid, mechanical processing, macro in situ)

Abbreviation key: ADICP = acid detergent insoluble CP, BL = blackline, GDU = growing degree day units, ML = milkline, NDICP = neutral detergent insoluble CP, TLC = theoretical length-of-cut.

INTRODUCTION

In recent years there has been a renewed interest in the factors that affect digestion and utilization of corn silage in lactating cows. Weather (growing degree day units **GDU**), water availability to the plant (Traxler et al., 1998), soil type, soil drainage, and soil fertility (Van Soest, 1994) can have a profound impact on carbohydrate composition of corn silage. Hybrid, maturity, and mechanical processing also influence the physical and chemical characteristics of carbohydrates present in corn silage (Johnson et al., 2002). The type and amount of carbohydrate present in corn silage will affect the

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rate of degradation in the rumen, impacting ruminal fermentation characteristics. It is important to characterize differences in corn silage that influence degradation rates of carbohydrates and to a lesser extent protein in the rumen so that the information can be available for ration balancing purposes.

The majority of the ruminal disappearance and degradation rate data for corn silage that has been published used dried and ground corn silage incubated in conventional in situ bags [10 × 20 cm; Hunt et al., 1989, 1992; Xu and Harrison, 1996]. This method eliminates physical differences in the corn silage due to hybrid, maturity, chop length, and mechanical processing. Recently, a new method was developed for evaluating wet unground corn silage in macro in situ bags (30 × 35 cm; Doggett, 1998). This method was sensitive to physical differences in hybrid, maturity, and mechanical processing of corn silage (Doggett, 1998). The developers of this method acknowledge that the effect of mastication is not accounted for in the disappearance estimates (communication with Carl Hunt, University of Idaho, Moscow). However, this technique allows the corn silage to be presented to the rumen microbial population in a form that is more representative of how it would appear when fed to a cow in a TMR than dried and ground samples.

Recently there have been a number of studies that have published data on DM, starch, and NDF disappearance and rate of disappearance of corn silage in the rumen using the macro in situ technique. Differences in DM disappearance after 24 and 48 h of incubation in the rumen were reported between corn silage hybrids (Doggett, 1998). Dry matter and starch disappearance after 24 h of incubation in the rumen have been reported to be greater at one-half milkline (**ML**) compared with blackline (**BL**; Johnson et al., 1999; Andrae et al., 2001). Numerous studies (Harrison et al., 1998; Doggett, 1998; Bal et al., 2000a; Andrae et al., 2001) have reported an increase in DM and starch disappearance after 24 h of incubation in the rumen when corn silage was mechanically processed compared to unprocessed. The rate of DM and starch disappearance in the rumen has also been reported to be greater for mechanically processed corn silage compared with unprocessed corn silage (Doggett, 1998; Andrae et al., 2001). Dry matter disappearance after 24 h of incubation in the rumen tended to be greater for corn silage harvested at a short theoretical length-of-cut (**TLC**; 0.95 cm) compared with long TLC (1.90 cm; Bal et al., 2000b). Results of NDF disappearance after 24 h of incubation in the rumen for corn silage differing in hybrid (Doggett, 1998), maturity (Johnson et al., 1999), and mechanical processing (Johnson et al., 1999; Bal et al., 2000a) have been variable.

The primary objective of this study was to provide ruminal disappearance and degradation rate data for the carbohydrate (starch and NDF) and protein fractions of corn silage. The corn silage was harvested over 3 yr and varied in hybrid, maturity, mechanical processing, and chop length. The macro in situ method was used to evaluate the corn silages. The secondary objective was to evaluate the effects of maturity and mechanical processing of corn silage and TMR containing corn silage separated into three particle size fractions with NASCO's Penn State Forage Particle Separator on DM disappearance in the rumen.

MATERIALS AND METHODS

Cows, Diets, and Experimental Design

The corn silage samples were obtained over 3 yr from five experiments. The experimental design, housing of animals, incubation schedule, and general diet composition for each experiment are presented in Table 1. In experiments 1a and 2, mature cows (BW = ~600 kg) were housed in a free-stall barn during the collection period at the University of Idaho. In experiments 1b, 3, 4, and 5, lactating Holstein cows were fed in a free-stall barn during the collection periods at Washington State University (Buckley, WA).

All cows were fitted with ruminal cannulas (Bar Diamond, Inc., Parma, ID) that had a 10.2-cm center diameter. The detailed composition of the diets is presented in Table 2. Cows were fed TMR once daily during the in situ incubations in experiments 1a, 1b, 3, 4, and 5 (Table 1). Cows were fed TMR twice daily in experiment 2 (Table 1). Cows were fed a 60% corn silage and 40% alfalfa hay diet (no concentrate because cows were not lactating) in experiments 1a and 2 (Table 1). Cows in experiments 1b, 4, and 5 were fed a 65% concentrate and 35% roughage diet, and cows in experiment 3 were fed a 68% concentrate and 32% roughage diet (Table 1). In experiment 1b, the roughage portion of the diet consisted of 32% grass silage, 32% corn silage, and 36% alfalfa hay (Table 1). In experiment 3, the roughage portion of the diet consisted of 38% grass silage, 21% corn silage, and 41% alfalfa hay (Table 1). In experiments 4 and 5, the roughage portion of the diet consisted of 35% grass silage, 28% corn silage, and 37% alfalfa hay (Table 1).

In experiments 1a, 1b, 2, 4, and 5, corn silage was stored in 122-cm high × 122-cm diameter tubes that were lined with Ag Bag (Ag Bag International Ltd., Warrenton, OR) bale bag material. Corn silage was packed by manually stomping the corn as it was added. Plywood was placed on the top of each tube and a 182-kg mass was added to the top of the corn silage to provide packing pressure. Each tube held approxi-

Table 1. Description of experiment, housing, ruminal incubations, and diets.

Exp.	Year	Description of experiment	Housing	Incubation	Diet
1a	1996	The experimental design was a 3×2 factorial, where whole plant corn silage was incubated in the rumen. Hybrid 3845 corn silage was harvested at three maturities (hard dough, one-third milkline [ML], and two-thirds ML), and at each maturity corn was ensiled with and without mechanical processing.	University of Idaho free-stall barn	Each treatment was replicated 4 times (duplicate bags in two cows)	TMR fed 1 time per day 60% corn silage 40% alfalfa hay
1b	1996	The experimental design was a $3 \times 3 \times 2$ factorial for the corn silage and TMR, respectively. Whole plant corn silage and TMR were separated into three fractions using NASCO's Penn State Forage Particle Separator. Each fraction from the particle separations were incubated in the rumen for each maturity (hard dough, one-third ML, and two-thirds ML) and processing method (with and without mechanical processing).	Washington State University free-stall barn	Each treatment was replicated 3 times (3 bags in 1 cow) if there was enough sample available.	TMR fed 1 time per day 65% concentrate, 35% roughage Roughage portion consisted of 32% grass silage, 32% corn silage, and 36% alfalfa hay
2	1997	The experimental design was a $2 \times 3 \times 2$ factorial, where whole plant corn silage was incubated in the rumen. Hybrids 3845 and Quanta corn silage were harvested at three maturities (one-third ML, two-thirds ML, and BL). At each maturity corn was ensiled with and without mechanical processing.	University of Idaho free-stall barn	Each treatment was replicated 3 times (one bag in three cows)	TMR fed 2 times per day 60% corn silage 40% alfalfa hay
3	1997	The experimental design was a 2×2 factorial, where whole plant corn silage was incubated in the rumen. Hybrid Quanta corn silage was harvested at two theoretical lengths of cut (TLC) (9.5 and 12.7 mm). At each TLC corn was ensiled with and without mechanical processing.	Washington State University free-stall barn	Each treatment was replicated 3 times (3 bags in 1 cow)	TMR fed 1 time per day 68% concentrate, 32% roughage Roughage portion consisted of: 38% grass silage, 21% corn silage, and 41% alfalfa hay
4	1998	The experimental design was a 3×2 factorial, where whole plant corn silage was incubated in the rumen. Hybrid 3845 corn silage was harvested at 3 TLC (11.1, 27.8, and 39.7 mm). At each TLC corn was ensiled with and without mechanical processing.	Washington State University free-stall barn	Each treatment was replicated 3 times (3 bags in 1 cow)	TMR fed 1 time per day 65% concentrate, 35% roughage Roughage portion consisted of: 35% grass silage, 28% corn silage, and 37% alfalfa hay
5	1998	The experimental design was a 2×2 factorial, where whole plant corn silage was incubated in the rumen. Hybrid Quanta corn silage was harvested at 2 TLC (27.8 and 39.7 mm). At each TLC corn was ensiled with and without mechanical processing.	Washington State University free-stall barn	Each treatment was replicated 3 times (3 bags in 1 cow)	TMR fed 1 time per day 65% concentrate, 35% roughage Roughage portion consisted of: 35% grass silage, 28% corn silage, and 37% alfalfa hay

mately 455 kg of wet corn silage. In experiment 3, corn silage was stored in 2.7-m diameter Ag Bags. The break pressure on the Ag Bag machine was set at 70.5 kg/cm².

In all experiments, corn silage was harvested with a self-propelled John Deere 5830 harvester (with a kernel processing unit) at a ground speed between 3.2 and 4 km/h. The processing equipment was fully active (two counter-rotating rolls positioned between the cutterhead and blower with their axis of rotation parallel to the cutterhead). In experiments 1 through 3, the harvester consisted of four knives per row, and there were 10 tangential rows. In experiments 4 and 5, the

harvester consisted of four knives per row, with 2 and 5 tangential rows depending on treatment. In all experiments, corn silage treatments differing in either maturity or chop length were harvested with the kernel processing rolls set 1 mm apart (processed), and with the kernel processing rolls set 15.9 mm apart (unprocessed). All corn silage was inoculated at the harvester with Pioneer 1132 (Pioneer Hi-Bred Int. Inc., Des Moines, IA) inoculant at the recommended rate of 1.0×10^5 cfu of bacteria per gram of fresh forage.

Weather data were collected on a daily basis during 1996 (experiment 1), 1997 (experiments 2 and 3), and

Table 2. Ingredients of the diets fed during in situ incubations in experiments 1a, 1b, 2, 3, 4, and 5 (DM basis).

Ingredient	Experiment			
	1a and 2	1b	3	4 and 5
	(%)			
Corn silage	60.0	11.1	6.7	9.9
Grass silage	...	11.4	12.0	12.0
Alfalfa hay	40.0	12.7	12.9	12.8
Whole cottonseed	...	8.3	10.7	10.4
Beet pulp	...	6.7	5.0	5.6
Corn grain, steam rolled	...	27.1	28.6	29.8
Barley grain, steam rolled	...	3.2	3.3	...
Soybean meal, 47% CP, expeller processed	...	9.4	6.4	2.8
Canola meal	...	...	4.7	7.1
Corn distillers	...	5.8	5.7	5.5
Prolak ¹	...	0.7	0.7	1.0
Sodium bicarbonate	...	1.4	1.4	1.3
Limestone	...	1.0	1.0	0.9
Salt	...	0.3	0.3	0.3
Biofos ²	...	0.5	0.3	0.3
Mg oxide	...	0.3	0.2	0.2
WSU mineral premix ³	...	0.1	0.1	0.1

¹Prolak, H.J. Baker & Bro., Inc., (Stamford, CT).

²Biofos, IMC, (Lake Forest, IL).

³WSU mineral premix, 5863 kIU/kg Vitamin A; 2640 kIU/kg Vitamin D; 14,674 IU/kg Vitamin E; 220 mg/kg of Co; 16,500 mg/kg of Cu; 660 mg/kg of Fe; 880 mg/kg of I; 44,000 mg/kg of Mn; 220 mg/kg of Se; 44,000 mg/kg of Zn.

1998 (experiments 4 and 5). Cumulative GDU, precipitation, and solar radiation for each month are reported in Table 3. Average monthly temperature was also reported in Table 3. Growing degree units was calculated using the equation: $GDU = (\text{maximum daily temperature} + \text{minimum daily temperature})/2 - 10$. There is limited growth when the temperature is below 10°C and greater than 30°C. Therefore, if the maximum temperature exceeded 30°C, then a value of 30°C was en-

tered, and if the minimum temperature was lower than 10°C, then a value of 10°C was used. The soil type where the corn silage was grown for each experiment was silt-loam.

Experiments 1a, 2, 3, 4, and 5 corn silage in situ incubations. Corn silage was incubated in macro in situ bags (30- × 35-cm nylon bags; pore size 53 μm; Ankom Technology, Fairport, NY) to determine the rate and extent of ruminal degradation (Doggett, 1998). In

Table 3. Accumulated growing degree-day units, precipitation, and solar radiation and average temperature each month in 1996, 1997, and 1998.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Growing degree day units (°C) ¹												
1996	17.3	30.9	46.4	87.8	86.6	148.6	229.8	220.8	154.8	88.2	26.0	2.2
1997	8.2	15.2	38.1	75.0	167.7	167.4	249.2	275.7	205.3	82.0	56.6	12.0
1998	22.4	30.2	49.9	87.9	118.0	179.0	284.7	263.8	207.3	97.9	31.0	11.1
Precipitation (mm)												
1996	174	173	52	154	40	8	9	11	34	123	153	144
1997	134	62	170	90	61	49	29	28	74	144	89	76
1998	174	56	98	27	55	19	4	5	8	70	254	169
Solar radiation (MJ/m ²)												
1996	80	190	288	373	432	546	611	486	361	223	106	73
1997	91	156	279	374	514	483	660	568	383	205	149	104
1998	102	158	293	457	345	506	558	581	457	238	102	83
Average temperature (°C)												
1996	4.4	4.8	7.4	10.4	10.9	14.1	17.4	16.8	13.5	10.2	6.1	4.1
1997	5.0	5.2	7.5	9.5	14.2	15.2	17.9	18.8	15.8	10.8	7.8	4.4
1998	5.6	7.2	7.9	9.9	12.8	15.5	19.1	18.1	15.4	10.1	8.1	4.3

¹Growing degree-day units: $GDU = (\text{maximum daily temperature} + \text{minimum daily temperature})/2 - 10$. If maximum temperature exceeds 30°C then a value of 30°C is used, and if the minimum temperature is below 10°C, then a value of 10°C is used.

experiment 1a, Pioneer hybrid 3845 corn silage was harvested during the 1996 growing season at three maturities (hard dough, one-third ML, and two-thirds ML) with and without mechanical processing. The TLC was 6.4 mm. Approximately 7 kg of corn silage from each treatment was obtained and frozen at -20°C . In experiment 2, Pioneer hybrids 3845 and Quanta corn silage were harvested during the 1997 growing season at three maturities (one-third ML, two-thirds ML, and BL) with and without mechanical processing. The TLC was 12.7 mm. Approximately 7 kg of corn silage from each treatment was obtained and frozen at -20°C . The corn silage in experiments 1a and 2 was shipped to the University of Idaho (Carl Hunt's Laboratory, Moscow, ID) to be incubated in situ.

