Relationships Between Fibre Digestibility and Particle Size for Lactating Dairy Cows

Rick Grant, Wyatt Smith, and Michael Miller

William H. Miner Agricultural Research Institute, Chazy, NY
Email: grant@whminer.com

Take Home Messages

- Feed intake and milk production are influenced by dietary neutral detergent fibre (NDF), although it does not explain all of the observed variation.
- Consideration of dietary physical form or particle size (i.e., physically effective NDF; peNDF) and digestibility or indigestibility (i.e., undigested NDF at 240 hours of in vitro fermentation; uNDF240) improves the prediction of dry matter intake (DMI) and milk production.
- A new concept that combines peNDF and uNDF240, called peuNDF, appears to be useful when interpreting and predicting cow DMI and energy-corrected milk responses to diets that are based on corn and haycrop silages.
- When forage fibre indigestibility is greater than desired, a finer chop will boost DMI to levels comparable to lower uNDF240 diets. However, we need to avoid chopping low uNDF240 forages too finely.
- Although the concept of combining physical effectiveness factor (i.e., particle size) with uNDF240 is encouraging, additional investigations with legumes, pastures, and non-forage sources of fibre are needed to test how robust the relationship is between peuNDF and DMI across a wide range of diet types and feeding environments.

Introduction

Portions of this conference proceedings have been previously published in the Proceedings of the Cornell Nutrition Conference for Feed Manufacturers (Grant et al., 2018), the Four-State Dairy Nutrition and Management Conference (Grant et al., 2019), and the Minnesota Nutrition Conference (Grant et al., 2019).

Economic, environmental, and social considerations encourage the use of more forage in dairy cattle rations (Martin et al., 2017). Although regional economics and forage availability determine the balance between dietary forage and non-forage sources of fibre, we appear to be at the threshold of a new era in our ability to effectively feed fibre to lactating dairy cows. Nutritionists have long realized that NDF content alone does not explain all of the observed variation in dry matter intake (DMI) and milk yield as the source of forage and its concentration in the diet vary. Incorporating measures of fibre digestibility and particle size improves our ability to predict DMI and productive responses.

Waldo et al. (1972) recognized that cellulose needed to be fractionated into digestible and indigestible pools for calculation of digestion rates. Together with Van Soest's development of the detergent system of feed analysis (Van Soest, 1994), these two concepts transformed ruminant nutrition. The recognition that there is an indigestible portion of fibre led to research that improved our understanding of the digestibility of fibre in ruminant diets and the development of dynamic models of fibre digestion. Recent research has focused on a three-pool model of ruminal NDF digestion: indigestible NDF measured as undigested NDF at 240 hours of in vitro fermentation, (uNDF240), a fast-fermenting pool of NDF and a slow-fermenting pool of NDF (Mertens, 1977; Raffrenato and Van Amburgh, 2010; Cotanch et al., 2014). To date more research has focused on defining biologically relevant digestion pools than particle size pools within the rumen, although both digestion and particle size characteristics of a fibre particle are important for explaining ruminal fibre turnover (Mertens, 2011). In a classic paper, Mertens (1997) laid out a comprehensive system for integrating NDF content and particle size, based on the 1.18-mm dry sieved fraction of particles, known as peNDF. Although the peNDF system is based solely on particle size as a measure of physical form, it explains a substantial amount of the variation in chewing activity, ruminal pH, and milk fat elicited when feeding different sources of forage.

Recently at Miner Institute, we have focused on the relationship between undigested and physically effective NDF (peNDF) and have conducted studies designed to assess the relationship between dietary uNDF240 and particle size measured as peNDF. The potential relationships between peNDF and uNDF240 are a hot topic among nutritionists with several practical feeding questions being asked in the field:

- What are the separate and combined effects of peNDF and uNDF240 in diets fed to lactating cows?
- Can we adjust for a lack of dietary peNDF by adding more uNDF240 in the diet?
- If forage uNDF240 is higher than desired, can we at least partially compensate by chopping the forage finer to maintain feed intake?

The bottom line question becomes: are there optimal peNDF concentrations as uNDF240 content varies in the diet and vice versa? The answer to this question will likely be affected by the source of fibre—forage or non-forage—since they differ dramatically in fibre digestion pools and particle size. Some nutritionists have even questioned how important particle size actually is as we better understand fibre fractions (i.e., fast, slow, and uNDF240) and their rates of digestion. This is a complicated question, but the short answer appears to be, yes, particle size is important, although for reasons we haven't always appreciated, such as its effect on eating behaviour, even more so than on rumination.

