12-2020

Predicting voluntary forage intake of supplemented beef cattle

Connor Biehler
cbiehler@vols.utk.edu

To the Graduate Council:

I am submitting herewith a thesis written by Connor Biehler entitled "Predicting voluntary forage intake of supplemented beef cattle." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Animal Science.

Jason K. Smith, Major Professor

We have read this thesis and recommend its acceptance:

Justin D. Rhinehart, Gary E. Bates

Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Predicting voluntary forage intake of supplemented beef cattle

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Connor Kristopher Biehler

December 2020

ACKNOWLEDGEMENTS

First, I would like to say thank you to my parents, Mr. and Mrs. Randy Biehler. For continuously pushing me to better myself, and allowing me to pursue the opportunities I have been blessed with. I would also like to say thank you to my sisters, Cayla Duckett and Dr. Paige Reese, for pushing me to pursue a post-secondary education. I would also like to say a special thank you to my grandparents, Mr. and Mrs. Dale Graham. Your guidance and the lessons you have taught me will continue to guide me in my personal life and professional career. I can only pray to become a man of the character that my Father and Grandfather possess.

Next, I would like to thank the friends I have made here during my time at the University of Tennessee. I would like to thank my roommates: Jarret Proctor, Kyla-Jo Farmer, and Nate Long. For your friendship, and also the roles you played in my research and successes here at UT. Also, a special thank you to Kamille Piacquadio and Kiernan Brandt for being there for each other through the failures and successes that come with pursuing a research degree.

Additionally, I would like to individually thank my committee members Dr. Justin Rhinehart and Dr. Gary Bates. Your guidance, practical knowledge, and professionalism will be some of the most valuable lessons I will take with me as I continue to take the steps of transitioning into a career. Most importantly, I want to thank Dr. Jason Smith for giving me the opportunity to work under him, and taking a chance on me to further my career as an applied ruminant nutritionist. I could not have assembled a better group of men to train me in your specific facets of the applied beef cattle industry and professional development.

ABSTRACT

A major priority of beef cattle production is to meet animal nutrient requirements in order to achieve a desired level of productivity. Accurately predicting voluntary forage intake (VFI) is necessary to accurately predict the total nutrient intake of grazing or forage-fed beef cattle that are also supplemented with other sources of nutrients. Therefore, the objectives of this experiment were to utilize data from published literature to 1) identify factors that explain variation in VFI, and 2) develop and validate one or more mathematical models that predict VFI or total nutrient intake of grazing or forage-fed and supplemented beef cattle. A comprehensive literature review was conducted to retrieve experimental means (n=609) and descriptive information from 131 feeding trials that measured VFI and supplement intake. Simple linear regression identified 43 continuous and 7 categorical variables that were related ($P < 0.05$) to forage DMI. Following randomization, 70% of published observations were used to develop predictive models, while the remaining 30% were used for validation. Categorical explanatory variables used to predict forage or total dry matter (DM) intake (DMI) included forage classification, forage harvest method, forage stem length, cattle production stage, and supplement feeding frequency, while continuous explanatory variables included shrunk body weight (BW), supplement neutral detergent fiber (NDF) intake (NDFI), supplement hemicellulose (HEM) intake (HEMI), supplement crude protein (CP) intake (CPI), forage CP content, forage NDF content, and forage HEM content, where supplement intake information was expressed in kg x hd^{-1} x d^{-1} and forage nutrient content was expressed as a % of forage DM. Development equations explained 70% (RMSE = 1.31; $P < 0.0001$) and 77% (RMSE = 1.31; $P < 0.0001$) of the variation in forage and total DMI, respectively. When applied to the validation dataset, these equations explained approximately 68% (RMSE = 1.32; $P < 0.0001$) and 72%

(RMSE = 1.31; $P < 0.0001$) of the variation in forage and total DMI, respectively. These models explained a substantial portion of the variation in forage and total DMI, and therefore can be used in production systems to aid in predicting total DMI.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

Introduction

Forages are the foundation of U.S. beef cattle production. Forage production utilizes 25% of the nation's arable land for pastures, range, and hay meadows (Oltjen and Beckett, 1996; Bouton, 2007). However, forage quality or availability is often insufficient to provide the amount of nutrients required for maintenance and/or growth of cattle (Jung and Allen, 1995). In such situations, supplementation programs are often utilized to address forage deficiencies.

The importance of supplementation is magnified during times of increased environmental stress and/or physiological demand. Under-supplementation could result in not meeting nutrient requirements, causing issues such as lower fertility rates, reduced growth, and fetal programming issues in un-born calves. The inability of gestating cows to meet nutrient requirements causes reductions in performance compared to calves from dams on adequate planes of nutrition (Funston et al., 2010). Additionally, overfeeding adds unnecessary expenses, which can cause over conditioning, and ultimately decrease profitability (van der Kolk et al., 2017).

Supplementation amount and nutrient composition potentially have varying effects on voluntary forage intake (VFI). Evidence suggests that certain commodities have the ability to increase or decrease VFI levels (Fleck et al., 1988; Chase Jr and Hibberd, 1989). Also, quality of forage influences VFI (NASEM, 2016). Meeting nutrient and energy requirements of beef cattle is imperative to ensure adequate fertility rates and to attain production goals, while growing cattle need to not only meet maintenance requirements, but also achieve growth expectations.

Overview

Forage quality is most often expressed by its nutritive value. High quality forages are those that are lush, leafy, protein rich, palatable, and have highly digestible fiber concentrations

(Moore et al., 1991). Lush, high quality forages are generally consumed in greater quantities than lower quality forages (Galloway et al., 1993). Low quality forages often have higher levels of neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) which are often associated with later stages of maturity (Salisbury and Ross, 1995). Fiber levels are directly related to the cell wall thickness (Wilson, 1993).

Greater levels of intake of high quality forages often allow cattle to meet or exceed nutrient requirements, which is regularly desired by producers from a cost and labor perspective (McCollum and Galyean, 1985). However, depending on the forage's persistence in pastures as well as maturity status, even lush forages could possibly need further supplementation (Koster et al., 1996). When supplementation programs are implemented, VFI is expected to increase or decrease, depending on the nutritive quality and amount fed (Winterholler et al., 2012). When VFI changes, the animal's overall nutrient intake, and thus the animal's total diet also changes. In such situations, cattle may be over-supplemented or under-supplemented if the respective changes in VFI have not been accounted for. Nonetheless, models that accurately predict VFI of supplemented cattle are currently lacking.

Undoubtedly, there are additional benefits of supplementing proper amounts of protein and energy while also accurately predicting VFI. These benefits include but are not limited to things such as procuring the proper amount of harvested roughage, or knowing how much harvested roughage to reserve in order to meet herd needs if roughages are self-produced, and determining the appropriate level of supplementation. Similarly, accurate VFI predictions would provide producers with the ability to strategically utilize supplementation to influence grazing outcomes and grazable forage resources, particularly during times of drought. These all have the potential to result in substantial economic benefits for producers. The proceeding literature review will discuss physical, chemical, and physiological factors and their impacts on VFI.

Forage-based systems

During ideal conditions and certain seasons, cattle generally have access to enough high quality forage to meet maintenance requirements for protein and energy, while also achieving moderate levels of growth or accretion of body condition. However, during times when forage is overly-mature or drought decreases forage availability, supplementation is required (Baumann et al., 2004). Grass forages generally obtain their highest quality during production stages that coincide with periods of the year that receive the greatest precipitation (Van Soest, 1982). For this reason, producers often plan and manage production cycles in ways that allow the highest nutrient requirements of cattle to overlap with the availability of high quality forages (Thomas et al., 2017).

If forages meet the nutrient requirements of cattle, there is generally no need to supplement. However, low quality forages frequently lack adequate protein, energy, and mineral content to support or sustain a high level of productivity. During extended drought conditions, forages become dormant, while also possessing relatively high levels of fiber and lower digestibility (Hannah et al., 1991). Cattle consume lower quantities of crude protein (CP) deficient forages due to depressed digestibility and passage rates, and VFI generally increases when protein is supplemented (McCollum and Galyean, 1985; Fleck et al., 1988). Reduced VFI can prevent cattle from consuming enough nutrients to reach their requirements for maintenance and/or growth. It is during these times that producers are faced with deciding to either spend money to feed a supplement or sacrifice productivity of the herd.

Grazing strategies

Identifying more cost-effective alternatives to feeding procured commodities to make up for forage deficiencies has been a popular area of research, and is of particular interest to beef cattle producers. The primary focus of these studies has been to reduce production costs and overgrazing of forage via extending grazing seasons and reducing the need for supplementation (Riesterer et al., 2000).

One such practice that has been adopted by producers that requires little initial cost (Kim et al., 2008) is commonly referred to as sectional or rotational grazing. Rotational grazing utilizes internal fencing to control access of cattle to a permitted grazing area, based on geographical and environmental factors (Hart et al., 1993). Once an area has been grazed enough to promote regrowth but not over-grazed, cattle are allotted access to fresh forage while the previously grazed area goes through a rest period (Riesterer et al., 2000). Rotational grazing increases fresh growth of forage before it becomes too mature and optimizes yield when compared to continuous grazing (Henning et al., 2000). This is a result of time-regulated rotation, which allows cattle access to consume high quality, available forage (Hart et al., 1993). Added benefits of rotational grazing include lower fiber levels and higher protein levels relative to continuous grazing scenarios. A more uniform grazing of the available forage allows for more persistent forage stands, as well as a higher mineral content in available forage, and improves gains as opposed to cattle in continuous grazing programs (Walton et al., 1981).

