Fiber quality and forage allocation throughout lactation.

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Introduction

Optimal forage allocation and supplementation strategies for dairy cattle must consider variation in forage quality characteristics as well as cow's responses to their diet throughout lactation. Forage quality characteristics can affect diet cost, energy intake and partitioning, feed conversion efficiency (FCE), and animal health. These characteristics include neutral detergent fiber concentration and digestion characteristics, the concentration, digestibility, and site of digestion of starch, particle size and fragility, and crude protein concentration and composition. Forages are unique among diet ingredients fed to ruminants because they provide fiber that is effective at retaining feed particles in the rumen, increasing their digestibility and increasing digesta mass and volume. Increased digesta mass in the rumen can reduce risk of ruminal acidosis and abomasal displacement but can also limit feed intake, depending upon the physiological state of animals. Control of feed intake by ruminal distension increases with milk yield and diet forage NDF concentration. This paper will discuss the relative importance of forage quality characteristics to cows and how they change throughout the lactation cycle.

Feed intake

Eating is controlled by the integration of signals in brain feeding centers. Whereas cow diets must contain a minimal concentration of relatively low-energy roughages for proper rumen function, signals from ruminal distension can control feed intake when the drive to eat is high and metabolic control of feed intake is diminished (e.g. cows at peak lactation). Signals derived from metabolism of fuels dominate the control of feed intake when signals from distension diminish (e.g. cows in late lactation). Therefore, effects of diet on feed intake vary with the physiological state of the animal.

Filling effect of forages

The extent to which ruminal distention limits feed intake is positively related with milk yield. This was shown in two studies from our laboratory in which groups of cows with a wide range of milk yield were offered diets differing in rumen fill. The first study compared brown midrib corn silage to control corn silage (Oba and Allen, 1999a). The two silages had similar DM and NDF concentrations but in vitro NDF digestibility (30 h) was nearly 10 units higher for the low-lignin brown midrib corn silage. When both forages were offered to a group of cows with a wide range of milk yield, response in DMI and FCM to the brown midrib corn silage compared with the control corn silage increased linearly with milk yield. Whereas the lower producing cows with ~30 kg/d milk yield had similar DMI and FCM for the two silages, FCM increased ~8 kg/d for the highest producing cows with ~55 kg/d milk yield. The second study compared diets differing in forage to concentrate ratio (Vœlker and Allen, 2000). Diets contained either 44% forage (24% NDF and 34% starch) or 67% forage (31% NDF and 23% starch). Response in DMI to the lower forage diet increased linearly (up to ~4.5 kg/d for the highest producing cows) and FCM yield increased ~2.2 kg per kg increase in DMI for cows producing over ~40 kg FCM/d. However, cows producing less than ~40 kg/d this had similar FCM for the two treatments. Therefore, high-producing dairy cows should be fed less-filling diets to maximize feed intake.

The filling effect of a diet is determined primarily by the <u>initial</u> bulk density of feeds, as well as their filling effect over time in the rumen. The overall filling effect is determined by forage NDF content, forage particle size, fragility of forage NDF affected by forage type (legumes, perennial grasses, annual grasses), and NDF digestibility within a forage family (Allen, 2000). Forage NDF is less dense initially, digests more slowly, and is retained in the rumen longer than other diet components. Increasing diet forage NDF concentration can dramatically reduce feed intake of high producing cows. Several studies in the literature reported a decrease in DMI of up to 4 kg/d when diet NDF content was increased from 25 to 35% by substituting forages for concentrates (Allen, 2000). Although most studies reported a significant decrease in DMI as forage NDF increased, the DMI response was variable, depending upon the degree to which intake was limited by ruminal fill and the filling effect of the forage NDF. Higher producing cows are limited by fill to the greatest extent and the filling effect of forage fiber varies depending upon particle size and fermentation characteristics.

Experiments that have evaluated effects of forage particle size have generally shown small effects on DMI (Allen, 2000). However, one experiment showed little effect of particle size of alfalfa silage when fed in high grain diets but a large reduction in DMI for the diet containing longer alfalfa silage when fed in a high forage diet (Beauchemin et al., 1994). Feed intake might have only been limited by ruminal fill in the high forage diet, which could explain the interaction observed.

