DETERMINATION OF FIRST LIMITING PHYSICAL FACTORS IN CORN SILAGE HYBRIDS: MODELING MULTIPLE POOLS OF RUMINAL aNDFom DIGESTION

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INTRODUCTION

The development of field usable models to describe nutrient supply and requirements has evolved and those models are now commonly used to evaluate most limiting nutrient supply on farms (NRC, 2001; Tylutki et al., 2008; Van Amburgh et al., 2015). To effectively use these models, characteristics of the forages, feeds, cattle and environment need to be inputted to establish the basis for the evaluation. Aside from the chemical composition of the forages and feeds being used, the other most relevant characteristics are the body weight (BW) and milk production of the cattle and their dry matter intake (DMI). From a modeling perspective, DMI is estimated by equations that are primarily developed using BW and energy corrected milk yield to drive demand (NRC, 2001; Tylutki et al., 2008). These equations account for approximately 60% of the variation in DMI and accordingly, other characteristics are used to describe intake such as particle size, feed availability, palatability, fermentation characteristics, cow time budgets, barn design, over-crowding and related functions that impact DMI (Grant and Albright, 2001; Allen et al., 2009; Gomez and Cook, 2010; De Vries et al. 2015).

Further, DMI can be affected by either physical or chemical fill mechanisms (Mertens, 1987; Allen, 2009) although few models have been able to fully describe these mechanisms. Among feeding systems, fiber has been described for its role in maintaining normal rumen health, chewing and rumination and milk composition (Mertens, 1997). Further, Mertens has indicated (Mertens, 1977; Mertens and Ely, 1979) that overall digestion is better predicted assuming that the potentially digestible NDF (pdNDF) fraction is the sum of two digestible fractions that can be described by two first order functions but with different rate constants. Following this, Ellis et al. (2005) demonstrated an improved fit of a two-pool pdNDF model that assumed two concurrently degrading sub-entities of pdNDF with different degradation rates. In addition, Huhtanen et al. (2008) has shown a marked improvement of a model when pdNDF was assumed to be comprised of rapidly and slowly degradable fractions.

The most recent version of the Cornell Net Carbohydrate and Protein System (CNCPS, v7) was developed based on these observations of multiple pools of aNDFom digestion. The model uses uNDF measured at 240 h in vitro digestibility (Raffrenato et al., 2018) and then partitions the aNDFom into two digestible pools, a “fast” and “slow” pool that are described relative to each other and digest concurrently with two distinctly different rates that most likely represent the degree of cross-linking between lignin and the carbohydrate fractions in the plant (Raffrenato et al., 2017). This approach, when linked to the appropriate passage rate, appears to allow for a better description of rumen disappearance of aNDFom because the size of the pools can shift based on the agronomic effects on the growth of the plant and these shifts are not explained by a single pool, integrated rate of digestion or by the chemical composition of the plant. As the size of the fast pool increases, the rate of passage decreases, but the extent of digestion increases and in cattle fed high quality forages, a large percentage of the disappearance can be explained by microbial activity, independent of the chewing and rumination and particle size reduction.

Further, corn silage hybrids and varieties have been evaluated by many metrics that have been useful at selecting improved forages (e.g. Milk 2006; Schwab et al., 2003). Those approaches consider digestibility, starch content and also provide economic benefits for forage yield, which is an important variable, but do not consider factors that might impact DMI, such as characteristics that might affect physical fill. The approach they take for digestibility improves the prediction of energy intake by increasing DMI by 0.27 lb for every % change in 30 h NDFD. Given that digestibility can be different by growing season and this can impact both the total NDFD and the uNDF, it is likely that forages vary from year to year and these differences in digestibility are currently not accounted for with respect to what limits intake among seasons and this would be helpful as the development of diets would improve if these characteristics were accounted for.