▪ Miner Institute Study: Undigested and Physically Effective Fibre

Dietary Treatments: peNDF and uNDF240

To begin addressing the questions above, we conducted a study in 2018 to assess the effect of feeding lower (8.9% of ration DM) and higher (11.5% of ration DM) uNDF240 in diets with either lower or higher peNDF (19 to 20 vs. approximately 22% of ration DM). The diets contained approximately 35% corn silage, 1.6% chopped wheat straw, and chopped timothy hay with either a lower physical effectiveness factor (pef; fraction of particles retained on ≥ 1.18 mm screen; 0.24) or a higher pef (0.58).

We used a Haybuster (DuraTech Industries International, Inc., Jamestown, ND) with its hammer mill chopping action to achieve the two particle sizes of dry hay. In addition, for the lower forage diets we partially replaced the timothy hay with nearly 13% pelleted beet pulp to help adjust the fibre fractions. The lower uNDF240 diets contained about 47% forage and the higher uNDF240 diets contained about 60% forage on a DM basis (Table 1).

In studies of this nature, dietary uNDF content can be varied by using the same forages harvested at differing stages of maturity which results in diets that differ in uNDF at similar forage percentages. These studies need to be conducted as they will provide a clean comparison of the effects of dietary forage content and fibre digestibility characteristics. In the present study, as a first effort at examining the relationships between uNDF and particle size, we simply adjusted forage content of the diet as a practical means of manipulating dietary uNDF, while understanding that this approach inevitably confounds forage content with dietary uNDF fractions.

Table 1. Ingredient and chemical composition of experimental diets (% of DM).

	Low uNDF240[1]		High uNDF240	
	Low peNDF[2]	High peNDF	Low peNDF	High peNDF
Ingredients				
Corn silage	34.7	34.7	34.7	34.7
Wheat straw, chopped	1.6	1.6	1.6	1.6
Timothy hay, short chop	10.5	---	24.2	---
Timothy hay, long chop	---	10.5	---	24.2
Beet pulp, pelleted	12.9	12.9	0.4	0.4
Grain mix	40.3	40.3	39.1	39.1
Composition				
Forage	46.8	46.8	60.5	60.5
aNDFom[3]	33.1	33.3	35.7	36.1
uNDF240om	8.9	8.9	11.5	11.5
peNDFom	20.1	21.8	18.6	21.9
peuNDF240[4]	5.4	5.9	5.9	7.1

[1]Undigested NDF at 240 hours of in vitro fermentation.
[2]Physically effective NDF.
[3]Amylase-modified NDF on an organic matter (OM) basis.
[4]Physically effective uNDF240 (physical effectiveness factor x uNDF240).

A New Concept: Physically Effective uNDF240

To explore the relationship between physical effectiveness and uNDF240 among these four diets, we calculated a "physically effective uNDF240" (peuNDF = pef x uNDF240). This value ranged from 5.4% of DM for the low uNDF240 + low peNDF diet to 7.1% of DM for the high uNDF240 + high peNDF diet (Table 1). By design, the two intermediate diets contained 5.9% of ration DM as peuNDF240. An important assumption underpinning our focus on a peuNDF value is that uNDF240 is uniformly distributed across the particle size fractions, particularly above and below the 1.18 mm screen when a sample has been dry sieved. Current research at the Miner Institute Forage Laboratory indicates that uNDF240 is relatively evenly distributed above and below the 1.18 mm screen for the diets fed in this study, with the average difference between the larger and smaller particle fractions being about 9% across the four diets.

When feeding these four diets, we expected the 'bookend' diets to elicit predictable responses in DMI based on their substantial differences in uNDF240 and particle size (Harper and McNeill, 2015). We considered them as bookends because these diets represented a range in particle size and indigestibility that would reasonably be observed in the field for these types of diets. Most importantly, we focused on the two intermediate diets to determine if they would elicit similar responses in DMI given their similar calculated peuNDF content.

