Using Physically Adjusted NDF in Formulating Rations for Dairy Cows

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Summary

Physically effective fiber (**peNDF**) is defined as that fraction of NDF that stimulates chewing activity and contributes to the floating mat of large particles in the rumen. A limitation of using peNDF is that it does not account for differences in rumen fermentability of nutrients, most notably rumen-degraded starch. The physically adjusted fiber (**paNDF**) system can be used to estimate TMR particle size and diet compositions needed to maintain target rumen conditions. The system is based on equations derived from a meta-analysis and estimates dietary physical and chemical characteristics required to maintain desired rumen conditions in lactating dairy cows. Effective fiber feeding recommendations are based upon diet ADF, NDF, forage NDF (**fNDF**), starch, and proportion of the ration as forage or cottonseed, as well as particle size measures.

Introduction

The physical nature of fiber consumed by the dairy cow is known to affect feed intake, chewing activities, rumen fermentation, and ultimately milk production and composition. In fact, because dairy cattle are grass and roughage eaters (Hofmann, 1989), and it is generally well understood that cows require coarse roughage and that this is "effective" in maintaining normal rumen fermentation, function, and overall health (Clark and Armentano, 1993). With this being established, a number of investigators have sought to develop methods to quantitatively measure coarseness of roughage and integrate these measures into general feeding recommendations (Santini et al., 1983; Mertens, 1997). Probably the most well-known measure is peNDF, which is defined as that fraction of NDF that stimulates chewing activity and contributes to the floating mat of large particles in the rumen (Mertens, 1997). It was proposed that peNDF of individual feedstuffs could be estimated by multiplying a chemical measure of fiber in a feed by a physical measure. Over the last 20 years, the Penn State Particle Separator (**PSPS**) has been widely used on-farm to measure the particle size of TMR (Lammers et al., 1996; Heinrichs and Kononoff, 2002). Additionally, researchers have used the PSPS to report the physical characteristics of both forages and TMR in peer review scientific publications. Although it has been proposed that particle size measures using the PSPS could be used to estimate peNDF (Zebeli et al., 2012), such application is not widespread. Recently, the concept of peNDF has been re-evaluated by quantitatively summarizing available literature reporting physical and chemical characteristics of total diets and deriving equations that relate these to feed intake, chewing behavior, and ruminal fermentation (White et al., 2017a). This physically adjusted fiber (paNDF) system can be used to estimate TMR particle size and diet

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compositions needed to maintain target rumen conditions. The objective of this paper is to provide an update on findings related to effective fiber and to also outline the paNDF system for on-farm application.

New Method to Assess Effective Fiber

Feeding diets low in effective fiber may precipitate and contribute to the cascade of factors associated with ruminal acidosis, but the interactive effects of dry matter intake, digestibility, and nonstructural carbohydrate levels should also be considered. Unfortunately, in many studies, it is difficult to draw a clear link between peNDF and rumen pH. This is often the case when peNDF is decreased as grain is added to the diet. In this case, particle size is reduced but the portion of readily digestible carbohydrate is also increased. Here rumen pH is almost always reduced, but this may be a function of reduced saliva flow and increased organic acid production, with the latter often having the greatest effect. Thus, a limitation of using peNDF is that it does not account for differences in rumen fermentability of nutrients, most notably rumen-degraded starch (Dijkstra et al., 2012). Feeding recommendations of carbohydrates of NRC (2001) were summarized in a simple table (see Table 4-3, Page 37 from that source). In this table, minimum concentrations of forage NDF (fNDF), NDF, and non-fiber carbohydrates could be determined through interpolation. This table has proven to be extremely useful, but it did not include starch and also did not offer any recommendations regarding the particle size of a TMR. In fact, the table caption specified that these recommendations assumed that the forage particle size was adequate. In addressing this void, it has been suggested that the peNDF index is an oversimplification (Plaizier et al., 2008) of a complex phenomenon. With this in mind, we evaluated different peNDF representations as some particle size measure multiplied by diet NDF consent and concluded, that despite the fact that this product does account for some variation in ruminal pH, these dietary factors should be separated as core components and this will allow for consideration of other dietary components that influence pH (White et al., 2017a). We further hypothesized that the utility of peNDF could be expanded and improved by dissociating NDF and particle size and considering other dietary factors, all integrated into a system that can be used to estimate minimum particle sizes of TMR and diet compositions needed to maintain ruminal pH targets (White et al., 2017b). The system is based on equations derived from a meta-analysis (White et al., 2017a) and estimates dietary physical and chemical characteristics required to maintain desired rumen conditions in lactating dairy cows. In practice, the paNDF system generates feeding recommendations for diet characteristics that are based upon computation. All particle size measures used in the paNDF system are determined with PSPS and on a DM basis.