Increasing diet NDF concentration by substituting non-forage fiber sources (NFFS) for concentrate feeds has shown little effect on DMI in studies reported in the literature (Allen, 2000). Non-forage fiber sources include byproduct feeds with significant concentrations of NDF such as soyhulls, beet pulp, cottonseeds, corn gluten feed, almond hulls and distiller's grains. Fiber in NFFS is much less filling than forage NDF because it is less filling both initially (smaller particle size) and over time in the rumen because it digests and passes from the rumen more quickly.

Forage NDF has a much longer ruminal retention time than other major dietary components. Retention time in the rumen is longer because of longer initial particle size, and greater buoyancy in the rumen over time, which differs greatly across forages. As forages mature, the NDF fraction generally becomes more lignified. Lignin is a component of plant cell walls that helps stiffen the plant and prevent lodging. It is also essentially indigestible by ruminal microbes and limits fermentation of cellulose and hemicellulose. Within a forage type, the degree to which NDF is lignified is related with the filling effects of the NDF. Fiber that is less lignified generally digests and clears from the rumen faster, allowing more space for the next meal. However, ruminal retention time of NDF from perennial grasses is generally longer than for legume NDF despite being less lignified (Oba and Allen, 1999b; Voelker Linton and Allen, 2008; Kammes and Allen, 2012a). Forage NDF from alfalfa was more fragile with a greater rate of breakdown of large particles than NDF from orchardgrass, allowing faster rate of passage of particles from the rumen (Kammes and Allen 2012b). Because of this, forage NDF from perennial grasses is more filling and should not be included in high concentrations in diets of cows for which feed intake is limited by ruminal fill, unless it is of exceptionally high quality. Corn is an annual grass, and corn silage NDF digests and passes from the rumen quickly compared to perennial grasses and can be an excellent source of forage NDF for high producing cows.

Ruminal starch fermentation

Diets with greater ruminal starch fermentability can depress feed intake and forages can greatly affect diet starch concentration and fermentability. Increasing ruminal starch fermentation by substituting a more fermentable starch source for a less fermentable starch source decreased feed intake of cows by more than 3 kg/d in several studies reported in the literature (Allen, 2000). Grain containing forages such as corn, sorghum, and small grain silages vary greatly in both starch concentration and fermentability. Starch concentration and fermentability vary by forage type, genetics, and maturity at harvest and starch fermentability also varies by moisture concentration and time ensiled. Other forages varying in NDF concentration can affect diet fermentability by affecting diet starch concentration; low NDF forages require higher forage diets to meet optimum diet forage fiber concentration, leaving less dietary space for grain possibly limiting dietary starch.

Depression in feed intake by a more fermentable diet is more likely for fresh cows and cows in late lactation when oxidation of fuels in the liver dominates control of feed intake. A more fermentable starch source (high moisture corn) decreased DMI and milk yield compared with dry ground corn when fed to fresh cows and the reduction in DMI and milk yield was greater when fed in diets containing 28% starch compared with 22% starch (Albornoz and Allen, 2018). Ruminal propionate production increases as diet fermentability increases and propionate might limit feed intake by stimulating more complete oxidation of mobilized fatty acids in the liver of fresh cows or by extending hepatic oxidation over time when its supply to the liver exceeds its rate of utilization which likely increases as milk yield declines through lactation (Allen et al., 2009). Forages with high concentrations of starch that is highly fermentable should be limited in diets of fresh cows and late lactation cows to enhance feed intake.

Importance of maintaining ruminal fill

Whereas ruminal distention becomes a primary limitation to feed intake as milk yield increases, it likely has less effect on feed intake when it is controlled primarily by oxidation of mobilized fatty acids in the liver during the transition period (Allen et al., 2009). Glucose demand of fresh cows is high when glucose utilization for milk production outpaces gluconeogenesis by the liver. Whereas cows require diets with adequate glucose precursors (i.e. starch from grains), it is important to also maintain rumen fill. Formulating diets to maintain rumen fill with ingredients that are retained in the rumen longer, and have moderate rates of fermentation and high ruminal digestibility will likely benefit transition cows several ways. Increased ruminal digesta mass can provide more energy over time when feed intake decreases at calving or from metabolic disorders, mastitis or infectious disease. This will help maintain plasma glucose and insulin concentrations preventing even more rapid mobilization of body reserves compared with when diets are formulated with ingredients that disappear from the rumen quickly. Ruminal digesta is very important to buffer fermentation acids and buffering capacity is directly related with the amount of digesta in the rumen. Therefore, diets formulated with ingredients that increase the amount of digesta in the rumen will have greater buffering capacity and will maintain buffer capacity longer if feed intake decreases. Inadequate buffering can result in low ruminal pH, decreasing fiber digestibility and acetate production, and increasing propionate production, possibly stimulating oxidation in the liver and decreasing feed intake. Low ruminal pH also increases risk of health problems such as ruminal ulcers, liver abscess, and laminitis, and causes stress, likely increasing mobilization of body reserves even further. Diets formulated with ingredients that maintain digesta in the rumen longer when feed intake decreases will likely decrease risk of abomasal displacement.