In experiment 3, Pioneer hybrid Quanta corn silage was harvested at two-thirds ML during the 1997 growing season. The treatments included corn silage harvested at two chop lengths (short TLC = 9.5 mm and long TLC = 12.7 mm) with and without mechanical processing. Approximately 7 kg of corn silage from each treatment was obtained and frozen at -20°C . In experiments 4 and 5, Pioneer hybrids 3845 and Quanta corn silages were harvested during the 1998 growing season. Pioneer hybrid 3845 was harvested at three chop lengths (TLC = 11.1, 27.8, and 39.7 mm) with and without mechanical processing, and Pioneer hybrid Quanta corn silage was harvested at two chop lengths (TLC = 27.8 and 39.7 mm) with and without mechanical processing. Approximately 9 kg of corn silage from each treatment was obtained and frozen at -20°C . In experiments 3 through 5, in situ incubations were done at Washington State University (Buckley, WA) using ruminally fistulated lactating Holstein cows.

Experiment 1b corn silage and TMR in situ incubations. Corn silage and TMR treatments were separated with NASCO's Penn State Forage Particle Separator (NASCO, Fort Atkinson, WI) into a top (sieve size = 19 mm), middle (sieve size = 8 mm), and bottom layer. The treatments consisted of both hybrid 3845 corn silage and TMR containing hybrid 3845 corn silage that had been harvested at three maturities (hard dough, one-third ML, and two-thirds ML) with and without mechanical processing (same corn silage treatments as in experiment 1a). The individual layers were incubated in the rumen using macro in situ bags (30 $\times$ 35 cm nylon bags; pore size 53 μm ; Ankom Technology) at various timepoints. The size of particles remaining on the top sieve was greater than 19 mm, the particles on the middle sieve were between 8 and 19 mm, and the particles on the bottom pan were less than 8 mm. The TMR fed in experiment 1b include corn silage (26.8% of diet DM), alfalfa hay (13.2% of diet DM), whole cottonseed (13.6% of diet DM), and concentrate mix (46.4% of diet

DM; Johnson et al., 2002). The concentrate mix included corn grain, barley grain, soybean meal, wheat millrun, Prolak (H. J. Baker and Bro., Inc.), beet pulp, molasses, and vitamins and minerals (Johnson et al., 2002).

Initial Preparation of Samples and Sample Collection

In experiments 1a, 2, 3, 4, and 5, approximately 20 g (DM basis) of wet unground corn silage was placed into a macro in situ bag (Doggett, 1998). The sample weight and bag weight were recorded before the macro in situ bags were sealed and compartmentalized in mesh bags by timepoint (experiments 1a, 2, 3, 4, and 5). The mesh bags were placed in the rumen underneath the rumen mat at 0800 h to ensure that the rumen environment was initially similar between incubation timepoints (experiments 3 through 5). No more than 40 in situ bags were placed in the rumen at one time to ensure that the samples would remain below the rumen mat.

In experiments 1a, 2, 3, 4, and 5, corn silage treatments were incubated in the rumen 8, 16, 24, 48, and 96 h. In experiment 3, corn silage treatments were also incubated in the rumen for 120 h. In experiment 1a, corn silage treatments, at each timepoint of incubation, were replicated four times (duplicate bags in two cows; Table 1). In experiment 2, corn silage treatments, at each timepoint of incubation, were replicated across three cows (Table 1). In experiments 3 through 5, corn silage treatments, at each timepoint, were replicated in triplicate within the same cow (Table 1). In each experiment, all the incubations were completed within a couple weeks of starting the incubations. Incubations were grouped together by timepoint, and all treatments, within a timepoint and experiment, were done simultaneously. However, not all timepoints, for an experiment, could be incubated at the same time because the number of samples was too large. For example, in experiment 2, the corn silage samples incubated for 24 and 48 h were done simultaneously and the corn silage samples at 8, 16, and 96 h were done simultaneously.

In experiments 1a through 5, the in situ bags containing corn silage were soaked for 15 min in cool tap water before being placed in the rumen. Measurements of the fraction of corn silage that instantly disappeared (0 h) were determined by soaking macro in situ bags with 20 g (DM basis) of wet unground corn silage in cold water for 10 to 15 min. In experiments 1a and 2, the fraction that instantly disappeared for each corn silage treatment was determined in duplicate. In experiments 3 through 5, the fraction that instantly disap-

peared for each corn silage treatment was determined in triplicate.

In experiment 1b, wet unground corn silage was separated into three fractions using NASCO's Penn State Forage Particle Separator; top (sieve size = 19 mm), middle (sieve size = 8 mm), or bottom layers. Also, in experiment 1b, wet unground TMR was separated into three fractions using NASCO's Penn State Forage Particle Separator; top (sieve size = 19 mm), middle (sieve size = 8 mm), or bottom layers. Approximately 20 g (DM basis) of each fraction of corn silage and TMR was placed into a macro in situ bag. The sample weight and bag weight were recorded before the bags were sealed and compartmentalized in mesh bags by timepoint. The mesh bags were placed in the rumen underneath the rumen mat at 0800 h to ensure that the rumen environment was initially similar between incubation timepoints. No more than 40 in situ bags were placed in the rumen at one time, to ensure that the samples would remain below the rumen mat. The TMR NASCO particle separation layers were incubated separately from the corn silage NASCO particle separation layers.

The TMR treatments remaining on the top, middle, and bottom layers of NASCO's Penn State Forage Particle Separator were incubated in the rumen for 4, 12, 24, 48, and 72 h (experiment 1b; Table 4). The corn silage treatments remaining on the top layer of NASCO's Penn State Forage Particle Separator were incubated in the rumen 4, 24, 36, 48, 72, and 96 h (Table 5). The corn silage treatments remaining on the middle layer of NASCO's Penn State Forage Particle Separator were incubated in the rumen 4, 24, 48, 72, and 96 h (Table 5). The corn silage treatments remaining on the bottom layer of NASCO's Penn State Forage Particle Separator were incubated in the rumen 4, 8, 24, 48, and 72 h (Table 5). Each treatment, at a timepoint, was incubated in triplicate in the same cow if there was enough sample remaining. All the incubations were completed over a 4-mo period.

Sample Preparation and Analysis

The chemical composition of the corn silage in experiments 1a, 2, 4, and 5 is presented in Tables 6, 7, and 8. The chemical and physical composition of the corn silage used in experiment 3 is presented in Table 9. The original corn silages, for all experiments, were ground through a Wiley mill (Arthur H. Thomas, Philadelphia, PA), and analyzed for DM and ash (AOAC, 1990), NDF with sulfite (Van Soest et al., 1991), ADF (Goering and Van Soest, 1970), lignin (Goering and Van Soest, 1970), CP (AOAC, 1990), starch (modified starch procedure of Holm et al., 1986; described in Johnson et al., 2002), and ether extract (AOAC, 1990). Nonfiber carbohydrates for

corn silage were calculated using the formula: $NFC = 100 - (NDF + CP + \text{ether extract} + \text{ash})$. Additional chemical analyses including acid detergent insoluble CP (**ADICP**; Goering and Van Soest, 1970) and neutral detergent insoluble CP (**NDICP**; Goering and Van Soest, 1970) were presented for experiment 3 in Table 9.

Post-ensiled corn kernels were separated from corn stover, and estimates were made of the percent whole intact vs. damaged kernels in experiments 1a (Table 6), 2 (Table 7), 3 (Table 9), and 4 and 5 (Table 8). In experiment 3, postensiled corn kernels were analyzed for DM (AOAC, 1990), and vitreousness (horny and floury endosperm) of corn kernels was estimated according to a method described in Johnson et al. (2002). Hemicellulose concentration of the corn silage was calculated by subtracting ADF concentration from NDF concentration, and cellulose concentration of the corn silage was calculated by subtracting lignin from ADF concentration in experiment 3 (Table 9).

Wet samples of corn silage were extracted (modified extraction procedure in Bulletin 749C; GC separation of VFA C2-C5; Supelco, Inc., Bellefonte, PA) and analyzed for VFA and lactate by GC (80/120 Carbowax B-DA/4% Carbowax 20M, Supelco, Inc.). Modifications to the extraction procedure in Bulletin 749C include: 1) in step number 2 of the bulletin, no thymol was used, 2) in step number 3 in the bulletin, samples were left in the cooler for 2 to 3 d instead of 6 or 7 d, 3) after step number 7, 4 ml of supernatant was extracted and 0.33 ml of 3 M sodium hydroxide was added to the supernatant and vortexed, 4) the next step was to add 0.33 ml of oxalic acid and vortex, and 5) the final extraction step was to centrifuge the sample for 10 min at 4000 rpm, and transfer the supernatant to VFA vials and cap. Wet samples of corn silage were also analyzed for pH, using a portable pH meter (Digital Mini-pH-meter, model 55, VWR Scientific, Inc.) and ethanol by gas chromatography (80/120 Carbowax B-DA/4% Carbowax 20M, Supelco, Inc.) in experiment 3.

In experiment 1b, wet corn silage and TMR for each treatment and period were analyzed for particle size and distribution using NASCO's Penn State Forage Particle Separator (NASCO, Fort Atkinson, WI) as described in Johnson et al. (2002). The wet corn silage and TMR were each composited across periods of the corresponding metabolism study (Johnson et al., 2002), in experiment 1b. The composited samples were weighed into macro in situ bags by sample type (corn silage vs. TMR), treatment (maturity $\times$ processing method), and NASCO's Penn State Forage Particle Separator layer (top sieve, middle sieve, or bottom).

In experiments 1a, 1b, 2, and 3, the samples were removed from the rumen and rinsed thoroughly by hand under tap water until the rinsate ran clear. In experi-

Table 4. NASCO's Penn State Forage Particle Separations of TMR were incubated in situ for DM disappearance and degradation rate in experiment 1b.

	Hard dough		1/3 Milkline		2/3 Milkline		SE	Mat	Proc	Mat by Proc
	Proc ¹	Unproc ²	Proc	Unproc	Proc	Unproc				
DM disappearance of top layer, ³ %										
Instantly disappeared	17.2	15.8	13.6	8.8	18.0	13.8	1.10	0.0009	0.002	0.16
4 h	29.0	22.6	28.3	24.2	22.5	19.4	3.18	NS	0.13	NS
12 h	35.8	29.8	28.2	28.2	35.1	30.4	2.38	0.08	0.07	NS
24 h	41.9	35.3	39.5	35.0	32.2	36.4	1.69	0.02	0.06	0.005
48 h	51.5	51.0	51.9	47.9	55.2	53.9	1.43	0.009	0.08	NS
72 h	58.6	54.7	52.3	50.8	52.2	56.0	1.11	0.001	NS	0.008
Disappearance rate, ⁴ %/h	3.24	4.86	9.35	5.13	1.39	6.43	...	...	...	...
DM disappearance of middle layer, ⁵ %										
Instantly disappeared	28.9	34.4	31.7	42.4	24.3	30.3	...	...	...	...
4 h	43.1	47.7	43.8	43.1	35.5	35.3	...	...	...	...
12 h	49.6	40.8	45.4	45.7	47.3	39.4	2.16	NS	0.07	NS
24 h	59.4	58.4	61.6	65.7	55.4	53.6	3.97	0.10	NS	NS
48 h	66.7	67.5	72.3	70.6	63.8	67.2	2.45	0.11	NS	NS
72 h	75.9	79.7	75.7	71.8	70.8	75.1	1.03	0.0006	0.06	0.002
Disappearance rate, %/h	2.98	2.52	5.37	8.29	3.58	3.82	...	...	...	...
DM disappearance of bottom layer, ⁶ %										
Instantly disappeared	34.5	41.6	39.7	NA	31.1	39.7	...	...	...	...
4 h	43.0	44.7	45.0	40.9	38.7	44.1	...	...	...	...
12 h	50.6	48.3	43.9	39.2	42.4	45.4	...	...	...	...
24 h	65.3	66.2	62.6	60.6	56.8	67.5	...	...	...	...
48 h	74.0	72.3	74.2	68.9	68.8	76.6	...	...	...	...
72 h	74.7	75.8	75.9	74.8	78.0	84.1	...	...	...	...
Disappearance rate, %/h	8.78	5.19	6.95	NA	3.45	4.07	...	...	...	...

¹Proc: The TMR contained corn silage that was harvested with a 5830 John Deere harvester with kernel processing rolls set 1 mm apart.

²Unproc: The TMR contained corn silage that was harvested with a 5830 John Deere harvester with kernel processing rolls set 15.9 mm apart.

³Top layer: TMR remaining on the top layer (particles greater than 19 mm) of NASCO's Penn State Forage Particle Separator.

⁴Disappearance rate: The least squares regression of logarithmic-transformed residuals with correction for undegraded residue method was used to calculate rate of disappearance (Nocek and English, 1986).

⁵Middle layer: TMR remaining on the middle layer (particles between 8 and 19 mm) of NASCO's Penn State Forage Particle Separator.

⁶Bottom layer: TMR on the bottom layer (particles less than 8 mm) of NASCO's Penn State Forage Particle Separator.

ments 1a, 2, and 3, the 0-h incubations were also rinsed thoroughly by hand under tap water until the rinsate ran clear. In experiments 4 and 5, the samples were removed from the rumen, rinsed by hand under tap water to remove large particles, and rinsed in a washing machine (Ultimate Care II Heavy Duty, Whirlpool Washer) for 40 min on super wash cycle. In experiments 4 and 5, the 0-h incubations were also rinsed in the washing machine for 40 min on super wash cycle.

For all experiments, the bags were placed in a forced-air oven and dried at 55°C for a minimum of 48 h. The weight of the in situ bag plus dry sample were recorded. Replicates within a timepoint for each treatment were composited within an experiment. The composited samples (except experiment 1b) were ground through a Wiley mill (Arthur H. Thomas) before being analyzed for DM (AOAC, 1990), starch (modified starch procedure of Holm et al., 1986; described in Johnson et al., 2002), NDF with sulfite (Van Soest et al., 1991), and CP (AOAC, 1990) concentrations.

For all experiments, DM, starch, NDF, and CP disappearance at each incubation timepoint were calculated.