The high uNDF240 + high peNDF diet did limit DMI compared with the lower uNDF240 diets (Table 2). When lower uNDF240 diets were fed, the peNDF did not affect DMI. But, a shorter chop length for the higher uNDF240 diet boosted DMI by 2.5 kg/day. As a result, NDF and uNDF240 intakes were highest for cows fed the high uNDF240 diet with smaller particle size. Overall, and as expected, uNDF240 intake was greater for the higher vs. lower uNDF240 diets. The important take-home result is the 0.45% of body weight DMI of uNDF240 for cows fed the high uNDF240 diet with hay that had been more finely chopped (Table 2).

The intake of peuNDF (calculated as the product of pef and uNDF240) was stretched by the bookend diets: 1.47 versus 1.74 kg/d for the low-low versus high-high uNDF240 and peNDF diets, respectively. Of greatest interest, we observed that the two intermediate diets resulted in similar peuNDF intake; we were able to elicit the same intake response by the cow whether we fed lower uNDF240 in the diet chopped more coarsely, or whether we fed higher dietary uNDF240 but with a finer particle size.

Table 2. Dry matter and fibre intake for cows fed diets differing in uNDF240 and peNDF.

	Low uNDF240[1]		High uNDF240		SE	*P*-value
Measure	Low peNDF[2]	High peNDF	Low peNDF	High peNDF		
DMI, kg/d	27.5[a]	27.3[a]	27.4[a]	24.9[b]	0.6	<0.01
DMI, % of BW	4.02[a]	4.04[a]	3.99[a]	3.73[b]	0.10	0.03
NDF intake, kg/d	9.12[b]	9.06[b]	9.74[a]	8.96[b]	0.19	0.008
uNDF240om[3] intake, kg/d	2.41[c]	2.43[c]	3.11[a]	2.87[b]	0.05	<0.001
uNDF240om intake, % of BW	0.35[c]	0.36[c]	0.45[a]	0.43[b]	0.01	<0.001
peNDFom intake, kg/d	5.56[b]	5.94[a]	5.07[c]	5.44[b]	0.11	<0.001
peuNDF240[4] intake, kg/d	1.47[c]	1.59[b]	1.61[b]	1.74[a]	0.03	<0.001

[abc]Means within a row with unlike superscripts differ ($P \leq 0.05$).
[1]Undigested NDF at 240 hours of in vitro fermentation.
[2]Physically effective NDF.
[3]Organic matter.
[4]Physically effective uNDF240 (physical effectiveness factor x uNDF240).

Lactational Responses to peNDF and uNDF240

An important question becomes: does lactational performance track with these observed responses in feed intake? Generally, unadjusted milk and energy-corrected milk (ECM) production responded similarly to peuNDF intake (Table 3). In particular, production of ECM was lowest for cows fed the high-high uNDF240 and peNDF diet and greatest for the low-low diet (Table 3). Tracking with DMI, the ECM yield was similar and intermediate for the low-high and high-low uNDF240 and peNDF diets. Interestingly, milk fat percentage appeared to be more related to dietary uNDF240 than peNDF content. More research is needed to understand the relative responsiveness of milk fat to uNDF240 and peNDF.

Table 3. Milk yield, composition, and efficiency of solids-corrected milk production.

	Low uNDF240[1]		High uNDF240		SE	*P*-value
Measure	Low peNDF[2]	High peNDF	Low peNDF	High peNDF		
Milk, kg/d	46.1[a]	44.9[ab]	44.0[bc]	42.6[c]	0.9	<0.01
Milk fat, %	3.68[b]	3.66[b]	3.93[a]	3.92[a]	0.10	0.03
Milk true protein, %	2.93[a]	2.88[ab]	2.96[a]	2.84[b]	0.06	0.04
Milk urea N, mg/dl	8.5[c]	9.4[bc]	10.1[ab]	11.0[a]	0.6	<0.01
Energy-corrected milk, kg/d	47.0[a]	45.7[ab]	46.4[ab]	44.6[b]	0.9	0.03
ECM/DMI, kg/kg	1.71[ab]	1.68[b]	1.70[ab]	1.79[a]	0.04	0.02

[abc]Means within a row with unlike superscripts differ ($P \leq 0.05$).
[1]Undigested NDF at 240 h of in vitro fermentation.
[2]Physically effective NDF.

Milk true protein appeared to be boosted by lower peNDF and cows fed the high-high uNDF240 and peNDF diet had the lowest milk protein percentage, with cows fed the low-high uNDF240 and peNDF diet being intermediate (Table 3). The milk urea nitrogen (MUN) concentration was reduced first as dietary uNDF240 decreased and then as peNDF decreased within a level of uNDF240.