Physically effective fiber

Optimum particle length of individual forages depends upon several factors including forage type, silo type (if ensiled), other forage(s) in the diet, the characteristics of the cow consuming the forage, stocking density/competition for feed, and diet fermentability. An adequate concentration of long particles is required to form a rumen mat to retain small particles that would otherwise escape, increasing diet digestibility, rumen fill, and buffering capacity. Some forages that are particularly fragile such as brown midrib corn silage benefit by chopping longer. Forages that are resilient to packing might have to be chopped shorter, particularly where packing is difficult (e.g. upright silos). Forages lacking physically effective fiber must be limited in diets and combined with forages with adequate particle length. When overcrowding causes competition at the feed bunk and slug feeding, diets with more physically effective fiber can limit rate of eating, decreasing risk of low ruminal pH, especially for highly fermentable diets.

Energy partitioning

Energy partitioning between milk production and body condition varies as physiological state changes throughout lactation. As lactation proceeds past peak, insulin concentration and sensitivity of tissues increases and energy is increasingly partitioned to body condition, sometimes at the expense of milk yield. Whereas high-starch diets can increase milk yield of high producing cows, they can result in excessive gain in body condition as milk yield declines and insulin sensitivity of tissues increase. We showed that a 69% forage diet (0% corn grain) containing brown midrib corn silage increased energy partitioned to milk, decreasing body weight gain while maintaining yield of milk compared to a 40% forage diet (29 % corn grain) containing control corn silage (Oba and Allen, 2003). In vitro NDF digestibility of the brown midrib corn silage was ~20% higher (55.9 vs 46.5%) than the control corn silage. In contrast, DMI and milk yield was reduced when the control corn silage was fed in the higher forage diets. We also showed that beet pulp decreased BCS without decreasing yields of milk or milk fat when substituted for high-moisture corn up to 12% of diet DM (Voelker and Allen, 2003). Similarly, an experiment conducted with cows in the last 2 months of lactation showed that substitution of beet pulp for barley grain linearly decreased body condition score, maintained milk yield and linearly increased milk fat yield (Mahjoubi et al., 2009). Decreased body condition score and increased milk fat yield might have been because of a linear decrease in plasma insulin concentration which linearly increased plasma NEFA concentration. However, lower ruminal pH was reported as starch concentration of the diet increased, which might have caused the milk fat depression through CLA production in the rumen (not measured). Harvatine et al. (2009) reported that CLA-induced milk fat depression decreased gene expression for enzymes and regulators of fat synthesis in adipose tissue. Decreasing fermentability of diets by increasing fiber from forages or NFFS can maintain milk yield while decreasing gain in body condition.

Feed conversion efficiency The efficiency for which feed is converted to milk is affected primarily by feed intake, digestibility, and energy partitioning. Greater milk yield, which is affected by energy intake and partitioning, increases FCE by diluting maintenance costs. Diet digestibility is affected by initial forage quality, forage supplementation, and animal characteristics. Therefore forage allocation and supplementation can have large effects on FCE.

Protein

Protein concentration and ruminal degradability vary greatly among forages and should be considered when allocating forages to different groups of animals. Overfeeding protein decreases efficiency of N utilization, increases excretion of N waste, increases feed costs and costs energy to excrete excess N as urea. Whereas forages with high protein concentrations are typically allocated to cows with higher protein requirements, forages with low NDF and high protein concentrations such as immature alfalfa can result in excessive diet protein concentration unless forage(s) with lower protein concentrations are also used in the diet.