The disappearance values were calculated without the fraction that instantly disappeared subtracted from the total disappearance at a given timepoint. Rates of DM, starch, NDF, and CP disappearance in the rumen were calculated with the fraction that instantly disappeared subtracted from the total disappearance. The fraction that instantly disappeared was subtracted for the rate calculations to evaluate degradation rates of the carbohydrate fractions (starch and NDF) as they appear in the Cornell Penn Miner ration evaluator model. The least squares regression of logarithmic-transformed residuals with correction for undegraded residue method was used to calculate rate of disappearance (Nocek and English, 1986). In experiments 1a, 2, 4, and 5, the potentially degradable fraction was assumed to be the proportion of silage disappearing by 96 h of incubation. In experiment 3, the potentially degradable fraction was assumed to be the proportion of silage disappearing by 120 h of incubation. In experiment 1b (NASCO's Penn State Forage Particle Separator), the TMR on the top, middle, and bottom layer, and the corn silage on the bottom layer remaining after 72 h was the proportion

Table 5. NASCO's Penn State Forage Particle Separations of corn silage were incubated in situ for DM disappearance and degradation rate in experiment 1b.

	Hard dough		1/3 Milkline		2/3 Milkline		SE	Mat	Proc	Mat by Proc
	Proc ¹	Unproc ²	Proc	Unproc	Proc	Unproc				
DM disappearance of top layer, ³ %										
Instantly disappeared	16.3	0.2	NA	NA	NA	NA	...	...	...	...
4 h	19.3	10.0	18.0	14.6	22.7	11.0	1.87	...	...	...
24 h	30.1	37.1	NA	27.8	NA	18.2	7.97	...	...	...
36 h	NA	44.4	NA	28.5	NA	NA	5.20	...	...	...
48 h	43.2	47.0	30.4	39.5	39.7	32.0	6.20	...	...	...
72 h	81.8	53.9	50.6	42.7	47.0	46.8	5.46	NS	NS	NS
96 h	85.7	61.6	63.8	52.6	57.5	61.7	10.63	NS	NS	NS
Disappearance rate, ⁴ %/h	3.90	2.72	NA	2.06	NA	1.79	...	...	...	...
DM disappearance of middle layer, ⁵ %										
Instantly disappeared	23.2	29.5	33.7	28.8	23.9	31.6	2.38	0.08	0.07	0.03
4 h	34.9	40.6	37.7	33.5	32.5	38.4	1.27	0.10	0.02	0.001
24 h	52.4	57.4	59.9	58.5	51.5	54.6	1.48	0.003	0.07	0.09
48 h	64.8	65.3	67.3	68.8	63.4	64.0	0.84	0.0005	0.17	NS
72 h	68.7	73.4	71.6	70.5	69.1	69.3	0.71	0.04	0.06	0.005
96 h	72.7	72.8	73.0	74.1	72.4	73.5	1.13	NS	NS	NS
Disappearance rate, %/h	3.37	3.15	4.59	3.62	3.66	3.09	...	...	...	...
DM disappearance of bottom layer, ⁶ %										
Instantly disappeared	34.1	37.7	41.7	37.4	24.9	30.4	1.09	0.0003	0.12	0.01
4 h	36.7	45.8	48.5	39.9	27.5	35.6	1.18	0.008	0.06	0.01
8 h	46.9	45.8	51.4	43.2	33.5	43.7	2.74	0.04	NS	0.04
24 h	57.0	58.0	63.9	56.5	41.4	50.3	2.22	0.0002	NS	0.009
48 h	63.5	63.1	63.8	61.8	56.5	60.4	1.66	0.02	NS	0.18
72 h	69.7	70.0	74.9	69.1	61.9	67.5	1.20	0.0001	NS	0.0009
Disappearance rate, %/h	3.65	2.78	2.04	3.21	4.11	3.22	...	...	...	...

¹Proc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 1 mm apart.

²Unproc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 15.9 mm apart.

³Top layer: Corn silage remaining on the top layer (particles greater than 19 mm) of NASCO's Penn State Forage Particle Separator.

⁴Disappearance rate: The least squares regression of logarithmic-transformed residuals with correction for undegraded residue method was used to calculate rate of disappearance (Nocek and English, 1986).

⁵Middle layer: Corn silage remaining on the middle layer (particles between 8 and 19 mm) of NASCO's Penn State Forage Particle Separator.

⁶Bottom layer: Corn silage on the bottom layer (particles less than 8 mm) of NASCO's Penn State Forage Particle Separator.

Table 6. Dry matter, chemical composition, and physical characteristics of corn silage fed in experiment 1a (hybrid 3845 harvested in 1996).

Item	Hard dough		1/3 Milkline		2/3 Milkline	
	Proc ¹	Unproc ²	Proc	Unproc	Proc	Unproc
DM, %	24.2	26.4	28.5	28.4	27.9	28.0
Ash, % of DM	6.6	5.9	5.1	5.6	5.4	6.6
NDF, % of DM	57.6	54.9	52.3	54.4	55.2	55.8
ADF, % of DM	38.6	37.0	34.7	35.4	35.8	36.0
Lignin, % of DM	5.2	4.6	4.6	4.4	4.8	4.9
CP, % of DM	8.3	8.3	7.9	9.1	8.8	8.6
NFC, ³ % of DM	25.7	28.9	32.4	29.1	28.7	27.1
Starch, % of DM	13.2	15.2	21.6	21.4	19.2	19.6
Crude fat, % of DM	1.9	1.9	2.3	1.8	1.9	2.0
Intact whole kernel, % of total kernels	0.0	0.0	0.0	9.5	6.7	5.6

¹Proc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 1 mm apart.

²Unproc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 15.9 mm apart.

³NFC: Nonfiber carbohydrates = 100 - (CP + NDF + ash + ether extract).

Table 7. Dry matter, chemical composition, and physical characteristics of corn silage fed in experiment 2 (hybrids 3845 and Quanta harvested in 1997).

Item	DM (%)	Ash (% DM)	NDF (% DM)	ADF (% DM)	Lignin (% of DM)	CP (% DM)	NFC ¹ (% DM)	Starch (% DM)	Crude fat (% of DM)	Intact kernels (% of total kernel)
Hybrid 3845										
1/3 milkline										
Processed	25.7	4.5	46.8	31.4	3.1	8.0	38.2	20.6	2.7	0.0
Unprocessed	28.4	4.4	44.9	31.4	2.9	8.0	40.3	20.0	2.7	6.7
2/3 milkline										
Processed	33.5	4.2	42.2	28.8	4.6	7.7	43.5	27.9	2.6	0.0
Unprocessed	33.1	4.1	41.4	28.4	2.7	7.7	44.4	30.0	2.6	20.0
Blackline										
Processed	38.0	4.1	42.8	28.6	3.0	7.5	43.3	28.8	2.6	0.0
Unprocessed	38.4	5.3	47.9	31.9	3.5	7.4	37.2	25.3	2.4	29.4
Hybrid Quanta										
1/3 milkline										
Processed	32.4	4.7	43.9	29.6	2.9	8.8	43.1	30.6	2.4	0.0
Unprocessed	35.7	4.6	42.7	28.3	2.2	8.7	40.3	32.5	2.5	0.0
2/3 milkline										
Processed	41.2	4.1	37.7	25.0	2.3	8.0	41.5	39.3	2.5	0.0
Unprocessed	41.8	4.1	40.3	26.3	2.5	7.7	47.7	40.5	2.7	17.4
Blackline										
Processed	44.6	4.3	39.1	25.7	2.7	8.2	46.3	35.9	2.8	2.5
Unprocessed	50.3	4.4	43.7	28.1	2.3	7.7	44.6	36.5	2.7	7.4

¹NFC: Nonfiber carbohydrates = 100 – (CP + NDF + ash + ether extract).

of sample that was determined to be potentially degradable. In experiment 1b (NASCO's Penn State Forage Particle Separator), the corn silage on the top and middle layers remaining after 96 h was the proportion of sample that was determined to be potentially degradable. In some experiments (experiments 2 and 3), there was high variability in the amount of NDF disappearance at 8 and 16 h of ruminal incubation. In those experiments (experiments 2 and 3), NDF disappearance and rate of NDF disappearance were analyzed and calculated using only the data from 24, 48, and 96 h.

Statistical Analysis

In experiment 1a, in situ disappearance of nutrients was analyzed as a randomized block design in SAS (2000) using Proc Mixed. The mixed model was:

$$Y_{ijk} = \mu + M_i + P_j + C_k + (M \times P)_{ij} + (M \times P \times C)_{ijk} + E_{ijk},$$

where μ = overall mean, M_i = maturity effect ($i = 1$ to 3), P_j = mechanical processing effect ($j = 1$ to 2), C_k =

Table 8. Dry matter, chemical composition, and physical characteristics of the corn silage fed in experiments 4 and 5 (DM basis).

Item	Experiment 4						Experiment 5			
	Short (11.1 mm)		Medium (27.8 mm)		Long (39.7 mm)		Medium (27.8 mm)		Long (39.7 mm)	
	Proc	Unproc	Proc	Unproc	Proc	Unproc	Proc	Unproc	Proc	Unproc
DM, %	32.7	31.4	32.1	32.1	33.4	33.8	39.3	37.7	40.1	38.5
Ash, % of DM	4.9	5.5	4.9	6.2	5.0	5.0	3.7	4.2	4.0	3.6
NDF, % of DM	46.1	46.5	43.7	47.4	43.9	47.2	41.1	42.8	44.4	44.3
ADF, % of DM	29.0	28.9	28.4	29.1	28.5	28.9	24.1	26.3	25.2	25.6
Lignin, % of DM	3.2	3.4	3.4	3.3	3.4	3.2	3.1	3.2	3.1	3.2
CP, % of DM	7.8	7.7	7.5	7.8	7.6	7.4	8.0	8.1	8.0	8.1
NFC, ¹ % of DM	38.1	37.4	41.0	35.5	40.5	37.5	44.3	41.9	40.5	41.0
Starch, % of DM	30.4	29.8	32.6	29.2	32.6	29.5	34.8	33.9	34.2	32.2
Crude fat, % of DM	3.1	2.9	2.9	3.1	3.0	2.9	2.9	3.0	3.1	3.0
Intact whole kernels, % of total kernel	23.3	16.1	17.7	18.2	20.5	20.5	5.3	8.3	2.8	8.5

¹NFC: Nonfiber carbohydrate = 100 – (NDF + CP + ether extract + ash).

Table 9. Dry matter, chemical composition, and physical characteristics of the corn silage in experiment 3 (DM basis).

	Medium ¹ Proc ³	Medium Unproc ⁴	Long ² Proc	Long Unproc
DM, %	32.8	32.8	31.5	32.5
Ash, % of DM	3.3	3.2	3.3	3.3
NDF, % of DM	40.0	39.7	41.6	42.1
ADF, % of DM	29.2	27.8	29.6	29.3
Cellulose, % of DM	25.6	24.5	25.5	25.1
Hemicellulose, % of DM	3.2	11.0	12.0	12.8
CP, % of DM	7.0	6.9	6.9	6.9
NFC, ⁵ % of DM	46.8	47.1	45.4	44.7
Starch, % of DM	38.1	35.2	38.0	31.7
Lignin, % of DM	3.6	3.3	4.1	4.2
ADICP, ⁶ % of DM	1.5	0.3	0.7	0.8
NDICP, ⁷ % of DM	2.1	0.8	0.7	0.7
NDICP, % of CP	30.0	11.6	10.1	10.1
Crude fat, % of DM	2.9	3.1	2.8	3.0
pH	4.16	3.91	4.14	3.84
Lactate, % of DM	1.14	1.56	1.29	1.48
Acetate, % of DM	1.84	1.10	0.77	1.21
Propionate, % of DM	ND ⁸	ND	ND	ND
Butyrate, % of DM	ND	ND	ND	ND
Ethanol, % of DM	0.52	0.60	0.40	0.55
Kernel DM, %	46.9	51.2	46.7	48.3
Intact whole kernel, % of total kernels	3.9	8.5	3.2	9.4
Preensiled horny endosperm ⁹	40.1	40.1	40.1	40.1
Preensiled floury endosperm ⁹	59.9	59.9	59.9	59.9

¹Medium chop: Harvester set with 10 rows of knives and a 18-tooth sprocket. TLC = 9.5 mm.

²Long chop: Harvester set with 10 rows of knives and a 24-tooth sprocket. TLC = 12.7 mm.

³Proc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 1 mm apart.

⁴Unproc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 15.9 mm apart.

⁵NFC: Nonfiber carbohydrates = 100 – (NDF + CP + ether extract + ash).

⁶ADICP: Acid detergent insoluble CP.

⁷NDICP: Neutral detergent insoluble CP.

⁸ND: Not detectable (less than 0.1% in the sample).

⁹Horny endosperm is referred to as 'vitreous'. Horny and floury endosperm were calculated as a % of total endosperm present.

cow effect ($k = 1$ to 2), $(M \times P)_{ij}$ = interaction effect of M_i and P_j , $(M \times P \times C)_{ijk}$ = error term, and E_{ijk} = residual (subsampling within cow). Cow effect was the random variable, and all other variables were fixed.

In experiment 2, in situ disappearance of nutrients was analyzed as a completely randomized design in SAS (2000) using Proc Mixed. The mixed model was:

$$Y_{ijkl} = \mu + H_i + M_j + P_k + C_l + (H \times M)_{ij} + (H \times P)_{ik} + (M \times P)_{jk} + E_{ijkl},$$

where μ = overall mean, H_i = hybrid effect ($i = 1$ to 2), M_j = maturity effect ($j = 1$ to 3), P_k = mechanical processing effect ($k = 1$ to 2), C_l = cow effect ($l = 1$ to 3), $(H \times M)_{ij}$ = interaction effect of H_i and M_j , $(H \times P)_{ik}$ = interaction effect of H_i and P_k , $(M \times P)_{jk}$ = interaction effect of M_j and P_k , and E_{ijkl} = error term. Cow effect was the random variable, and all other variables were fixed.

In experiments 1b, 3, 4, and 5, in situ disappearance of nutrients was analyzed as a completely randomized design in SAS (2000) using Proc Mixed. The mixed model was:

$$Y_{ijk} = \mu + M_i + P_j + R_k + (M \times P)_{ij} + E_{ijk},$$

where μ = overall mean, M_i = chop length effect, P_j = mechanical processing effect ($j = 1$ to 2), R_k = replication effect ($k = 1$ to 3), $(M \times P)_{ij}$ = interaction effect of M_i and P_j , and E_{ijk} = error term. R_k was the random variable, and all other variables were fixed. In experiment 1b, there are some means that do not have P values reported due to lack of replication [not enough material (corn silage or TMR) available to replicate at some timepoints].

In all experiments, treatment means were separated using the least significant difference test when a sig-

Table 10. Macro in situ DM, NDF, starch, and CP disappearance and degradation rate in experiment 1a.

