Precision Chewing Management: A Dynamic Approach to Forage Particle Size

R. J. Grant
Member, Board of Trustees
William H. Miner Agricultural Research Institute, Chazy, NY

Introduction

Precision feeding management aims to optimize the rumen environment as efficiently as possible. Two management pillars support this approach: 1) feeding the right forage to the right cows, and 2) management that bolsters the cow's eating experience and optimizes feed intake (Grant, 2024). Because the rumen resides within the cow, ensuring cow well-being and her ability to practice natural behaviors is as important as optimizing ruminal fermentation. As a ruminant, nothing is more fundamental to cow health and productivity than meeting her needs for ruminating, resting, and eating as precisely and efficiently as possible.

Herd management and forage fiber are key factors given their effect on chewing activity. Within an optimized feeding environment, forage particle size can be adjusted dynamically to complement forage fiber degradability, fragility, and moisture with the goal of achieving the correct balance between chewing while eating and chewing during recumbent rumination. The goal is to make eating efficient for the cow and allow ample time for ruminating while lying down. Recent research tells us that when this occurs, cows have healthier rumens, eat more feed, and produce more milk components. With its focus on precisely managing particle size tailored to forage-fiber characteristics and feeding environment, precision chewing management provides the basis of successful dairy management systems whether we recognize it explicitly or not.

Chewing Response in the Balance

Forage fiber exerts its effect on chewing inescapably within the context of the cow's social and physical environment. Consequently, feeding management must be optimized. Key components of the management environment – such as feed availability, stall comfort, and stocking density, to name a few – profoundly affect eating, resting, and ruminating. Chewing behavior is controlled and modulated through a combination of animal factors, herd management, and physicochemical characteristics of the diet – notably fiber. Eating is affected by dietary neutral detergent fiber (NDF) content, NDF degradability, and particle size. Rumination is influenced by NDF intake, forage particle size, fragility (resistance of particles to breakdown during milling or chewing), and undegradable fiber (Beauchemin, 2018; Grant and Cotanch, 2023).

Figure 1 illustrates the requisite relationship between eating and rumination while resting, termed recumbent rumination. Albright and Arave (1997) reviewed the biological importance of sternal recumbency in that it positions the rumen optimally for the process of rumination. The goal of precision chewing management is to optimize forage-fiber and herd management inputs that modulate the balance between eating and recumbent rumination. Animal factors such as health and stress level also affect the balance between eating and recumbent rumination and are in turn influenced by this balance.

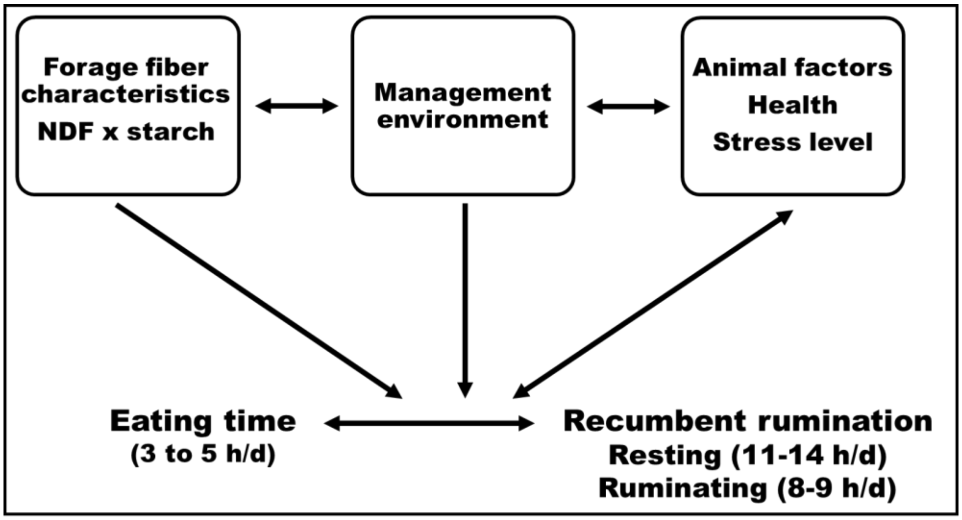

Figure 1. Balance between time spent eating and ruminating while lying down (i.e., recumbent rumination). Optimizing this chewing and resting relationship is the goal of precision chewing management.