Another grazing strategy that is commonly utilized to reduce supplementation requirements is stockpiling perennial forages to accumulate biomass through summer and fall. The purpose of this practice is to utilize accrued herbage mass for winter grazing (Hitz et al., 1997). This strategy prolongs the life and persistence of available forage stands (Riesterer et al., 2000). Utilizing the aforementioned strategies, producers and nutritionists can build programs in order to prolong or increase forage availability, as well as extend the grazing season (Poore and Drewnoski, 2010).

Factors such as geographic region and weather also play a role in prolonging pasture grazing. The Southeastern region of the U.S. has warmer climates, a prolonged growing seasoning, and greater precipitation relative to other regions of the country. This allows for greater forage persistence (Hoveland, 1986). When combined with the added geographical factors of smaller pastures, these factors allow for the previously-mentioned grazing strategies to be implemented far easier than other places, such as the inter-mountain West. The annual precipitation of aforementioned regions is not only far lower, but topography of the land is generally hillier and rockier, making the aforementioned strategies more difficult to execute (Hepworth et al., 1991).

Forage type and composition

In addition to the previously mentioned strategies there are other, natural occurring factors that influence VFI. Seasonal variation and herbage mass both influence nutrient composition of forages (NASEM, 2016). Consequently, time of year causes variation in forage moisture and nutrient content (Hitz et al., 1997). This implies some hay meadows/pastures could be lush and have high nutritive values during certain seasons, but during other times these same forages become dryer and more mature. These changes are often observed in both quantity and quality (Thomas et al., 2017). Forage nutritive quality can be described as the chemical composition and digestibility of forage, while forage quality can be determined by nutritive value and average animal intake (NASEM, 2016). Low quality forages are generally high in fiber, unpalatable, low in protein, stemmy, and lack trace minerals (Church and Santos, 1981).

Stage of forage maturity at harvest or grazing has greater influence on forage quality than any other factor (Van Soest, 1982). It is often assumed that forage yield is related to forage quality, however high forage yields do not correlate to high quality forages (Van Soest, 1982). Often times when forage yield is at its highest during later stages of maturity is when nutritive value is at its lowest. This is due to increasing levels of lignin, a non-soluble fiber, as forage matures (Jung and Vogel, 1986).

Maturity at harvest and stem length both affect forage intake. During certain seasons when pastures contain adequate moisture and optimum forage quality, intake levels will increase relative to dryer times of the year (Koster et al., 1996). Even though more mature dormant forages generally have greater quantity, they often lack in quality compared to lusher forages (Hitz et al., 1997). Mastication of mature, long-stem forages is not as effective at breaking down cell walls as is decreasing particle size via processing forage (Judkins et al., 1991). The breakdown of cell walls is vital to access and digest non-structural carbohydrates located in the cell wall. Without the breakdown of the cell wall the contents located inside the cell will not be digested.

Cool and warm season forages

Warm and cool season forages have considerable differences in their chemical and physical properties. These differences inherently influence VFI and digestion (Galloway Sr et al., 1991). The main dissimilarity between cool and warm season plants is the anatomy of their photosynthetic systems. Cool season forages only utilize the Calvin Cycle, which is driven by production of rubisco in the stroma of chloroplasts (Salisbury and Ross, 1995). Since this pathway occurs throughout the mesophyll cells of leaves, high levels of water are lost via transpiration (Salisbury and Ross, 1985).

Warm season forages differ by having Kranz anatomy in their bundle sheath cells. The mesophyll cells of warm season forages also differ from cool season forages by utilizing a four-carbon compound pathway with an extra step and additional enzyme (Salisbury and Ross, 1995). This step is the initial fixing of the carbon enzyme, phosphoenolpyruvate carboxylase (Hatch and Slack, 1968). While this is occurring in the mesophyll, the Calvin Cycle is occurring only in the bundle sheath portion of leaves, prompting the stomates to spend less time open, allowing carbon dioxide in (Salisbury and Ross, 1995). These efficiencies reduce transpiration due to the stomata not remaining open as long, making warm season forages more water efficient in hot, dry climates than cool season forages (Moser et al., 2004). Thus, warm season forages are better adapted to tropical climates, where extended warm periods promote growth (Moser et al., 2004).

Both grasses have versatility in their respective production uses. Most fields and pastures contain combinations of cool and warm season forages to provide greater forage availability throughout the year (Henning et al., 2000). Cool season grasses also provide available nutrients during periods of the year when warm season forages are dormant, and warm season grasses provide nutrients during periods of the year when cool season forages are dormant (Hardin et al., 1989). Despite warm season grasses being more photosynthetically efficient than cool season grasses, they maintain higher amounts of dry matter (DM) and often have inferior nutritive value (Salisbury and Ross, 1995). In order for the starches located in the plant cells to be digested, the fiber of the cell wall is first required to be degraded (Salisbury and Ross, 1995). Thicker cell walls of warm season grasses caused by increased fiber levels makes cell contents less bio-available in the rumen as opposed to the more readily available nutrients of cool season grasses (Jones et al., 1988).

Cool season forages are generally more lush and palatable with lower proportions of DM (Jones et al., 1988). Furthermore, the origin of these contrasts begin in the cell structure of the plants. Cellular structure of warm season grasses are arranged more densely and compact than cool season grasses (Salisbury and Ross, 1995). These cellular differences cause copious levels of cellulose and lignin in warm season forages, making them difficult to digest (Lagasse et al., 1990). This further provokes greater amounts of fibrolytic bacteria degradation to occur in warm season rather than cool season grasses (Brake et al., 1989).

Physical differences in forage composition between warm and cool season grasses cause differences in the ruminal functions and microbial population. These dissimilarities include alterations of potential hydrogen (pH), rate of fiber degradation, and may differentiate with additional supplementation (Jones et al., 1988). It has been determined that feeding certain supplemental grains with warm season grasses increases synthesis of microbial protein due to low levels and slow releasing nonstructural carbohydrates (Jones et al., 1988; Hardin et al., 1989).

Grazing cover crops

Some producers graze cover crops during specific seasons as an alternative or addition to more traditional grazing systems. Cover crops provide valuable roughage sources for both the stocker and cow-calf sectors of beef production in the Southern United States (Adams et al., 1996). Grazing cattle on small grain pastures, such as oats or rye, (*Avena sativa or Secale cerale*, respectively) allows for higher protein levels (CP = 16.5-19.0 % of DM) and greater total digestible nutrients (TDN = >60 % of DM) relative to more traditional grass forages (Islas and Soto-Navarro, 2011; NASEM, 2016). Similarly to grazing dormant grass forages, cattle stocked on dormant cover crops receive insufficient nutrients to meet requirements. Protein nitrogen is often the limiting factor in grazing dormant cover crops, where cattle lack the protein needed for microbial population growth in order to metabolize protein from not only the forages, but also the microbes (Reed et al., 2007). In such situations, this would be expected to cause a reduction in VFI, and protein should be supplemented to make up for deficiencies.

Brassicas such as turnips (*Brassica rapa*) are also a viable option for grazing cover crops in the late fall if forage is unable to be stockpiled (Haramoto and Gallandt, 2005). These crops are generally thought of for consumption by humans or in wildlife plots, but can supply high quality nutrients to beef cattle. This is due to a rapid establishment rate in the late summer, and ability to provide forage before the drier months of fall. Brassicas are high in readily fermentable carbohydrates, and require lower intakes to meet nutrient requirements relative to grass forages (Barry, 2013). However, brassicas possess the potential to accumulate nitrogen in immature plants, which can cause nitrate poisoning in cattle (Brakenridge, 1956). If adequate growth is provided, nitrate levels should decrease as the plant matures and nitrate levels decline. Brassicas also present other risks such as pasture bloat and anemia (Shull and Cheeke, 1983).

Legumes

Legumes such as alfalfa (*Medicago sativa*) and clover (*Trifolium*) are high nitrogen sources for both ruminants and soil fertility alike (McKey, 1994). Straight stands of legumes can be grazed, but are commonly cohabitated with grass forages. This allows them to work as a companion species when mixed with cool and warm season grasses (Ball et al., 2009). Feeding legumes and grass hay jointly causes alterations of ruminal activity. Legumes are highly digestible due to their high levels of the soluble fiber, pectin, which is almost entirely degraded in the rumen (NASEM, 2016). Legume and grass-legume mixtures promote rumination compared to grasses fed alone due to higher crude protein levels (Lagasse et al., 1990).

Similarly to grass forages, legumes can be utilized for hay production. Alfalfa is highly revered legume hay, and regularly has more desirable nutritive quality comparatively to grass hay (Burns et al., 2007). Supplementing alfalfa hay along with grass hay is another common practice to increase VFI and degradability of low quality, energy deficient forages (Lintzenich et al., 1995). High roughage quantities present in alfalfa hay can help control a pH drop in high grain rations, and helps to increase dry matter intake (DMI) and average daily gain (ADG; Farran et al., 2006).

However, legumes rich in soluble proteins, such as alfalfa and certain clovers, cause pasture bloat, which is a combination of free gas bloat and frothy bloat (Fay et al., 1980). In instances where cattle bloat from grazing legumes, a nonionic surfactant such as poloxalene can be administered, commonly in a block form or as a feed additive to reduce bloat (Bartley, 1965). If utilized, poloxalene should begin to be administered 48-72 hours prior to cattle being granted access to bloat-inducing legumes. Even though bloat is a concern for certain legumes, others such as sainfoin (*Onobrychis viciifolia*) and birdsfoot trefoil (*Lotus corniculatus*) are considered bloat safe due to high levels of tannins (Majak et al., 1995).