MATERIALS AND METHODS

2017 NY and VT Corn Silage Hybrid Trials

In 2017 a total of 72 hybrids were evaluated in New York and Vermont from 16 suppliers (Table 1). Seed companies were invited to submit hybrids into either maturity group for a fee. The purpose of this trial was to provide independent, local data to aid in producer's decision making and consultation recommendations. Twenty-three hybrids were entered into the 80-95 day relative maturity group (Early-Mid) and were tested at two locations in NY (Hu-Lane Farm in Albion and the Willsboro Research Farm in Willsboro) and one location in VT (Borderview Farm in Alburgh). Forty-nine hybrids were entered into the 96-100 day relative maturity group (Mid-Late) and were tested at two locations in NY (Greenwood Farms in Madrid and the Musgrave Research Farm in Aurora) and one location in VT (Borderview Farm in Alburgh).

The average Growing Degree Days (GDD; 86-50°F system) from May through August for years 2005 to 2017 is 2031 GDD at Albion, 2025 GDD at Willsboro, 1971 GDD at Alburgh, 2071 GDD at Aurora, and 1939 GDD at Madrid (Table 2a and 2b).

All hybrids were planted using a two-row planter at 34,000 plants/acre. Each plot consisted of four 20' rows spaced 30 inches apart with harvest of the inner two rows. The early-mid hybrids were planted in Alburgh, VT on May 18th, in Albion, NY on May 17th, and in Willsboro on May 21st. The mid-late hybrids were planted in Alburgh, VT on May 17th, in Madrid, NY on May 18th, and in Aurora, NY on May 25th. Hybrids were planted in a randomized complete block design, with 3 replications. The Albion, NY site has a Hilton loam soil type, was previously planted with soybeans and received 32 units N/acre at planting and an additional 132 units N/acre was applied as side-dress. The Willsboro, NY site has a Stafford fine sandy loam soil type, was previously planted with Fallow, received 15 units N/acre at planting and 90 units N/acre were applied as side-dress.

Table 1. Seed companies that participated in this hybrid evaluation process.

Hubner Seed	Dyna-Gro
Schlessman Hybrids	King Fisher
Growmark FS	Seedway
Dekalb	Augusta Seed
Pioneer	Wolf River Valley Seeds
Dairyland Seed	Doelber's
NK Syngenta	Channel
Masters Choice	Dyna-Gro

Both Alburgh, VT sites have a Covington silty clay loam soil type, were previously planted with corn and received 25 units N/acre at planting. Additionally, 125 units N/acre were applied as side-dress at both VT locations. The Aurora, NY site has a Honeoye silt loam soil type, was previously planted with winter wheat, and received 25 units N/acre at planting and an additional 107 units N/acre were applied as side-dress. The Madrid, NY location has a Stockholm loamy fine sand soil type, was previously planted with 4^{th} year corn and received 94 units of manure N/acre prior to planting with an additional 32 units N/acre at planting. The Madrid site did not receive side-dress nitrogen.

The early-mid hybrids were harvested on Sept. 12^{th} in Albion, Sept. 26^{th} in Willsboro, and Sept. 20^{th} in Alburgh. The mid-late hybrids were harvested on Sept. 20^{th} in Aurora, Sept. 28^{th} in Madrid, and Sept. 28^{th} in Alburgh. From planting to harvest, the early-mid hybrids had 2004 GDD in Albion, 2131 GDD in Willsboro, and 1928 GDD in Alburgh (86-50 system). From planting to harvest, the mid-late hybrids had 1975 GDD in Aurora, 2087 GDD in Madrid, and 2077 GDD in Alburgh (86-50 system). The goal was to harvest all hybrids at about 65% (±3%) moisture at a target cutting height of 6 to 8 inches.

A sample, approximately 500 g, was taken in duplicate per plot replicate, resulting in 18 samples per entry across the three sites. Samples were sealed in a gallon-sized freezer bag and placed in a chest freezer with the addition of ice packs for transportation back to Cornell University or the University of Vermont where they were transferred to a -20°C freezer and/or shipped overnight for immediate analysis. One of the duplicate samples from each plot was kept as a retained sample while the other sample (9 samples/hybrid entry across the three sites) was submitted to Cumberland Valley Analytical Services (Waynesboro, PA) where NIR procedures were used to determine CP, starch, lignin, ash, total fatty acids (**TFA**), aNDFom, NDF digestibility (**NDFD**; 12, 30, 120, 240 h), undigested NDF (**uNDFom**; 30, 120, and 240 h) and 7-h starch digestibility. Several companies paid an additional fee for wet chemistry analysis on NDFD at 30 h.