Chewing Response to peNDF and uNDF240

Dietary uNDF240 and peNDF had a greater impact on eating than on ruminating time (Table 4). The substantial effect of dietary fibre characteristics on chewing during eating and total time spent eating has been observed in multiple studies. A recent review found that higher forage content, greater NDF or peNDF content, and lower NDF digestibility may all increase time spent eating for a wide range of forages (Grant and Ferraretto, 2018). In our study, cows fed the high-high uNDF240 and peNDF diet spent 45 minutes/day longer eating and yet consumed nearly 3 kg/day less DM than cows fed the low-low uNDF240 and peNDF diet (Table 4). We need to bear in mind that dietary uNDF240 content was varied by adjusting the forage percentage in the diet. In future studies, we need to assess whether similar results would be obtained if uNDF240 content were adjusted by varying harvest date and forage maturity.

A practical management question is whether or not cows would have sufficient time to spend at the bunk eating a diet with greater dietary uNDF240 that is too coarsely chopped? And if we consider an overcrowded or otherwise competitive feed-bunk environment, the constraint on feeding time could be even more deleterious.

Cows fed the high-high peNDF and uNDF240 diet had the greatest eating time compared with cows fed the low uNDF240 diets (Table 4). Finely chopping the hay in the high uNDF240 diet reduced eating time by about 20 minutes/day and brought it more in-line with the lower uNDF240 diets.

Table 4. Chewing behavior as influenced by dietary uNDF240 and peNDF.

	Low uNDF240[1]		**High uNDF240**		**SE**	***P*-value**
Measure	**Low peNDF[2]**	**High peNDF**	**Low peNDF**	**High peNDF**		
Eating time, min/d	255[b]	263[b]	279[ab]	300[a]	12	<0.01
Ruminating time, min/d	523	527	532	545	16	0.36

[abc]Means within a row with unlike superscripts differ ($P \leq 0.05$).
[1]Undigested NDF at 240 h of in vitro fermentation.
[2]Physically effective NDF.

Part of the reason why eating time was more affected than was rumination time is related to the observation that cows tend to chew a bolus of feed to a relatively uniform particle size before swallowing. Grant and Ferraretto (2018) summarized research that showed that particle length over a wide range of feeds was reduced during ingestive chewing to approximately 10 to 11 mm (Schadt et al., 2012). Similarly, in our current study, we confirmed that cows consuming all four diets swallowed boli of total mixed ration with a mean particle size of approximately 7 to 8 mm (Table 5) regardless of uNDF240 or peNDF content of the diet.

Table 5. Particle size of swallowed total mixed ration bolus vs. diet offered (% retained on sieve; DM basis).

	Sieve size, mm						**Mean particle size, mm**
Diet	**19.0**	**13.2**	**9.50**	**6.70**	**4.75**	**3.35**	
Low peNDF[1], low uNDF240[2]	3	27	33	20	10	7	9.36
High peNDF, low uNDF240	12	27	29	16	9	6	10.42
Low peNDF, high uNDF240	9	21	23	22	14	11	9.19
High peNDF, low uNDF240	32	13	17	20	11	7	11.55
Bolus							
Low peNDF, low uNDF240	1	11	38	26	14	10	7.96
High peNDF, low uNDF240	3	11	22	29	20	16	7.46
Low peNDF, high uNDF240	2	11	26	29	19	13	7.51
High peNDF, low uNDF240	5	12	19	28	21	14	7.78

[1]Physically effective NDF. [2]Undigested NDF at 240 hours of in vitro fermentation.

Ruminal Fermentation: peNDF and uNDF240

Mean ruminal pH followed the same pattern of response as DMI and ECM yield (Table 6). Although not significant, time and area below pH 5.8 numerically appeared to be more related with dietary uNDF240 content than peNDF. Total volatile fatty acid (VFA) concentration followed the same pattern as DMI, ECM yield, and mean ruminal pH, with cows that consumed similar peuNDF240 having similar total ruminal VFA concentrations (Table 6). Tracking with milk fat percentage, the ruminal acetate + butyrate:propionate ratio was more influenced by uNDF240 than by peNDF.