Other forages

Harvested crop residues are generally nutrient deficient, but high in dry matter foliage mass (Fike et al., 1995). Protein digestion of wheat straw is inhibited due to high lignin levels (Liu et al., 2005). As previously mentioned, high lignin levels make degradable starches located in the cell more difficult to access. In order to add more digestible protein to wheat straw, producers have the option to ammoniate it. Ammoniating wheat straw improves the quality of wheat straw because the added ammonia can be used as a source of nitrogen by fibrolytic microbial populations, which aids in their growth (Horton, 1978; Fike et al., 1995). This increase in fibrolytic bacteria speeds up digestion and increases microbial crude protein synthesis of fibrous wheat straw.

Supplementation programs

Overview

Feed costs vary tremendously due to geographical location and management, but commonly make up approximately 50-70% of an operation's annual expenses (Eversole et al., 2005; Ramsey et al., 2005; Shike, 2013). Because of this supplementation programs often represent opportunities for cost savings, and at times, make up a large portion of these costs. As shown in multiple studies, supplementation programs can influence the intake and digestion of forage to varying degrees, based on the nutrient composition and amount supplemented (Fleck et al., 1988; Chase Jr and Hibberd, 1989; Winterholler et al., 2012). These changes in degradation rate can be advantageously used when implementing supplementation programs to cattle. As previously mentioned, when quality and intake of forage are insufficient to meet nutrient requirements for maintenance and/or growth, producers supplement cattle in order to provide the lacking nutrients (Kouakou et al., 1994; Weder et al., 1999). Generally, supplements are hand fed in pasture-based settings, either directly onto the ground or in a bunk.

Supplementation systems are generally based on an average daily intake of supplement set at a restricted rate. Cattle that are supplemented with limited amounts of feed have greater digestibility, ultimately leading to prolonged passage rates (Löest et al., 2001). Added benefits of feeding supplements to cattle in grazing scenarios include the potential to increase stocking rate and forage persistence (Islas and Soto-Navarro, 2011). This allows producers to save harvested forage for inclement conditions.

Supplemented cattle are more selective of forages relative to non-supplemented cattle (Hess et al., 1994; Scholljegerdes and Kronberg, 2010). This generally means that supplemented cattle consume a greater portion of high-quality leaves and are more likely to avoid the stems of more mature forages. As previously mentioned, cattle generally consume greater amounts of high-quality forages, but when compared to low-quality forages, high-quality forages provide cattle with a higher nutritive value when consumed in iso-quantities.

Utilization of high-quality forages allows producers to feed non-structural carbohydrates, to decrease total DMI, but still sufficiently meet nutrient requirements for growth or maintenance while preserving forages. For example, supplementing non-structural carbohydrates can aid in reducing VFI, which in turn can help to extend hay reserves into dormant seasons (Chase Jr and Hibberd, 1989). When only low-quality roughage is available, and nutrient intake levels are insufficient, protein supplementation is often assumed to speed up digestion and rate of passage, thus increasing VFI (Fleck et al., 1988).

Forage intake suppressors

Starchy grain supplementation decreases digestibility of fiber when at levels > 0.872 ; kg x hd^{-1} x d^{-1} on a DM basis in cows, slowing down rate of passage (Chase Jr and Hibberd, 1988). Some production systems attempt to lower VFI in order to prolong forage stands. Supplements fed in these programs are often commonly referred to as forage stretchers or extenders. Reducing forage intake in ruminants receiving stretching rations promotes increased forage selection of pasture or range (Gai et al., 2018).

Unsaturated fatty acids found in lipid-rich supplements are energy dense but decrease ruminal digestion rates of protein, starch, and carbohydrates (Kouakou et al., 1994; Hussein et al., 1995). Un-saturated fatty acids undergo the processes of lipolysis then biohydrogenation in the anaerobic ruminal environment, which saturates fatty acids (Jenkins et al., 2008). These fatty acids can either be incompletely or entirely biohydrogenated. In the rumen, un-saturated fats are more toxic to cellulolytic bacterial populations than saturated fats, meaning un-saturated fats cause decreased fiber degradability (Johnson and McClure, 1972; Hussein et al., 1995). Lipid-rich supplements should be included at low amounts (crude fat of <5% of DM) in diets to prevent inhibited fiber digestion (NASEM, 2016).

Forage intake stimulators

In certain production scenarios, increasing forage intake is desired. It is a common practice for producers to provide specific supplements to increase rate of passage and digestion, thus increasing VFI. A common example of this could include stocking growing cattle on dormant range/pasture, and adding a supplementation program to optimize productivity. If ample amounts of dormant or harvested forage are stockpiled, supplements are regularly fed to increase VFI when the quality of grazed forages is low. Increasing low quality forage intake may help to provide cattle with adequate nutrients to meet requirements (Judkins et al., 1991). Supplementing protein to cattle grazing low quality forage increases VFI by increasing rate of passage (Koster et al., 1996; Bandyk et al., 2001). Rate of passage is increased due to fibrolytic and cellulolytic bacteria using the available amino acids or ammonia, found in protein-rich feedstuffs, as nitrogen sources to promote growth (Atasoglu et al., 2001), which accelerates fiber digestion (Fike et al., 1995). Supplementing high fiber by-products promotes rapid fiber digestion when fed with poor quality forage, due to an increase in cellulolytic microbial populations. This allows digesta to be degraded more rapidly, increasing passage rate (Farmer et al., 2001).

Frequency and time of supplementation

For varying reasons, producers are often reluctant to supplement herds daily. Certain feeding programs reduce the number of days supplemented from daily to alternating days, three times a week, or once weekly. These common reductions of feeding occurrence reduce fuel usage, time, and labor requirements, decreasing costs of supplementation programs (Farmer et al., 2001; Loy et al., 2008). However, studies have found that supplementing protein once a week to cows grazing low-quality forages causes loss of body condition compared to those supplemented daily or three times a week (Huston et al., 1999). Other studies have found that un-supplemented cattle walk further distances daily and practice more selectivity of the forages they graze (Adams, 1985). This selectivity allows cattle to avoid mature forages that are lower in nutritive quality. Selection of more nutrient-rich forages speeds up passage rate, in turn increasing VFI, which often allows cattle to meet nutrient requirements (Ball et al., 2009). Other studies have shown that even though non-supplemented cows were able to be more selective in the forages they graze, they were still unable to overcome deficiencies and lost greater amounts of body condition (Huston et al., 1999).

Other studies utilizing growing cattle found that supplementing corn or distiller's grains three times per week decreased forage intake and ADG relative to contemporary groups that were supplemented daily (Loy et al., 2007). Whereas, hay intake of groups of cattle fed soy hulls or corn gluten feed is lower when supplementation occurs on alternating days rather than daily (Drewnoski and Poore, 2012).

Another factor that is associated with frequency of feeding that also affects time spent grazing and ultimately VFI is time of day of supplementation (Hess et al., 1994). A study conducted by Adams (1985) showed that steers supplemented in the evening voluntarily consumed 0.3% of BW more forage than counterparts supplemented in the morning. This depression of VFI in the morning supplemented group was likely due to these steers being more selective in grazing than those supplemented in the evening (Adams, 1985). Depending on the goals of a producer, either scenario could be beneficial if properly implemented in accordance with production goals. If decreased VFI is a priority, then feeding in the morning is more appropriate. If increased VFI and/or to utilize dormant forages before the growing season begins are priorities, then supplementing in the evening would be more appropriate.

Commodities

When implementing supplementation programs, two of the biggest concerns of producers are cost and logistics of feed delivery (Loy et al., 2008). Certain geographic areas are more conducive for transporting and obtaining specific commodities than others. This is dependent upon varying production agriculture or industries that utilize and/or produce certain agricultural commodities and byproduct feedstuffs in respective regions. Proximity to these industries is correlated to commodity cost (Kocoloski et al., 2011). For example, producers in the Northern Plains have less access to cottonseed products, but greater access to distiller's dried grains (DDG) relative to producers in the Southeast. These aforementioned factors provide their own benefits and challenges and should be accounted for by cattle producers implementing supplementation programs.

Wheat middlings

Wheat middlings, more commonly referred to as wheat midds (WM), are a by-product of wheat flour production. They are comprised of post milling screenings that are separated after flour has been extracted from the seed (Dhuyvetter et al., 1999). Consisting mostly of bran and germ portions of the seed from the cleaning of screens, WM can either be formed into a pellet or fed loosely. While WM generally contain greater concentrations of fiber (NDF = 38% of DM) and protein (CP = 18.5% of DM) than wheat grain, they contain lower levels of starch (25.5% of DM) and energy (TDN = 73.9% of DM) than wheat (NASEM, 2016). When supplemented to gestating cows grazing dormant forages, extra energy and adequate protein provide for greater total intake than cattle fed iso-nitrogenous levels of a corn and soybean meal (SBM) supplement (Dhuyvetter et al., 1999). However, it has been identified by Marston and Lusby (1995) that cow body weight (BW) and condition did not improve when lactating cows were fed a greater theoretical amount of energy via inclusion of WM when compared to SBM at iso-nitrogenous levels of 2.60 kg of CP per kg of BW. This is likely due to the higher protein levels in SBM increasing the rate of digestion through increasing levels of proteolytic microorganisms, in turn increasing VFI of low quality forages. Containing moderate protein levels of highly rumen degradable protein (RDP; 68.2% of DM), WM are a compatible supplement for increasing VFI of cattle consuming low-quality forages (Ovenell et al., 1991). When WM are supplemented at 0.78% of BW on a DM basis and soybean hulls (SBH) are supplemented at 0.91% of BW on a DM basis, to yearling cattle fed low-quality forages, WM would be expected to increase total intake by 0.22% of BW on a DM basis (Garces-Yepez et al., 1997).