	Hard dough		1/3 Milkline		2/3 Milkline		SE	Mat	Proc	Mat by Proc
	Proc ¹	Unproc ²	Proc	Unproc	Proc	Unproc				
DM disappearance, %										
Instantly disappeared	22.0	25.7	20.8	21.8	17.9	19.6	2.30	0.06	NS	NS
8 h	33.4	30.6	36.2	26.7	28.7	25.0	0.83	0.0007	0.0001	0.009
16 h	38.2	39.3	38.8	34.9	37.7	32.7	0.60	0.002	0.0009	0.003
24 h	52.7	44.3	49.1	42.2	41.5	41.7	0.80	0.0003	0.0001	0.002
48 h	59.9	58.9	61.8	59.5	57.1	55.9	1.40	0.02	NS	NS
96 h	69.3	67.1	69.5	68.2	67.8	66.2	1.57	NS	NS	NS
Disappearance rate, ³ %/h	3.46	3.79	3.99	4.00	3.48	3.52	...	...	...	...
NDF disappearance, %										
8 h	25.3	28.8	18.3	21.2	22.3	17.9	1.21	0.0002	NS	0.01
16 h	28.9	34.5	20.4	27.9	24.9	20.7	1.23	0.0001	0.02	0.003
24 h	45.5	42.4	35.0	37.1	30.4	33.3	1.01	0.0001	NS	0.03
48 h	55.7	56.7	46.2	51.6	52.2	47.0	1.53	0.0005	NS	0.01
96 h	65.4	66.9	58.4	62.8	60.4	59.2	1.85	0.007	NS	NS
Disappearance rate, %/h	3.89	3.39	3.26	3.37	3.95	3.19	...	...	...	...
Starch disappearance, %										
Instantly disappeared	56.9	68.1	40.0	57.7	18.6	37.3	1.12	0.0001	0.0001	0.04
8 h	73.7	81.0	73.1	69.6	39.5	65.9	0.67	0.0001	0.0001	0.0001
16 h	86.4	91.9	76.2	77.4	79.5	80.4	0.42	0.0001	0.0001	0.0001
24 h	90.2	96.7	86.5	79.2	83.5	93.3	0.31	0.0001	0.0001	0.0001
48 h	92.6	98.8	97.5	98.5	95.5	96.2	0.12	0.0001	0.0001	0.0001
96 h	97.5	100.0	99.1	98.9	98.2	98.6	0.08	0.0001	0.0001	0.0001
Disappearance rate, %/h	3.55	6.73	7.29	11.16	7.17	6.56	...	...	...	...
CP disappearance, %										
Instantly disappeared	56.2	55.7	48.0	61.3	59.2	54.3	0.94	NS	0.02	0.0005
8 h	65.6	59.2	63.7	67.5	57.0	53.4	0.70	0.0001	0.004	0.0001
16 h	67.1	63.8	62.5	68.5	63.1	67.6	0.86	NS	0.002	0.0001
24 h	71.2	66.3	68.1	74.3	70.8	69.1	1.06	0.03	NS	0.0002
48 h	73.0	74.2	75.6	76.6	72.4	74.6	0.91	0.01	0.05	NS
96 h	79.6	76.4	76.4	76.9	77.5	75.1	1.20	NS	0.07	NS
Disappearance rate, %/h	2.09	5.29	8.31	9.14	2.74	8.84	...	...	...	...

¹Proc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 1 mm apart.

²Unproc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 15.9 mm apart.

³Disappearance rate—The least squares regression of logarithmic-transformed residuals with correction for undegraded residue method was used to calculate rate of disappearance (Nocek and English, 1986).

nificant treatment effect ($P < 0.05$) or trend ($P < 0.10$) was observed (SAS, 2000).

RESULTS AND DISCUSSION

Maturity by Mechanical Processing Experiments

Dry matter disappearance. The nutrient profile of corn silage used in experiments 1a and 2 is presented in Tables 6 and 7, respectively. In situ DM disappearance of corn silage that differed in hybrid, stage of maturity, and mechanical processing were evaluated using the macro in situ bag technique (experiments 1a and 2; Tables 10 and 11; Figures 1a and 1b). Corn silage that was mechanically processed had significantly greater in situ DM disappearance than unprocessed corn silage in experiments 1a and 2 at 8 ($P < 0.0001$; experiment 1a), 16 ($P < 0.0009$ and $P < 0.0009$), 24 ($P < 0.0001$ and $P < 0.0001$), 48 ($P < 0.0001$; experiment 2), and 96 h ($P < 0.007$; experiment 2; Tables 10 and 11; Figures 1a and 1b) of ruminal incubation. Others have reported

an increase in DM disappearance due to mechanically processing corn silage (Doggett et al., 1998; Johnson et al., 1999; Bal et al., 2000a; Bal et al., 2000b; Andrae et al., 2001).

There were maturity $\times$ processing and hybrid $\times$ processing interactions at some of the timepoints. In experiment 2 (Table 11) processing had less of an effect on DM disappearance for the early maturity (one-third ML) of corn silage compared with the advanced maturities (two-thirds ML and BL). There was no difference ($P = 0.80$) in DM disappearance between processed and unprocessed corn silage at one-third ML at 24 and 96 h of ruminal in situ incubation (experiment 2; Table 11). This was similar to results reported by Andrae et al. (2001), where processing enhanced DM disappearance to a greater extent at full ML than half ML at 24, 48, and 96 h of ruminal incubation. In experiment 2, processing had a greater impact on DM disappearance for hybrid Quanta corn silage. There was no difference in DM disappearance between processed and unpro-

Table 11. Macro in situ DM disappearance in experiment 2.

	Instantly disappeared	8	16	24	48	96	Disappearance rate ¹
	(%)						(%/h)
Hybrid 3845							
1/3 milkline, proc ²	31.6	36.6	49.0	52.9	63.3	66.1	5.85
1/3 milkline, unproc ³	28.9	34.4	39.8	54.7	59.1	69.2	3.15
2/3 milkline, proc	14.8	28.0	33.6	42.6	55.5	64.7	3.58
2/3 milkline, unproc	19.9	26.0	30.3	40.6	44.3	59.9	2.10
Blackline, proc	15.2	25.7	39.9	47.7	50.5	65.7	2.20
Blackline, unproc	25.6	30.0	42.9	46.6	50.2	66.6	1.75
Hybrid Quanta							
1/3 milkline, proc	37.4	40.3	48.9	59.2	67.0	71.5	4.90
1/3 milkline, unproc	31.5	37.3	46.3	52.7	54.3	71.2	1.52
2/3 milkline, proc	33.8	40.4	48.9	56.9	61.4	72.8	2.52
2/3 milkline, unproc	31.0	34.6	36.7	41.4	49.2	67.4	1.52
Blackline, proc	34.6	39.8	49.4	53.9	63.8	71.4	3.50
Blackline, unproc	30.7	33.2	40.7	45.5	54.9	64.1	2.99
SE	1.72	2.89	1.52	1.79	3.13	1.34	...
Hybrid	0.0001	0.0002	0.0007	0.0003	0.003	0.0001	...
Maturity	0.0001	0.01	0.0005	0.0001	0.0001	0.005	...
Processing	NS	0.12	0.0009	0.0001	0.0001	0.007	...
Hybrid × maturity	0.0009	0.15	0.06	0.05	0.02	0.01	...
Hybrid × processing	0.0008	0.10	0.09	0.0001	0.04	0.01	...
Maturity × processing	0.02	NS	NS	0.03	0.12	0.007	...

¹Disappearance rate: The least squares regression of logarithmic-transformed residuals with correction for undegraded residue method was used to calculate rate of disappearance (Nocek and English, 1986).

²Proc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 1 mm apart.

³Unproc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 15.9 mm apart.

cessed corn silage for hybrid 3845 at 24 ($P = 0.70$) and 96 ($P = 0.93$) h of ruminal incubation. However, for hybrid Quanta, there was a significant increase (24 h, $P < 0.0001$ and 96 h, $P < 0.0004$) in DM disappearance for processed compared with unprocessed corn silage (experiment 2; Table 11). Others have reported that the degree to which processing will influence DM disappearance is affected by the hybrid of corn silage (Andrae et al., 2001).

The difference in DM disappearance between processed and unprocessed corn silage at some timepoints (16, 48, and 96 h) was greater in experiment 2 (year = 1997) than experiment 1a (year = 1996; Figures 1a and 1b). The change in response between years may be related to different climatic and possibly soil conditions. During the first year (experiment 1a), the corn silage matured differently than corn silage from the second year (experiment 2) due to heavy precipitation during the winter and spring (January through May precipitation; 1996 = 593 mm and 1997 = 517 mm) along with cooler temperatures and lower growing degree-days through the summer and fall (May through September; Table 3). Therefore, it appears that when there is less precipitation and the air temperature is warmer during the growing season, the corn plant may develop in a way that makes it less digestible in the rumen. In exper-

iment 2, mechanical processing altered some of the physical characteristics of corn silage that was grown in the warmer temperatures and enhanced DM disappearance in the rumen.

Mechanical processing had no effect on the fraction of corn silage DM that instantly disappeared (0 h) in experiments 1a and 2 (Tables 10 and 11). Rate of DM disappearance differed between years in experiments 1a and 2. During the first year (1996 season; experiment 1a) the rate of DM disappearance was similar between processed and unprocessed corn silage within a maturity (Table 10). However, during the second year (1997 season; experiment 2), the rate of DM disappearance was greater for processed corn silage at all maturities (Table 11). Others have reported an increase in rate of DM disappearance due to mechanical processing (Andrae et al., 2001). In experiment 2, the largest difference in the rate of DM disappearance occurred at one-third ML for both hybrids 3845 (processed, 5.9% vs. unprocessed, 3.2%) and Quanta (processed, 4.9% vs. unprocessed, 1.5%; Table 11). The reason for the largest difference in rate of DM disappearance between processed and unprocessed corn silage occurring at the earliest maturity is unknown. The authors would have anticipated the largest difference to be at the advanced maturity when the corn silage is more difficult to digest.

Figure 1. Effect of mechanical processing on DM disappearance of corn silage over time incubated in the rumen in experiment 1a (a) and experiment 2 (b). Processed (◆) and unprocessed (■) corn silage. Each data point represents a mean for each treatment in experiments 1a and 2.

Maturity of corn silage also affected macro in situ DM disappearance in experiments 1a and 2. In experiment 1a ($P < 0.06$) and for hybrid 3845 ($P < 0.0009$) in experiment 2, the portion of DM that instantly disappeared was lower at advanced maturities (two-thirds ML and BL; Tables 10 and 11). However, in experiment 1a, the rate and extent (96-h disappearance) of DM disappearance were similar between maturities (Table 10). This may suggest that as the corn plant matured in experiment 1a, there was a smaller amount of DM that rapidly disappeared (0 h); however, once digestion began, there was a similar amount of the corn plant that was available for digestion at all maturities.

Corn silage harvested at the advanced maturity (two-thirds ML), in experiment 1a, had lower disappearance of DM than the earlier maturities (hard dough and one-thirds ML) at 8 ($P < 0.0007$), 16 ($P < 0.002$), 24 ($P < 0.0003$), and 48 ($P < 0.02$) h of incubation in the rumen (Table 10). This was similar to results observed by Bal et al. (2000a), where ruminal in situ DM disappearance was lower ($P < 0.01$) for corn silage harvested at BL

than early dent, one-fourth ML, and two-thirds ML maturities. In experiment 2, the corn silage harvested at the earliest maturity (one-third ML) had greater disappearance of DM at 8 ($P < 0.01$), 16 ($P < 0.0005$), 24 ($P < 0.0001$), 48 ($P < 0.0001$), and 96 ($P < 0.005$) h of ruminal incubation than at advanced maturities (two-thirds ML or BL; Table 11). The increased DM disappearance at the early maturity (one-third ML) observed during the second year (1997) of the in situ studies (experiment 2) may be related to increased disappearance of stover DM (not measured) at early maturities. Hunt et al. (1989) reported that in situ DM disappearance decreased in the stover portion of corn silage as maturity advanced from one-third ML to black layer. In this study, NDF disappearance was measured and can be used as an indication of the digestibility of the stover fraction of the corn plant. Disappearance of NDF was greater for corn silage harvested at one-third ML than advanced maturities (two-thirds ML and BL) at 24 ($P < 0.002$), 48 ($P < 0.003$), and 96 ($P < 0.0001$) h of incubation in the rumen in experiment 2 (Table 12). Others (Xu et al., 1995) reported a decrease in in vitro DM digestibility of the stover portion of corn silage as maturity advanced from milk to BL.

For hybrid 3845 in experiment 2, rate of DM disappearance actually declined as maturity advanced from one-third ML (4.5%) to two-thirds ML (2.84%) to BL (1.98%; Table 11). The lower rate of DM disappearance observed as maturity advanced may have been due to an increase in the DM concentration of corn silage as maturity advanced (Tables 7 and 11). The rumen microbes may have had more difficulty initially penetrating the outer coating of the stalk and corn kernels as maturity advanced, partially because of the drier material, therefore decreasing the rate at which DM disappeared. No trend in rate of DM disappearance was observed across maturities in experiment 1a and for hybrid Quanta in experiment 2 (Table 11).

Hybrid of corn silage also affected the disappearance of DM. The proportion of DM that instantly disappeared (0 h) was significantly greater ($P < 0.0001$) for hybrid Quanta (33.2%) than hybrid 3845 (22.9%) corn silage (Table 11). Dry matter disappearance was also significantly greater for hybrid Quanta corn silage compared with hybrid 3845 corn silage at 8 ($P < 0.0002$), 16 ($P < 0.0007$), 24 ($P < 0.0003$), 48 ($P < 0.003$), and 96 ($P < 0.0001$) h of ruminal incubation in experiment 2 (Table 11). The increased DM disappearance can be partially explained by the increased starch disappearance at all timepoints for hybrid Quanta compared with hybrid 3845 corn silage (Table 13). Hybrid Quanta corn silage also had significantly lower ($P < 0.0001$) NDF concentrations than hybrid 3845 corn silage (Table 7; Johnson et al., 2002). Differences in DM disappearance observed

Table 12. Macro in situ NDF disappearance in experiment 2.

	24	48	96	Disappearance rate ¹
	(%)			(%/h)
Hybrid 3845				
1/3 milkline, proc ²	18.0	36.4	43.9	5.24
1/3 milkline, unproc ³	25.3	33.9	49.9	1.53
2/3 milkline, proc	4.9	23.3	38.0	3.10
2/3 milkline, unproc	20.3	25.3	39.4	0.82
Blackline, proc	16.7	27.3	41.3	2.33
Blackline, unproc	22.9	24.2	45.8	0.04
Hybrid Quanta				
1/3 milkline, proc	29.0	40.3	51.2	2.98
1/3 milkline, unproc	16.8	20.6	49.3	0.39
2/3 milkline, proc	15.5	24.6	45.9	1.48
2/3 milkline, unproc	...	21.7	38.1	NA
Blackline, proc	22.4	39.4	50.4	3.65
Blackline, unproc	12.7	25.4	39.3	2.37
SE	2.47	3.19	2.27	...
Hybrid	NS	NS	0.02	...
Maturity	0.002	0.003	0.0001	...
Processing	NS	0.004	NS	...
Hybrid × maturity	NS	0.06	NS	...
Hybrid × processing	0.0001	0.007	0.0001	...
Maturity × processing	0.09	0.07	0.07	...