When we assessed ruminal pool size and turnover, we found that the pool size of NDF tended to be greater for cows fed higher uNDF240 diets and that the pool size of uNDF240 was greater for cows fed these same diets (Table 6). Ruminal turnover rate of NDF tended to be slower for cows fed the higher uNDF240 diets with the high-high uNDF240 and peNDF diet having the slowest ruminal turnover of fibre. Overall, the differences among diets in ruminal pool size and turnover were small but it appeared that higher uNDF240 diets increased the amount of uNDF240 in the rumen and slowed the turnover of NDF. The higher ruminal NDF turnover for cows fed the finely chopped high uNDF240 diet helps to explain the observed increase in DMI.

If future research confirms the results of this initial study, it suggests that when forage fibre digestibility is lower than desired, a finer forage chop length may well boost feed intake and lactational response. The enhanced lactational performance was associated with less eating time as well as more desirable ruminal fermentation and fibre turnover for cows fed the higher uNDF240 diet with lower peNDF.

An important topic remains how rumen fermentable starch may interact with various dietary concentrations of uNDF240 or peuNDF240. On-going studies at the Institute aim to answer this question.

Table 6. Ruminal fermentation and dynamics of fibre turnover.

	Low uNDF240[1]		**High uNDF240**		**SE**	***P*-value**
Measure	**Low peNDF[2]**	**High peNDF**	**Low peNDF**	**High peNDF**		
24-h mean pH	6.11[b]	6.17[ab]	6.22[ab]	6.24[a]	0.05	0.03
Time pH < 5.8, min/d	253	208	166	164	61	0.24
AUC, pH < 5.8[3]	52.0	49.6	33.5	30.0	15.0	0.29
Total VFA, m*M*	122.8[a]	120.6[ab]	118.3[ab]	112.3[b]	4.1	0.05
Acetate+butyrate:propionate	3.33[c]	3.39[bc]	3.58[a]	3.54[ab]	0.16	<0.01
Ruminal pool size, kg						
OM	12.7	12.3	12.9	12.4	0.5	0.44
aNDFom	8.2	7.9	8.7	8.4	0.4	0.06
uNDF240om	3.8[b]	3.7[b]	4.5[a]	4.4[a]	0.2	<0.01
Ruminal turnover rate, %/h						
OM	8.7	8.8	8.4	8.0	0.4	0.15
aNDFom	4.4[x]	4.4[x]	4.2[xy]	3.9[y]	0.2	0.04
uNDF240om	2.7	2.8	3.0	2.7	0.1	0.29

[abc]Means within a row with unlike superscripts differ ($P \leq 0.05$).
[xy]Means within a row with unlike superscripts differ ($P \leq 0.10$).
[1]Undigested NDF at 240 h of in vitro fermentation.
[2]Physically effective NDF.
[3]Area under curve pH < 5.8; ruminal pH units below 5.8 by hour.

▪ Preliminary Synthesis: Physically Effective, Undigested NDF vs. Dry Matter Intake and Milk Responses

We have combined data from four experiments conducted at the Institute to further explore the relationship between dietary uNDF240 and DMI and ECM yield as well as the relationship between dietary peuNDF240 and DMI and ECM yield. The dietary formulations for these three studies were:

Study 1: the study just described (see Table 1; Smith et al. 2018a; 2018b).
Study 2: approximately 50 or 65% forage in the ration DM, with 13% haycrop silage (mixed mostly grass), and between 36 and 55% corn silage (either brown midrib 3 or conventional) in the ration DM (Cotanch et al., 2014).
Study 3: approximately 42 to 60% corn silage (brown midrib 3 or conventional) and 2 to 7% wheat straw (finely or coarsely chopped) in the ration DM (Miller et al., 2017).
Study 4: approximately 55% conventional or brown midrib 3 corn silage and 2.3% chopped wheat straw (Miner Institute, unpublished, 2019).

Details of ration formulation may be found in the references for each study. All of the diets fed in these four experiments were based heavily on corn silage, contained some combination of haycrop silage and chopped straw, and in Study 1 (the current study) two of the diets also contained substantial pelleted beet pulp to formulate the lower uNDF240, lower forage diet.

Figures 1 and 2 illustrate the relationships that we observed when we combined the data from these studies. For these types of diets, both uNDF240 and especially peuNDF240 appear to be usefully related with DMI and ECM production.