Soybean byproducts

The thin outer layer of the soybean is the hull. This portion is removed from the soybean during the soy oil extraction process (NASEM, 2016). Soybean hulls contain minimal levels of starch (1.1% of DM) and lignin (2.47% of DM), a high level of fiber (NDF = 65% of DM), and a moderate level of protein (CP = 12.4% of DM; NASEM, 2016). Soybean hulls can be added to forage-based diets to increase gain in growing cattle while having little to no effect on VFI when supplemented at < 0.5% of BW on a DM basis, but have been reported to decrease VFI when supplemented at 0.66% of BW on a DM basis (Martin and Hibberd, 1990; Galloway et al., 1993).

Supplementing SBH at a rate of 0.50 kg x hd^{-1} x d^{-1} on an as fed basis in a high roughage diet, comprised of 87.5% corn stalks, led to lower gains than corn supplemented at the same amount (Anderson et al., 1988; Martin and Hibberd, 1990). However, in another study SBH-based diets were more efficient in their gain:feed ratio than group whose diet consisted of 65% of low-quality forage (Löest et al., 2001). Collectively, this serves as an indication that SBH-based supplementation programs are less effective than corn when supplemented at low rates, but more effective than high-roughage diets, that are low in energy and digestibility, at stimulating growth of cattle. These factors make them a viable option for producers intending to add lean growth without over conditioning to extent of cattle becoming too fleshy.

Soybean meal consists of the ground portion of the soybean that remains following the extraction of soy oil, with the addition of either some or no previously removed hulls. High levels of protein (CP = 45-53% of DM) make SBM a valuable feedstuff (NASEM, 2016). Supplementing ruminally-available nitrogen via SBM increases VFI of cattle grazing mature forages (Stokes et al., 1988b; Mathis et al., 2000). Natural proteins found in SBM promote greater VFI of wheat straw when dietary nitrogen comes from SBM rather than non-protein nitrogen (NPN) from ammoniation (Church and Santos, 1981). This is likely caused by the lack of energy present in the wheat straw, required to breakdown ammonia into microbial crude protein. Mature cows supplemented with 0.68 DM kg x hd^{-1} x d^{-1} of SBM had greater VFI when compared to cows supplemented with 1.57 DM kg x hd^{-1} x d^{-1} of CGF or cows that were not supplemented (Fleck et al., 1988). Another study conducted by Church and Santos (1981) found an increasing effect on VFI as well as greater total DMI when compared to contemporary groups fed iso-nitrogenous levels of a liquid supplement up to 4 kg of CP x kg^{-1} of $BW^{0.75}$ in growing cattle. If supplementing SBM toxicity has been observed when supplemented at amounts greater than > 2% of BW in DM (Raboisson et al., 2013). This is a specific example for SBM, however feeding most commodity by-products at high levels come along with the risk of causing negative health effects. When supplemented above the aforementioned level, ruminal pH drops and ammonia levels increase, causing greater levels of ammonia to diffuse across the rumen.

Corn milling byproducts

The major by-product of wet corn milling, which is comprised of residual corn post removal of the starch and germ, is referred to as corn gluten feed (Fleck et al., 1988). Corn gluten feed can be fed wet, or dried, and has potential to be formed into a pellet. This byproduct feedstuff contains high levels of degradable fiber and low levels of starch (NASEM, 2016). The low starch levels allow for rapid fiber digestion, due to lack of competition between amylolytic and cellulolytic bacteria to degrade fiber (Farran et al., 2006). Corn gluten feed provides high levels of degradable fiber and protein (NDF = 35% of DM and CP = 21% of DM), and as a result possesses the ability to enable rumen microbes to break down and digest available protein at more rapid rates in grazing scenarios (NASEM, 2016). In vitro cell wall digestibility of CGF has been determined to be > 80% (Abe and Horii, 1978). It has been determined that cows grazing native dormant range forage consumed more hay than non-supplemented cows when supplemented with 1.60 kg x hd^{-1} x d^{-1} of CGF pellets on a DM basis (Fleck et al., 1988). However, VFI of cows supplemented with CGF was inferior to contemporary groups fed iso-nitrogenous amounts of SBM at a rate of 0.68 kg x hd^{-1} x d^{-1} on a DM basis (Fleck et al., 1988). Corn gluten feed can be utilized for supplementing to meet protein requirements.

One of the major byproducts of dry milling corn or other cereal grains to produce ethanol is DDG. Often, a portion of the solubles will be added back to the grain to make distiller's dried grains with solubles (DDGS; NASEM, 2016). Distiller's grains plus solubles are the most common feed byproduct currently used in US beef production (NASEM, 2016), and are often available in wet, modified, or dried forms. The remaining nutrient concentration is increased in DDG relative to the original grain (CP = 31% of DM, crude fat = 10.73% of DM, and ash = 5.3% DM; NASEM, 2016). When compared to corn, DDGs are approximately three-fold higher in crude fat and CP, and contain six times the level sulfur (0.66% of DM; Islas et al., 2014; NASEM, 2016).

Distiller's grains can either be fed as a loose feedstuff, or made into pellets of varying sizes. Also, distiller's grains are highly palatable and promote increased VFI due to their highly digestible fiber, high protein, and low starch content (Stock et al., 1990; Winterholler et al., 2012). Because of this, DDGS have become a highly desirable feedstuff, and are often used to enhance low quality forages, roughages, and dry lot diets. Late gestating cows fed 0.3% of BW on a DM basis of DDG as a supplement consumed more low-quality forage than un-supplemented cows, but give birth to lighter calves (Kennedy et al., 2016). When compared to supplementation of iso-nitrogenous levels of SBM to cows at a rate of 0.47 kg x hd^{-1} x d^{-1} on a DM basis, cows supplemented with DDG voluntarily consumed greater levels of forage (Winterholler et al., 2012). However, Luepp (2009) determined that VFI of cattle supplemented with DDGS increased when supplemented up to 0.9% of BW on a DM basis before showing a decline in VFI.

Cottonseed by-products

Cottonseed hulls and cottonseed meal are the by-products produced during the cottonseed oil extraction process. Cottonseed hulls are the outer layer of the seed that are removed prior to oil extraction (Hall and Kononoff, 2011). Hulls contain high levels of fiber (NDF = 81.07 % of DM) that is primarily composed of cellulose (45.8 % of DM), low levels of protein (CP = 6.7 % of DM) and are low in digestibility (TDN = 42.0 % of DM; NASEM, 2016). The high palatability of cottonseed hulls, and high bulk density aids in the influence of increased intake in high concentrate diets of growing cattle (Hall and Kononoff, 2011). A study conducted by Kononoff and Heinrichs (2003) found that when cottonseed hulls replaced roughage levels of 8% DM in a total mixed ration that voluntary intake increased. These aforementioned factors make hulls a valuable resource to producers utilizing forage stretching rations, or as a partial replacement of forages in grazing settings.

Cottonseed meal is the portion of the seed that remains after the hull has been removed, the seed has been crushed, and the oil has been extracted (NASEM, 2016). As a result of high protein levels (CP = 45.0 % of DM) cottonseed meal is regularly supplemented to cattle grazing nutrient-deficient forages. Due to its ability to increase digestibility of those forages, cottonseed meal increases particle passage rate, resulting in increased VFI (McCollum and Galyean, 1985). Cottonseed meal is commonly fed in the southeast due to its widespread availability.

Cereal grains

Conveniences of little to no processing and widespread availability of starchy cereal grains such as corn, sorghum, oats, wheat, and barley create an appealing feedstuff for producers to utilize. However, since sorghum, wheat, and barley are utilized predominately for human consumption, most of the available crop produced in the U.S. is not utilized for livestock feeds due to price competition. Differences in physical composition of the grains cause different rates and extents of fermentation in the rumen. Certain grains including corn are known for slow release fermentation, whereas others such as wheat or barley are more rapidly fermented (McAllister et al., 1994). Since these feedstuffs do not ferment or digest at the same rates, they are expected to have different effects on VFI.

Approximately 47% of all corn production in the U.S. is utilized for livestock feeds (NASS, 2020). Although, due to a constantly shifting supply and demand, the amount of corn produced that is used for livestock feedstuffs varies from year to year. Fluctuations in numbers of livestock on feed, bushels of corn produced, and other environmental and economic factors drive the price up and down prompting shifts in levels of corn utilized for livestock feeds. While a crucial component of feedlot finishing rations, starchy cereal grains can have depressive effects on VFI when utilized in grazing or forage-based scenarios. Supplementing corn at 0.8 kg x hd^{-1} x d^{-1} on a DM basis to mature cattle consuming medium quality forage decreases in vivo digestibility of cellulose, but levels lower than this do not decrease VFI (Carey et al., 1993). In other experiments, supplementing heifers at 0.35% of BW on an a DM did not affect VFI. However, when supplemented at > 0.4% of BW and grazing medium and high quality forage, VFI was reduced due to a decline in fiber digestion (Hall et al., 1990; Brokaw et al., 2001).

Level of grain supplementation influences forage OM digestion. The rumen microbial population shifts from higher levels of cellulolytic bacteria that degrade fiber from the forage, to higher populations of the starch degrading amylolytic bacteria, promoting a decreasing effect on extent of digestion and passage rate (Chase Jr and Hibberd, 1989). One of the major associative effects of this is decreased VFI. In certain scenarios however, this can have its own advantages.

Supplementing cattle grazing crop residue with a source of readily available starch has the potential to allow for increases in stocking rates by up to 33% (Islas and Soto-Navarro 2010).

Processing of starchy cereal grains alters the site and extent of starch digestion within the gastro-intestinal tract of ruminants (Owens et al., 1986). Processing methods can be either wet or dry. The most common dry processing methods include grinding grain in a hammer mill or roller mill. These processes use mechanical stress to compress the grain and break the kernel, which reduces particle size and increases the surface area of particles (NASEM, 2016). Due to this increased surface area, interaction of starch with amylolytic bacteria is heightened (Owens et al., 1986; McAllister et al., 1994).