¹Disappearance rate: The least squares regression of logarithmic-transformed residuals with correction for undegraded residue method was used to calculate rate of disappearance (Nocek and English, 1986).

²Proc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 1 mm apart.

³Unproc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 15.9 mm apart.

in this study due to the concentration of NDF in the corn silage (high vs. low) followed similar trends to results from Bal et al. (2000a). Dry matter disappearance for the low NDF corn silage was greater than the high NDF corn silage due to increased starch disappearance (Bal et al., 2000a).

Starch disappearance. The effects of hybrid, maturity, and mechanical processing of corn silage on macro in situ starch disappearance varied across experiments 1a and 2 (Tables 10 and 13). In experiments 1a ($P < 0.0001$) and 2 ($P < 0.0001$), the unprocessed corn silage had significantly greater disappearance of the fraction of starch that instantly disappeared (0 h; Tables 10 and 13). However, the percentage of starch that disappeared at 8, 16, 24, 48, and 96 h of incubation demonstrated variable results (Tables 10 and 13).

Starch disappearance at 8 ($P < 0.0001$), 16 ($P < 0.0001$), 24 ($P < 0.0001$), 48 ($P < 0.0001$), and 96 ($P < 0.0001$) h of ruminal incubation was significantly lower for processed compared with unprocessed corn silage in experiment 1a (Table 10; Figure 2a). Starch disappearance at 16 ($P < 0.002$), 24 ($P < 0.0001$), 48 ($P < 0.007$), and 96 ($P < 0.004$) h was significantly greater for processed compared with unprocessed corn silage in experiment 2 (Table 13; Figure 2b). Although there was a significant difference between processed and un-

processed corn silage in both experiments, the difference was greater in experiment 2 (16, 24, 48, and 96 h) than experiment 1a (Figures 2a and 2b). The difference in starch disappearance between experiments for processed and unprocessed corn silage can partially be explained by the percentage of intact (not crushed or cracked) corn kernels present in the silages (Tables 6 and 7). In experiment 2, the unprocessed corn silage, at many of the maturities, tended to have a greater percentage of the kernels that were intact compared with unprocessed corn silages in experiment 1a. It is difficult for rumen microbes to digest the starch inside the intact corn kernels because they have to penetrate to outer layer of the corn kernel. Therefore, in situations where there are more intact corn kernels there tends to be lower ruminal starch disappearance, as was demonstrated in experiment 2.

In both experiments, there were significant maturity × processing interactions for starch disappearance. In experiment 1a at the earliest (hard dough) and advanced (two-thirds ML) maturities, the unprocessed corn silage tended to have greater ruminal starch disappearance at 8 ($P < 0.0001$), 16 ($P < 0.0001$), 24 ($P < 0.0001$), 48 ($P < 0.0001$), and 96 ($P < 0.0001$) h of incubation (Table 10). However, at the middle maturity (one-third ML; experiment 1a) there was variability in the

Table 13. Macro in situ starch disappearance in experiment 2.

	Instantly disappeared	8	16	24	48	96	Disappearance rate ¹
	(%)						(%/h)
Hybrid 3845							
1/3 milkline, proc ²	60.2	82.5	93.0	95.3	98.6	99.1	8.69
1/3 milkline, unproc ³	54.6	67.1	81.1	95.5	96.3	99.2	5.97
2/3 milkline, proc	26.4	60.0	79.6	85.2	95.2	98.0	6.36
2/3 milkline, unproc	37.4	40.7	52.7	73.0	68.7	84.4	2.49
Blackline, proc	39.7	53.5	66.4	85.4	81.3	95.8	2.57
Blackline, unproc	56.2	65.9	80.2	83.2	89.3	98.8	2.81
Hybrid Quanta							
1/3 milkline, proc	80.4	81.5	88.6	97.9	98.9	99.2	10.43
1/3 milkline, unproc	76.5	83.4	91.1	95.5	95.9	99.1	3.85
2/3 milkline, proc	73.8	76.7	87.2	96.1	97.7	99.4	6.47
2/3 milkline, unproc	78.7	79.8	80.2	88.8	93.9	97.7	4.15
Blackline, proc	64.9	66.8	82.9	91.4	95.5	98.4	5.67
Blackline, unproc	88.6	71.8	87.0	84.9	93.4	97.0	NA
SE	1.31	1.11	1.31	0.67	0.68	0.41	...
Hybrid	0.0001	0.0001	0.0001	0.0001	0.0001	0.001	...
Maturity	0.0001	0.0001	0.0001	0.0001	0.0003	0.0002	...
Processing	0.0001	NS	0.002	0.0001	0.007	0.004	...
Hybrid × maturity	0.0001	0.0001	0.007	0.0001	0.007	0.0004	...
Hybrid × processing	NS	0.0007	0.03	NS	0.14	0.11	...
Maturity × processing	0.0001	0.0001	0.0001	0.0001	0.0005	0.0001	...

¹Disappearance rate: The least squares regression of logarithmic-transformed residuals with correction for undegraded residue method was used to calculate rate of disappearance (Nocek and English, 1986).

²Proc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 1 mm apart.

³Unproc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 15.9 mm apart.

data (Table 10). In experiment 2, there was maturity × processing interaction at all timepoints of ruminal incubation. In situ starch disappearance tended to be similar between processed and unprocessed corn silage harvested at the earliest maturity (one-third ML) at 24 ($P < 0.22$), 48 ($P < 0.38$), and 96 ($P < 0.99$) h of ruminal incubation (Table 13). However, at the medium maturity (two-thirds ML), processed corn silage had greater in situ starch disappearance than unprocessed corn silage at all timepoints (Table 13). The advanced maturity (BL) in experiment 2 had variable results, and by 48 h there was no difference in starch disappearance between processed and unprocessed corn silage. Others who have used the macro in situ method to evaluate differences in starch disappearance between processed and unprocessed corn silage have reported that processing corn silage tends to improve starch disappearance (Doggett et al., 1998; Johnson et al., 1999; Bal et al., 2000a, 2000b; Andrae et al., 2001).

Maturity of corn silage had an effect on starch disappearance in experiments 1a and 2. The greatest difference in starch disappearance across maturities occurred at 8 ($P < 0.0001$), 16 ($P < 0.0001$), and 24 ($P < 0.0001$) h of ruminal incubation in experiment 1a. Corn silage harvested at the earliest maturity (hard dough) had greater ruminal starch disappearance than corn

silage harvested at the advanced maturities (one-third ML and two-thirds ML; Table 10 and Figure 3a). However, after 48 h of incubation, starch disappearance was greater ($P < 0.0001$) at one-third ML than the other maturities (hard dough and two-thirds ML; Table 10 and Figure 3a). In experiment 2, corn silage harvested at the earliest maturity (one-third ML) had greater starch disappearance at 0 ($P < 0.0001$), 8 ($P < 0.0001$), 16 ($P < 0.0001$), 24 ($P < 0.0001$), 48 ($P < 0.0003$), and 96 h ($P < 0.0002$) of ruminal incubation compared with corn silage harvested at advanced maturities (two-thirds ML and BL; Table 13 and Figure 3b). Results from experiment 2 suggest that as the corn plant matured, the starch present in the corn grain fraction of corn silage was less available. These results were similar to others that reported that ruminal starch disappearance, measured via the macro in situ method, was greater after 24 and 48 h of incubation for corn silage harvested at one-half ML compared with BL (Andrae et al., 2001; Doggett, 1998). Others (Bal et al., 2000a) reported that 24-h ruminal starch disappearance (macro in situ method) was greater at early dent, one-fourth ML, and two-thirds ML than BL.

There were significant hybrid × maturity and hybrid × processing interactions for in situ starch disappearance at some of the ruminal incubation timepoints in

Figure 2. Effect of mechanical processing on starch disappearance of corn silage over time incubated in the rumen in experiment 1a (a) and experiment 2 (b). Processed (◆) and unprocessed (■) corn silage. Each data point represents a mean for each treatment in experiments 1a and 2.

experiment 2. However, these differences will not enhance or change the discussion in the previous paragraphs about the effects of corn silage maturity and processing method on macro in situ starch disappearance. Starch disappearance at 0 ($P < 0.0001$), 8 ($P < 0.0001$), 16 ($P < 0.0001$), 24 ($P < 0.0001$), 48 ($P < 0.0001$), and 96 h ($P < 0.001$) of incubation in the rumen was significantly greater for hybrid Quanta (low NDF) compared with hybrid 3845 (high NDF) corn silage (Table 13). These results are similar to Bal et al. (2000a), where low NDF corn silage had greater starch disappearance at 24 h of ruminal incubation compared with high NDF corn silage.

Maturity and mechanical processing of corn silage in experiments 1a and 2 affected rate of starch disappearance. In experiment 1a, at hard dough and one-third ML, unprocessed corn silage had a greater rate of starch disappearance than processed corn silage (Table 10).

Figure 3. Effect of maturity on starch disappearance of corn silage over time incubated in the rumen in experiment 1a (a) and experiment 2 (b). Experiment 1a: hard dough (◆), one-third milkline (■), and two-thirds milkline (▲) maturities of corn silage. Experiment 2: one-third milkline (◆), two-thirds milkline (■), and blackline (▲) maturities of corn silage. Each data point represents a mean for each treatment in experiments 1a and 2.

However, in experiment 2, at one-third ML and two-thirds ML, rate of starch disappearance was greater for processed corn silage than for unprocessed corn silage (Table 13). In experiment 2, rate of starch disappearance tended to decrease as maturity advanced from one-third ML to BL (Table 13). Others (Andrae et al., 2001) have also reported that rate of starch disappearance was greater for processed corn silage compared with unprocessed corn silage, and rate of starch disappearance tends to decrease as maturity advances.

NDF disappearance. The NDF disappearance data was highly variable in experiment 2, therefore only NDF disappearance at 24, 48, and 96 h after incubation were measured. Processing did not have a large effect on NDF disappearance in experiments 1a and 2 (Tables 10 and 12). Significant differences were reached at one timepoint in each experiment; however, in general, NDF disappearance was similar between processed and unprocessed corn silage. Others have reported that it was difficult to determine consistent trends between processed and unprocessed corn silage for NDF disappearance over time of incubation in the rumen using

Figure 4. Effect of maturity on NDF disappearance of corn silage over time incubated in the rumen in experiment 1a (a) and experiment 2 (b). Experiment 1a: hard dough (◆), one-third milkline (■), and two-thirds milkline (▲) maturities of corn silage. Experiment 2: one-third milkline (◆), two-thirds milkline (■), and blackline (▲) maturities of corn silage. Each data point represents a mean for each treatment in experiments 1a and 2.

the macro in situ method (Doggett et al., 1998; Bal et al., 2000a; Andrae et al., 2001). In fact, Bal et al. (2000a) suggested that the macro in situ method should not be used to evaluate differences in NDF disappearance because it tends to underestimate NDF disappearance due to the short incubation period and particle size reduction during eating and rumination.

Maturity of corn silage influenced NDF disappearance in the rumen. Corn silage harvested at early maturities (experiment 1a, hard dough and experiment 2, one-third ML) had significantly greater NDF disappearance at all rumen incubation timepoints (8 h, $P < 0.0002$; 16 h, $P < 0.0001$; 24 h, $P < 0.0001$; and $P < 0.002$; 48 h, $P < 0.0005$ and $P < 0.003$; 96 h, $P < 0.007$ and $P < 0.0001$) than corn silage harvested at the more advanced maturities (experiment 1a, one-third ML and two-thirds ML and experiment 2, two-thirds ML and BL; Tables 10 and 12; Figures 4a and 4b). Others reported a decrease in in situ fiber degradation as maturity advanced (Johnson et al., 1999; Bal et al., 2000a; Andrae et al., 2001).

There was a substantial difference in the extent of NDF disappearance between years (1996 = ~58 to 67% and 1997 = ~38 to 50%) for hybrid 3845 corn silage (Tables 10 and 12). These results suggest that the growing and harvest conditions between years had an impact on how the stover portion of the plant matured. During the dry (January through May 1997; Table 3) and warm (May through September 1997) growing season (Table 3), the plant matured at a rapid rate, which appeared to decrease the disappearance of the fiber portion of the plant. In the first year (1996), when the growing conditions were wet (January through May; Table 3) and cool (May through September 1996; Table 3), the corn plant matured more slowly. For the growing conditions that promoted slower maturing of the corn plant, it appeared that the fiber portion of the plant was more available for digestion in the rumen.

Rate of NDF disappearance in the rumen was measured in experiments 1a and 2. In experiment 1a, the rate of NDF disappearance was similar between processed and unprocessed corn silage within a maturity (Table 10). This was similar to rate of DM disappearance estimates in experiment 1a (Table 10). Across maturities, in experiment 2, the processed corn silages tended to have a greater rate of NDF disappearance than the unprocessed corn silage (Table 12). Maturity of corn silage tended to affect rate of NDF disappearance for hybrid 3845 in experiment 2. As maturity advanced from one-third ML to BL, the rate of NDF disappearance decreased (Table 12). This was similar to others (Andrae et al., 2001) who reported a decrease in rate of NDF disappearance as maturity advanced.

Crude protein disappearance. The effects of hybrid, stage of maturity, and mechanical processing of corn silage on CP disappearance were evaluated in experiments 1a and 2 (Tables 10 and 14). The amount of CP that instantly disappeared was fairly consistent across experiments. It usually ranged from 48 to 61%. At one-third ML in experiment 1a ($P < 0.0005$) and for hybrid Quanta in experiment 2 ($P < 0.006$), the processed corn silage had a significantly lower percentage of CP that instantly disappeared (0 h) compared with the unprocessed corn silage (Tables 10 and 14). In experiment 2, the amount of CP that instantly disappeared significantly decreased ($P < 0.0001$) as maturity advanced from one-third ML to BL (Table 14).

Mechanical processing had an effect on CP disappearance in experiment 2 at later timepoints (24, 48, and 96 h); however, there was no trend for CP disappearance between processed and unprocessed corn silage in experiment 1a (Table 10; Figure 5a). Crude protein disappearance was greater for processed corn silage in experiment 2 at 24 ($P < 0.0001$), 48 ($P < 0.09$), and 96 h ($P < 0.0001$) of ruminal incubation compared with unpro-

Table 14. Macro in situ CP disappearance in experiment 2.

