Gut Fill Revisited

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Summary

Generally, a dairy cow's daily dry matter intake **(DMI)** will be under the influence of the physical capacity of the rumen. This is known as gut fill. As demonstrated by several research groups, the undigested NDF pool is related to gut filling effect of a ration. Specifically, it is suggested that $\text{NDF}_{u30}^{\copyright}$, i.e., the undigested NDF pool remaining after 30 hr of in vitro rumen incubation, is an appropriate proxy for gut fill. The proposed gut fill index for a ration is pounds of $\text{NDF}_{u30}^{\copyright}$ supplied from forages and other products that are larger than 4 mm. Monitoring a ration's gut fill index will assist in identifying ration changes that may impact DMI. However, rumen environments which change overall fiber digestibility will bias the gut fill index. Under higher acid conditions, fiber digestibility will be compromised, leading to a falsely lower gut fill capacity. Rations with low particle size will result in increased passage rates, leading to a falsely higher gut fill capacity. In general, corn silage will have the lowest $\text{NDF}_{u30}^{\copyright}$ pool size of forages, with most grasses having $\text{NDF}_{u30}^{\copyright}$ pools size approximately 35% larger. $\text{NDF}_{u30}^{\copyright}$ is meant to be an indicator of gut fill that is appropriate for evaluating forages as well as, the gut fill load for a ration's forage base.

Introduction

Gut fill is generally referred to as the physical distention of the rumen resulting in cessation of a meal. This phenomenon has been recognized for decades. Perhaps one of the earliest characterizations of gut fill was presented by Conrad (1966) where several digestion trials were summarized. These trials suggested that as dry matter disappearance **(DMD)** increases to 66%, that DMI concomitantly increases. It is appropriate to conclude that DMD defines gut fill in this discussion. Beyond 66% DMD, DMI decreases as DMD increases presumable due to factors other than gut fill. Studying the relationship between chemical composition of feeds and DMD, Goering and Van Soest (1970) published the following equation:

$$\text{DMD} = \text{NDF}^{*}\text{NDFD} + 0.98\ \text{NDS} - 12.9,$$

where NDF = neutral detergent fiber, NDFD = digestibility of the NDF, and NDS = neutral detergent solubles which is defined as 1-NDF. On the surface, this equation seems difficult to interpret. Mertens (2010) mathematically rearranged this equation, revealing the following equation:

$$\text{DMD} = 87.1 - (0.98 - \text{NDFD})^{*}\text{NDF}$$

This equation suggests that the maximal DMD is 87.1% and will decrease as NDF increases and

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NDFD decreases. It has recently been suggested that the proper interpretation of this equation is that DMD is related to the pool size of undigested NDF defined as (1-NDFD)*NDF (Jones, 2014). Logically, it can be demonstrated that gut fill is related to the pool size of undigested NDF.

The Rise of NDFd and Subsequently NDF$_{u30}^{\copyright}$

Even though NDF digestibility has been in the scientific discourse since the 1960's, the classic view is that NDF as a percent of body weight **(BW)** is a principle influencer of DMI. The following equation was utilized in Merten's (2010) intake model:

$$\text{NDF intake} = 1.25\% * \text{BW}$$

Waldo (1986) suggested that cell wall concentration (i.e., NDF) of forage diets is the best single chemical predictor of DMI by ruminants.

However, it is clear that increasing NDF digestibility increases intake (Oba and Allen, 1999). This understanding led to forages being characterized by NDF digestibility (NDFd; % of NDF). Allen (2000) concluded that "Digestibility of NDF measured in vitro or in situ using a constant incubation time was a significant indicator of the filling effects of NDF …".

A common convention is to use a 30-hr in vitro incubation to estimate NDF digestibility (NDF$_{d30}$,% of NDF). Feeds with higher NDF$_{d30}$ (% of NDF) are generally found to promote more intake. However, the effect of the potentially digestible NDF fraction on gut fill was not clear when evaluated by Allen and Mertens (1988).

Jones and Siciliano-Jones (2013) proposed that the proper characterization of fiber related to intake is the pool size of undigested fiber (NDF$_{u}$; % of DM). Following the convention presented above, the pool size of undigested fiber after a 30-hr *in vitro* incubation was introduced (NDF$_{u30}^{\copyright}$; % of DM, Copyright FARME Institute, Inc).