More detail is provided in Grant and Cotanch (2023; available online at https://www.appliedanimalscience.org/article/S2590-2865(23)00027-7/pdf) but briefly, recumbent rumination is unmistakably the cow's signature behavior and super power. Cows with a greater proportion of their rumination occurring while sternally recumbent have higher ruminal pH (Campbell and Grant, 2016), consume more dry matter (DM), and produce milk with greater fat and protein content (McWilliams et al., 2022). In an unpublished study conducted at Miner Institute in 2023, Holstein cows ranging in milk fat percentage from 3.2 to 6.4% were observed for 72 h; of all behaviors recorded, the strongest positive correlation was between rumination while lying down and milk fat. Rumination time (min/d) is sensitive to diet, health, and cow well-being. As such it has been monitored extensively in precision management systems. However, it is increasingly clear that cow posture during rumination is equally important. In the future, we need to ensure that pens are monitored to observe whether individual cows are ruminating while lying down or standing. Ideally, 80% or more of daily rumination should occur while the cow is recumbent. Fortunately, the commonly measured rumination index (cows ruminating/cows lying in stalls) is well correlated with 24-h rumination time, and in fact, an index value of 50% relates to approximately 500 min/d of daily rumination time (Campbell, 2017). So, until a precision monitoring technology is available, judicious use of the rumination index will help to practically monitor recumbent rumination on-farm.

From a precision management perspective, future advances in technology need to allow monitoring of recumbent rumination given its fundamental biological importance to the cow. At the same time, eating behavior is critical for its obvious relation with DM intake (DMI) and it must be monitored as well. Research summarized by Grant and Albright (2001) indicates that, for normal feeding patterns, daily eating time should fall between 3 and 5 h for dairy cows. Eating time also needs to fall within this range to allow sufficient time for recumbent rumination. Any dietary or management factor that pushes a cow's eating time beyond approximately 5 h/d necessitates a compensatory loss of time for another behavior - often resting - hence the fundamental importance of the balance between these two behaviors. Precision management of forage and ration particle size makes eating efficient for the cow. That means chopping forages and mixing rations that are enriched with the fraction of particles retained on the second tier of the Penn State Particle Separator (more about this later). These particles, along with those on the 4-mm sieve (i.e., third tier), stimulate rumination effectively but can also be easily eaten and swallowed by the cow (Grant and Cotanch, 2023; Grant, 2024).

Fiber Content, Degradability and Dynamically Adjusting Particle Size to Optimize Chewing

Dietary NDF content, degradability, and particle size affect chewing response. As dietary forage-NDF content increases, we observe longer meal times, greater eating time, and potentially more sorting. As NDF degradability increases, or as lignin content decreases, we observe greater fragility and more rapid particle breakdown during chewing. Fragility has been positively related to 24-h NDF digestibility in a linear fashion up to approximately 60% when the relationship plateaus (Grant, 2010). Fragility may also pertain to brittleness of stems in forages such as legumes. Overall, there is less chewing with greater NDF degradability, fragility, or brittleness. As an example, Miller et al. (2021) replaced conventional with brown midrib corn silage (~10%-unit greater NDF degradability and up to 31% greater fragility) and observed approximately 30 min/d less chewing. Likewise, Grant and Ferraretto (2018) found that reduced DMI, relative to corn silage, was accompanied by longer eating time for conventional and even some brown midrib sorghums which were less degradable and less fragile. Well-accepted targets for 30-h NDF degradability are: >50% for legumes, >60% for grasses, >60% for corn silage, and >65% for brown midrib corn silage.

Over the past decade, measurement of undegraded NDF at 240 h of in vitro fermentation (uNDF240) has become commonplace in the dairy industry given its sensitivity to maturity at harvest, growing environment, and plant genetics. It is used to calculate potentially degraded NDF and is related to ruminal turnover, gut fill, and the physical effectiveness of forages (Cotanch et al., 2014; Raffrenato et al., 2018).

More recently, we have investigated the interaction between fiber (un)degradability and particle size. Researchers at Miner Institute proposed a new metric, physically effective uNDF240 (peuNDF240), that combines uNDF240 and the physical effectiveness factor (pef; Mertens, 1997). The pef is the fraction of particles retained on the 1.18-mm sieve or greater with dry vertical sieving or the 4.0-mm sieve of the Penn State Particle Separator for as-fed samples [see Grant (2023) for discussion and limitations of each method]. Farricker et al. (2022) assembled a 7-study data set and reported that, for corn silage- and haycrop silage-based diets, uNDF240 had a negative relationship with DMI (r

= -0.69), but the relationship between peuNDF240 (pef x uNDF240) and DMI was stronger (r = -0.85; Figure 2). Using peuNDF240, Smith (2018) evaluated the concept of manipulating forage particle size to complement variable dietary uNDF240. In essence, forages that had greater uNDF240 and lower NDF degradability were chopped more finely to avoid expected reductions in DMI. The results of this research led to the concept of dynamically adjusting particle size in relation to forage-fiber characteristics. For example, as forage matures (higher uNDF240, lower NDF degradability) it should be chopped finer. Or, for another example, when growing conditions enhance lignification (e.g., hot, wet weather) the forage crop may be proactively chopped finer. Importantly, Smith (2018) found that peuNDF240, since it integrated uNDF240 and pef, tracked better than uNDF240 alone with DMI, energy-corrected milk (ECM), chewing activity, and ruminal pH for lactating dairy cows. Notably, a 2.2 kg/d increase in DMI was observed when forage particle size was adjusted downward to complement higher dietary uNDF240 (Smith, 2018). A peuNDF240 of 5.9% of ration DM resulted in similar DMI, whether it was comprised of low UNDF240 chopped coarsely, or high uNDF240 chopped more finely. This DMI was similar to a diet with peuNDF240 of 5.4% and greater than a diet with peuNDF240 of 7.1%.