Specific recommendations

Testing: All forages should be tested for concentrations of DM, NDF, CP, as well as lignin or in vitro NDF digestibility. Some laboratories report lignin as a % of DM, which isn't useful because lignin only limits digestion of fiber and not other fractions of DM. Therefore, lignin (% of DM) should be divided by NDF (% of DM) to determine the extent to which the NDF is lignified. There are several measures of lignin used although the predominant measure is acid detergent sulfuric acid lignin (ADL). Acid detergent lignin as a percent of NDF ranges from ~3 to 9 % for corn silage and from ~11 to 20% for alfalfa (hay and silage). Within a forage type, forage NDF with the lowest ADL/NDF is likely the least filling. Additionally, mixed grass-legume forages should be tested for ADF to help determine the fraction of grass and legume in the forage; ADF/NDF is ~0.8 for legumes and ~0.6 for grasses. Mixed forages with more grass are more filling and should be limited for high producing cows with intake limited by rumen fill. Ensiled forages should be tested for pH, ammonia, and fermentation profile as well.

In vitro NDF digestibility (NDFD) varies greatly by NDF source (from forage and NFFS). NDFD is the percentage of initial NDF that is fermented in vitro by rumen microbes over a specific period of time such as 30 h (NDFD30) or 48 h (NDFD48). The time selected is supposed to represent the retention time of the feed in the rumen of the target cow. However, it is affected by forage source, diet and dry matter intake (DMI) as discussed below. The opposite of NDFD is uNDF, which is the percentage of initial NDF that remains after in vitro fermentation for a specific time period such as 30 h (uNDF30) or 240 h (uNDF240). The very long fermentation time of 240 h is used to approximate the percentage of NDF that is completely indigestible. This fraction is called indigestible NDF (iNDF) and is the same as uNDF240. The NDFD30 and uNDF30 percentages add to 100% of NDF and because they are perfectly related, they explain the same amount of variation in rumen fill and DMI. Similarly, the percentages of potentially digestible NDF (pdNDF) and iNDF sum to 100%. The pdNDF fraction is used to calculate NDF digestibility using models based on rates of digestion and passage.

Dietary forage NDF percentage is recommended as a primary basis for diet formulation because it is an actual measurement that has been demonstrated to be related with feed intake and rumen pH in published, peer-reviewed research. However, it must be adjusted for various factors including forage particle size (particularly when forages are chopped very finely) when formulating diets. Other measures are affected by the rates of digestion in, and passage from the rumen; both of which vary with source of feed, diet composition, animal characteristics, and their interactions. The peNDF fraction is typically determined based upon the NDF comncentration and particle size of the feed. However, it is also affected by the NDFD and fragility of forages, both of which vary greatly both among, and within, forage families. Forage fragility affects the rate of particle size reduction during eating and rumination. Increased forage fragility will decrease the physical effectiveness of the NDF by decreasing ruminal retention time.

Measures of NDFD or uNDF are determined in vitro with dried, ground feeds. However, grinding increases rate of digestion by increasing the surface area available to microbes compared with feeds as fed. In addition, the retention times selected (e.g. 30 h or 48 h) are only estimates and actual rumen retention times in the cow differ greatly among feeds. Therefore, NDFD30 and uNDF30 do not accurately represent the digested or undigested fractions in the rumen. For instance, forage legumes such as alfalfa are more fragile, and pass from the rumen more quickly than cool-season grasses so using the same retention time for both over-predicts digestibility of the legume and under-predicts digestibility of the grass. Despite this, the digestibility of NDF measured in vitro or in situ (such as NDFD30) within a forage family (grass or legume) is a useful measurement because it is positively related with DMI of lactating cows. However, it is very important to note that it is *negatively* related with DMI across these forages. This is because grasses have higher NDFD than legumes but lower DMI, as discussed below. In addition, NDFD30 is not necessarily related with NDF digestibility in vivo, which depends upon the effect of diet on DMI and rumen retention time. Therefore, it should not be used to adjust the energy content of feeds. The positive relationship between NDFD and DMI (and milk yield) within, but not across forage family (legumes, grasses) has been shown in individual studies as well as several statistical analyses of treatment means from the literature. uNDF240 has been proposed as proxy for DMI potential with the idea that forages with low uNDF240 should allow greater DMI. However, cool-season grasses have lower uNDF240 and lower DMI compared with legume forages. This is because legumes digest and pass from the rumen more quickly, increasing ruminal clearance rate and decreasing rumen fill compared with grasses. Therefore, like NDFD, uNDF240 cannot be used to rank forages for intake potential across forage family. Whereas uNDF240 might be related with DMI within forage family, there is not enough data reported to conduct a statistical analysis to verify this claim or to compare it with NDFD30. It is important to note that all measures of NDFD or uNDF should be measured on individual feeds and not the entire diet. This is because NDF from non-forage sources have little effect on DMI, regardless of their digestibility or indigestibility.