Hall (2013) discussed a debate over which incubation time is most appropriate for estimating NDF digestibility (Figure 1). The NRC (2001) uses a 48 hr incubation time to estimate energy derived from NDF. Our purpose is to estimate "gut fill" which must take into account passage rate. The 30-hr incubation time point seems appropriate given static in vitro fermentation and a standard particle passage rate. If the remaining particles have not been fermented or passed, they contribute to gut fill.

It is important to differentiate between the terms of "undigested" and "indigestible". The former refers to the ability to be digested given a finite time. In this case, 30 hr. The latter refers to the ability to be digested given infinite time. Usually, this is estimated at 240 hr of incubation in rumen fluid.

Examining previous work on the NDF digestibility, expressed as percent of the NDF fraction, we can substitute the measure of NDF$_{u30}^{\copyright}$ expressed as pool size. Previous work that increased NDF digestibility in diets also decreased NDF$_{u30}^{\copyright}$, usually without noting it. For example, Allen (2000) notes that "DMI by cows will be less limited by distention in the gastrointestinal tract as NDF digestibility increases." The concept of fiber digestibility impacting gut fill is not new. However, the proper representation and utilization of NDF$_{u30}^{\copyright}$ as a gut fill indicator is new.

$\mathrm{NDF}_{u30}^{\copyright}$ in Ration Design

In February 2015, the US Patent Office issued a patent which contains claims for the use of undigested NDF and starch digestibility for ration formulation (Weakley, 2015).

$\mathrm{NDF}_{u30}^{\copyright}$ is proposed as an indicator of gut fill to be used in designing certain dairy cow rations (Jones and Siciliano-Jones, 2014). First, it is only appropriate to discuss $\mathrm{NDF}_{u30}^{\copyright}$ in rations where DMI is limited by gut fill. This is typical of intakes during peak production (Mertens, 2010). Situations where DMI is limited by low energy requirement or acid load will likely not respond to manipulating $\mathrm{NDF}_{u30}^{\copyright}$ content.

$\mathrm{NDF}_{u30}^{\copyright}$ acts as a gut fill factor only when fed particle size is large enough to inhibit passage from the rumen. The threshold particle size allowing passage from the rumen appears to be 2 to 4 mm (Allen and Mertens, 1988). Consequently, undigested NDF in particles below this threshold will not be expected to contribute to gut fill as they are not retained in the rumen. Therefore, we propose calculating the pool size of $\mathrm{NDF}_{u30}^{\copyright}$ only on feeds that have a particle size above 4 mm. In general, only forages and certain large particle by-products (e.g., whole cotton seed) are included in calculating the gut fill load.

Our basic procedure is to calculate the $\mathrm{NDF}_{u30}^{\copyright}$ content (i.e., gut fill) in the forage portion of a ration for a high producing group of cows. As a starting point, high producing large Holstein cows appear to eat to gut fill of approximately 6.2 to 6.5 lb/day of $\mathrm{NDF}_{u30}^{\copyright}$. However, what is important is how this $\mathrm{NDF}_{u30}^{\copyright}$ content changes over time relative to DMI (Jones, 2014). If a forage or ration change results in increased gut fill in the proposed ration, there is a high probability that DMI will decrease such that the group's actual threshold of $\mathrm{NDF}_{u30}^{\copyright}$ capacity is not exceeded.

Using the above procedure requires 2 assumptions. First, it is assumed that gut fill is the rations most constraining factor. Second, a forage base (including all significant sources of $\mathrm{NDF}_{u30}^{\copyright}$) must be the initial component of ration design. Designing a ration with $\mathrm{NDF}_{u30}^{\copyright}$ starts with a forage base that does not violate a gut fill. This is also intuitive since a ration should be first balanced for the rumen and then for the animal.

It is tempting to discuss $\mathrm{NDF}_{u30}^{\copyright}$ as a percent of ration dry matter. This has benefits for ration formulation but does not reflect the underlying subject that gut fill is a pool size issue. Let's start with a farm specific assumption that the highest producing cows have not historically consumed more than 6.3 lb of $\mathrm{NDF}_{u30}^{\copyright}$. Problems arise when a group is balanced for a DMI which is below that consumed by the highest producing cows. For example, a group ration might be balanced for 53 lb of DMI. However, the highest producing cows might be eating 70 lb of DM to support peak milk production. A typical calculation is to determine the percentage of $\mathrm{NDF}_{u30}^{\copyright}$ to ensure that the highest producing cows are not challenged with more than 6.3 lb of $\mathrm{NDF}_{u30}^{\copyright}$ intake. In this case, the base ration needs to be 9% $\mathrm{NDF}_{u30}^{\copyright}$ (6.3 lb $\mathrm{NDF}_{u30}^{\copyright}$/70 lb intake). Conversely if $\mathrm{NDF}_{u30}^{\copyright}$ percentage is calculated from the group intake (6.3 lb $\mathrm{NDF}_{u30}^{\copyright}$/53 lb intake), the $\mathrm{NDF}_{u30}^{\copyright}$ content will increase such that the highest producing cows will reach their fill capacity at a reduced DMI. Recommendations for $\mathrm{NDF}_{u30}^{\copyright}$ as a percentage of DM should be avoided for this reason. This calculation is only useful in determining if the base ration for a group will support the highest producing cows.