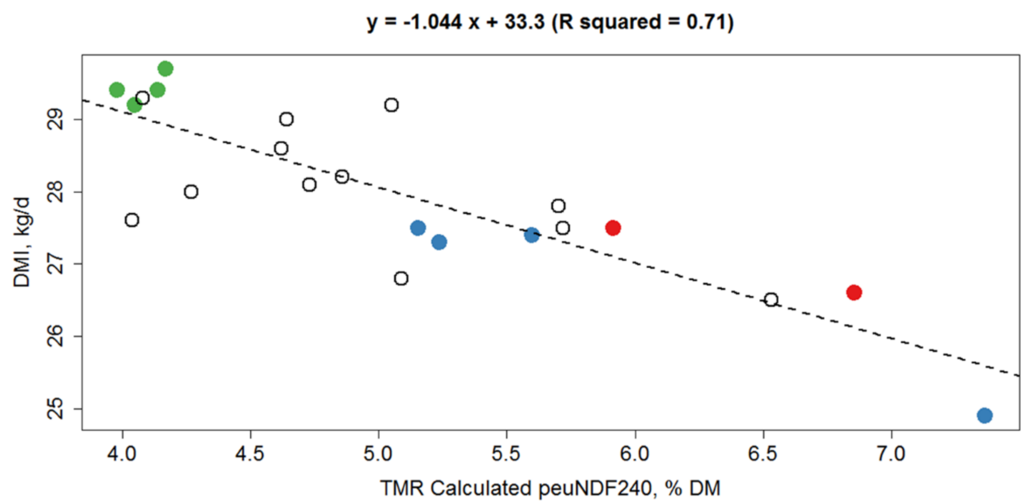

Figure 2. Relationship between dietary peuNDF240 (pef x uNDF240) and DMI from a 7-study data set based mainly on corn silage and haycrop silage diets (Farricker et al., 2022).

So there appears to be value in integrating two measures of fiber – uNDF240 and pef – when formulating rations based on corn silage, hay, and haycrop silage (perhaps alfalfa too but more work is needed). Pasture operates differently in that lush forage particles may be folded rather than comminuted during eating, so our focus is mainly on harvested and preserved forages. Forage testing laboratories report peuNDF240 in the range of 3 to 9% of ration DM based on samples received. Miner Institute data ranges from approximately 4 to 7% of ration DM, and an optimal range may be 4 to 6% of ration DM, though this certainly remains a work-in-progress. The bottom line, from a precision management perspective, is that 1) we can use this dynamic particle size concept to optimize the relationship between eating and recumbent rumination, and 2) we can use peuNDF240 as a relatively simple metric to quantitate combinations of particle size and undegradability. With the limited data to-date, a ration target of 4 to 6% peuNDF240 (DM basis) is proposed as a range where forage-fiber characteristics should allow eating time to fall within 3 to 5 h/d and with predicted DMI achieved.

One technical note: calculated peuNDF240 assumes that uNDF240 is uniformly distributed above and below the pef sieve which will not always be the case depending on dietary ingredients and forage characteristics. Directly assaying uNDF240 in the pef fraction ensures that unNDF240 in larger particles is accurately measured (Smith et al., 2020). However, this method is time-consuming as it requires an in vitro analysis on a sieved sample. We have compared the two methods, and they are highly and linearly correlated with a slope of 1.8 indicating that the directly measured peuNDF240 is 1.8x the calculated value (Farricker et al., 2022). Look for this analytical story to evolve, but at the moment it appears that, for many feeding situations, the simpler calculated value is sufficient.

Chewing and Resting Responses to Dietary Fiber: Biology Behind Precision Chewing Management