At the moment, it is important to restrict these inferences to similar diets (i.e., corn silage with hay and fibrous byproducts) because more research is required with varying forage types and sources of uNDF (forage vs. non-forage) to determine the robustness of the relationships shown in Figures 1 and 2. In particular, legumes such as alfalfa contain more lignin and uNDF240 but have faster NDF digestion rates than grasses, and we might expect different relationships between dietary uNDF240 and DMI for legume- vs. grass-based rations. In fact, research has shown that high levels of uNDF240 intake may be achieved when lactating cows are fed finely chopped alfalfa hay (Fustini et al., 2017) in part because alfalfa contains more uNDF240 than do grasses (Palmonari et al., 2014; Cotanch et al., 2014).

Interestingly, a 2018 field study using 59 commercial dairy herds assessed the influence of corn silage uNDF measured at 30 and 240 hours with near infrared reflectance spectroscopy on herd DMI and performance (Geiser and Goeser, 2019). Negative relationships between uNDF240 and DMI and and between uNDF240 and ECM were noted. In the future, we hope that potential relationships between uNDF, peuNDF, and DMI and milk yield will be explored for a wide range of diets and management scenarios on commercial dairy farms.

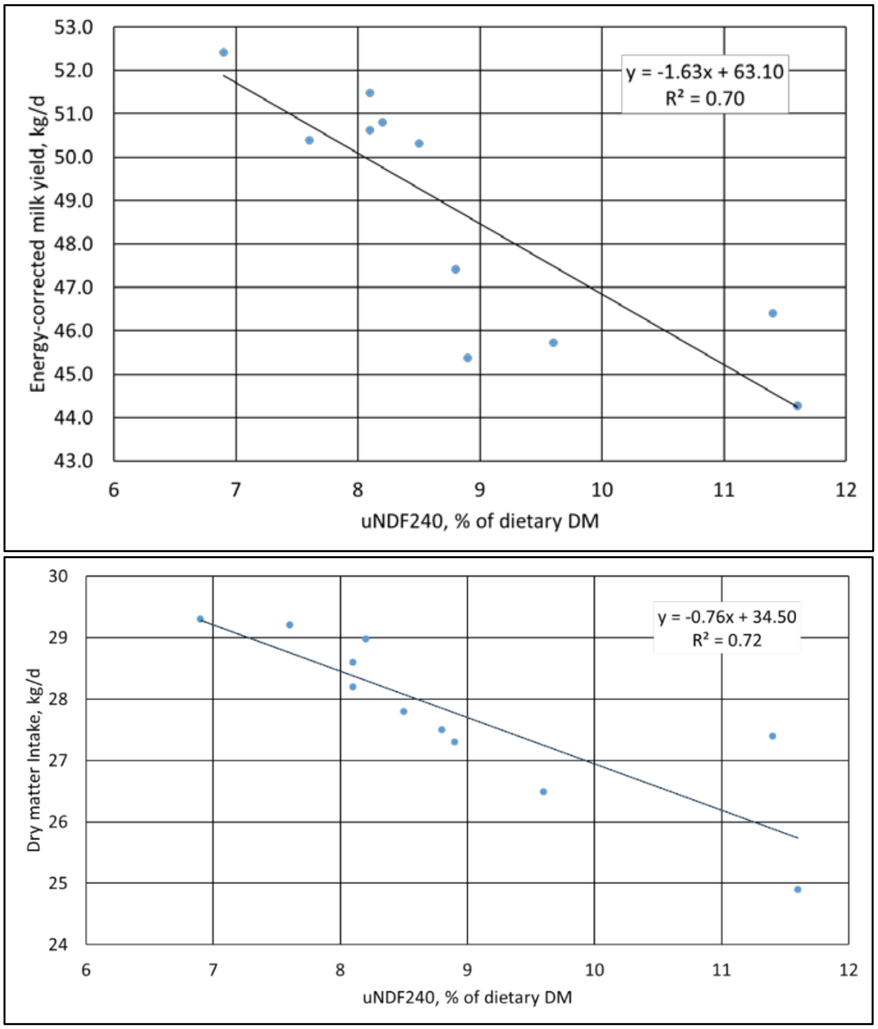

Figure 1. Relationship from four studies between dietary uNDF240 and DMI and ECM yield for cows fed diets based on corn silage, haycrop silage, and chopped wheat straw.