	Instantly disappeared	8	16	24	48	96	Disappearance rate ¹
		(%)					(%/h)
Hybrid 3845							
1/3 milkline, proc ²	59.4	61.6	65.6	74.4	75.6	75.8	12.1
1/3 milkline, unproc ³	57.8	60.7	67.2	76.3	75.1	79.3	3.6
2/3 milkline, proc	56.2	62.9	70.3	72.1	75.2	76.3	6.1
2/3 milkline, unproc	54.9	58.9	62.8	64.1	68.8	75.9	2.1
Blackline, proc	49.2	52.0	66.1	69.1	66.6	77.5	1.6
Blackline, unproc	53.2	59.5	67.8	71.0	71.6	74.0	4.2
Hybrid Quanta							
1/3 milkline, proc	57.5	60.9	68.3	78.2	78.6	79.0	9.8
1/3 milkline, unproc	60.0	62.0	73.3	75.3	75.4	77.7	4.0
2/3 milkline, proc	52.2	58.2	67.2	71.8	72.8	79.2	2.6
2/3 milkline, unproc	57.4	61.6	64.3	64.7	68.9	73.2	2.4
Blackline, proc	52.4	56.8	68.7	71.4	72.3	78.9	2.6
Blackline, unproc	56.9	57.7	64.5	65.4	71.5	72.7	6.4
SE	1.11	0.89	1.05	1.11	1.04	0.70	...
Hybrid	0.19	NS	NS	NS	NS	NS	...
Maturity	0.0001	0.02	0.10	0.0001	0.004	0.0001	...
Processing	0.006	NS	NS	0.0001	0.09	0.0001	...
Hybrid × maturity	0.06	NS	0.04	0.18	0.11	NS	...
Hybrid × processing	0.02	NS	NS	0.02	NS	0.0001	...
Maturity × processing	0.11	0.06	0.01	0.0008	0.04	0.0001	...

¹Disappearance rate: The least squares regression of logarithmic-transformed residuals with correction for undegraded residue method was used to calculate rate of disappearance (Nocek and English, 1986).

²Proc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 1 mm apart.

³Unproc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 15.9 mm apart.

cessed corn silage (Table 14). The increase in CP disappearance for processed corn silage can mainly be attributed to greater CP disappearance of hybrid Quanta processed corn silage than hybrid Quanta unprocessed corn silage (24 h, $P < 0.02$ and 96 h, $P < 0.0001$; Table 14; Figure 5b). Crude protein disappearance tended to be similar between processed and unprocessed corn silage at the majority of the ruminal incubation time-points for hybrid 3845 (Table 14 and Figure 5c).

In experiment 2 there were maturity × processing interactions (Table 14). At 24 ($P < 0.0008$), 48 ($P < 0.04$), and 96 h ($P < 0.0001$) of ruminal incubation, the processed corn silage had greater CP disappearance than the unprocessed corn silage (except at 48 h for BL) at advanced maturities (two-thirds ML and BL; Table 14). Crude protein disappearance between processed and unprocessed corn silage at the earliest maturity (one-third ML) were similar at 24 and 48 h in experiment 2 (Table 14).

Maturity had an effect on CP disappearance in experiments 1a and 2 (Tables 10 and 14; Figures 6a and 6b). In experiment 1a, corn silage harvested at the medium maturity (one-third ML) had significantly greater CP disappearance than the other maturities (hard dough and two-thirds ML) at 8 ($P < 0.0001$), 24 ($P < 0.03$), and 48 h ($P < 0.01$) of ruminal incubation (Table 10; Figure

6a). However, the extent (96 h) of CP disappearance was similar between maturities (Table 10; Figure 6a). In experiment 2, at 8 ($P < 0.02$; one-third ML greater than BL), 16 ($P < 0.10$), 24 ($P < 0.0001$), 48 ($P < 0.004$), and 96 ($P < 0.0001$) h of ruminal incubation, the corn silage harvested at the earliest maturity (one-third ML) had greater CP disappearance compared with the advanced maturities (two-thirds ML and BL; Table 14 and Figure 6b). These results suggest that harvesting corn silage at one-third ML will maximize ruminal CP disappearance between 24 and 48 h.

Rate of CP disappearance was variable between processed and unprocessed corn silages within a maturity. In experiment 1a, the unprocessed corn silage tended to have a greater rate of CP disappearance compared with the processed corn silage. In experiment 2, the rate of CP disappearance was greater for the processed corn silage at one-third (both hybrids) and two-thirds ML, (hybrid 3845; Table 14).

Chop Length by Mechanical Processing Experiments

Three experiments (experiments 3 through 5) evaluated the effects of TLC and mechanical processing of corn silage on macro in situ nutrient (DM, starch, NDF,

Figure 5. Effect of mechanical processing on CP disappearance of corn silage over time incubated in the rumen in experiment 1a (a), for hybrid Quanta in experiment 2 (b), and for hybrid 3845 in experiment 2 (c). Processed (◆) and unprocessed (■) corn silage. Each data point represents a mean for each treatment in experiments 1a and 2.

and CP) disappearance. Across studies, the TLC of corn silage ranged from 9.5 to 39.7 mm. Experiments 3 and 5 utilized hybrid Quanta corn silage harvested at approximately two-thirds ML stage of maturity, and experiment 4 utilized hybrid 3845 corn silage harvested at two-thirds ML stage of maturity. Experiment 3 was

Figure 6. Effect of maturity on CP disappearance of corn silage over time incubated in the rumen in experiment 1a (a) and experiment 2 (b). Experiment 1a: hard dough (◆), one-third milkline (■), and two-thirds milkline (▲) maturities of corn silage. Experiment 2: one-third milkline (◆), two-thirds milkline (■), and blackline (▲) maturities of corn silage. Each data point represents a mean for each treatment in experiments 1a and 2.

conducted during the 1997 growing season, and experiments 4 and 5 were conducted during the 1998 growing season. The chemical composition of the corn silage used in experiments 3 through 5 is presented in Tables 8 and 9.

Dry matter disappearance. There were some significant differences reported in DM disappearance between processed and unprocessed corn silage in experiments 3 through 5 (Figure 7a through c). However, when the data were plotted over incubation time in the rumen, the differences were smaller than experiments 1a and 2 (Figures 1a and 1b). In experiment 5, there was greater DM disappearance at the earlier timepoints [8 ($P < 0.02$), 16 ($P < 0.007$), 24 ($P < 0.007$)] for the processed corn silage than for the unprocessed corn silage (Table 15; Figure 7c). In experiment 4, the DM disappearance at 48 ($P < 0.004$) and 96 h ($P < 0.003$) of ruminal incubation was greater for processed compared with unpro-

Figure 7. Effect of mechanical processing on DM disappearance of corn silage over time incubated in the rumen in experiment 3 (a), experiment 4 (b), and experiment 5 (c). Processed (◆) and unprocessed (■) corn silage. Each data point represents a mean for each treatment in experiments 3 through 5.

cessed corn silage (Table 16; Figure 7b). In experiment 3, the differences in DM disappearance between processed and unprocessed corn silage were smaller than the other experiments (experiments 1a, 2, 4, and 5). The processed corn silage tended to have greater DM disappearance at 16 ($P < 0.01$) and 120 h ($P < 0.05$) than unprocessed corn silage (Table 17; Figure 7a). There was a chop length $\times$ processing interaction in

experiment 4, and the processed corn silage harvested at the longer chop length (TLC = 27.8 and 39.7 mm) had greater DM disappearance than the unprocessed corn silage at 96 ($P < 0.008$) h of ruminal incubation (Table 16). However, at the shorter TLC (11.1), the DM disappearance was similar between processed and unprocessed corn silage (96 h; Table 16).

Chop length of corn silage had an impact on DM disappearance in experiments 3 through 5. In experiment 3, corn silage harvested with a shorter chop length (TLC = 9.5 mm) had greater DM disappearance at 16 ($P < 0.02$), 24 ($P < 0.002$), 48 ($P < 0.09$), and 96 h ($P < 0.07$) of incubation in the rumen than the corn silage harvested with a slightly longer chop length (TLC = 12.7 mm; Table 17). However, there was no trend in DM disappearance among corn silage differing in chop length in experiment 5, where the TLC for all corn silages was longer than experiment 3 (Table 15). In experiment 4, there was a chop length effect on DM disappearance at 8, 24, and 96 h of ruminal incubation (Table 16). The medium (TLC = 27.8 mm) chop length had lower DM disappearance at 8 ($P < 0.0001$), 24 ($P < 0.03$), and 96 h ($P < 0.003$) of ruminal incubation than the short (TLC = 11.1 mm) and long (TLC = 39.7 mm; except at 8 h) chop lengths (experiment 4; Table 16).

In experiments 3 and 5, where hybrid Quanta corn silage was incubated in the rumen, the processed corn silage had a significantly greater (experiment 3, $P < 0.05$ and experiment 5, $P < 0.003$) percentage of DM that instantly disappeared (0 h) compared with unprocessed corn silage (Tables 15 and 17). This differed from the results in experiments 1a and 2, where there was no difference in the percentage of DM that instantly disappeared between processed and unprocessed corn silage (Tables 10 and 11). Therefore, for hybrid Quanta (experiments 3 and 5), it appeared that processing altered the physical structure of corn silage, and it increased the amount of material that was able to instantly disappear.

Starch disappearance. The effect of chop length and mechanical processing of corn silage on starch disappearance was evaluated in experiments 3 through 5 (Tables 15, 16, and 17). The fraction of starch that instantly disappears was very high for all corn silage treatments ($>70\%$; except for experiment 5 long chop unprocessed corn silage). Nine of the 14 treatments had starch fractions that instantly disappeared (0 h) that were greater than 80% (experiments 3 through 5). The extent of starch disappearance was also very high ($>99\%$) in experiments 3 through 5.

Mechanical processing had an effect on starch disappearance in experiments 3 through 5. In experiments 3 and 4, processing had a significant effect on starch disappearance at the majority of the timepoints. How-

Table 15. Macro in situ DM, NDF, starch, and CP disappearance and degradation rate in experiment 5.

	Medium ¹ (27.8 mm) Proc ³	Medium (27.8 mm) Unproc ⁴	Long ² (39.7 mm) Proc	Long (39.7 mm) Unproc	SE	Chop	Proc	Chop by Proc
DM disappearance, %								
Instantly disappeared	53.1	45.2	42.6	42.6	0.88	0.0003	0.003	0.003
8 h	61.8	52.2	59.2	51.9	1.91	NS	0.02	NS
16 h	65.2	58.7	66.9	62.9	1.46	0.05	0.007	NS
24 h	72.8	65.9	67.7	64.6	1.08	0.03	0.007	0.12
48 h	77.4	72.9	73.9	75.8	0.66	NS	0.10	0.003
96 h	83.0	74.5	80.2	83.7	1.29	0.05	0.10	0.007
Disappearance rate ⁵ , %/h	3.38	6.79	2.76	3.36	...	...	...	...
NDF disappearance, %								
8 h	22.9	10.9	25.5	24.3	3.68	0.12	0.17	NS
16 h	29.1	23.4	37.6	34.0	1.34	0.001	0.009	NS
24 h	43.7	37.5	38.7	39.1	1.46	NS	0.13	0.10
48 h	50.2	40.7	49.8	54.5	1.48	0.003	0.12	0.003
96 h	62.5	46.3	59.2	69.5	1.07	0.002	0.06	0.001
Disappearance rate, %/h	2.93	4.54	3.00	2.82	...	...	...	...
Starch disappearance, %								
Instantly disappeared	90.3	82.3	89.6	58.9	0.50	0.0001	0.0001	0.0001
8 h	95.6	90.0	94.0	77.1	0.73	0.0003	0.0001	0.0008
16 h	96.8	89.6	97.5	85.9	0.47	0.009	0.0001	0.001
24 h	99.2	95.9	98.8	89.2	0.13	0.0001	0.0001	0.0001
48 h	99.6	99.0	99.7	98.5	0.02	0.0001	0.0001	0.0001
96 h	99.9	99.9	99.9	99.9	0.009	NS	NS	0.03
Disappearance rate, %/h	7.06	6.47	8.66	7.02	...	...	...	...
CP disappearance, %								
Instantly disappeared	75.6	72.8	75.2	67.7	0.47	0.0009	0.0001	0.002
8 h	82.7	81.0	80.5	77.6	0.89	0.04	0.07	NS
16 h	86.2	82.8	88.6	83.2	0.27	0.004	0.0001	0.01
24 h	89.2	85.8	85.4	85.1	0.46	0.003	0.007	0.01
48 h	91.3	88.9	90.2	89.9	0.26	NS	0.002	0.006
96 h	93.6	91.6	91.9	93.3	0.52	NS	NS	0.02
Disappearance rate, %/h	3.83	3.46	4.06	3.70	...	...	...	...

¹Medium: Harvester set with two rows of knives and a 10-tooth sprocket. TLC = 27.8 mm.

²Long: Harvester set with two rows of knives and a 16-tooth sprocket. TLC = 39.7 mm.

³Proc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 1 mm apart.

⁴Unproc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 15.9 mm apart.

⁵Disappearance rate: The least squares regression of logarithmic-transformed residuals with correction for undegraded residue method was used to calculate rate of disappearance (Nocek and English, 1986).

ever, there was no trend between processed and unprocessed corn silage across timepoints. This was partially due to the pronounced disappearance of starch by 24 h of ruminal incubation (experiment 3, $\geq 98\%$ and experiment 4, $\geq 94\%$; Tables 16 and 17). In experiment 5, the processed corn silage had greater starch disappearance at 8 ($P < 0.0001$), 16 ($P < 0.0001$), 24 ($P < 0.0001$), and 48 h ($P < 0.0001$) of ruminal incubation than the unprocessed corn silage (Table 15). The greater starch disappearance for processed corn silage in experiment 5 can be partially explained by the lower percentage of whole intact corn kernels present in the processed corn silage than in the unprocessed corn silage (Table 8). It is difficult for rumen microbes to penetrate the outer layer of the corn kernel. Therefore, it is common for the silage with a greater percentage of intact corn kernels to have lower starch disappearance, as was the situation in this study.

Chop length had an effect on starch disappearance in experiments 3 through 5. In experiment 3, the longer chop (TLC = 12.7 mm) corn silage had greater starch disappearance than the short chop (TLC = 9.5 mm) corn silage at 8 ($P < 0.0001$), 16 ($P < 0.0001$), 24 ($P < 0.0001$), and 48 h ($P < 0.0001$) of ruminal incubation (Table 17). Experiments 4 and 5 followed a different pattern. In experiment 5 the medium chop (TLC = 27.8 mm) corn silage had greater starch disappearance at 8 ($P < 0.0003$), 16 ($P < 0.009$), 24 ($P < 0.0001$), and 48 h ($P < 0.0001$) of ruminal incubation than did the long chop (TLC = 39.7 mm) corn silage (Table 15). This is consistent with data found elsewhere in the literature (Johnson et al., 2003). In experiment 4, the shorter chop (TLC = 11.1 mm) corn silage had greater starch disappearance than the medium (TLC = 27.8 mm) and long (TLC = 39.7 mm) chop corn silage at 16 ($P < 0.004$), 24 ($P < 0.0005$), 48 ($P < 0.0001$), and 96 h ($P < 0.0001$) of ruminal

Table 16. Macro in situ DM, NDF, starch, and CP disappearance and degradation rate in experiment 4.