Modeling "Rumen Conditions" with Ensemble Models

Accurately modeling the rumen environment is challenging for several reasons. First, rumen conditions are difficult to measure and report, and this leads to uncertainty (Sarhan and Beauchemin, 2015). Second, it is difficult to identify or build datasets that possess sufficient independent variation within independent variables. This may make derivation of useful parameters estimates somewhat problematic. In practice, no single study can possibly evaluate all of dimensions simultaneously. The challenge of accurately modeling and predicting "*conditions*" is also existent in the field of weather forecasting (Meier et al., 2014). To overcome these challenges, some climatologists employ what is known as "*ensemble modeling*" and use the approach to generate predictions of weather patterns as affected by various driving forces (Meier et al., 2014). We chose to use this multi-dimensional approach to predict dietary physical and chemical characteristics required to maintain desired rumen conditions (White et al., 2017a). Our target for prediction of the desired "rumen conditions" was mean ruminal pH. Ruminal pH was chosen because it was frequently reported in many of the studies included in our dataset, but it should be noted that other measures that were rarely reported, such as minimum or maximum pH and time under some specific pH, may better represent risk of acidosis. As already mentioned, this paNDF system can be used to estimate TMR particle size and diet compositions needed to maintain target rumen conditions.

Structure of the Ensemble

An ensemble modeling approach is used to generate means and confidence intervals to describe the need for particle size, fiber, and other dietary components in diets for lactating cows. In this approach, a "mixture of expert" (**MEx**) models from a range of dietary scenarios, such as high or low starch diets, are identified and rumen pH is then predicted with each expert model individually (Figure 1). The mean of the predicted pH is estimated based on dietary composition using expert algorithms. A confidence range is then estimated based on the minimum and maximum predictions of the ensemble. In practice, an ensemble of models aggregates predictions from multiple different models (Table 1) to yield a mean and range of responses. Compared with individual models, ensembles may provide more reliable predictions of events, estimate confidence in the reliability of those predictions, and are less likely to generate systematic errors. For example, rather than forcing integration of all models over an entire range of conditions such that the full range has areas of instability, the ensemble approach integrates equations with varying weighting factors over the entire range of conditions. Compared with individual models, an ensemble approach has improved utility, particularly in situations where minimal data is available for equation development. As illustrated in Figure 1, the individual expert models correspond to "model 1, model 2, model 3," with each model being selected as an "expert" based on its performance against subsets of the data. In our case, the available input data were then run through each model, resulting in 6 predictions of pH. An algorithm was then used to consolidate those 6 predictions into a single pH prediction. The predicted pH was then back-calculated and a recommendation of material to be retained on the 8 mm sieve of the PSPS is generated.

Rumination Activity and Rumen pH

A general concept related to physically effective fiber is that coarse fiber particles stimulate chewing activity, and this in turn stimulates saliva production that buffers the ruminal environment (Beauchemin et al., 2008). Although total chewing time, as the sum of time eating and ruminating, is commonly reported in studies which have evaluated effective fiber, in our study the effects of total chewing time, as well as eating time and ruminating time (and these factors divided by DMI) on rumen pH was evaluated. Interestingly, of all of the chewing activities tested, only rumination time per unit of DMI was observed to significantly affect rumen pH (Table 1). In general compared to time spent eating, the time spent ruminating likely has a greater influence on rumen pH (Zebeli et al., 2010) and has been observed experimentally (Beauchemin et al., 2003). This may be because cows spend as much as twice the amount of time ruminating than eating and more saliva is produced from rumination activities (Maekawa et al., 2002a,b). The importance of rumination is not only limited to saliva production and rumen pH, as the act of ruminating is also believed to be closely integrated with reticulo-ruminal motility and consequently overall gut health (Van Soest, 1994). The equation used to predict rumination time is listed in Table 1 and factors observed to affect it included particle size measures of the TMR, NDF and starch contents of the TMR, and DMI.