Feed Chemistry Information and Management

All 648 replicates of the pre-ensiled material were submitted, as frozen samples, and a full suite of analysis was requested with aNDFom fermentation time point of 30h, 120h and 240h all by NIR analysis. Given the pre-ensiled nature of the forages, feed fractions such as soluble protein, ammonia, VFAs, organic acid, 7-h starch digestibility were discarded and replaced with the closest representative CNCPS feed library example of corn silage that matched the CP, starch content, aNDFom, ADF, lignin, ash, and the aNDFom digestibility. The corn silages were edited to reflect the chemistry and the digestibility of the trial forages.

Table 2a: The 2017 rainfall and growing degree days for the 80-95 RM corn silage varieties planted in New York and Vermont.

	Rainfall, inches			Growing Degree Days (GDD), 86/50		
	Alburgh, VT	Albion, NY	Willsboro, NY	Alburgh, VT	Albion, NY	Willsboro, NY
May	3.81	6.46	4.10	243	244	251
June	7.02	2.64	8.23	435	498	471
July	5.38	5.26	2.99	544	622	595
August	4.74	3.26	2.14	522	573	574
September	1.92	1.55	2.34	428	459	450
May-August	20.95	17.62	17.46	1743	1936	1890
May-September	22.87	19.17	19.80	2171	2395	2339
Average 2005-2017						
May-August	18.26	13.74	15.77	1971	2031	2025
May-September	22.30	16.90	18.77	2355	2443	2434

Table 2b: The 2017 rainfall and growing degree days for the 96-110 RM corn silage varieties planted in New York and Vermont.

	Rainfall, inches			Growing Degree Days (GDD), 86/50		
	Alburgh, VT	Aurora, NY	Madrid, NY	Alburgh, VT	Aurora, NY	Madrid, NY
May	3.81	4.54	6.88	243	253	249
June	7.02	4.14	5.84	435	467	453
July	5.38	6.99	6.76	544	595	555
August	4.74	1.56	3.81	522	529	514
September	1.92	2.29	2.05	428	424	407
May-August	20.95	17.23	23.29	1743	1843	1771
May-September	22.87	19.52	25.34	2171	2267	2177
Average 2005-2017						
May-August	18.26	14.28	16.97	1971	2071	1939
May-September	22.30	17.84	20.87	2355	2483	2320

In order to utilize the fermentation time points we calculated the rates and pool sizes for the aNDFom using the calculations of Raffrenato et al. (2018, accepted).

A large range in aNDFom and uNDF content and aNDFom digestibility among the corn forage samples was observed (Figure 1). This introduced complications as it was not feasible to evaluate all hybrids utilizing one standard diet at one initial intake level. Therefore, it was decided to split the data file into two distinct datasets, based on hybrid aNDFom content (roughly 30-40% and 40-50%). After assembling the feed analysis from each hybrid and a corresponding CNCPS corn forage template, a mass balance check was conducted for each hybrid to ensure accurate description of complete feed chemistry (i.e. CP + aNDFom + Sugar + Starch + Ether extract + Soluble fiber + Organic acid + Ash = 100). At this point, the corn forage feed chemistry data was in a compatible format that could be then imported into CNCPS version 7.0.