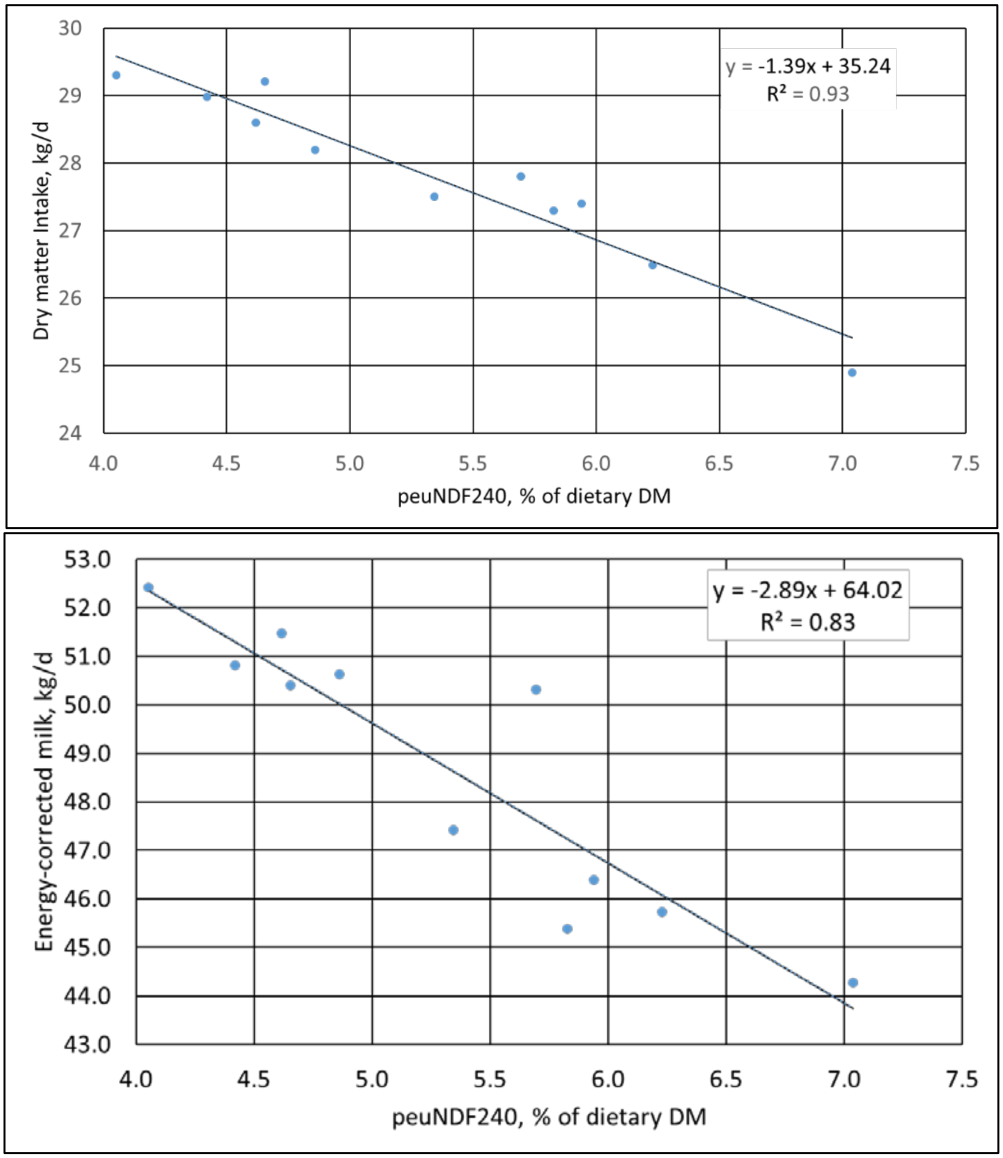

Figure 2. Relationship from four studies between dietary peuNDF240 and DMI and ECM yield for cows fed diets based on corn silage, haycrop silage, and chopped wheat straw (peuNDF240 = physically effective undigested NDF measured at 240 hours of in vitro fermentation).

▪ Summary and Perspectives: A Tale of Two Fibres

The calculated 'physically effective uNDF240' (pef x uNDF240) appears to be a useful concept when interpreting cow response to the diets fed in this study and studies with similar types of diets. Our goal is not to invent yet another nutritional acronym but to focus on a potentially useful concept. We were able to elicit the same response by the cow whether we fed lower uNDF240 in the diet with greater peNDF, or whether we fed higher uNDF240 but chopped the dry hay more finely. In other words, the peuNDF240, or integration of pef and uNDF240, was highly related to DMI and ECM yield.