The objective of creating the paNDF system was NOT to develop a predictive equation of rumen pH but to use it as a target for desirable rumen conditions. Ruminal pH is known as a key physicochemical measure of rumen fermentation (Aschenbach et al., 2011a; Penner et al., 2011). If too low, it can negatively affect rumen microbes and inhibit fiber digestion (Krajcarski-Hunt et al., 2002) and also the flow of microbial CP out of the rumen (Firkins, 1996, 2010; Russell and Wilson, 1996). In our ensemble approach, two different models were used to predict rumen pH (Table 1). As the consumption of starch leads to the increased production of organic acids (Firkins, 1996), it was not surprising that starch was used in both models to predict pH. Currently, there is not agreement for the "best or optimal ruminal pH" for lactating dairy cows, but White et al. (2017b) used 6.1 as an example. Overall, our quantitative findings provide a comprehensive approach to estimating the effective fiber needs of dairy cattle as both TMR particle size and diet NDF influence both DMI and rumination time and this is in agreement with mechanistic expectations, and these factors in turn were integrated into a system that could be robustly related to observed ruminal pH in dairy cattle.

Forage Fragility, a New Consideration

Fragility of a feed has been defined as the rate at which plant tissues contained in a feed particle are further fragmented into small particles (Grant, 2010). Compared to fiber in grasses, the fiber in legumes is thought to be more fragile and can be more easily fragmented (Kammes and Allen, 2012). Consequently, legumes stimulate less rumination and in turn, salivary buffer production. Grasses also have a higher content of hemicellulose (Van Soest, 1994), which crosslinks with lignin, may be less fragile, and might be more effective in stimulating chewing activity (Mertens, 1997). In an attempt to account for this, we included ADF/NDF as an indirect measure of forage fragility. A laboratory method to measure forage fragility has been developed (Farmer et al., 2014), but it is not widely used either in the field or in published studies.

The Importance of fNDF and Inclusion of Article Size

Time and application has proven recommendations of minimum fiber and maximum nonfiber carbohydrates outlined in Table 4-3 of the Dairy NRC (2001) to be extremely robust and applicable. This is in part because of its simplicity, but as already mentioned, the table does not account for feed particle size. The influence of effectiveness of fiber using the ensemble approach without any measure of particle size was also evaluated using something called Lin's concordance correlation coefficient (**CCC**). This value ranges from 0 to 1 like a regular correlation coefficient but is more robust at comparing across different models of diverging structures. When using only forage NDF, the unadjusted CCC was only moderately lower (worse) than the CCC from the more complicated ensemble model (0.52 vs 0.59), but the ensemble model still is much more robust and flexible. It explored broader sources of variation affecting animal chewing and ruminal pH, which cannot readily be measured on farms, while also controlling multicollinearity (the latter term refers to trends which tend to follow each other; for example, various protein sources rising and falling in price on average). Of course, just because we can generalize doesn't mean we always should. In the above example, when protein sources are out of synch, that is when you can lower feed costs, but of course you would need to do this consistently because relative prices change. Similarly, we think expanding the fNDF model allows more robustness and flexibility when assessing rumen health.

For the current discussion, Table 4-3 in the NRC (2001) documents the need to decrease non-structural carbohydrate (now better measured as starch plus sugars) simultaneously as fNDF decreases. Some studies in the literature have followed these or similar recommendations just like some farms have. In that case, decreasing fNDF would be statistically associated with decreasing starch in diets; however, what about the flexibility of using nonforage NDF to replace part of both forage and grain? Let's look at two contrasting examples. First, consider that forage price is relatively high in a certain region. In some herds with excellent management, would a nutrition advisor be willing to take more risk of lower ruminal pH and its associated responses (lower NDF digestibility or depressed milkfat) to lower diet cost? Balancing for fNDF and starch certainly is a good place to start. However, in addition, the ensemble model embeds dietary components associated with ruminal NDF and starch digestibilities; these components are combined with fNDF and other dietary factors while also adding the dimension of increasing chop size of forage. A diet can be formulated along with directions on how coarse to chop hay while subsequently assessing TMR sieve data. Second, what if forage price is relatively low in certain regions; wouldn't a nutrition advisor now be willing to assess how to optimize that forage's inclusion level while potentially shortening chop size to help prevent depressed dry matter intake? What if corn silage is chopped very coarsely on one farm but not on another in the same region? The ensemble model allows these types of varying conditions to be assessed in diets with less trial feeding to cows.