A key paper that illustrates how dietary fiber affects chewing while eating and ruminating is Jiang et al. (2017). They fed four diets ranging in forage content from 40 to 70% of DM (blend of corn silage, alfalfa, and alternative forages). As forage content increased, estimated uNDF240 content increased from 10.4 to 15.0% of ration DM (not reported in the paper but estimated based on ingredient chemical composition and known composition of similar diets). Reported pef increased from 0.42 to 0.67 using the 4.0-mm sieve of the Penn State Particle Separator. Consequently, the peuNDF240 values were estimated as 4.2, 6.2, 7.9, and 10.1% of ration DM for the 40, 50, 60, and 70% forage diets, respectively. As forage percentage increased, DMI dropped by 3.7 kg/d, especially beyond 50% dietary forage. Eating time increased by 107 min/d but rumination time crept up just 35 min/d. As we now know, this differential response in chewing is explained by the fact that cows take the time and effort during ingestive chewing to reduce dietary particle size to a relatively uniform size before swallowing regardless of dietary particle length. This concept is absolutely critical to understanding precision chewing management and the importance of not feeding too many long particles in the ration. Again, detailed discussion can be found in Grant and Cotanch (2023). The bottom line is that total chewing time increased by 141 min/d, driven by eating time, and to balance the daily behavioral time budget, resting time decreased by 141 min/d. It is noteworthy that eating time exceeded 300 min/d (i.e., 5 h/d which is the upper limit for normal eating behavior) when forage content exceeded 50% and peuNDF240 exceeded 6.2% of ration DM. For diets less than 50% forage the concept of adjusting particle size to maintain DMI is less important since there will likely be no fill constraint on intake. Rather, with lower forage diets particle size adjustment is focused on ensuring adequate chewing, rumen health, and milk composition.

Particle size of the ration is not the particle size of the swallowed bolus while eating. The bolus particle is more uniform, and Smith (2018) observed up to a 6-fold reduction in size for the longest particles during eating. Work by Schadt et al. (2018) found that particle size ranged from approximately 8 to 12 mm in the swallowed bolus while eating, which corresponds to the size of the particles retained on the 8-mm sieve of the Penn State Particle Separator. When cows were fed longer particles, they expended more chews per unit of NDF to reduce the particle size. Hence, our goal should be to mimic the cow when chopping forages for inclusion in the ration – that is the essence of precision chewing management from the cow's perspective. For corn silage and haycrop silage-based rations, this means enriching the total mixed ration with particles retained on the 8-mm sieve of the Penn State Particle Separator and minimizing particles retained on the 19-mm sieve.

We need to avoid dietary particles that are too long. Aside from potentially extending eating time beyond 5 h/d and thereby impinging on adequate time for recumbent rumination, there are several important reasons to avoid excessively long particles. Particles of total mixed ration that are retained on the 19-mm sieve of the Penn State Particle Separator are most likely to be sorted by the cow. Particles retained on the 19-mm sieve are associated with greater variation in chewing, ruminal pH, DMI, and milk yield in early lactation cows. Additionally, the percentage of particles retained on the 19-mm sieve is negatively associated with DMI, ECM, and milk fat percentage. Herds with the highest milk fat test have >50% of total mixed ration particles retained on the 8-mm sieve, and perhaps unsurprisingly, particles retained on the 8-mm sieve are more effective at stimulating chewing than particles on the top sieve (Kononoff et al., 2003; McCarthy et al., 2018; Piran Filho et al., 2023; Ferraretto et al., 2014).

What if the dietary particle size is finer than the cow would naturally swallow in the feed bolus while eating? Research shows that feed particles that are 8 mm or less tend to not be further reduced in particle size during eating. But the cow is inescapably populating her rumen with smaller than normal particles if we feed a diet chopped finer than 8 mm. One example would be a compact total mixed ration where the delivered ration has too many particles retained on the 4.0-mm sieve and pan. The particle size would be less than 8 mm, on average, in the ration and consequently feed efficiency would be low. Overall, it may be difficult to boost rumination with long particles, but we can surely depress it by chopping forages more finely than the cow would herself. Part of precision management is ensuring that the ration particle size is not less than the cow would create herself; or not chopping to particle sizes less than 8 mm. The management goal is to attain eating time between 3 and 5 h/d – not to minimize it.

Considerations with dry hay-based diets

Bauer et al. (2023) found that, when meadow hay-based rations were fed to lactating dairy cows, particle distributions of 21% retained on the 19-mm sieve, 20% on the 8-mm sieve, 20% on the 4.0-mm sieve, and 39% in the pan resulted in greater DMI, but lower total tract digestibility likely due to rapid particle passage rate. High quality alfalfa may not stimulate chewing as much as moderate quality alfalfa. Fine stems are more brittle and easily broken down as they are chewed or processed prior to feeding. In our limited experience with finely chopped alfalfa hay diets, we do see greater risk of cows going off-feed and we attempt to chop the hay coarser (i.e., 5 to 10% on 19-mm sieve; 2.5- to 4.0-

cm particle length to avoid sorting). However, Fustini et al. (2017) successfully fed finely chopped alfalfa hay with lower and higher NDF degradability with <1% retained on the 19-mm sieve and >80% on the 1.18-mm sieve and pan. The peNDF ranged from only 11.2 to 12.9% of ration DM in that study. They included chopped wheat straw in their diets, and it may have been an important part of their success because straw elicits about 1.5 times the chewing response as similarly sized alfalfa hay and it contains a high content of uNDF240 and slowly degrading NDF. Straw should be chopped finely enough so that cows cannot sort it (i.e., 20% on 19-mm sieve, 40% on 8-mm sieve, 20% on 4-mm sieve, and 20% in pan using Penn State Particle Separator; H. Dann, Miner Institute). One more point, purely observational: every good stockperson knows the value of providing long-stemmed hay to cows that are off-feed. It bears emphasizing that the particle size guidelines to be presented in the next section assume a generally healthy herd and these guidelines are intended to maintain a high level of productivity and herd health.