Common ration design rules can violate the gut fill capacity of cows, resulting in lower milk production. For example, a common ration feature is inclusion of 3 lb of WCS (DM basis) in all diets. Assuming that WCS is 40% $\text{NDF}_{\text{u30}}^{\copyright}$, WCS contributes 1.2 lbs of $\text{NDF}_{\text{u30}}^{\copyright}$ to these diets. In a year when NDF digestibility of corn silage is poor (e.g., $\text{NDF}_{\text{u30}}^{\copyright}$ increases from 15 to 18%), a ration containing 20 lb of corn silage will see an increase of 0.6 lb of $\text{NDF}_{\text{u30}}^{\copyright}$. Without adjusting the WCS or the corn silage inclusion rates, the high producing cows will have DMI limited by gut fill due to excess $\text{NDF}_{\text{u30}}^{\copyright}$.

A common consequence of exceeding the gut fill capacity of high producing cows is lower than expected peak production. When DMI is limited by gut fill, the highest producing cows will be impacted the most due to the inability to consume sufficient DMI. When older animals are peaking poorly compared to their younger cohorts, especially when persistency is high, a gut fill problem should be suspected.

Distribution of $\text{NDF}_{\text{u30}}^{\copyright}$ in Forages

Figure 2 contains the distribution of NDF_{u30} for both corn silage and hay crop silage in the Cumberland Valley Analytical Services (Hagerstown, MD) database. Corn silage has a mean $\text{NDF}_{\text{u30}}^{\copyright}$ value of 17.2%. For hay crop silage, the mean is 23.9% NDF_{u30}. Hay crop silage is about 35% higher in $\text{NDF}_{\text{u30}}^{\copyright}$ than corn silage.

The variance seen in these distributions suggest fairly large gut fill differences. First, it becomes clear why high corn silage diets generally result in less gut fill. The average corn silage sample has nearly 7 percentage points less $\text{NDF}_{\text{u30}}^{\copyright}$. A ration that contains equal amounts of average corn silage and average haylage with a constraint of 6 lb of $\text{NDF}_{\text{u30}}^{\copyright}$ will contain 29 lb of forage. Conversely, a diet with 80% average corn silage and 20% average haylage will allow 32 lb of forage.

A common scenario occurs when a growing year results in lower fiber digestibility (i.e., higher NDF_{u30}). Consider again a 80:20 corn silage:haylage diet when the $\text{NDF}_{\text{u30}}^{\copyright}$ changes from an excellent corn silage (25% quartile; 14.97 % $\text{NDF}_{\text{u30}}^{\copyright}$) to a poor corn silage (75% quartile, 19.12% $\text{NDF}_{\text{u30}}^{\copyright}$). The $\text{NDF}_{\text{u30}}^{\copyright}$ content of the diet will increase from 6 to 7.3 lb. If our group was eating 66 lb of DM (9% $\text{NDF}_{\text{u30}}^{\copyright}$), the intakes will probably decrease to 54 lb due to increased gut fill.

A related topic is the accuracy of NDF digestibility as measured in the laboratory. One should remember that digestibility testing has been common since the 80's (Nocek and Russell, 1988) and was intended to be a qualitative test for ranking forages since the variability is much higher than typical chemical analyses performed on forages. Hall and Mertens (2012) reported that within a given laboratory, 95% of the digestibility results for a given forage sample fall between ± 4.9% NDFD from the mean. If we use a typical forage consisting of 40% NDF and a 50% NDFd, then the $\text{NDF}_{\text{u30}}^{\copyright}$ will be 20%. If the NDFd measure varies from 45 to 55%, then the $\text{NDF}_{\text{u30}}^{\copyright}$ will vary from 18 to 22%. This does not take into account the variation inherent in NDF chemical analysis which would further increase the range of values. Using $\text{NDF}_{\text{u30}}^{\copyright}$ as a gut fill index is consistent with the notion of a qualitative index.