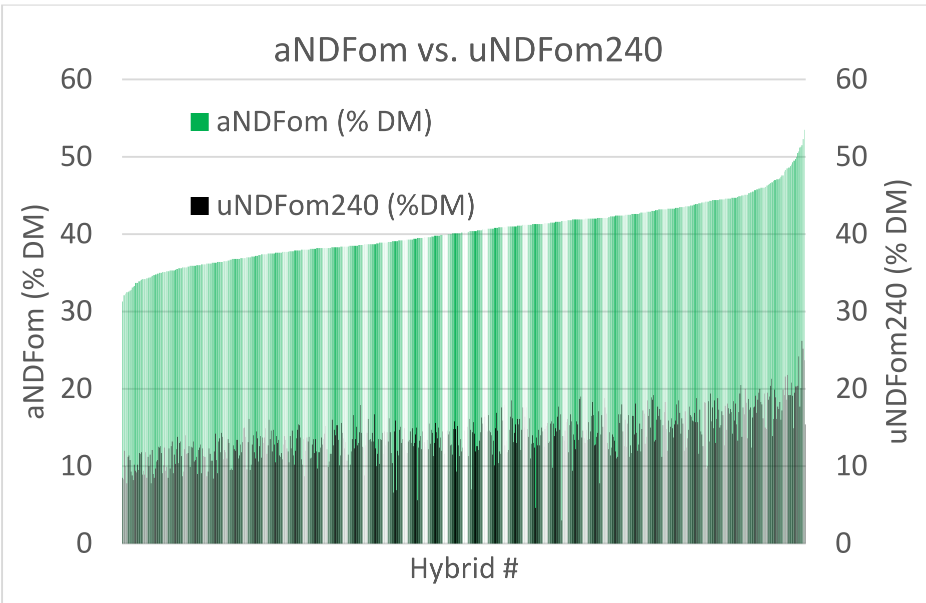

Figure 1. The aNDFom and uNDF of 648 replicates of 72 corn silages grown in three different locations in the Northeastern U.S. sorted on aNDFom from lowest to highest content.

Model Set Up

Two typical New York high corn silage-based diet (forage at ~60% of diet DM; corn silage ~70% of forage DM) were formulated in the CNCPS v7. Corn silage inclusion levels were maximized as much as possible as this was the variable of interest. Due to the higher levels of aNDFom and relatively high proportion of uNDFom of the corn silage analyzed, a digestible grass silage with low uNDFom was selected to complement this corn silage. Urea was also included as a rumen ammonia source to ensure adequate rumen ammonia levels so that fiber digestion by microbial action would not be impeded. The remaining ingredients are all typically included in Northeast diets and were included at levels so that diet formulation would match the standard animal requirements.

All diet ingredients were the same between both corn silage databases however, inclusion levels, in particular forage inclusions levels, were reduced to adjust for the moderate quality corn silage database. Ingredients included and nutrient composition of the standard diets are in Table 3. The two standard diets differed in the proportion of forage that comprised the diet and the total dry matter intake achieved. These two differences were largely due to the average quality/digestibility variation between the two corn silage databases. For each model simulation iteration, the corn silage hybrid and associated chemistry analysis was the only variable changing among runs. These diets were then fed to two standardized groups of cattle. The standardized cattle were developed based on typical Northeastern cattle parameters such as average body weight and performance capability. Dry matter intake was calculated to meet animal demands ensuring that intake (3-3.3 %BW) was realistic along with aNDFom intake (1% BW). The aNDFom intake levels were lower than typically achieved again due to the moderate quality of the corn silage being evaluated. The animals were 110 days in milk and were designed to be in a state where no tissue was being mobilized or deposited. Animal inputs of the two standard cows are described in Table 4.

Table 3. Base diet ingredients for CNCPS evaluations.	kg DM	% DM
Corn silage processed 35 DM 41 NDF medium	10.19	42
Grass silage 20 CP 48 NDF 5 LNDF	4.59	19
Corn grain ground fine	4.16	17
Canola meal solvent	0.99	4
Corn dist ethanol	0.38	2
Soybean hulls ground	0.50	2
Citrus pulp dry	0.50	2
Wheat midds	1.00	1
Extruded soybeans	0.89	4
Blood meal average	0.42	2
Energy Booster 100	0.17	1
MinVit +urea + rumen protected methionine	0.70	3.1
Total	24.49	100

Initially, all hybrids were simulated through the model at equal intakes. The simulated intakes were purposely lower than typically achieved (aNDFom intake <1.2% BW) as this year's corn silage had consistently lower digestibility than previous years. Typically, in this scenario, forage inclusion rate in the diet would decrease however as this was the variable of interest, corn silage inclusion was maintained as high as possible. Through utilization of the dynamic approaches of CNCPS v7, rumen aNDFom fill numbers were generated at steady state for each hybrid evaluated. Subsequently, the first limiting fill number was determined based on the quantity of aNDFom or uNDF fill in the rumen for each hybrid as every other ingredient in the diet was held constant.