Particle Size Recommendations to Optimize Chewing Behavior

The following tables are adapted from Grant and Cotanch (2023) and summarize current recommendations for: 1) forage particle size that allows the ration to fall within the peuNDF240 target range, and 2) rations that allow cows to achieve the proper balance between eating and recumbent rumination. Table 1 presents recommended particle distributions for total mixed rations with interpretive comments for each particle size fraction. The original version was published by Cotanch (2017) in the Miner Institute Farm Report. Keep in mind that these recommendations, aimed at minimizing particles on the 19-mm sieve and focusing instead on the 8-mm sieve, are part of an overall feeding system that includes feed availability 24/7 and ample access to comfortable stalls.

Table 1. Recommended total mixed ration particle size recommendations using the Penn State Particle Separator (PSPS) to optimize balance between eating and recumbent rumination (adapted from Grant and Cotanch, 2023).

Sieve size, mm	PSPS 2013, % of DM	Miner 2020, % as fed	Comments
19	2-8	2-5	Sortable particles; increases time needed for eating, especially if >10%. Length of 1.3 to 2.5 cm maximum
8	30-50	>50	Physically effective, more so than 4- and 19-mm particles; maximize amount on this sieve, 50 to 60%
4	10-20	10-20	Functions as physical effectiveness factor (pef) sieve; total of the top 3 sieves = pef
---	30-40	25-30	40 to 50% grain diet results in at least 25 to 30% in the pan

To achieve these recommended ration particle size distributions, the dynamic approach in Figure 3 should be used. It is adapted from a similar figure in Grant and Cotanch (2023) and is a concept originally proposed by Woodley (2021).

Figure 3 presents the recommended range in theoretical length of cut (TLC) for forages that are harvested at commonly recommended maturity and moisture content. A sliding scale is proposed for TLC between approximately 12 and 22 mm (~⅜ to ¾ of an inch). Below this range faster passage rates from the rumen may reduce feed efficiency. Above this range, the risk of sorting ramps up. Within the recommended range, the optimal length of chop can be adjusted based on factors such as maturity at harvest, fragility of the crop, and moisture content. As the haycrop becomes more mature (i.e., uNDF240 increases) it should be chopped finer. Likewise, with less mature haycrop, it should be chopped coarser. Drier and more fragile alfalfa should be chopped coarser whereas dry and less fragile grass needs to be chopped more finely. Although not shown in the figure, conventional versus brown midrib corn silage fall into the categories of lesser and greater forage fragility and conventional corn silage generally is chopped more finely than brown midrib.

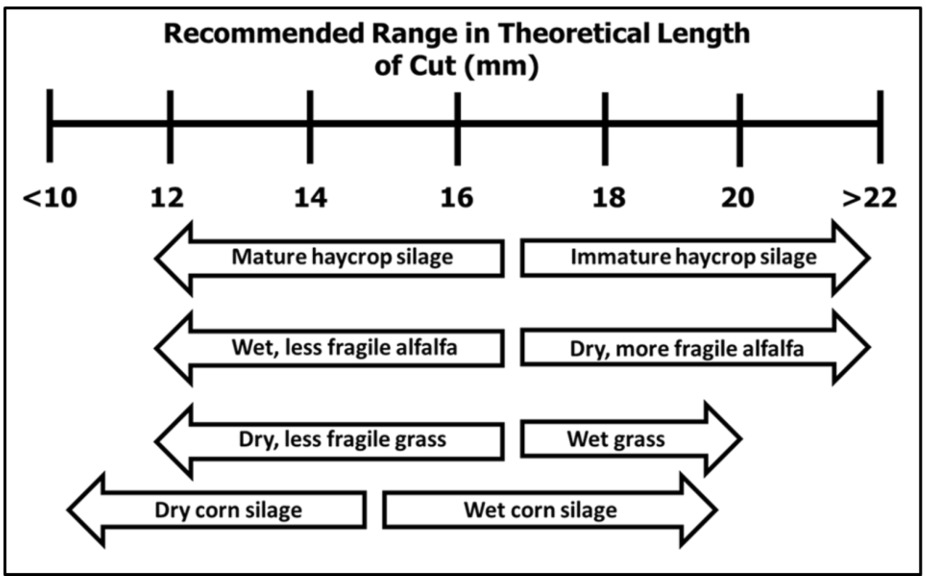

Figure 3. Recommended chop lengths for silages varying in maturity, fragility, and moisture content. Adapted from original concept of Woodley (2021) as described in Grant and Cotanch (2023).