When Does Predicted $\text{NDF}_{\text{u30}}^{\copyright} \neq$ Actual $\text{NDF}_{\text{u30}}^{\copyright}$?

As forage analysis evolves, it is becoming more biological than chemical in nature. For example, measuring starch content is a simple chemical analysis. Conversely, estimating starch availability requires mimicking the biology of starch digestion. This is also true for NDF digestibility. To correctly apply $NDF_{u30}^{©}$ in ration design, it is important to explore scenarios where the predicted $NDF_{u30}^{©}$ does not properly estimate the biological $NDF_{u30}^{©}$.

As an example, consider the haylage sample shown in Figure 3. The NDF_{u30} is 27% of the DM. If our new diet design calls for 2 lb of $NDF_{u30}^{©}$ from haylage, we will limit inclusion in the diet of this haylage to 7.5 lb of DM. In this scenario, the cows will almost certainly increase DMI. Why? The $NDF_{u30}^{©}$ is not really 27%. This analysis demonstrates a classic example of NDF which is not corrected for ash contamination. Looking closer at this sample, there is a 9 point difference between aNDF and aNDFom. Further, the NDF_{d30} and $NDF_{u30}^{©}$ are calculated from aNDF (13.7% + 27% = 40.7%). From a typical haylage, the $NDF_{u30}^{©}$ is overestimated by approximately 6 to 7 points. A better estimate is 21% NDF_{u30} which now allows an inclusion of 9.5 lb of haylage in our example diet. When there is high ash content (> 3%) in the NDF fraction, the undigested portion will be overestimated when calculated using aNDF which is not corrected for ash content.

A second scenario which will overpredict the gut fill impact of forages is finely chopped diets. $NDF_{u30}^{©}$ calculated *in vitro* is independent of passage rate. When passage rate increases, the amount of particles remaining in the rumen at a specific time decreases. Consequently, excessive $NDF_{u30}^{©}$ intake can be an indicator of increased NDF passage. Another documented scenario is that passage rate changes with the animal's cold stress. Hence, gut fill capacity may change during periods of cold stress.

Ration characteristics that reduce fiber digestibility constitute a third scenario where gut fill is higher than predicted. The most common scenario is increased acid load that inhibits fiber digesting bacteria. Low ruminal pH from highly fermentable feeds can decrease rate of fiber digestion and increase the filling effect of the diet (Allen and Mertens, 1988). Recently, ration starch has been a focus as a dietary component that lowers ruminal pH. This focus has ignored the reality that digestible NDF can also be highly fermentable and contribute to acidosis. In a recent popular press summary, Fredin (2014) showed that replacing starch with non-forage fiber sources did not change rumen pH. It should not be surprising that low starch diets combined with other sources of highly fermentable carbohydrate can result in low rumen pH, which will depress fiber digestion. This, in turn, increases actual $NDF_{u30}^{©}$ and the gut fill characteristics of the diet.

Differences in particle retention time for different types of forage NDF can cause predicted $NDF_{u30}^{©}$ to not correspond to actual $NDF_{u30}^{©}$. In general, NDF in legumes is thought to have less filling effect than NDF in grasses (Oba and Allen, 1999). An example of this effect was seen in a study to examine perennial ryegrass silage compared to alfalfa silage, where the alfalfa silage was found to support greater DMI (Hoffman et al., 1998). Recalculating their data into a gut fill context, the alfalfa silage was 20.9% NDFu while the perennial ryegrass was 16.8% NDFu as a percent of DM. However, in this case, the cows consuming the alfalfa silage ate nearly 5 lb more DM than the perennial ryegrass. The differing gut fill effect of different forage types argues for monitoring the gut fill effects in diet specific scenarios (Jones, 2014).