Table 4. Animal characteristics and model inputs for the higher and lower intake evaluation groups. Two diets were developed because the upper and lower limits were not achievable using the entire database given the range in both aNDFom and uNDF240.

Animal inputs	Base High	Base Low
Dry matter intake, kg	24.50	22.84
Milk production, kg	41	36
Milk fat, %	3.7	3.7
Milk true protein, %	3.1	3.1
Milk lactose, %	4.78	4.78
Body condition score	3	3
Target body condition score	3	3
Age of first calving	22	22
Days in milk	110	110
Days pregnant	30	30
Calving interval	13	13
Calf birthweight, kg	44	44
Mature weight, kg	803	803
Age, months	39	39
Current weight, kg	750	750

There was a large range in predicted changes in DMI due to the range in aNDFom, uNDF and digestibility among the hybrids. The standard diets were formulated to achieve pre-determined rumen fill numbers based on rumen evacuation studies carried out at Cornell University and Miner Institute (Cotanch et al., 2014). These studies emptied the rumen contents on a number of animals and then tested a representative sample for aNDFom and uNDFom concentration. The maximum rumen uNDFom level in these studies was 0.66% BW. For our evaluation this resulted in a rumen uNDFom of 4.8 kg which corresponded to a total rumen aNDFom of 8.1 kg, which was ~1 % of body weight. These numbers were then established as the rumen fill set points. Hybrids that caused overfilling of the rumen by uNDF (i.e. poor digestibility), had to reduce their total diet DMI compared to those that under filled the rumen (i.e. high digestibility), where the calculated DMI was increased to achieve the set point. The set point was used to determine the difference in DMI from the standard diet as digestibility changed based on the rumen fill value from simulations at equal intake divided by standard diet rumen set point number (e.g. 5.24 lb/4.82 lb = 1.08). In this example, the rumen overfilled by 8%, which was determined infeasible based on rumen volume and therefore total DMI had to be reduced to achieve 100% of allowable fill (Figure 3). The fill adjustment factors were calculated for both total rumen aNDFom and uNDFom pool size and were applied on the basis of a first limiting physical fill approach. After the adjustment factors were applied to the total diet DMI, another model run was conducted, with the DMI adjusted to the first limiting levels based on the hybrid effect on rumen fill as described above. The total diet DMI was adjusted accordingly so that each hybrid met the first limiting allowable fill level. The resulting outcome due to altered DMI and corn silage digestibility, on allowable ME and MP milk production was recorded.

MODEL SIMULATION RESULTS

The model runs were conducted and examples are provided for two corn forages from the data set that are from each end of the range in digestibility to demonstrate the predictions for fill limitations. The potential to describe rumen fill based on aNDFom is in Figure 3. The base diet, with the average digestibility corn silage from the respective group, is the middle line on the curve and is highlighted by the rumen fill capacity line. The less digestible corn forage diet is described by the top line (Figure 3) and indicates at the given DMI, the rumen will overfill on aNDFom, so the DMI is infeasible with either the current inclusion level of corn silage or simply with the current diet formulation. The more highly digestible diet is described by the lower line and demonstrates that the digestion rate of the aNDFom is high enough to overcome an aNDFom fill limitation of that diet due to the difference in hybrid digestibility.