Liquid supplements

Liquid supplements are commonly comprised of mainly sugarcane molasses, sugar beet molasses, or condensed corn distiller's solubles, along with potentially added levels of protein and/or NPN and various mineral and vitamin ingredients. Digestibility and VFI increase when cattle are fed liquid supplements while grazing low quality, dormant forages (Bowman et al., 1999). Liquid supplementation programs can be implemented to grazing cattle. However, just as in commodity-based rations utilizing NPN on cattle grazing low-quality forages, inferior performance in cattle fed NPN is to be expected when compared to cattle supplemented with a commodity-based feedstuff or liquid supplement with natural protein (Church and Santos, 1981). This is caused by the rumen converting urea into ammonia which can be incorporated in their body in the form of amino acids. These increased ammonia levels, present in the rumen, promote more rapid ammonia absorption. The residual ammonia, that is not synthesized, is absorbed by the GI tract and recycled into the blood stream, which can result in downstream effects and ultimately leading to urea toxicity (Shaikat et al., 2012). Molasses supplements contain high sulfur levels (0.4-0.6% DM), so should be avoided if feeding large quantities of sulfur via other commodities, or water sources contain high sulfur levels (NASEM, 2016).

Ionophores

A standard practice that has widely been adopted by conventional U.S. beef producers is the utilization of ionophores in the diet. Ionophores are antimicrobial drugs that are not medically important to humans, but shift fermentation patterns, resulting in changes in volatile fatty acid (VFA) production. Production of VFAs are shifted to reducing acetate production, and increasing propionate which lowers the acetate:propionate ratio. These changes in acetate:proprionate yield lower methane production levels as well as increase performance by influencing feeding efficiency and promoting weight gains (Bergen and Bates, 1984). Two ionophores that are frequently utilized in forage-based settings include monensin and lasalocid (Russell and Strobel, 1989).

These changes result in increased feed efficiency, especially when administered to cattle fed high forage diets. When grazing cattle are supplemented rations containing grain and an ionophore, total DMI voluntary intake should be expected to decrease, but feed:gain will be enhanced (Bergen and Bates, 1984). Ionophores do not decrease intake or digestion when fed at levels of 0.5 mg/kg of BW in diets utilizing *ad libitum* forage and supplement fed at 0.42% of BW (Galloway et al., 1993). In the second trial of the preceding study it was determined that ionophores improved NDF and OM digestion, as well as increased dry matter VFI by 0.14 kg when fed at 1 mg/kg of BW and supplement was administered in iso-quantities (Galloway Sr et al., 1993).

Ionophores can be implemented into diets via feed or mineral supplementation. Supplementing ionophores in mineral to beef cows and bred heifers fed hay improves efficiency and increases body condition score (Sprott et al., 1988). When monensin is fed at a rate of 33 mg/kg of supplement on a DM basis, intake fluctuations decrease, as opposed to cattle not fed an ionophore. Rather than grazing greater amounts in fewer forage meals, cattle break-up their grazing bouts throughout the course of the day into smaller amounts, but increase the number of these smaller events (Stock et al., 1990). Along the same lines, ionophore supplementation decreases VFI in cattle grazing low-quality forages (Galloway Sr et al., 1993).

Feeding ionophores also allows the ability to feed greater amounts of highly fermentable grains while also partially preventing acidosis (Russell and Strobel, 1989; Stock et al., 1990). Ionophores have no effect on pregnancy rates of lactating or non-lactating cows and heifers, however promote earlier pubertal age in heifers (Sprott et al., 1988). Therefore, ionophores can be a useful investment for growing cattle or replacement heifers as it promotes feed efficiency and decreases VFI.

Non-medicated feed ingredients

Supplements can either be delivered as a single commodity or a blend of commodities with or without other ingredients and feed additives. Additives serve varying purposes, and are often utilized in specific programs for necessary preventative measures. Some common non-medicated additives are sodium chloride (salt), sodium bicarbonate, and calcium bicarbonate (limestone). Salt is often added to supplements as a natural limiter that also promotes eating lesser amounts when included in the supplement at relatively high levels (Kunkle et al., 2000). Salt is commonly used because it possesses the ability to be fed safely and is readily available (NASEM, 2016). However, feeding high levels of salt to cattle consuming corn silage has been shown to limit protein and energy absorption, but does not appear to have this effect on cattle grazing cool season forages (Kunkle et al., 2000). This means that if cattle are grazing cool season forages and are fed a commodity-blend feed or mineral supplement that is high in salt, VFI could decrease without any associative effects on protein or energy absorption.

Sodium bicarbonate and calcium carbonate are commonly used to buffer the acidic hydrogen ions in the rumen (NASEM, 2016). Adding sodium bicarbonate to diets at an inclusion rate of 0.75% of dietary DM in growing cattle supplemented with high levels of fermentable starches decreases DMI of starchy concentrate-based diets, but has no effect on carcass weight, dressing percentage or marbling score (Zinn and Borques, 1993). Cattle fed high starch diets are at risk of developing subacute ruminal acidosis (SARA) and bloat due to incidences of low rumen pH (Keunen et al., 2003). Adding sodium bicarbonate or calcium carbonate allows amylolytic and fibrolytic bacteria to maintain proper populations needed for starch and fiber degradation (Loy et al., 2007). When ruminal microbial populations are adequate, rate of passage and digestion accelerate, promoting increased VFI (Loy et al., 2007). However, non-medicated feed additives that are added to diets of grazing cattle may also aid in animal health, but should not always be expected to influence VFI.

Cattle production class

Production class and type of cattle influences VFI. Variables such as breed type, and age of cattle can affect DMI (NASEM, 2016). For instance, Holsteins have been reported to consume 8% more DM when compared to English or Continental Bos taurus beef cattle of similar weight. However, diets including high levels of fiber have equivalent DMI in both dairy and beef cattle (Tjardes et al., 2002). This is likely due to high roughage, independent of silage diets causing ruminal fill to occur more quickly than in larger framed cattle with greater visceral organ mass.

Stage of production influences intake. During lactation, cows consume increased amounts of forage as opposed to gestating or dry stages, due to increased nutrient requirements (Houghton et al., 1990). Lactation increases DMI of beef cows by approximately 28% relative to gestating cows (Marston and Lusby, 1995). Other studies have shown that VFI, when expressed as a % of BW, increases through the last two weeks of gestation in heifers, in which time it starts to decrease, but remains constant through gestation in multiparous cows (Linden et al., 2014). Intake of multiparous and primiparous cows is similar when expressed as a percentage of BW, but considering heifers are growing at initiation of conception they differ in terms of total amount (Johnson et al., 2003).

Specific nutrition-related factors affecting forage intake

Protein digestion

In numerous studies, protein supplementation has been shown to increase total DMI and improve performance (Guthrie and Wagner, 1988; Carey et al., 1993; Rude et al., 2002). This is an expected result when protein is inadequate for microbial growth. Supplements providing sufficient protein to cattle grazing low quality pasture improve performance due to increased VFI and rate of passage through an increase in microbial populations, thus increasing rate of digestibility (Hannah et al., 1991). Adding protein to the diet of cattle grazing low quality forage speeds up the rate of passage. This increased rate of passage decreases the amount of time that cattle remain full and results in a net increase in VFI.

Protein supplementation can affect VFI by increasing growth rate of ruminal microorganisms. Therefore scenarios utilizing low quality hay, can achieve greater nutrient intakes by feeding supplemental protein to meet nutrient requirements. Supplementing natural protein at 150% of requirements has no effect on fertility when supplemented to non-lactating beef cows (Gunn et al., 2014). This information contradicts previous research that suggests over-supplementing protein has associative effects of impairing fertility (Elrod et al., 1993). The difference observed between the two is likely a function of protein source. The non-protein nitrogen degraded in the rumen used in the Elrod (1993) experiment was likely the causation of lowering uterine pH, whereas the natural protein in DDGS used by Gunn (2014) supplied higher levels of RUP, promoting lower levels of excess protein diffusing out of the rumen and into circulation. Ultimately, protein digestibility is influenced by supplement type, amount, and nutrient composition (Carey et al., 1993).

However, feeding iso-nitrogenous amounts of protein through greater total supplement intake does not increase VFI to the same extent that feeding the same amount of CP through a lesser total amount of supplement (Hannah et al., 1991). This is likely a function of gut fill occurring quicker due to an increased total amount of supplement. Adding a source of dietary NPN such as urea or ammonia decreases competition between fermentable carbohydrates and nitrogenous compounds via rumen microorganisms (Judkins et al., 1991). Urea is converted to a biologically usable amino acids via ammonia and carbon dioxide production (Sewell, 1993). Without this conversion, NPN is biologically unavailable for ruminants to convert to a usable protein (Satter and Slyter, 1974). If fed improperly to cattle grazing low quality forage, NPN compounds will be unable to be converted to a biologically usable form, preventing rumen microbes from hydrolyzing at rates for proper use, thus causing excess diffusion of ammonia across the rumen (Gribbins, 1954). This in turn causes excessive ammonia to build up in the rumen, resulting in excessive levels of ammonia entering and circulating through the bloodstream. Ammonia entering the bloodstream can increase alkalinity of blood, and cause negative effects to the peripheral tissues potentially causing lethal implications (Shaikat et al., 2012).

Protein nitrogen is provided to ruminants by both feed and rumen microorganisms (Pathak, 2008). True protein exists in either a rumen degradable (RDP) or rumen un-degradable (RUP) form. If protein is RUP it passes through the GI tract unchanged, and is digested and absorbed in the small intestine (Lewis, 1957). Extent of intestinal digestibility of protein varies across feedstuffs. For instance the RUP level of cottonseed hulls is more than threefold that of barley silage (70.1% and 20.8% respectively; NASEM, 2016). Even though protein is a required nutrient for maintenance and growth, there are negative toxic effects of over-supplementing protein, which include scouring or urea toxicity. Protein requirements need to be identified and met depending upon the applied scenario (NASEM, 2016).