The take-home message is that using fNDF and starch alone is good but can be better. In most diets assessed, TMR particle size in our dataset was near recommendations more of the time than it was not (i.e., fNDF and starch are ok), but the divergence of diets that were very short or very coarse under different fNDF and starch concentrations also allowed opportunity. Shouldn't a Penn State shaker box be routinely used, anyway? With minimal extra data, then the ensemble approach allows more information to be integrated and provided in a user-friendly format for nutrition advisors to think "outside of the box". Interestingly, models developed to predict rumen pH did not include any measure of particle size; however, the relationship of particle size to rumen conditions appears by way of its effects on feed intake and rumination time (Table 1). Driving factors that influence rumen pH include rumen degradation of carbohydrate, fNDF, and rumination activities. Given the inter-relatedness of these factors, it is impossible to determine which is more "important" or which has more influence on rumen conditions and the ensemble approach considers them all.

Towards On-Farm Application of paNDF

Figure 2 illustrates how inputs are used to generate feeding recommendations for target rumen conditions. The proportion of TMR on the top screen (19-mm) varied on the top axis by 6, 12 or 18%, while fNDF varied on the bottom axis, starch varied on the right axis, and the model solves for the left axis which is the proportion of TMR on the second screen (8-mm). In the top left graph of this figure, depicting 6% of TMR DM retained on a 19-mm screen and 15% TMR DM starch, two inflection points are visible. One occurs at approximately 16.0%

fNDF and the other at approximately 26.5% fNDF. This figure can be interpreted to suggest that ruminal pH can be maintained in a diet low in fNDF (16.0 %) by increasing the proportion of TMR (between 40 and 60%) retained on the 8-mm sieve. Alternatively, when feeding a diet high in fNDF (26.6%), a lower proportion of TMR (< 20 %) retained on the 8-mm sieve is needed. In practice, a true recommendation for the percentage of DM material on the 8-mm sieve should be based on the diet target fNDF and likely lies somewhere between these 2 inflection points. An additional example can be found in the figure depicting 6% of TMR DM retained on a 19-mm screen and 25% TMR DM starch, in which one inflection point at approximately 22% fNDF is visible. This figure can be interpreted to suggest that longer TMR particles plays a lesser of a role in maintaining pH when fNDF is greater than 22 %.

For deriving solutions or feeding recommendations with the paNDF system, a mobile phone application will be available free of charge early in 2018. To use the application, users will simply key in desired rumen conditions; diet ADF, NDF, fNDF, starch, proportion of the ration as forage; and cottonseed, as well as particle size measures. Users can then use the application to determine the proportion of TMR that should be retained on the second sieve (8-mm) of the PSPS to maintain a defined rumen pH. The application will also provide a confidence interval for all recommendations. It should be stressed that meeting the derived feeding recommendations will not guarantee a specific average rumen pH in the herd. The application was designed to generally predict rumen conditions as affected by major diet factors. Other factors are known to affect rumen pH and could not be included in the system. These include the concentration of other carbohydrates, such as water-soluble carbohydrates and soluble fiber (Hall et al., 1999); chemical or physical processing of feed; use of ionophores (Firkins and Yu, 2015); feeding management and behavior (Miller-Cushon and DeVries, 2010), associative rumen effects, such as volatile fatty acid and ammonia absorption and urea secretion in rumen (Aschenbach et al., 2011b); and dietary cation-anion difference (Iwaniuk and Erdman, 2015).

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Table 1. Models developed by White et al. (2017a) through during ensemble model training (units of all parameters on a DM basis) and used to generate feeding recommendations for effective fiber (adapted from White et al., 2017b).

Response	Equation[1]
DMI, kg/day	$-0.889 - 0.460 \times MPS + 0.0203 \times BW + 0.110 \times Forage + 0.794 \times NDF - 0.0117 \times (NDF \times NDF)$
	$-1.74 – 0.432 \times MPS + 0.0218 \times BW + 0.163 \times Cottonseed + 0.117 \times Forage – 0.238 \times fNDF + 0.771 \times NDF – 0.0116 \times (NDF \times NDF)$
Rumination Time, min/day	$-357 – 16.7 \times MPS + 4.34 \times 19\ mm + 2.49 \times 8\ mm + 71.5 \times DMI – 1.54 \times (DMI \times DMI) + 4.78 \times NDF – 1.68 \times dNDF – 2.35 \times dStarch$
pH	$12.0 + 0.0112 \times fNDF – 0.0190 \times Starch + 0.0003448 \times (Starch \times Starch) – 0.679 \times CP + 0.0186 \times (CP \times CP) + 0.01052 \times (Rumination\ Time/DMI)$
	$6.72 + 0.0137 \times fNDF + 0.00798 \times Starch – 0.0456 \times CP – 0.00835 \times dStarch + 0.0204 \times (Rumination\ Time/DMI)$