This dynamic approach to forage chop length allows us to match the correct particle size more precisely with a given set of forage-fiber characteristics to produce a forage that optimizes chewing responses of the cow. The combination of pef and uNDF240 can be monitored using peuNDF240 (with some adjustment for fragility if a routine method is developed) and hopefully in the future monitoring of eating and recumbent rumination time will become economically feasible for on-farm use. This system of adjusting chop length means that you would not use one chopper setting throughout a harvest season or always chop dry forages with a standard set of screens. Rather, chop length would be variable with advancing maturity, by growing season, or as the crop becomes drier, especially corn silage. This dynamic approach may become more important over time with the effects of climate change on crop growth and harvesting; something to ruminate on at any rate.

To use this approach, one also needs to consider the potential for further particle size reduction beyond the silo. What silage or dry forage handling and mixing techniques are used on the farm? Think about silage removal and any potential impact of a defacer on reducing particle size. Consider mixer knife sharpness, mixing time, and other factors that all may contribute to a reduction in ration particle size between the silage/hay and the delivered ration. These considerations may necessitate some adjustments to the recommendations in Figure 3 for some farms.

Finally, Table 2 provides some approximate guidelines for recommended particle distributions for common forages that ought to result in total mixed ration particle distributions recommended in Table 1. The information in this table is based on feedback from nutritionists in the field and not research. Remember that considerable variation may exist between TLC and silage particle size distribution. Ultimately, the goal should be a chop length, for any given farm and its unique circumstances, which ensures good silage packing to reduce DM losses and, of course, optimizes chewing and DMI responses of the herd.

Table 2. Suggested particle distributions using the Penn State Particle Separator.

Screen, mm	Total mixed ration	Corn silage	Alfalfa silage	Grass silage
19-mm	<5	3-8	5-15?	5-15
8-mm	>50	50-65	50-75	50-75
4-mm	10-20	30-40	25-30	20-30
Pan	25-30	<5	<5	<5

The suggestions in Table 2 are definitely a work-in-progress and based on feedback and input from the field. As an example, recent feedback from Mexico and the US (Hugo Ramirez, personal communication, August 2025) suggests the need to revise the recommended particle distributions for corn silage. Ramirez pointed out that, with advancements in kernel processing, he is observing a larger proportion of particles passing through the 4.0-mm sieve into the pan of the Penn State Particle Separator reflecting the fact that many corn kernel fragments now pass through with better corn silage processing. More work is needed, but when Kernel Processing Score is >70% then the proper recommendation may be closer to 15 to 25% for the 4.0-mm sieve and <20% for the pan. Based on his observations, it seems likely that these recommendations may change with time, as equipment evolves, but always with the end goal being dietary particle distributions that optimize chewing and resting behavior.

Figure 4 depicts six primary components of precision chewing management that should result in optimized chewing and DMI. Fully implementing this approach will require some advancements in monitoring technology for eating and recumbent rumination. However, the core concept of mimicking the cow relative to particle size reduction and managing to ensure the correct balance between eating and recumbent rumination can be achieved now.

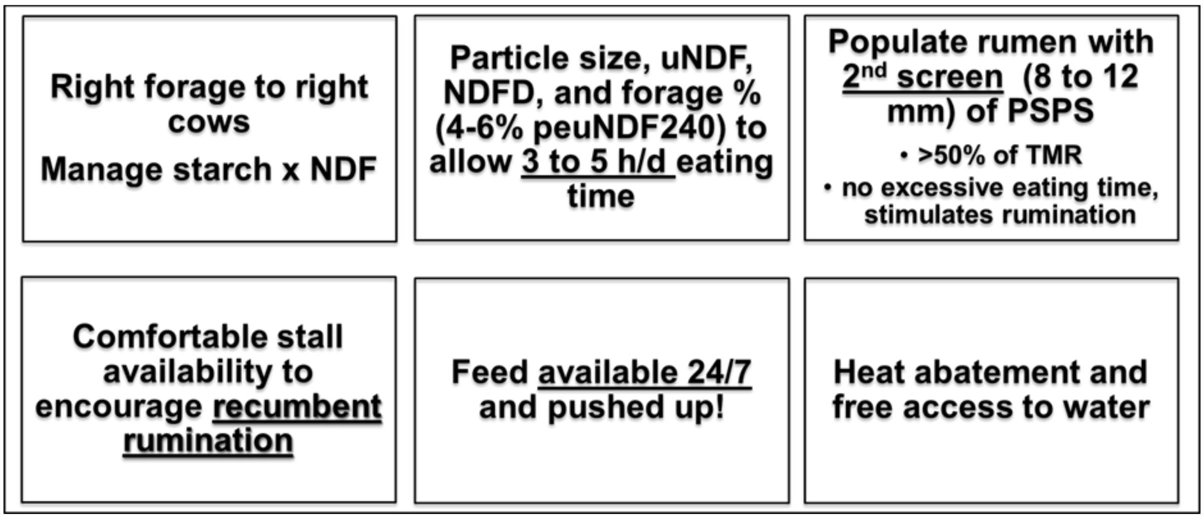

Figure 4. Major components of successful precision chewing management.