Fiber digestion

Fiber is composed of the three surrounding layers of cell wall which include hemicellulose, lignin, and cellulose (Salisbury and Ross, 1995). Nutrients such as starch and carbohydrates are located within the fiber, which must be degraded prior to starch and carbohydrates being digested by cattle (Van Soest, 1982). This implies that cell walls must be digestible in order to obtain other nutrients.

Cell wall thickness is associated with plant stage of maturity, with thickness increasing as maturity progresses (Van Soest, 1982). As previously mentioned, warm season grasses have thicker cell walls relative to cool season forages (Salisbury and Ross, 1995). Therefore, due to the difficulty of breaking down these cell walls prior to digesting carbohydrates, supplementing fermentable carbohydrates, such as corn, depresses fiber digestion to a greater extent in warm season than cool season forages (Galloway Sr et al., 1991). This results in increased ruminal degradability of cellulose and lignin in beef cattle grazing cool season forages and being supplemented with corn as opposed to warm season forages in the same scenario (Jones et al., 1988). Hemicellulose is the most digestible, while cellulose is only moderately digestible. Lignin, however, is the least digestible and almost impossible to break down in the rumen (Salisbury and Ross, 1985). With NDF (which includes hemicellulose, cellulose, and lignin) and ADF (which includes cellulose and lignin) being the portions of fiber in the cell, degradation of these portions are necessary to access starches located within the cell (Van Soest, 1982). Some commodities such as SBH have low levels of lignin making their fiber more digestible (Löest et al., 2001).

Another factor that influences fiber digestion is particle size. The thicker cell walls found in warm season grasses promote less particle reduction via mastication and rumination as opposed to cool season forages (Stokes et al., 1988a). Rumination occurs to further break down fiber, and access contents found inside the cell wall to allow for greater microbial digestion (Stokes et al., 1988a). Supplements containing highly digestible fiber and low starch levels typically increase VFI and rate of passage relative to cereal grains (Ovenell et al., 1991). As previously discussed, fiber digestibility also increases when cattle are supplemented with protein (Sunvold et al., 1991).

Starch digestion

As previously mentioned, feeding low to moderate levels of natural protein elevates utilization and intake of low-quality forages, but some scenarios require decreased VFI. Such strategies include feeding starchy grains at high levels, which decreases VFI and provides varying sources of energy for rumen microorganisms (Bodine et al., 2001). In starch-rich diets, populations of cellulolytic bacteria that generally digest fiber decrease, and populations of amylolytic bacteria that favor starch increase, thus decreasing rate and extent of fiber digestion (Hall et al., 1990). Cereal grain supplements decrease VFI as a result of decreased rate and extent of fiber digestion which is directly linked to decreased forage NDF disappearance (Freeman et al., 1992; Garces-Yepez et al., 1997). However, supplementing beef cattle with cereal grain supplements at levels < 0.35% of BW on an organic matter basis has been reported to have no effect on VFI (Brokaw et al., 2001).

High inclusion of starchy cereal grains typically increases ADG (Roberts et al., 2009). However, starch degradation elicits a more acidic ruminal environment (Loy et al., 2007). Inclusion of starchy grains to diets should be administered with caution. High levels of starch can lead to digestive issues such as bloat, or SARA (NASEM, 2016). Starch grains depression of VFI is caused by a shift in microbial populations in favor of starch digesting microbes breaking down fermentable carbohydrates and decreasing populations of cellulolytic bacteria (Judkins et al., 1991).

Lipid digestion

The ultimate goal of beef production is to provide "fat cattle" for harvest, and ultimately a quality product for consumers. Excessive energy supplemented to cattle, meaning that which is not used for maintenance or lean tissue growth, is stored in reserves as triglycerides (van der Kolk et al., 2017). This is an indication that efficient gains and proper adipose development are critical for all classes of cattle, but delivering fat via diet at proper levels is economically vital (Kouakou et al., 1994). Commonly, cattle grazing forages alone consume and digest minimal quantities of fat due to the inherently low lipid content of forages (Van Soest, 1982). Therefore, supplementation programs should be administered to make up for energy, but over feeding fat can have depressive effects on digestion.

Lipid-rich supplements are included in diets to increase dietary energy density, but it is often mis-conceptualized that if cattle are energy deficient, feeding high fat supplements will make up for the energy deficiency without adverse consequences. When fat is included at levels < 2% of dietary DM there is no depression of ruminal fiber digestion (Hardin et al., 1989). When fat is supplemented to cattle on concentrate diets, consuming up to 6% fat will not hinder digestibility of other nutrients (Bodine et al., 2001; Hess et al., 2008). Beyond these aforementioned levels, fiber digestion should be expected to decrease, which would be expected to decrease VFI. Supplementing DDGS to growing cattle at < 0.4% of BW on a DM basis does not decrease VFI of moderate-quality forage. However, for every 1 kg increase of DDGs beyond that level, a 0.55 kg depression of VFI occurs (Leupp et al., 2009). If lipid-rich supplements are utilized properly, producers possess the ability to lower VFI and stretch forage or increase stocking rates.

Nitrogen metabolism

A portion of all consumed protein is transformed to ammonia in the rumen. The rumen microorganisms use ammonia as a source of nitrogen available for microbial growth (NASEM, 2016). This is accelerated by nutrient-rich forages and the previously mentioned supplementation programs and commodities (Stokes et al., 1988a). This explains elevated levels of VFI and digestion in protein supplemented cattle.

The production of microbial protein in the rumen is limited by the level of readily available starch and fat when fed with high fiber, warm season forages (Jones et al., 1988). Feeding minimal amounts of fermentable starch grains and fats to growing cattle increases microbial nitrogen that makes it to the small intestine (Jones et al., 1988). Limit-fed diets may reduce the rate of protein turnover in situations where inadequate total levels of protein do not meet the needs of microorganisms for microbial CP synthesis. However, ruminants possess the ability to conserve available nitrogen through ruminal recycling (Hume et al., 1970). Feeding relatively high levels of RUP may lead to greater efficiency of protein utilization when fed at lower levels due to less loss of ruminal and metabolic nitrogen via the fermentation process (Sawyer et al., 2012).

Nitrogen is a direct expression of CP in feed and forage, making up approximately 16% of CP (NASEM, 2016). Nitrogen content can be determined for organic and total nitrogen using the Kjeldahl method (Kirk, 1950; Bradstreet, 1954). The difference between total nitrogen and total organic nitrogen is that total nitrogen includes the ammonia portion. Protein level can be calculated by multiplying the nitrogen level by 6.25 (NASEM, 2016). Supplementing cattle with ruminally-available nitrogen may increase VFI. This is caused by increasing amounts of absorbable amino acids, thus increasing intake of low protein forages when consumption of forage alone provides less protein than required for growth or maintenance (Stokes et al., 1988a). Nitrogen metabolism can have direct effects on VFI. If cattle lack metabolizable nitrogen in diets, rate of digesta degradation will decrease and in turn decrease VFI.

Rumen pH

Ruminal pH levels are dependent upon a ruminant animal’s ability to ferment, digest, and obtain proper microbial populations. If the rumen pH drops to levels of 5.7-6.2, reduced levels of growth rate of cellulolytic bacteria occur (Loy et al., 2007). Rapidly fermentable grains generally decrease ruminal pH, and increase the risk of developing digestive issues such as SARA (Stock et al., 1990). In occurrences where grain is supplemented at a level that decreases pH, growth of fibrolytic bacteria is delayed, which in turn may lower a diet’s digestible energy by decelerating rate of fiber digestion (Hall et al., 1990). This is caused by shifting rumen microbial population (Brake et al., 1989).

Complications caused by feeding high grain diets to growing and maintenance cattle is a result of increased incidents of digestive disorders such as SARA and frothy bloat (Xu et al., 2013). Increasing levels of RDP causes ruminal pH to drop as a result of increased ruminal fermentation rates, but has no detrimental effects on cellulolytic bacteria populations (Koster et al., 1996). Using a buffer to regulate pH accelerates fiber digestion in diets rich in starch (Hall et al., 1990), which can prevent a decrease in VFI in cattle supplemented with cereal grains. However, in the same study it was determined that extent of fiber digestion increased when supplemented with corn at 0.5 % of BW on an as fed basis, but decreased when fed at 1% of BW on an as fed basis to Holstein steers (Hall et al., 1990). Although ruminal pH is not easily monitored in production settings, physical signs such as bloat are commonly an indicator of low ruminal pH. Low ruminal pH can cause a reduction in VFI, and if these aforementioned symptoms arise, buffers should be utilized to aid in restoring proper pH levels and can aid in the increase of VFI.

Physical constraints limiting intake

Another factor limiting intake is gut fill, described as the distension of digestive organs due to the fill of undigested and partially digested feed and forage (Van Soest, 1982). Two main digestive organs where distension limits intake are the reticulorumen and abomasum. Distension from fill of digesta in these organs is due to impeded passage rate of particles (Allen, 1996). This might explain why Mertens (1987) believed slow passage rate of high fiber in diets resulted in reduced intake from gut fill. Greater forage digestibility results in accelerated particle passage, reduced bulk fill, and increased VFI (Bowman et al., 1999).

A ruminant animal's ability to postpone the effects of bulk fill is dependent upon volume and weight of the rumen, the size of the ruminant, and feeding history of the animal (Tjardes et al., 2002). Cattle that have been limit fed have smaller visceral organs than those that have been fed *ad libitum*. Consequences of decreased intake from bulk fill occurs quicker in smaller framed cattle (Tjardes et al., 2002). Decreased intake caused by bulk fill has direct effects on lowering VFI.