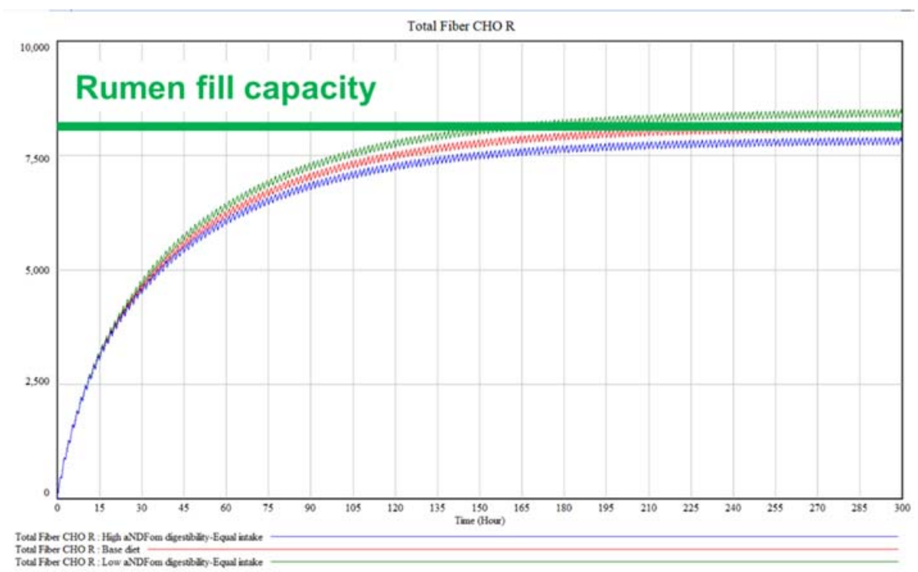

Figure 3. An example of an aNDFom rumen fill calculation from CNCPS v7 for diets a low, medium and high digestible corn silages.

A simple mathematical description of this behavior can be obtained by integrating the predicted passage rate and digestion rate of the respective pools of digestible aNDFom. In this example, we are using the passage rate for aNDFom incorporated in CNCPS v7 and with the current DMI, aNDFom level and BW, the passage rate is approximately 0.024/h. For one of the high digestibility forages, the fast pool is digesting at 0.012/h and is almost 70% of the total aNDFom, whereas for the low digestibility forage the fast pool is digesting at 0.07/h and is 53% of the aNDFom. Simple integration demonstrates that the fast pool of the higher digestibility corn silage is digesting 41% faster with an extent of digestion that is 11% greater than the lower digestibility corn silage. This difference creates more space in the rumen and potentially allows for greater intake because of the more rapid rumen disappearance (0.12/(0.12+0.024) =0.83 vs (0.07/(0.07+0.024) = 0.74. By integrating over time, in a dynamic model like CNCPS v7, this provides the capability of predicting first limiting physical fill characteristics, whether it was total aNDFom or if the uNDF fraction is large enough to create a fill limitation (Figure 3).

The base diet was the reference diet and represented the average corn silage in the split data set (high and low digestibility and aNDFom). The comparisons were made on either an aNDFom or uNDF basis and this is demonstrated in Table 5 where a high and low digestibility corn silage were used to compare to the base diet. In this comparison, the first limiting factor for physical fill for the low digestibility corn silage was the uNDF240 where it was predicted to be 420 g over the base diet limit. Conversely, the high digestibility diet was not limited by uNDF240 and further, didn't meet the fill expectation of aNDFom by approximately 300 g, thus, cattle fed this diet would be expected to consume more total dry matter, assuming based on diet formulation that other nutrients were not first limiting.

Table 5. The predicted amount of aNDFom in the fast, slow and uNDF pools based on the digestibility of the corn silage hybrids represented in this comparison at a constant dry matter intake. The fill limits for each aNDFom pool are described in the standard diet.

	Low aNDFom digestibility diet	**Base aNDFom digestibility diet**	**High aNDFom digestibility diet**
aNDFom fast pool, g	1,588	1,632	1,698
aNDFom slow pool, g	1,588	1,655	1,715
uNDF240, g	5,239	4,819 (0.64% BW)	4,395
Total rumen NDF, g	8,415	8,106 (1.1% BW)	7,809
Formulated DMI, kg	24.5	24.5	24.5

The low digestibility diet was decreased in intake by the equivalent of 420g of uNDF and the adjusted calculations for pool sizes and dry matter intakes are found in Table 6. After adjustment for physical fill, the DMI for the low digestibility diet was 2 kg lower than the base diet, whereas the high digestibility diet was predicted to consume 900 g additional DMI to reach the aNDFom fill level, thus the ME and MP allowable milk predictions are described by those DMI differences.