In summary, the key elements of precision chewing management are:

- Dynamically selecting forage particle size as a function of dietary forage NDF content, NDF degradability (and fragility?), uNDF240, and moisture content.
    - Chop forage finer or coarser depending on maturity and growing conditions.
- Particle size target should mimic what the cow does naturally as she chews and swallows a feed bolus (i.e., particle size from the cow's perspective).
    - Make eating as efficient as possible, target 3 to 5 h/d eating time.
    - Enrich ration with particles retained on 8-mm sieve of Penn State Particle Separator; minimize particles on 19-mm sieve as promoting inefficient chewing.
    - Use recommendations for particle size of forages and total mixed rations presented here.
- Ensure ample time for recumbent rumination [11 to 14 h/d resting with 80^{+}% of rumination (8 to 9 h/d) occurring while recumbent].
    - Need technology to monitor eating behavior and recumbent rumination, times per day and when they occur. In the meantime, rumination index will be useful as a practical on-farm tool.
    - Does cow have ability to consume a meal naturally and then lie down comfortably and ruminate undisturbed?

  - Herd management inputs will affect the eating and recumbent rumination balance profoundly. Is feed available? Is resting area comfortable?
- Using peuNDF240 target of ~4 to 6% of ration DM appears to be a good metric for achieving desired eating and recumbent rumination balance; allows dynamic approach to optimize forage fiber characteristics, chewing behavior, and DMI.

Precision chewing management aims to optimize eating and recumbent rumination to boost DMI and healthy production of milk components. The focus is on forage fiber degradability and particle size combined with the feeding environment. Unlocking the nutritional potential of forage demands this overarching focus on cow comfort and forage quality.

References

Albright, J. L. Albright, and C. W. Arave, 1997. The behaviour of cattle. CAB Int. New York, NY.

Bauer, K., M. Eghbali, T. Hartinger, A. Haselmann, B. Fuerst-Waltl, W. Zollitsch, Q. Zebeli, and W. Knaus. 2023. Effects of particle size reduction of meadow hay on feed intake, performance, and apparent total tract nutrient digestibility in dairy cows. Arch. Anim. Nutr. 77:452-467.

Beauchemin, K. A. 2018. Invited review: Current perspectives on eating and rumination activity in dairy cows. J. Dairy Sci. 101:4762-4784.

Campbell, M. A. 2017. Interaction of stocking density and the feeding environment in lactating Holstein dairy cows. PhD Diss. Dept. Anim. Vet. Sci., Univ. of Vermont, Burlington.

Campbell, M. A., and R.J. Grant. 2016. Interactions between the feed and feeding environment. Pages 49-60 in Proc. 78th Cornell Nutr. Conf. Feed Manufacturers.

Cotanch, K. W. 2017. Miner Institute specs on TMR particle size distribution. Page 9 in The William H. Miner Agricultural Research Institute Farm Report. Feb. 9, 2017. Chazy, NY.

Cotanch, K. W., R. J. Grant, M. E. Van Amburgh, A. Zontini, M. Fustini, A. Palmonari, and A. Formigoni. 2014. Applications of uNDF in ration modeling and formulation. Pages 114-131 in Proc. Cornell Nutr. Conf. Feed Manufacturers. East Syracuse, NY. Cornell University, Ithaca, NY. East Syracuse, NY. Corbell Univ., Ithaca, NY.

Farricker, M., J. Darrah, A. Pape, M. Miller, and R. Grant. 2022. Ration content of undegradable and physically effective neutral detergent fiber and its relationship with dry matter intake and energy-corrected milk yield of Holstein cows. J. Dairy Sci. 105 (E-Suppl. 1):246. (Abstr.)

Fustini, M., A. Palmonari, G. Canestrari, E. Bonfante, L. Mammi, M. T. Pacchioli, C. J. Sniffen, R. J. Grant, K. W. Cotanch, and A. Formigoni. 2017. Effect of undigested neutral detergent fiber content of alfalfa hay on lactating dairy cows: Feeding behavior, fiber digestibility, and lactation performance. J. Dairy Sci. 100:4475-4483.

Grant, R. J. 2010. Forage fragility, fiber digestibility, and chewing response in dairy cattle. Pages 27-40 in Proc. 19th Ann. Tri-State Dairy Nutr. Conf. Ft. Wayne, IN.