[1]MPS, estimated mean particle size from PSPS data in mm; BW, body weight in kg; All dietary concentrations are on a DM basis: Forage, % of forage in the TMR; NDF, % NDF in the TMR; Cottonseed, % of cottonseed in the TMR; fNDF, % of forage NDF in the TMR; 19-mm, % of TMR retained on the 19-mm sieve of the PSPS; 8-mm, % of TMR retained on the 8-mm sieve of the PSPS; DMI, dry matter intake, kg/d; dNDF, rumen degraded NDF as estimated by White et al., 2017a; dStarch, rumen degraded starch as estimated by (White et al., 2016); Starch, % of starch in the TMR; CP, % of CP in the TMR; Rumination time, time spend ruminating, min/day.

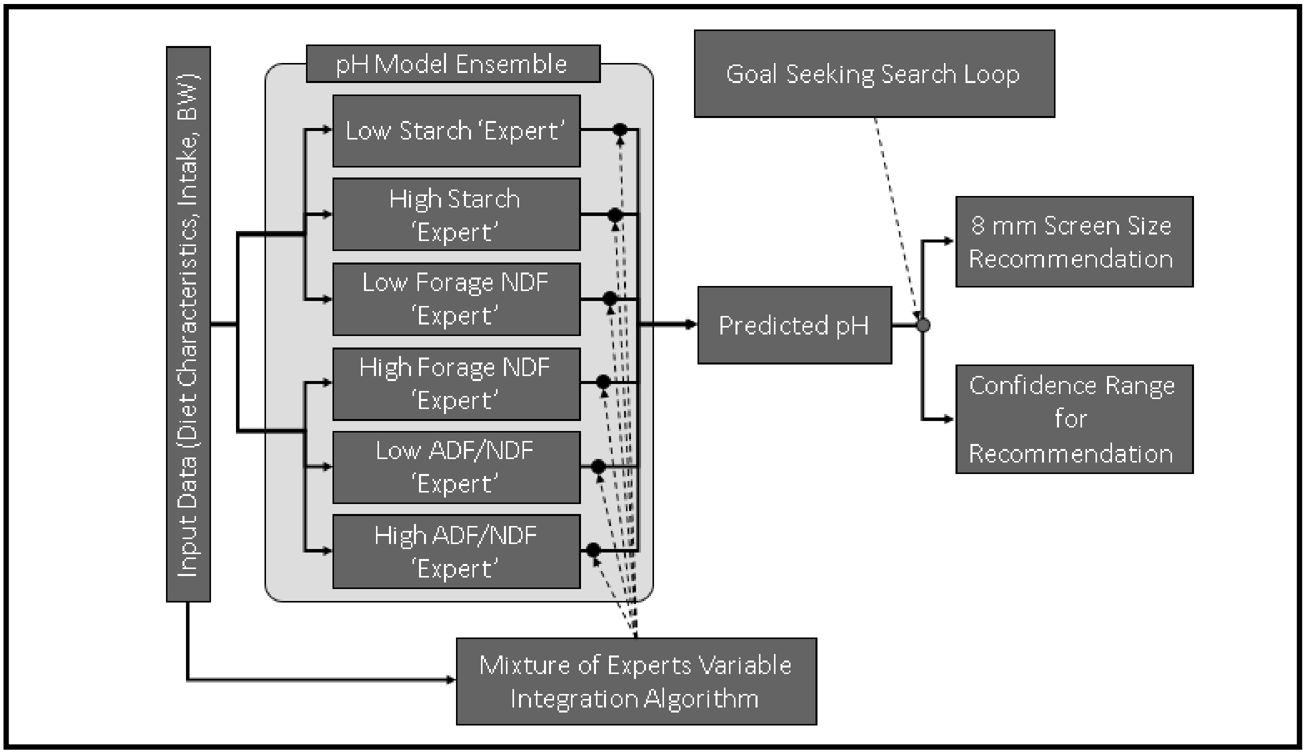

Figure 1. Depiction of strategy to estimate mean and confidence range of pH responses estimated by the model ensemble. Various "expert" models are identified (high starch vs. low starch) and pH is estimated with all expert models individually. The weighted mean of the predicted pH from 6 equations is estimated based on dietary composition using the variable mixture of experts integration algorithm. The confidence range is estimated based on the minimum and maximum predictions of the ensemble (adapted from White et al., 2017b).