Over the entire dataset, the predicted difference in milk yield per kg of DMI was 2.6 kg which is most likely high given the intake opportunity, and is being evaluated to understand why the model estimated such a feed efficiency (Figure 4). However, it was uniform among the forage comparisons, so we believe it represented the differences among forages. The prediction of milk yield represents the effect of increased DMI with changes in the digestibility of the forage that captures the energy of increased starch, sugar and fat intakes, and also represents the additional energy derived from the higher digestible forage itself.

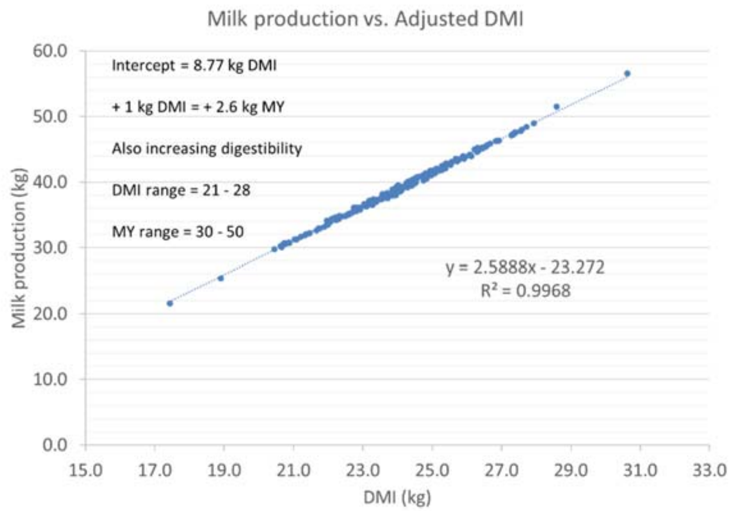

Figure 4. The prediction of dry matter intake and milk yield from the evaluation of the corn silage hybrids based on physical fill limitations of either aNDFom or uNDF240. The range in DMI among the data was 21 to 28 kg and the range in milk yield (MY) was 30 to 50 kg/d. The intercept of 8.77 kg represents the amount of intake needed to meet maintenance requirements.

Table 6. The predicted amount of aNDFom in each of the pools and total aNDFom in the rumen, and the overall dry matter intake and ME and MP allowable milk predictions after adjustment for rumen fill effects of either aNDFom or uNDF240. For the low digestibility diet, the fill was limited by uNDF240, whereas for the high digestibility diet, the fill was limited by total aNDFom which allowed for greater predicted dry matter intake on the high digestibility diet.

	Low aNDFom digestibility diet	**Base aNDFom digestibility diet**	**High aNDFom digestibility diet**
aNDFom fast pool, g	1,464	1,632	1,763
aNDFom slow pool, g	1,462	1,655	1,780
uNDF240, g	4,819	4,819	4,563
Total rumen NDF	7,745	8,106	8,106
Dry matter intake, kg	22.5	24.5	25.4
ME allowable milk, kg	35.8	40.9	43.3
MP allowable milk , kg	36.4	40.9	43.3

SUMMARY

The objective of this work was to develop an approach to rank the corn forage hybrids based on what we understand about rumen fill that integrated all of our current understanding of the behavior of aNDFom digestion in the rumen. The approach taken in this paper demonstrates the potential utility of having information and a procedure to evaluate the concepts of physical fill and DMI in conjunction with other components of the diet. This approach requires refinement to better describe intake limits due to chemical characteristics and rumen fill effects. However, through utilization of the dynamic mechanistic structure of CNCPSv7 and basing our assumptions on rumen evacuation data, a more robust prediction of the potential impact of each hybrid on DMI and milk production can be achieved. Ultimately the goal is to help forward predict the productive capability of the corn silage hybrid or any forage and gain a greater understanding of how to proactively formulate/complement these forages.