Grant, R. J. 2023. Symposium review: Physical characterization of feeds and development of the physically effective fiber system. J. Dairy Sci. 106:4454-4463.

Grant, R. J. 2024. Optimize eating time with precision chewing management. Pages 356-357 in July 2024 issue Hoard's Dairyman. W. D. Hoard & Sons Co., Fort Atkinson, WI.
Grant, R. J., and J. L. Albright. 2001. Effect of animal grouping on feeding behavior and intake of dairy cattle. J. Dairy Sci. 84 (E. Suppl.):156-163.
Grant, R. J., and K. W. Cotanch. 2010.
Grant, R. J., and K. W. Cotanch. 2023. Perspective and commentary: Chewing behavior of dairy cows: Practical perspectives on forage fiber and the management environment. Appl. Anim. Sci. 39:146-155.
Grant, R. J., and L. F. Ferraretto. 2018. Silage review: Silage feeding management: Silage characteristics and dairy cow feeding behavior. 101:4111-4121.
Jiang, F. G., X. Y. Lin, Z. G. Yan, Z. Y. Hu, G. M. Liu, Y. D. Sun, X. W. Liu, and Z. H. Wang. 2017. Effect of dietary roughage level on chewing activity, ruminal pH, and saliva secretion in lactating Holstein cows. J. Dairy Sci. 100:2660-2671
Kononoff, P. J., A. J. Heinrichs, and H. A. Lehman. 2003. The effect of corn silage particle size on eating behavior, chewing activities, and rumen fermentation in lactating dairy cows. J. Dairy Sci. 86:3343-3353.
McCarthy, M. M., T. R. Overton, G. D. Mechor, D. E. Bauman, T. C. Jenkins, and D. V. Nydam. 2018. Short communication: Field study to investigate the associations between herd-level risk factors for milk fat depression and bulk tank milk fat percent in dairy herds feeding monensin. J. Dairy Sci. 101:3118-3125.
McWilliams, C. J., A. J. Schwanke, and T. J. DeVries. 2022. Is greater milk production associated with dairy cows who have a greater probability of ruminating while lying down? JDS Comm. 3:66-71.
Miller, M. D., C. Kokko, C. S. Ballard, H. M. Dann, M. Fustini, A. Palmonari, A. Formigoni, K. W. Cotanch, and R. J. Grant. 2021. Influence of fiber degradability of corn silage in diets with lower and higher fiber content on lactational performance, nutrient digestibility, and ruminal characteristics in lactating Holstein cows. J. Dairy Sci. 104:1728-1743.
Mertens, D. R. 1997. Creating a system for meeting the fiber requirements of dairy cows. J. Dairy Sci. 80:1463-1481.
Piran Filho, F. A., J. M. Bragatto, C. S. Parra, S. M. S. Silva, P. J. Roco, L. F. Ferraretto, M. N. Pereira, and J. L. P. Daniel. 2023. Physical effectiveness of corn silage fractions stratified with the Penn State Particle Separator for lactating dairy cows. J. Dairy Sci. 106:604106059.
Pupo, M. R., and L. F. Ferraretto. 2024. Meta-analysis on the effects of physical characteristics of dairy rations on animal performance and feeding behavior in lactating dairy cows. J. Dairy Sci. 107(Suppl. 1): 135. (Abstr.)
Raffrenato, E., D. A. Ross, and M. E. Van Amburgh. 2018. Development of an in vitro method to determine rumen undigested aNDFom for use in feed evaluation. J. Dairy Sci. 101:9888-9900.
Schadt, I., J. D. Ferguson, G. Azzaro, R. Petriglieri, M. Caccamo, P. Van Soest, and G. Licitra. 2012. How do dairy cows chew? Particle size analysis of selected feeds with different particle length distributions and of respective ingested bolus particles. J. Dairy Sci. 95:4707-4720.

Smith, K. M., A. Obata, K. Hirano, H. Uchihori, S. Y. Morrison, J. W. Darrah, H. M. Dann, C. S. Ballard, M. D. Miller, and R. J. Grant. 2020. Effects of undigested physically effective neutral detergent fiber and rumen fermentable starch on lactation performance and total tract digestibility of lactating cows. J. Dairy Sci. 103 (Suppl. 1): 168. (Abstr.)

Smith, W. A. 2019. Relationships between undigested and physically effective fiber in lactating dairy cow diets. MS Thesis. Department of Animal Science. University of Vermont. Burlington.

Woodley, W. 2021. Redefining forage particle size for ruminants. Progressive Dairy. Mar. 31, 2021. Progressive Publ. Jerome, ID. Accessed Aug. 28, 2025. https://www.agproud.com/articles/44766-redefining-forage-particle-size-for-ruminants.