	Short ¹ (11.1 mm)		Medium ² (27.8 mm)		Long ³ (39.7 mm)		SE	Chop	Proc	Chop by Proc
	Proc ⁴	Unproc ⁵	Proc	Unproc	Proc	Unproc				
DM disappearance, %										
Instantly disappeared	43.3	39.3	37.9	35.2	36.5	39.9	1.09	0.007	NS	0.02
8 h	54.8	53.9	49.1	48.2	47.9	48.4	0.69	0.0001	NS	NS
16 h	62.1	59.9	59.2	55.6	59.8	60.4	1.53	0.10	NS	NS
24 h	68.9	64.9	61.9	61.4	65.2	66.0	1.67	0.03	NS	NS
48 h	75.2	73.3	75.3	72.7	76.3	73.5	1.05	NS	0.004	NS
96 h	80.4	81.1	79.9	73.9	81.1	78.3	0.89	0.003	0.003	0.008
Disappearance rate, %/h	3.94	3.10	4.72	7.17	4.78	4.42	...	...	...	...
NDF disappearance, %										
8 h	24.8	24.4	10.6	14.1	14.9	17.8	0.27	0.0001	0.0008	0.004
16 h	33.9	32.2	25.7	22.3	27.0	35.3	1.61	0.01	NS	0.03
24 h	42.9	39.4	29.1	37.6	33.3	40.4	3.21	0.12	0.14	0.15
48 h	54.4	51.1	51.3	50.7	54.9	49.1	1.09	0.14	0.002	0.05
96 h	61.5	65.0	60.2	53.0	62.1	63.3	0.45	0.0001	0.05	0.0001
Disappearance rate, %/h	4.16	2.69	4.29	7.24	4.95	2.67	...	...	...	...
Starch disappearance, %										
Instantly disappeared	82.7	71.5	77.2	75.6	82.1	83.8	0.36	0.0001	0.0001	0.0001
8 h	84.3	84.9	84.5	86.2	76.0	83.4	0.30	0.0001	0.0001	0.0001
16 h	91.4	91.0	91.1	87.4	90.2	89.8	0.37	0.004	0.002	0.005
24 h	96.5	95.7	94.0	95.3	93.8	97.1	0.21	0.0005	0.0001	0.0001
48 h	99.1	99.2	98.8	98.9	98.0	97.2	0.09	0.0001	0.005	0.0001
96 h	99.7	99.5	99.7	99.3	99.2	99.5	0.02	0.0001	0.0004	0.0001
Disappearance rate, %/h	8.32	9.42	6.98	9.32	6.26	3.54	...	...	...	...
CP disappearance, %										
Instantly disappeared	72.5	67.3	67.7	66.2	68.2	70.7	0.57	0.008	0.04	0.0006
8 h	81.5	79.7	78.5	80.8	76.3	77.9	0.51	0.0001	0.09	0.003
16 h	83.1	84.7	84.0	83.0	83.5	83.6	0.70	NS	NS	NS
24 h	86.3	83.2	85.1	85.6	86.8	88.8	0.66	0.003	NS	0.008
48 h	90.4	88.2	89.9	89.8	90.5	90.1	0.44	0.04	0.01	0.03
96 h	91.7	92.2	92.7	88.5	90.5	92.4	0.35	0.006	0.04	0.0001
Disappearance rate, %/h	5.31	2.60	3.89	6.17	8.38	4.59	...	...	...	...

¹Short: Harvester set with five rows of knives and a 10-tooth sprocket. TLC = 11.1 mm.²Medium: Harvester set with two rows of knives and a 10-tooth sprocket. TLC = 27.8 mm.³Long: Harvester set with two rows of knives and a 16-tooth sprocket. TLC = 39.7 mm.⁴Proc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 1 mm apart.⁵Unproc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 15.9 mm apart.⁶Disappearance rate: The least squares regression of logarithmic-transformed residuals with correction for undegraded residue method was used to calculate rate of disappearance (Nocek and English, 1986).

incubation (Table 16). However, there was an inconsistent pattern in starch disappearance over time of incubation in the rumen between medium and long chop length corn silage in experiment 4 (Table 16). The reason for the difference in starch disappearance among chop lengths is difficult to explain because there were no consistent trends across experiments, and the chemical and physical characteristics of the corn silage do not help in the interpretation. However, there is an indication that starch disappearance tends to be improved at the shorter chop lengths (experiment 4, TLC = 11.1 vs. 27.8 and 39.7 mm; experiment 5, TLC = 27.8 vs. 39.7 mm; Tables 15 and 16).

Rate of starch disappearance did not follow a pattern for processed and unprocessed corn silage across experiments. The processed corn silage tended to have a greater rate of starch disappearance than the unpro-

cessed corn silage for the long chop length (TLC = 39.7 mm) in experiments 4 and 5 (Tables 15 and 16). However, for the short chop length (TLC = 9.5 mm) in experiment 3 and for the short (TLC = 11.1 mm) and medium (TLC = 27.8 mm) chop lengths in experiment 4, the unprocessed corn silage tended to have a greater rate of starch disappearance than processed corn silage (Tables 16 and 17). The variability in trends for the rate of starch disappearance between processed and unprocessed corn silage is partially due to the large amount of starch that was digested for all treatments by 8 h of ruminal incubation. It appears that at very long chop lengths (TLC = 39.7 mm) the rate of starch disappearance may be improved by processing.

In experiment 4, the rate of starch disappearance was lower for the long chop length (TLC = 39.7 mm) corn silage than the short (TLC = 11.1 mm) and medium

Table 17. Macro in situ DM, NDF, starch, and CP disappearance and degradation rate in experiment 3.

	Short ¹ (9.5 mm) Proc ³	Short (9.5 mm) Unproc ⁴	Long ² (12.7 mm) Proc	Long (12.7 mm) Unproc	SE	Chop	Proc	Chop by Proc
DM disappearance, %								
Instantly disappeared	37.4	33.3	37.4	35.6	1.18	NS	0.05	NS
8 h	48.0	47.9	44.9	47.2	1.00	0.12	NS	NS
16 h	54.9	54.3	54.5	48.6	0.97	0.02	0.01	0.02
24 h	60.1	62.8	56.2	55.9	1.08	0.002	NS	NS
48 h	69.7	70.4	67.2	67.4	1.72	0.09	NS	NS
96 h	72.2	71.7	69.9	69.2	1.21	0.07	NS	NS
120 h	78.1	75.0	76.3	75.8	0.73	NS	0.05	NS
Disappearance rate, ⁵ %/h	1.84	2.39	1.75	1.78	...	...	...	...
NDF disappearance, %								
24 h	8.2	26.0	18.4	15.5	1.09	NS	0.02	0.01
48 h	27.1	40.9	41.2	41.9	2.67	0.03	0.03	0.04
96 h	33.0	42.7	44.6	43.4	2.39	0.03	0.09	0.04
120 h	49.9	51.5	56.7	57.6	1.40	0.004	NS	NS
Disappearance rate, %/h	1.16	1.33	1.45	1.32	...	...	...	...
Starch disappearance, %								
Instantly disappeared	85.6	73.7	86.1	85.2	0.41	0.0001	0.0001	0.0001
8 h	91.5	88.3	93.2	96.0	0.24	0.0001	NS	0.0001
16 h	97.7	93.2	97.2	99.8	0.07	0.0001	0.0001	0.0001
24 h	98.4	99.1	98.9	99.8	0.03	0.0001	0.0001	0.02
48 h	99.4	99.1	99.6	99.7	0.03	0.0001	0.02	0.001
96 h	99.5	100.0	99.9	99.5	0.01	0.02	0.0001	0.0001
120 h	99.8	99.4	99.1	99.1	0.02	0.0001	0.0001	0.0009
Disappearance rate, %/h	3.09	6.38	7.68	NA	...	...	...	...
CP disappearance, %								
Instantly disappeared	63.4	59.2	59.5	58.3	0.71	0.01	0.009	0.09
8 h	74.4	72.5	67.8	68.5	0.56	0.002	NS	0.08
16 h	69.8	69.8	66.1	65.7	0.40	0.0004	NS	NS
24 h	75.8	79.2	69.3	68.0	0.72	0.0002	NS	0.02
48 h	79.9	74.4	72.7	71.8	1.46	0.009	0.04	0.09
96 h	79.3	76.3	76.5	79.2	0.45	NS	NS	0.007
120 h	80.4	78.1	79.9	80.1	0.54	NS	0.08	0.07
Disappearance rate, %/h	2.51	1.87	1.66	3.51	...	...	...	...

¹Short chop: Harvester set with 10 rows of knives and a 18-tooth sprocket. TLC = 9.5 mm.

²Long chop: Harvester set with 10 rows of knives and a 24-tooth sprocket. TLC = 12.7 mm.

³Proc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 1 mm apart.

⁴Unproc: Corn silage was harvested with a 5830 John Deere harvester with kernel processing rolls set 15.9 mm apart.

⁵Disappearance rate: The least squares regression of logarithmic-transformed residuals with correction for undegraded residue method was used to calculate rate of disappearance (Nocek and English, 1986).

(TLC = 27.8 mm) chop length corn silage (Table 16). Rate of starch disappearance was especially lower for the long chop (TLC = 39.7 mm) unprocessed corn silage compared with the other treatments. The corn kernels for this treatment would have had the least opportunity to be cracked or damaged due to processing (mechanical processing or shorter chop length). Therefore, the kernels were more likely less damaged (although it was not detected through the measurements we collected; Table 8), and the amount of starch digested per hour was lower because it took longer for the rumen microbes to penetrate the outer coating of the corn kernel.

NDF disappearance. Mechanical processing and chop length had an effect on NDF disappearance in experiments 3 through 5 (Tables 15, 16, and 17). Disappearance of NDF was variable for corn silage in experiment 3; therefore, only data for 24, 48, 96, and 120 h

of incubation were reported (Table 17). In experiment 3, unprocessed corn silage had a greater NDF disappearance at 24 ($P < 0.02$), 48 ($P < 0.03$), and 96 h ($P < 0.09$) of incubation in the rumen than processed corn silage (Table 17; Figure 8a). The greater NDF disappearance for unprocessed corn silage was mainly due to the greater NDF disappearance for the short chop length (TLC = 9.5 mm) unprocessed corn silage at 24 ($P < 0.01$), 48 ($P < 0.04$), and 96 h ($P < 0.04$) compared with the short chop length (TLC = 9.5 mm) processed corn silage (Table 17). In experiments 4 and 5, processed corn silage had a greater NDF disappearance at many of the ruminal incubation timepoints (16 h, experiment 5, $P = 0.009$; 24 h, experiment 5, $P = 0.13$; 48 h, $P = 0.002$ and $P = 0.12$; and 96 h, $P = 0.05$ and $P = 0.06$) than unprocessed corn silage (Tables 15 and 16; Figure 8b and c). The greater NDF disappearance for processed

Figure 8. Effect of mechanical processing on NDF disappearance of corn silage over time incubated in the rumen in experiment 3 (a), experiment 4 (b), and experiment 5 (c). Processed (♦) and unprocessed (■) corn silage. Each data point represents a mean for each treatment in experiments 3 through 5.

corn silage than for unprocessed corn silage at 48 (experiment 5— $P < 0.001$) and 96 h ($P < 0.0001$ and $P < 0.001$) of ruminal incubation was mainly due to greater NDF disappearance of the medium (TLC = 27.8 mm) chop length processed corn silage compared with the medium chop length (TLC = 27.8 mm) unprocessed corn silage (Tables 15 and 16).

It appeared that mechanical processing enhanced NDF disappearance for corn silages (both hybrids) harvested during the third year (1998; experiments 4 and 5). However, processing had a negative effect on NDF disappearance for corn silage harvested during the second year (1997 growing season; experiment 3). Starch disappearance was very high across all experiments (experiments 3 through 5); therefore, the differences in NDF disappearance between years was probably related to other factors that affected the physical and chemical characteristics of the corn silages or rumen environment between years. There was less precipitation from February to October in 1998 (342 mm) than 1997 (707 mm), and the growing degree-days were greater each month from February to July (except May) in 1998 than 1997. These differences in weather patterns between years may have contributed to differences in NDF disappearance between years. It appeared that during the year (1998) in which the weather conditions were drier and warmer, NDF disappearance was enhanced by mechanical processing.

In experiments 3 and 5, the longest chop length within an experiment, tended to have greater NDF disappearance over incubation time in the rumen (16 h, experiment 5, $P = 0.001$; 48 h, $P = 0.03$ and $P = 0.003$; 96 h, $P = 0.03$ and $P = 0.002$; 120 h, experiment 3, $P = 0.004$; Figures 9a and 9c). Bal et al. (2000b) reported an increase ($P < 0.04$) in total tract NDF digestibility when the chop length of corn silage increased from 0.95-cm TLC to 1.9-cm TLC, and Johnson et al. (2003) reported an increase ($P < 0.11$) in total tract NDF digestibility as TLC increased from 27.8 to 39.7 mm. In experiment 4, the opposite trend occurred (Table 16). At 8 ($P < 0.0001$), 16 ($P < 0.01$), and 96 h ($P < 0.0001$) of ruminal incubation, corn silage harvested at the shortest (TLC = 11.1 mm) chop length had greater NDF disappearance than the medium (TLC = 27.8 mm) chop length (Table 16; Figure 9b). However, in experiment 4, the long (TLC = 39.7 mm) chop length had significantly greater NDF disappearance at 8 ($P < 0.0001$), 16 ($P < 0.01$), and 96 h ($P < 0.0001$) of ruminal incubation than did the medium (TLC = 27.8 mm) chop length (Table 16; Figure 9b). This was similar to results observed in experiment 5, where the long chop length had greater NDF disappearance than the medium chop length (Table 15; Figure 9c). Results of the effect of chop length on NDF disappearance from these experiments are difficult to interpret, and it may be due to problems associated with the microenvironment present in the nylon bags as described by Andrae et al. (2001).