Stage of lactation

Far-off dry cows: Goal is to maintain body condition score and limit visceral fat accumulation.

Allocation: Forages with high NDF and low crude protein concentrations such as mature grass hay or silage and straw to limit energy intake close to requirements. Forages with lower NDF digestibility and long ruminal retention times can be utilized. Limit corn silage with high grain concentration.

Supplementation: Add grain to meet energy requirements and limit body condition gain.

Close-up dry cows: Goal is to maintain rumen fill through the transition period. The pool of ruminal digesta will provide energy, buffering capacity and distention to reduce risk of ketosis, acidosis, and displaced abomasums, respectively.

Allocation: Wheat straw digests and likely passes from the rumen slowly and it has been used to dilute energy density of corn silage in TMRs for dry cows. Grass silage or hay is likely more beneficial because the fiber is more digestible and it provides energy for a longer time when feed intake decreases at calving. However, grass with high potassium concentrations might require anionic salts in prepartum diets to reduce milk fever following calving. Avoid finely chopped silages (to ensure adequate rumen retention time) and forages with high protein concentration (to avoid excessive protein in diets).

Supplementation: Include a limited amount of moderately fermentable grains to stimulate insulin secretion and limit fat mobilization while maintaining rumen fill. Non-forage fiber sources do not provide glucose precursors or rumen fill and should be avoided.

Fresh cows: Goal is to maintain rumen fill to reduce risk of displaced abomasum and acidosis and to provide glucose precursors in a form that will maximize energy intake.

Allocation: Forages with moderate to high NDF concentration with high NDF digestibility but long ruminal retention times such as grass hay or silage. Use of forage with higher NDF concentration will allow adequate dietary space for grain while maintaining rumen fill. Avoid finely chopped silages. Some long fiber particles are necessary to form a mat and increase digesta retention in the rumen, but excessive length of cut can increase sorting, particularly for dry diets. Corn silage can be used but highly fermentable corn silage (e.g. aged corn silage ensiled more than one year, corn silage less than 30% DM, over-processed corn silage) should be limited.

Supplementation: Avoid feeding highly fermentable starch sources to fresh cows because rapid production and absorption of propionate will stimulate oxidation in the liver and suppress feed intake (Allen et al., 2009; Albornoz and Allen, 2018). Starch sources with moderate ruminal fermentability and high digestibility in the small intestine, such as dry ground corn, will provide glucose precursors and less propionate to stimulate oxidation and suppress feed intake. Dry ground corn is the preferred starch source because rumen fermentability is moderate but whole-tract digestibility is high. Non-forage fiber sources can be used to dilute starch when high NDF forages are used but should otherwise be limited because they provide few glucose precursors and little rumen fill.

High producing cows Goal is to feed a low-fill, highly fermentable diet as gut fill begins to dominate control of feed intake. This might be only 7 to 10 days after calving for some cows in the herd or more than 3 weeks for others and is likely indicated by lower plasma NEFA and ketone concentrations, visual observation of cow gut distension, and steadily increasing feed intake.

Allocation: Forages with fiber that is broken down by digestion and chewing quickly (increased fragility) such as brown-midrib corn silage and hay and silage from legumes will clear from the rumen and allow greater feed and energy intake than forages that have long retention times in the rumen (e.g. mature grasses). Adequate long particles are needed to retain potentially fermentable particles, increasing diet digestibility. Forages with low NDF concentrations (except corn silage) might limit diet space for starch (needed to provide glucose precursors) and should be used sparingly.

Supplementation: High producing cows respond favorably to highly fermentable diets and low-density steam-flaked corn, high moisture corn and rolled barley work well in these diets. However, starch sources that are very rapidly fermented such as ground wheat should be limited. Because feed intake is limited to a large extent by ruminal fill, feed ingredients that can depress ruminal motility such as fat and sugar sources should be limited. Non-forage fiber sources can be used to dilute starch, if needed, but should otherwise be limited because they provide few glucose precursors.