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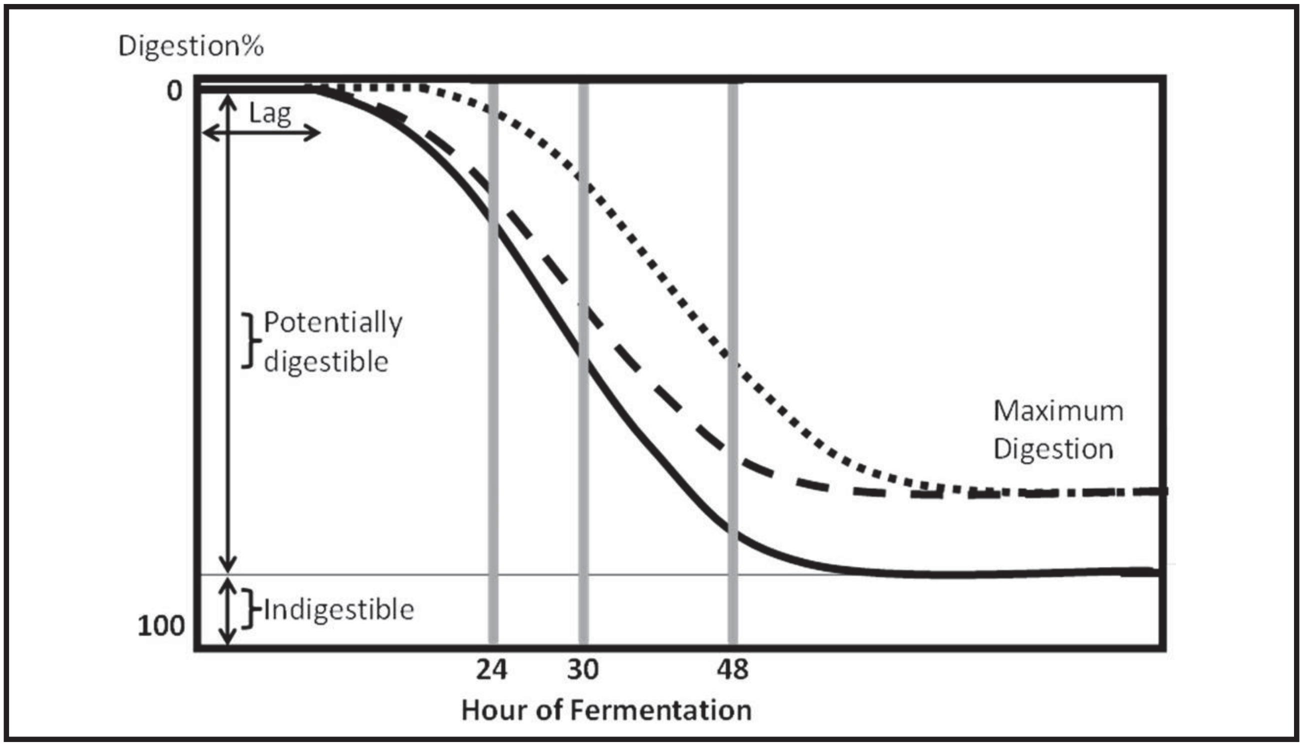
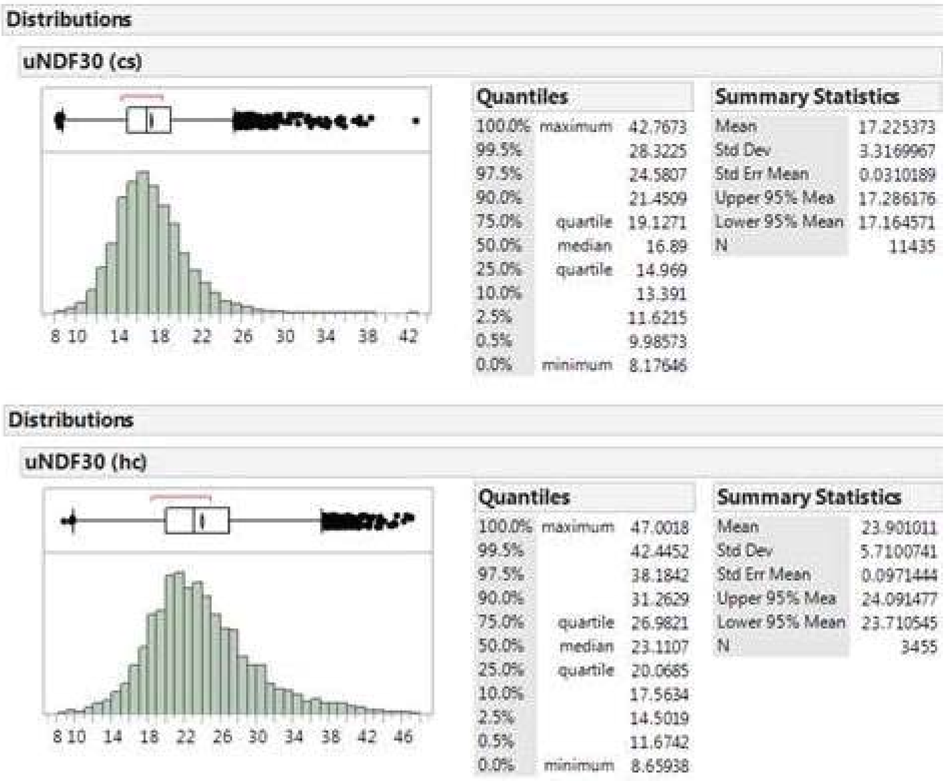


Figure 1. Rate of digestion as seen at different time points given different digestion rates and lag times (Hall, 2013).