REFERENCES

Allen, M. S., B. J. Bradford and M. Oba. 2009. BOARD-INVITED REVIEW: The hepatic oxidation theory of the control of feed intake and its application to ruminants. J Anim Sci. 87:3317-3334.

Cotanch, K. W., R. J. Grant, M. E. Van Amburgh, A. Zontini, M. Fustini, A. Palmonariand A. Formigoni. 2014. Applications of uNDF in ration modeling and formulation. Pp 114-131. Proc. Cornell Nutr. Conf.

De Vries, A., H. Dechassa and H. Hogeveen. 2015. Crowding your cows too much costs you cash. WCDS Advances in Dairy Technology 27: 275-285.

Ellis, W. C., M. Mahlooji and J. H. Matis. 2005. Models for estimating parameters of neutral detergent fiber digestion by ruminal microorganisms. J. Anim. Sci.83:159-1601. https://doi.org/10.2527/2005.8371591x

Gomez, A., N. B. Cook. 2010. Time budgets of lactating dairy cattle in commercial freestall herds. J Dairy Sci. 93:5772-81. doi: 10.3168/jds.2010-3436.

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.):E156-E163

Huhtanen, P., A. Seppälä, S. Ahvenjärvi and M. Rinne. 2008a. Prediction of in vivo NDF digestibility and digestion rate of potentially digestible NDF: Comparison of models. J. Anim. Sci. 86:2657-2669.

Mertens D. R. 1987. Predicting intake and digestibility using mathematical models of ruminal function. J. Anim. Sci. 64:1548-1558.

Mertens, D. R. 1997. Creating a system for meeting the fiber requirements of dairy cows. J Dairy Sci. 80:1463–1481.

Mertens, D. R. and L. O. Ely. 1979. A dynamic model of fiber digestion and passage in the ruminant for evaluating forage quality. J. Anim. Sci. 49:1085-1095.

Mertens, D. R. 1977. Dietary fiber components: Relationship to the rate and extent of ruminal digestion. Fed. Proc. 36:187-192.

Milk 2006. Shaver, R. T. https://shaverlab.dysci.wisc.edu/spreadsheets/

NRC, 2001. Nutrient Requirements of Dairy Cattle. 7th. Rev. ed. Natl. Acad. Sci., Washington, DC.

Raffrenato, E., C. F. Nicholson and M.E. Van Amburgh. 2018. Development of a mathematical model to predict pool sizes and rates of digestion of two pools of digestible NDF and an undigested NDF fraction within various forages. J. Dairy Sci. (accepted)

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. (in press)

Raffrenato E., R. Fievisohn , K. W. Cotanch, R. J. Grant, L.E. Chase, M.E. Van Amburgh. 2017. Effect of lignin linkages with other plant cell wall components on in vitro and in vivo neutral detergent fiber digestibility and rate of digestion of grass forages. J Dairy Sci. 100:8119-8131.

Schwab, E. C., R. D. Shaver, J. G. Lauer and J. G. Coors. 2003. Estimating silage energy value and milk yield to rank corn hybrids. Anim. Feed Sci. and Tech.109:1–18.

Tylutki, T.P., D.G. Fox, V.M. Durbal, L.O. Tedeschi, J.B. Russell, M.E. Van Amburgh, T.R. Overton, L.E. Chase and A.N. Pell. 2008. Cornell Net Carbohydrate and Protein System: A model for precision feeding of dairy cattle. Anim. Feed Sci. Tech. 143:174 – 202.

Van Amburgh M.E., E. A. Collao-Saenz, R. J. Higgs, D. A. Ross, E. B. Recktenwald, E. Raffrenato, L. E. Chase, T.R. Overton, J. K. Mills, A. Foskolos. 2015. The Cornell Net Carbohydrate and Protein System: Updates to the model and evaluation of version 6.5. J Dairy Sci.98:6361-80. doi: 10.3168/jds.2015-93 78.