Maintenance group Goal is to maintain body condition score (preventing further gain) while also maintaining or increasing milk yield. Feed a more filling, less fermentable diet as milk yield declines. As lactation progresses past mid-lactation, the highly fermentable diet that is optimal for high-producing cows can depress feed intake as milk yield and glucose demand decreases. Therefore, cows should be switched to a less fermentable and more filling diet as milk yield declines. This will increase feed intake and provide a more consistent supply of fuels, partitioning more energy to milk rather than body condition. Furthermore, the less fermentable, more filling diet will increase ruminal pH and decrease risk of milk fat depression and late lactation abomasal displacement.

Allocation: Forages with a wide range of NDF concentration can be used in these diets but the NDF should be potentially digestible. More grass can be included in these diets; although grass fiber may have longer retention time in the rumen and be more filling, it is also more digestible. Highly fermentable corn silage should be limited to avoid partitioning energy to body condition. High-protein forages should be limited to avoid feeding excess protein.

Supplementation: Limit highly fermentable starch sources (e.g. high moisture corn, ground barley, wheat) by substituting less fermentable feeds such as dry ground corn or NFFS. These "flex-fuel" cows have lower requirements for glucose precursors and can better utilize non-starch feeds to provide energy in a form to spare glucose. Unsaturated fats likely decrease feed intake and increase risk of milk-fat depression and subsequent partitioning of energy to body condition and should be avoided.

Conclusions

Consideration of physiological changes occurring through lactation and the physical and digestion characteristics of diets beyond their nutrient composition is required to optimize forage allocation and supplementation for lactating cows. Whereas more research is needed to better understand animal response to diets, the concepts presented in this paper will help to formulate diets to improve animal health and farm profitability.

References

Albornoz, R. I. and M. S. Allen. 2018. Highly fermentable starch at different diet starch concentrations decreases feed intake and milk yield of cows in the early postpartum period. J. Dairy Sci. 101:8902-8915.

Allen, M.S. 2000. Effects of diet on short-term regulation of feed intake by lactating dairy cattle. J. Dairy Sci. 83: 83:1598-1624.

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.

Beauchemin, K.A., B.I. Farr, L.M. Rode, G.B. Schaalje. 1994. Effects of alfalfa silage chop length and supplementary long hay on chewing and milk production of dairy cows. J. Dairy Sci. 77:1326-1339.

Harvatine, K. J., J. W. Perfield II, and D. E. Bauman. 2009. Expression of enzymes and key regulators of lipid synthesis is upregulated in adipose tissue during CLA-induced milk fat depression in dairy cows. J. Nutr. 139: 849–854.

Kammes, K. L. and M. S. Allen. 2012a. Nutrient demand interacts with forage family to affect digestion responses in dairy cows. J. Dairy Sci. 95:3269-3287.

Kammes, K. L. and M. S. Allen. 2012b. Rates of particle size reduction and passage are faster for legume compared to cool-season grass, resulting in lower rumen fill and less effective fiber. J. Dairy Sci. 95:3288-3297.

Mahjoubi, E., H. Amanlou, D. Zahmatkesh, M. Ghelich Khan, and N. Aghaziarati. 2009. Use of beet pulp as a replacement for barley grain to manage body condition score in over-conditioned late lactation cows. Animal Feed Science and Technology 153: 60–67.

Oba, M. and M. S. Allen. 1999a. Effects of brown midrib 3 mutation in corn silage on dry matter intake and productivity of high yielding dairy cows. J. Dairy Sci. 82:135-142.

Oba, M. and M. S. Allen. 1999b. Evaluation of the importance of the digestibility of neutral detergent fiber from forage: effects on dry matter intake and milk yield of dairy cows. J. Dairy Sci. 82:589-596.

Voelker, J.A. and M.S. Allen. 2003. Pelleted beet pulp substituted for high-moisture corn: 1. Effects on feed intake, chewing behavior, and milk production of lactating dairy cows. J. Dairy Sci. 86:3542-3552.

Voelker Linton, J. A. and M. S. Allen. 2008. Nutrient demand interacts with forage family to affect intake and digestion responses in dairy cows. J. Dairy Sci. 91:2694-2701.

Voelker, J. A., G. M. Burato, and M. S. Allen. 2002. Effects of pretrial milk yield on responses of feed intake, digestion, and production to dietary forage concentration. J. Dairy Sci. 85:2650-2661.