Crude protein disappearance. The effects of chop length and mechanical processing on CP disappearance were reported in Tables 15, 16, and 17. In experiments 3 and 4, there were differences that reached statistical

Figure 9. Effect of chop length on NDF disappearance of corn silage over time incubated in the rumen in experiment 3 (a), experiment 4 (b), and experiment 5 (c). Experiment 3: 2.7 mm TLC (◆) and 9.5 mm TLC (■) corn silage. Experiment 4: 39.7 mm TLC (◆), 27.8 mm TLC (■), and 11.1 mm TLC (▲) corn silage. Experiment 5: 39.7 mm TLC (◆) and 27.8 mm TLC (■) corn silage. Each data point represents a mean for each treatment in experiments 3 through 5.

significance; however, when the data were plotted over incubation time in the rumen, there were no trends due to mechanical processing (Tables 16 and 17). In experiment 5, the processed corn silage had greater CP

Figure 10. Effect of mechanical processing (a) and chop length (b) on CP disappearance of corn silage over time incubated in the rumen. Figure 10a: experiment 5; processed (◆) and unprocessed (■). Figure 10b: experiment 3; 12.7 mm TLC (◆) and 9.5 mm TLC (■) corn silage. Each data point represents a mean for each treatment in experiments 5 and 3.

disappearance at 8 ($P < 0.07$), 16 ($P < 0.0001$), 24 ($P < 0.007$), and 48 h ($P < 0.002$) of ruminal incubation compared with the unprocessed corn silage (Table 16; Figure 10a). Also in experiments 4 and 5, there were differences among chop lengths that reached statistical significance; however, when the data were plotted over incubation time in the rumen, there were no trends (Tables 15 and 16). In experiment 3, CP disappearance tended to be greater at the early incubation timepoints (8, $P < 0.002$; 16, $P < 0.0004$; 24, $P < 0.0002$; and 48 h, $P < 0.009$) for the shorter chop length (TLC = 9.5 mm), compared with the long chop length (TLC = 12.7 mm; Table 17; Figure 10b).

Rate of CP disappearance tended to increase as chop length increased, and tended to be greater for processed corn silage at many of the chop lengths in experiments 4 and 5 (Tables 15 and 16).

Chop length and mechanical processing in experiments 3 through 5 affected the fraction of CP that instantly disappeared. The fraction of CP that instantly

disappeared was greater for corn silage harvested at a shorter chop length in experiments 3 (TLC = 9.5 vs. 12.7 mm; $P < 0.01$), 4 (TLC = 11.1 vs. 27.8 mm; $P < 0.008$), and 5 (TLC = 27.8 vs. 39.7 mm; $P < 0.0009$; Tables 15, 16, and 17). The fraction of CP that instantly disappears was also greater for corn silage that had been mechanically processed compared with unprocessed corn silage in experiments 3 ($P < 0.009$), 4 ($P < 0.04$), and 5 ($P < 0.0001$). However, in each experiment, there were chop length $\times$ processing interactions, and only at certain chop lengths within each experiment was the fraction of CP that instantly disappeared greater for mechanically processed corn silage than for unprocessed corn silage. In experiments 3 ($P < 0.09$) and 4 ($P < 0.0006$), the fraction of CP that instantly disappeared was greater for mechanically processed corn silage compared with unprocessed corn silage at the short chop length (experiment 3, TLC = 9.5 mm and experiment 4, TLC = 11.1 mm). In experiment 5 ($P < 0.002$), the fraction of CP that instantly disappeared was greater for the mechanically processed corn silage at both chop lengths (TLC = 27.8 and 39.7 mm). In general, when CP disappearance was affected in experiments 3 through 5, the shorter chop length or processed corn silage had greater CP disappearance.

NASCO's Penn State Forage Particle Separator In Situ Incubations

It is becoming a common practice on commercial dairies for nutrition consultants or advisors to evaluate the particle size of forages and TMR fed to lactating cows. A practical particle separator (NASCO's Penn State Forage Particle Separator) was designed for use on commercial farms to evaluate rations for adequate particle size to maintain rumen health and milk production and composition. Some literature has reported how the chemical composition of the different fractions of NASCO's Penn State Forage Particle Separator can differ due to mechanically processing corn silage (Weiss and Wyatt, 2000). However, no data have been published evaluating the effects of maturity and mechanical processing on DM disappearance evaluated via the macro in situ method. Therefore, corn silage and TMR from the first year of this study (1996; experiment 1a) was separated into the three fractions of NASCO's Penn State Forage Particle Separator (top, middle, and bottom) and each fraction was incubated in the rumen. Tables 4 and 5 reported DM disappearance at the various hours of incubation in the rumen for the NASCO's Particle Separation of corn silage and TMR.

The physical characteristics of the corn silage particles remaining on each layer will be described in the following paragraph. Corn silage particles remaining

on the top sieve (particles greater than 19 mm) usually included cob disks and pieces of husk and stalk that were greater than 19 mm in length. Cob disks were present only in the unprocessed corn silages because processing tended to break cob disks into smaller fractions. The middle sieve (particles between 8 and 19 mm) usually contained corn kernels, cob disks that had been broken into smaller pieces, and stalk, husk, and leaves that were between 8 and 19 mm in length. The bottom pan (particles less than 8 mm) contained material that was so small it was difficult to identify the portion of the corn plant that the particles originated from. However, Weiss and Wyatt (2000) reported that corn silage particles in the bottom pan had 3 to 5 times the starch concentration and 2 to 3 times less NDF concentration as particles remaining on the top sieve. This is an indication that many of the particles present in the bottom pan were fractions of the corn kernel.

Corn silage—DM disappearance. Dry matter disappearance by 72 h of incubation in the rumen tended to be similar between particles remaining on the middle sieve (69 to 73%) and bottom pan (62 to 75%), and was lower for particles remaining on the top sieve (~43 to 54% for five of the six treatments) of NASCO's Penn State Forage Particle Separator (Table 5).

There were not enough replications of DM disappearance on the top layer of corn silage to do statistical analysis due to a shortage of particles available for in situ incubations. However, from the information that was collected, it appeared that DM disappearance of the particles of corn silage remaining on the top sieve did not plateau by 96 h of incubation in the rumen (Figure 11a). The data also suggests that mechanical processing enhanced DM disappearance of particles remaining on the top layer (slow digesting fraction of corn silage) compared with unprocessed top layer corn silage particles at 72 and 96 h of in situ incubation (Figure 11a).

The difference was minimal between the processed and unprocessed corn silage with particle size between 8 and 19 mm (middle layer) and less than 8 mm (bottom layer), when plotted across incubation time in the rumen (experiment 1b; Table 5). However, statistically, at some of the incubation timepoints (4 h, middle $P < 0.02$ and bottom $P < 0.06$; 24 h, middle $P < 0.07$; and 72 h, middle $P < 0.06$), there was greater disappearance of unprocessed corn silage particles (Table 5).

Maturity of corn silage affected DM disappearance of the different-sized particles in the corn silage (Table 5). Dry matter disappearance data plotted over incubation time in the rumen suggest that corn silage particles >19 mm (top layer) harvested at the most immature maturity (hard dough) had greater DM disappearance at 36, 48, 72, and 96 h of incubation in the rumen

Figure 11. Effect of mechanical processing (a) and maturity (b and c) on DM disappearance of corn silage over time incubated in the rumen. Figure 11a: experiment 1b, top layer of NASCO's Penn State Forage Particle Separator (particles > 19 mm); processed (◆) and unprocessed (■). Figure 11b: experiment 1b, top layer of NASCO's Penn State Forage Particle Separator (particles > 19 mm); hard dough (◆), one-third milkline (■), and two-thirds milkline (▲) corn silage. Figure 11c: experiment 1b, bottom layer of NASCO's Penn State Forage Particle Separator (particles < 8 mm); hard dough (◆), one-third milkline (■), and two-thirds milkline (▲) corn silage. Each data point represents a mean for each treatment in experiment 1b.

compared with corn silage harvested at the advanced maturities (one-third ML and two-thirds ML; Figure 11b). Dry matter disappearance of the corn silage particles that were less than 8 mm (bottom pan) was significantly lower at the advanced maturity (two-thirds ML) compared with the less mature silages (hard dough and one-third ML) at 4 ($P < 0.008$), 8 ($P < 0.04$), 24 ($P < 0.0002$), 48 ($P < 0.02$), and 96 h ($P < 0.0001$) of ruminal incubation (Table 5; Figure 11c). These results suggest that the corn silage becomes less digestible as maturity advances. Although particle size does have an impact on DM disappearance, particles of many sizes (>19 to <8 mm) can have reduced DM disappearance as the maturity of corn silage advances.

Total mixed rations—DM disappearance. Total mixed rations containing the same corn silages that were incubated in experiment 1a (Table 10; corn silage included in TMR at approximately 27% DM) were separated using NASCO's Penn State Forage Particle Separator (Johnson et al., 2002), and the separated fractions were incubated in the rumen. Dry matter disappearance after 72 h of incubation in the rumen tended to be similar between particles remaining on the middle sieve (71 to 80%) and bottom pan (75 to 84%), and was lower for particles remaining on the top sieve (~50 to 59%) of NASCO's Penn State Forage Particle Separator (Table 4).

The effect of mechanical processing on DM disappearance in the rumen complimented trends that were observed with corn silage fractions separated with NASCO's Penn State Forage Particle Separator (Table 5; Figures 11a through 11c). The top fraction (>19 mm) of TMR containing processed corn silage had greater DM disappearance than the top layer of TMR containing unprocessed corn silage at 12 ($P < 0.07$), 24 ($P < 0.06$), and 48 ($P < 0.08$) h of ruminal incubation (Table 4; Figure 12). Minimal to no difference was observed in DM disappearance plotted over time of incubation in the rumen between processed and unprocessed corn silage remaining on the middle sieve (between 8 and 19 mm particle size) and bottom pan (>8 mm particle size; Table 4).

The effect of maturity on DM disappearance of TMR remaining on the different fractions of the particle separator did not follow similar trends as the corn silage particle separation layers. Significant differences among maturities were reached at some of the ruminal incubation timepoints for the top and middle layers; however, there was no trend over time (Table 4).

CONCLUSIONS

Disappearance of DM, starch, NDF, and CP from corn silage incubated in the rumen varied between year,

Figure 12. Effect of mechanical processing on DM disappearance of TMR remaining on top layer of NASCO's Penn State Forage Particle Separator (particles > 19 mm) over time incubated in the rumen; processed (◆) and unprocessed (■). Each data point represents a mean for each treatment in experiment 1b.

hybrid, maturity, mechanical processing, and chop length. Dry matter disappearance was greater for processed corn silage compared with unprocessed corn silage at the majority of timepoints in experiments 1a, 2 (two-thirds ML and BL), 3, 4, and 5. It appears that the improvement in DM disappearance of processed corn silage in experiment 1a was due to increased disappearance of the particles that were greater than 19 mm in size (experiment 1b). Starch disappearance was greater for unprocessed corn silage in experiment 1a (hard dough and two-thirds ML), and was greater for processed corn silage in experiments 2 and 5. However, there were no consistent trends in starch disappearance between processed and unprocessed corn silage in experiments 3 and 4. This can be partially explained by the almost complete disappearance of starch (experiment 3, $\geq 98\%$ and experiment 4, $\geq 94\%$) by 24 h of incubation in the rumen. Minimal differences were detected in NDF disappearance between processed and unprocessed corn silage across maturities. However, processing tended to enhance NDF disappearance at the medium chop length (TLC = 27.8 mm) in experiments 4 and 5. Crude protein disappearance was improved at some of the timepoints due to mechanical processing in experiments 2 and 5. Rate of DM, starch (one-third ML and two-third ML), and NDF disappearance was greater due to processing corn silage in experiment 2.

Processing enhanced nutrient disappearance in experiment 2 to a greater extent than in experiment 1a. The authors speculate that the difference between experiments can be partially attributed to different climatic conditions and different chop lengths between

years. In experiment 1a (1996), the average daily temperature was lower and the precipitation was greater during the growing season compared with experiment 2 (1997). Also, the chop length was shorter in experiment 1a (TLC = 6.4 mm) than in experiment 2 (TLC = 12.7 mm). Both the short TLC and the cool and wet climatic conditions partially contributed to the minimal effect of mechanical processing on improved nutrient disappearance in experiment 1a.

Maturity of corn silage at harvest had an influence on disappearance of nutrients. Dry matter disappearance was lower at the advanced maturity (two-thirds ML) compared with the early maturities (hard dough and one-third ML) and starch disappearance was lower at the middle and advanced maturities (one-third ML and two-thirds ML) compared with the early maturity (hard dough) at the early timepoints (8, 16, and 24 h) in experiment 1a. The lower DM disappearance at the advanced maturity (two-thirds ML) in experiment 1a was mainly due to the decrease in DM disappearance of particles less than 8 mm in size for the advanced maturity (two-thirds ML) compared with the less mature (hard dough and one-third ML) corn silage (experiment 1b). Dry matter, starch, and CP disappearance tended to be greater for corn silage harvested at the early maturity (one-third ML) compared with the advanced maturities (two-thirds ML and BL) in experiment 2. Disappearance of NDF was greater at the early maturities than at the advanced maturities in experiments 1a and 2. Rate of DM (hybrid 3845), starch, and NDF (hybrid 3845) disappearance tended to decrease as maturity advanced from one-third ML to BL in experiment 2. Results from both experiments support that nutrient disappearance will decrease with increasing corn silage maturity, and mechanical processing has the opportunity to enhance DM disappearance to a greater extent at advanced maturities (two-thirds ML and BL, experiment 2) under weather conditions that promote rapid growth and development during the growing season.

Hybrid of corn silage and year the experiment was conducted had an effect on nutrient disappearance. The hybrid with low NDF concentrations (hybrid Quanta) had greater DM and starch disappearance in the rumen at all incubation timepoints than the hybrid with high NDF concentrations (hybrid 3845). Between years (1996 and 1997), the extent of NDF disappearance for hybrid 3845 corn silage was lower when the weather was warmer and drier. Also, both DM (1997 > 1996) and NDF (1998 > 1997) disappearance were enhanced due to mechanical processing when the weather was warmer and drier. These results suggest that the corn silage develops in a way that makes it less digestible to the cow when the average temperature is higher and precipitation is lower during a growing season.

The effect of corn silage chop length on macro in situ nutrient disappearance (DM, starch, NDF, and CP) was variable. There were no trends on the effect of chop length on DM, starch, and CP disappearance across experiments (3 through 5). Fiber (NDF) disappearance tended to be greater for the long chop corn silage in experiments 3, 4 (long TLC = 39.7 mm vs. medium TLC = 27.8 mm), and 5 than the shorter chop lengths. However, in experiment 4 the shortest chop length (TLC = 11.1 mm) had greater NDF disappearance than the medium chop length (TLC = 28.7 mm).

In conclusion, it appears that the macro in situ method (used in the experiments presented in this paper) can be a useful tool for evaluating DM, starch, and CP disappearance of corn silage. Fewer differences were observed between processed and unprocessed corn silage treatments for fiber (NDF) disappearance. However, it is unclear whether it is an artifact of the assay (does not account for mastication and rumination and/or changes in the microenvironment of the in situ bag that affect the bacteria's ability to digest fiber), or whether there were limited differences in fiber disappearance due to processing in these experiments. The macro in situ method did detect differences in fiber (NDF) disappearance between maturities and chop lengths in these experiments.

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