If future research confirms this relationship between dietary uNDF240 and DMI, it suggests that when forage fibre digestibility is lower than desired, a finer forage chop length will boost feed intake and lactational response. In addition to investigating potential and probable differences between legumes and grasses, we also must understand the potential responses to forage and non-forage sources of fibre.

As Charles Dickens wrote in his classic novel *Tale of Two Cities* "It was the best of times, it was the worst of times." When it comes to fibre, it looks like we can have the best of times when we are able to integrate two measures of fibre—uNDF240 and peNDF—when formulating rations (Grant, 2018). Research is needed to test this relationship in alfalfa-based diets, pasture systems, and other feeding scenarios that differ markedly from a typical Northeastern and upper Midwestern U.S. diet based primarily on corn silage.

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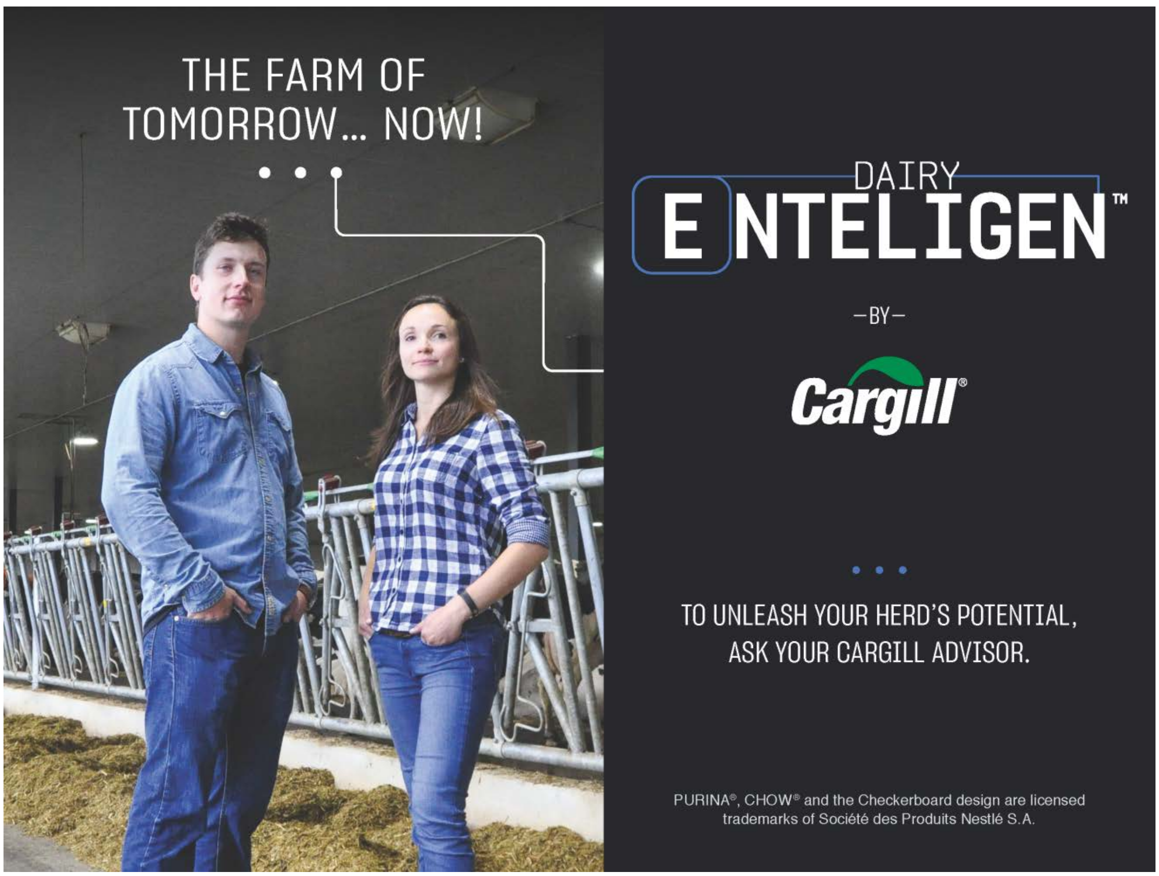
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