Particle passage rate

A biological factor that can either limit or increase VFI is particle passage rate through the digestive tract (Whetsell et al., 2004). Slow passage rate results in lower intake levels due to bulk fill, whereas accelerated passage rates promote intake (Allen, 1996). Protein supplementation increases particle passage rate in cattle grazing low-quality forages. As a result, this increase in passage rate increases VFI in response to protein supplementation (Baumann et al., 2004). Passage rates of nutrient-deficient forages are decelerated due to decreased numbers of microorganisms in the rumen necessary for digestion (Brake et al., 1989). Such forages are typically high in indigestible fiber, and if they can be broken down at all, breakdown of such fibers is often difficult and slow due to high lignin levels (Prigge et al., 1990). The rate of particle passage from the reticulum to the omasum is dependent on the particle size reduction that occurs via rumination (Prigge et al., 1990). Taking the aforementioned information into consideration, particle passage rate has the ability to influence VFI. Nutritionists benefit from utilizing the aforementioned factors when formulating diets if they would like to promote or impede intake levels. Therefore, accurately predicting VFI of supplemented cattle is vital. Precisely predicting intake allows for a clearer understanding of total nutrient intake.

Efforts to predict feed intake

Previous research has been conducted to predict total intake of growing cattle and cows. Currently-accepted models to predict total intake of growing cattle and cows use body weight and/or net energy for maintenance (NE_m) as predictors (NASEM, 2016). Currently, these models predict approximately 60% of the variation in total DMI. These model are only suggested for use within a TDN range of 50-60% of DM. This prohibits their use for scenarios with forages that fall outside this range, and development of models beyond this range are currently lacking. Similarly, these models cannot be used for forage-fed cattle that are also supplemented with other sources of nutrients, as VFI and therefore total dietary energy content are unknown factors.

Another drawback of the currently accepted NASEM models is their lack of ability to predict intake in protein-deficient forages due to lack of knowledge of the effects of rumen degradable protein levels in low quality forages (NASEM, 2016). Often-times producers utilize low quality forages for mature cows in production stages that require less energy. This means that models that apply to these scenarios should also be developed. Another hindrance of the aforesaid models is their utilization of NE_m. Since energy has the ability to be calculated in multiple ways, certain methods of predicting energy might cause inaccuracies when applied to models.

Prior models developed by Moore et al (1999) utilized TDN and CP intake on an OM basis. It was noted that presentation of supplement decreased VFI when TDN exceeded 0.7% of BW on an OM basis or VFI prior to supplementation was > 1.75 % of BW on an OM basis. It was also concluded that only slight changes of VFI occurred due to CP and TDN of supplement. The accuracy of the aforementioned models ranged from +1 to -1 % of BW on an OM basis, and implied that these inconsistencies are likely a function of the TDN:CP ratio in forages (Moore et al., 1999). This model however, was designed with the intention to estimate the associative effects on digestibility, and for this reason utilized VFI as an explanatory variable, meaning that these models do not possess the ability to predict VFI.

Another model that has been developed to predict total intake of cows managed in forage- or roughage-based settings utilizes forage NDF content (Mertens, 1987). While this model has been widely used, either in its original form or with slight adjustments, it has not been validated in in applied feeding scenarios to verify its accuracy. Additionally, this model is only suggested for use on non-gestating, non-lactating (dry) cows or well as lactating cows, and has been suggested that this model should not be used on cows in their second or third trimester of pregnancy. This means that models for cows in their last two trimesters are still lacking and further research needs to be conducted in order to accurately predict intake.

Summary

Based on the preceding information, refinements to current models taking the aforementioned factors into account would benefit producers and nutritionists. Since forage and feedstuff composition have varying effects on intake and digestion, obtaining a greater understanding of the aforesaid metrics will provide the ability to greater predict VFI. Going forward, this information will allow producers and nutritionists alike to make more accurate decisions when implementing supplementation programs. Each supplementation scenario differs for numerous reasons, whether that be in forage nutrient composition, commodity availability, or cattle-specific information. When taking these factors into consideration, producers would be able to implement supplementation programs that meet the specific needs of cattle and production goals of the operation in the most economical way possible.

Chapter 1: Development and validation of models that predict voluntary forage or total dry matter intake of supplemented beef cattle

ABSTRACT

A major priority of beef cattle production is to meet animal nutrient requirements in order to achieve a desired level of productivity. Accurately predicting voluntary forage intake (VFI) is necessary to accurately predict the total nutrient intake of grazing or forage-fed beef cattle that are also supplemented with other sources of nutrients. Therefore, the objectives of this experiment were to utilize data from published literature to 1) identify factors that explain variation in VFI, and 2) develop and validate one or more mathematical models that predict VFI or total nutrient intake of grazing or forage-fed and supplemented beef cattle. A comprehensive literature review was conducted to retrieve experimental means (n=609) and descriptive information from 131 feeding trials that measured VFI and supplement intake. Simple linear and logistic regressions identified 43 continuous and 7 categorical variables that were related ($P <$ 0.05) to forage DMI. Following randomization, 70% of published observations were used to develop predictive models, while the remaining 30% were used for validation. Categorical explanatory variables used to predict forage or total dry matter (DM) intake (DMI) included forage classification, forage harvest method, forage stem length, cattle production stage, and supplement feeding frequency, while continuous explanatory variables included shrunk body weight (BW), supplement neutral detergent fiber (NDF) intake (NDFI), supplement hemicellulose (HEM) intake (HEMI), supplement crude protein (CP) intake (CPI), forage CP content, forage NDF content, and forage HEM content, where supplement intake information was expressed in kg x hd^{-1} x d^{-1} and forage nutrient content was expressed as a % of forage DM. Prediction models initially explained 70% (RMSE = 1.31; $P < 0.0001$) and 77% (RMSE = 1.31; $P < 0.0001$) of the variation in forage and total DMI, respectively. When applied to the independent validation dataset, these equations explained approximately 68% (RMSE = 1.32; P

< 0.0001) and 72% (RMSE = 1.31; $P < 0.0001$) of the variation in forage and total DMI, respectively. These models explained a substantial portion of the variation in forage and total DMI, and therefore can be used in production systems to aid in predicting forage or total DMI.

Introduction

Beef cattle production, particularly the cow calf and stocker industries, rely heavily on forage production. Nonetheless, producers commonly implement supplementation programs during times when forage quantity and quality do not sufficiently meet nutrient requirements. Meeting the nutrient requirements of beef cattle is imperative to meet growth performance targets or productivity goals.

A number of factors influence rate and extent of nutrient digestion and passage rate, and thus influence voluntary forage intake (VFI). Two of the major factors include the nutritive quality of forages (Minson and Wilson, 1994), as well as supplementation practices (Fleck et al., 1988; Chase Jr and Hibberd, 1989; DelCurto et al., 1990). These factors ultimately have the ability to influence overall nutrient intake. Certain scenarios of altered VFI could lead to nutrient deficiencies or excess, which both result in their own economic consequences.

Proper supplementation levels are vital to ensure animal nutrient requirements are being met, but not over supplemented to the point of adding unnecessary expense or excessive body condition. Accurately predicting the overall nutrient intake of forage-fed cattle that are also supplemented with other sources of nutrients is critical to meeting nutrient requirements without under- or over-feeding. The NASEM (2016) identified developed equations used to predict VFI that can be applied to forage-based production settings as a necessary area of research. Therefore, the objectives of this experiment were to utilize data from the published literature to 1) identify factors that explain variation in VFI or total dry matter (DM) intake (DMI), and 2) develop and validate one or more mathematical models that accurately and precisely predict VFI or total nutrient intake of forage-fed cattle supplemented with other sources of nutrients.

Materials and methods

Dataset population

An extensive literature review was conducted using Google Scholar, the Journal of Animal Science, and the Web of Science database. Within this, journals and publication resources that were accessed and retrieved for inclusion in a primary dataset included (in alphabetical order) Animal Feed Science and Technology, Annals of Animal Science, Archives of Animal Nutrition, Asian-Australasian Journal of Animal Science, Brazilian Journal of Veterinary and Animal Science, Canadian Journal of Animal Science, Journal of Animal Science, Journal of Applied Animal Research, Journal of Dairy Science, Journal of Livestock Science, Journal of Tropical Animal Health and Production, Nebraska Beef Report, Oklahoma State University Animal Science Research Report, and Translational Animal Science.

Experimental treatment means and supporting information from peer-reviewed journal publications were collected and used to populate a preliminary dataset. The basic criteria for retrieval included that the publication reported both VFI and either supplement DMI or total DMI as separate observations. As for non-supplemented, control groups, supplementation values were expressed as “0” for all potential continuous supplementation metrics. This preliminary dataset also included cattle specific information, forage intake and nutrient composition information, forage-specific descriptive information (including processing, taxonomy, and harvest information), supplement intake, nutrient composition, and nutrient intake, as well as total nutrient intake and total dietary composition.

Cattle-specific information that was retrieved and included in the preliminary dataset included initial body weight (BW), final BW, average BW, average daily gain, age, sex, breed type, and production stage. Forage-specific information that was retrieved for the dataset included processing characteristics/status, harvest method, forage classification and taxonomy, nutrient composition, and average daily DMI. Supplement-specific information that was retrieved included type, feeding frequency, nutrient composition, amount fed, and average daily DMI.

Major factors that resulted in publications or data being excluded from the dataset included lack of reported or calculable forage and/or supplement intake, BW, forage and/or supplement nutrient composition, contained obviously incorrect or biologically unrealistic values, forage consumption was restricted, the diet was fed as a total mixed ration, or the experiment utilized practices or conditions that are not commonly practiced in U.S. beef production.