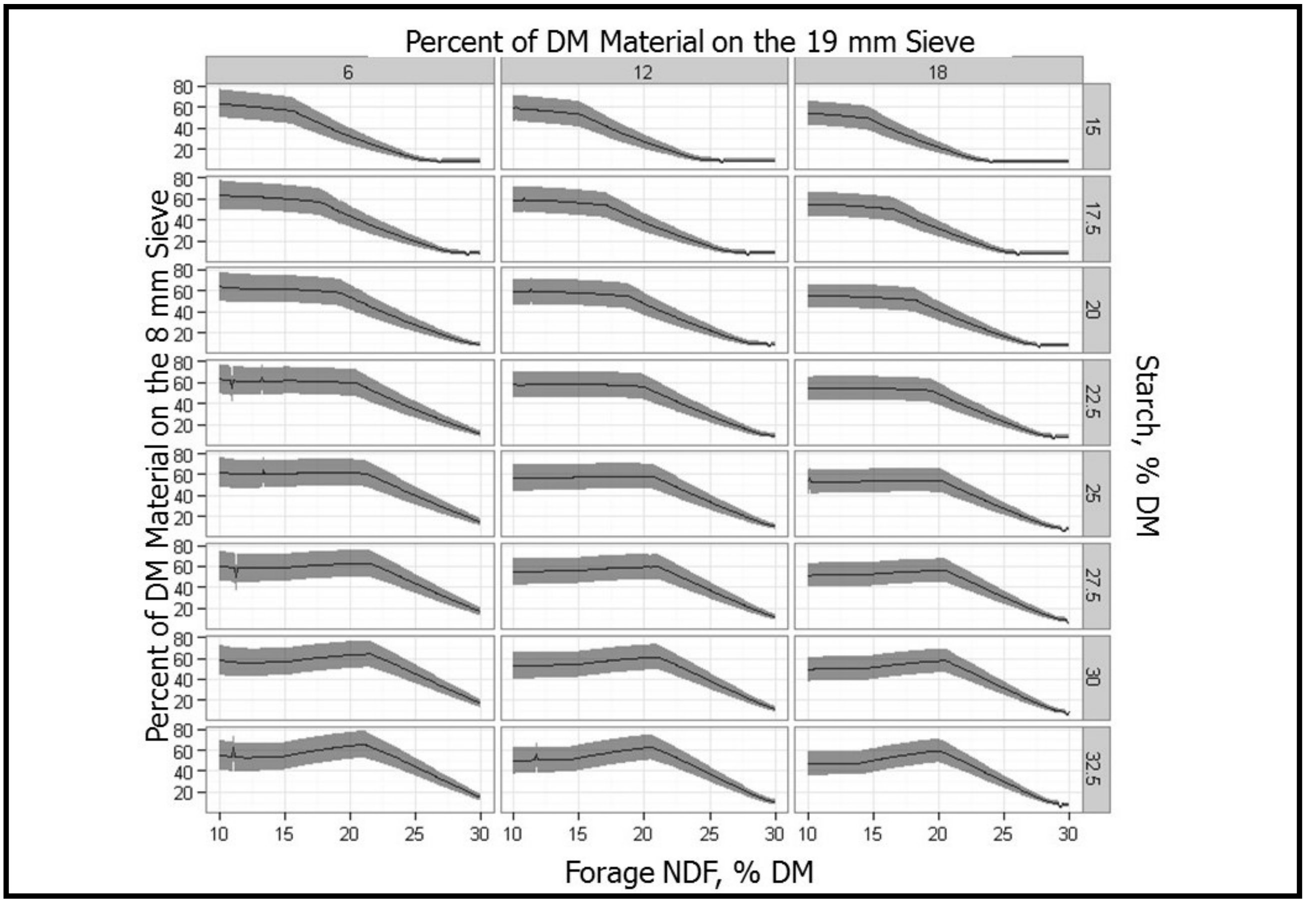

Figure 2. Response surfaces generated by the multi-model ensemble for a target pH of 6.1. Curves were generated by iterating through the system of equations (adapted from White et al., 2017b).