Distributions

uNDF30 (cs)

Quantiles		
100.0%	maximum	42.7673
99.5%		28.3225
97.5%		24.5807
90.0%		21.4509
75.0%	quartile	19.1271
50.0%	median	16.89
25.0%	quartile	14.969
10.0%		13.391
2.5%		11.6215
0.5%		9.98573
0.0%	minimum	8.17646

Summary Statistics	
Mean	17.225373
Std Dev	3.3169967
Std Err Mean	0.0310189
Upper 95% Mea	17.286176
Lower 95% Mean	17.164571
N	11435

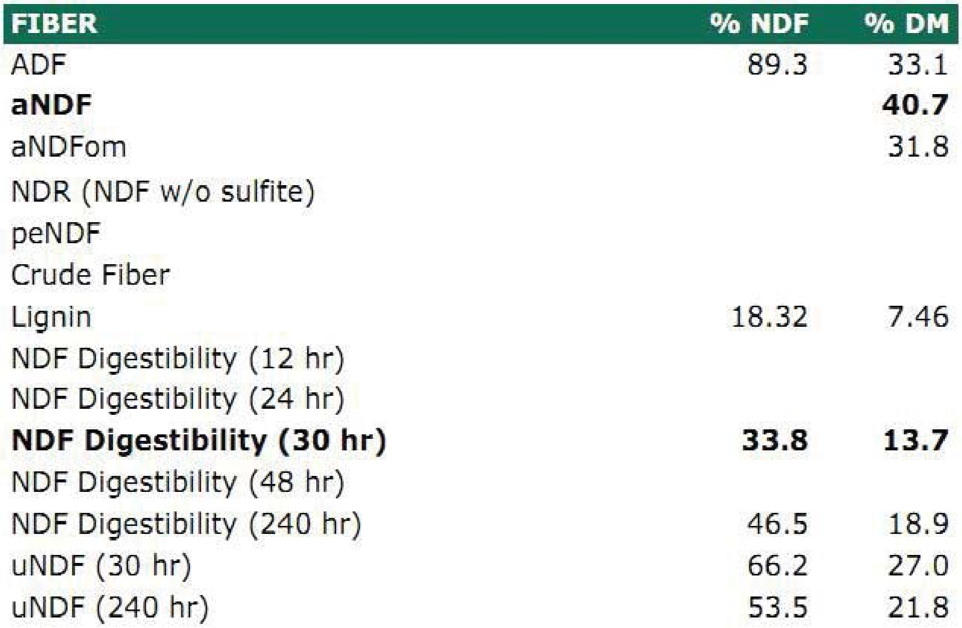
Distributions

uNDF30 (hc)

Quantiles		
100.0%	maximum	47.0018
99.5%		42.4452
97.5%		38.1842
90.0%		31.2629
75.0%	quartile	26.9821
50.0%	median	23.1107
25.0%	quartile	20.0685
10.0%		17.5634
2.5%		14.5019
0.5%		11.6742
0.0%	minimum	8.65938

Summary Statistics	
Mean	23.901011
Std Dev	5.7100741
Std Err Mean	0.0971444
Upper 95% Mea	24.091477
Lower 95% Mean	23.710545
N	3455

Figure 2. Distribution of NDF_{u30} content for corn silage and haylage observed in the Cumberland Valley Analytical Service database (provided by R. Ward, 2013, Cumberland Valley Analytical Services, Hagerstown, MD).



FIBER	% NDF	% DM
ADF	89.3	33.1
aNDF		**40.7**
aNDFom		31.8
NDR (NDF w/o sulfite)		
peNDF		
Crude Fiber		
Lignin	18.32	7.46
NDF Digestibility (12 hr)		
NDF Digestibility (24 hr)		
NDF Digestibility (30 hr)	**33.8**	**13.7**
NDF Digestibility (48 hr)		
NDF Digestibility (240 hr)	46.5	18.9
uNDF (30 hr)	66.2	27.0
uNDF (240 hr)	53.5	21.8

Figure 3. Example fiber analysis in a forage sample that contains ash contamination in the NDF fraction.