Dataset refinement

The preliminary dataset was refined to ensure data format and unit homogeneity. If average BW was not reported, initial and final trial BW were averaged and used as an average BW during the intake measurement period. Similarly, single, unspecified BW means or descriptive information were assumed to represent the average BW during the intake measurement period. Body weights that were not described as shrunk weights were multiplied by 0.96 to calculate shrunk BW. Nutrient composition that was not reported was calculated if the necessary information existed. Calculated nutrients included neutral detergent fiber (NDF, % of DM = hemicellulose + cellulose + lignin), acid detergent fiber (ADF, % of DM = cellulose + lignin), hemicellulose (HEM, % of DM = NDF – ADF), cellulose (cellulose, % of DM = ADF – lignin), acid detergent lignin (ADL, % of DM = ADF – cellulose), organic matter (OM, % of DM = 100 – ash), and ash (ash, % of DM = 100 – OM). Supplement nutrient composition and body weight were used to calculate average daily nutrient intake, expressed in kg x hd^{-1} x d^{-1}, as a % of BW x d^{-1}, and in g x kg^{-1} of $BW^{0.75}$.

Supplement DMI, forage DMI (also referred to herein as VFI), and total DMI were also expressed in kg x hd^{-1} x d^{-1}, % of BW x d^{-1}, and g x kg^{-1} of $BW^{0.75}$. Energy content and intake was calculated for experiments that did not report energy but provided sufficient information that allowed for energy calculations. If TDN was provided, digestible energy (DE) could be calculated as DE = ((TDN/100) x 2), where TDN was expressed as a % of DM, and DE was expressed in Mcal per pound of DM, TDN kg^{-1} = ((DE/2) x 100). Obtaining a value for DE, whether reported or calculated, provided the ability to calculate other metrics of energy such as metabolizable energy (ME, Mcal x kg^{-1} = (0.929 x (DE x 2.20462) - (0.0056 x CP) + (0.0343 x EE)+(0.0042 x starch) - 0.3612), where CP, EE, and starch are all expressed as a % of DM, and DE is expressed in Mcal x kg^{-1}), net energy for maintenance (NE_m, Mcal x kg^{-1} = 0.0316 x ME^3 - 0.2086 x ME^2 + 1.1104 x ME - 0.353, where ME is expressed in Mcal x kg^{-1}), and net energy for gain (NE_G, Mcal x kg^{-1}= 0.0369 x ME^3 - 0.2641 x ME^2 + 1.1376 x ME - 0.5887).

Categorical observations were refined into meaningful and logical groups that represented real-world practical application to U.S. beef production systems. Breed type classifications were refined and categorized as Bos taurus beef cattle, Bos indicus or Bos indicus X Bos taurus beef cattle, and dairy cattle. Production stage classifications were refined as best as possible using information provided by experiments, which was often limited. If the publication did not define cattle as belonging to a specific production stage, all available information was considered, and cattle were assigned to the most appropriate of four production stage classifications, which included calves, yearlings, late gestation and early lactation cows, or early and middle gestation cows. All cattle < 250 kg were considered calves, while all growing cattle ≥ 250 kg were considered ye/arlings. All mature cattle consisting of cows, heifers, and steers > 30 months of age were classified by the most appropriate production stage. If cows were gestating or lactating it was expressed and refined by the stage of respective conditions and categorized as either early and middle gestation or late gestation and early lactation. These respective stages were combined due to similarities in nutrient requirements. Mature steers were classified as early and middle gestation cows due to similarities in nutrient requirements and the objective of achieving outcomes that are useful in the field.

Forages were classified by harvest method, forage classification, and stem length. Forages that were harvested as dry hay were classified as harvested, while ensiled forages were classified as silage/haylage, and grazed forages were classified as such. Forages were classified by type as either warm season annuals, warm season perennials, cool season annuals, or cool season perennials based upon the predominant forage species. Forages that were mechanically-harvested were also categorized by stem length as either finely processed (average < 5 cm), coarsely processed (average 5-10 cm), long stem (harvested but not processed), and grazed. The supplementation frequency categories included not supplemented, as well as alternating days, once daily, and twice daily.

Factor identification

Data were initially analyzed using the Fit Y by X function of JMP Pro (version 15.0.0; SAS Institute Inc., Cary, NC 27513) to identify factors explaining significant ($P < 0.05$) portions of the variation in forage DMI or OM intake (OMI) expressed in either kg x hd^{-1} x d^{-1}, % of BW x d^{-1}, or g x kg^{-1} of $BW^{0.75}$. These initial factor screenings were conducted to identify factors that should potentially be included ($P < 0.05$) during the model development process. Factors that did not account for a significant ($P \geq 0.05$) portion of the variation in forage DMI or OMI were excluded from further consideration for model development.

Individual distributions of continuous explanatory variables and frequencies of individual categorical explanatory variables were configured and calculated using the 'Distribution' procedure of JMP Pro. This process was used to identify particular explanatory variables to potentially be included in prediction model development, which aided in excluding factors that may have explained a significant portion of variation, but included few treatment means and lacked the ability to be used in a comprehensive prediction models.

Randomization was conducted prior to assigning a specific treatment and its corresponding information to either the development or validation dataset in order to eliminate any potential experimental bias between the two datasets. This randomization was then replicated a total of ten times, and replications were evaluated to determine homogeneity across the development and validation datasets. Treatments and their corresponding information were then assigned to either the development or validation dataset. The randomization and corresponding development and validation assignments that resulted in the most homogenous frequencies and distributions of variables across both the development and validation datasets was chosen and used to split the complete dataset into development and validation datasets that were then used for the remainder of the project. Approximately 70% of observations were assigned to be used for model development, while the remaining 30% of observations were assigned to be used for model validation. Observations used for model development were excluded during the validation process, and observations utilized for model validation were excluded during model development.

Model development

Initial exploratory modelling was conducted on the refined dataset (n=205 treatments) using the "Fit Model" function of JMP Pro. This procedure was used to develop individual mixed regression models that explained the greatest portion of variation in forage DMI or total DMI, expressed in units of kg x hd^{-1} x d^{-1}, % of BW x d^{-1}, or g x kg^{-1} of $BW^{0.75}$, using shrunk BW, un-shrunk BW, shrunk $BW^{0.75}$, or un-shrunk $BW^{0.75}$. The categorical explanatory variables that were initially entered into the models included cattle breed type, production stage, forage harvest method, forage classification, forage stem length, and supplementation frequency. Continuous explanatory variables that were initially entered into the models included BW, forage CP content, forage NDF content, forage ADF content, forage HEM content, supplement DMI, supplement CPI, supplement NDFI, supplement ADFI, supplement HEMI, and supplement EEI. All forage nutrient information was expressed as a percentage of forage DM, and supplement intake information was expressed on a kg x hd^{-1} x d^{-1} basis. Models were reduced in a backward stepwise fashion until all remaining explanatory variables explained a significant ($P < 0.05$) portion of the variation in the respective response variable, and were not collinear as defined by having a variance inflation factor (VIF) of < 10. Actual values were regressed against predicted values in order to determine the goodness of fit of the model, while y-intercept statistics and residuals were used to assess any potential bias associated with the individual models.

Model validation

The prediction equations obtained upon completion of the model development phase were applied to the independent validation dataset in order to evaluate the ability of the equations to predict forage or total DMI. Residuals were calculated as the difference between actual and predicted intake, which were then plotted in order to quantify goodness of fit. The y-intercept statistics were also evaluated in combination with the average of residuals in order to evaluate any potential bias individual models.

Results and discussion

Dataset characterization

Treatment means from published peer-reviewed experiments and information pertaining to respective treatments were used to populate the dataset as individual observations. This resulted in the development of a complete preliminary dataset that contained observations and descriptions associated with a total of 609 treatments from 131 publications. After further refinement, this dataset was reduced to a level that contained observations and descriptions associated with 205 treatments from 58 publications. Years of published experiments ranged from 1979 to 2019. The mean published year for the refined dataset was 1999 with a standard deviation (SD) of 10.55. The distribution for year of publication can be found in Figure 1.1. The included data was compiled from 13 different peer-reviewed journals or research reports. A more detailed description of the number of publications per journal or research report can be found in Table 1.1.

Cattle-specific categorical data used in the final dataset included breed type and production stage. Forage-specific categorical data used in the final dataset included forage harvest method, forage classification, and forage stem length. The only supplement-specific categorical variable used in the final dataset was supplementation frequency. This was intentionally done in order to ensure that the validation data ranges corresponded with the development dataset ranges. Randomization and development/validation assignment was successful due to apparent homogeneity of the data across the two datasets. Frequencies of the aforementioned categorical variables and their potential descriptors for the complete dataset, as well as the model development and validation datasets are summarized in Table 1.2.

The supplementation frequency category only included four potential options in the model development and validation dataset, excluding four that were initially in the complete dataset. Those not represented in the model development and validation datasets included *ad libitum*, four times daily, once weekly, and three times a day, which are rarely observed in U.S. production with the exception of *ad libitum* (n=5 in preliminary dataset) diets, which if utilized, are generally fed to growing cattle, finishing cattle, or include a self-limiter. Due to lack of sufficient available data for inclusion, models developed from this experiment should not be used in scenarios utilizing *ad libitum* supplementation programs.

Distribution of metrics including mean, minimum, maximum, and standard deviation values for forage nutrients and supplement intake for the complete dataset as well as the model development and validation datasets can be found in Table 1.3. The range for forage nutrient composition metrics and their standard deviations for the complete, preliminary dataset include: forage NDF (42.6 to 86.4 % of DM; SD = 8.64), forage CP (1.94 to 19.1 % of DM; SD = 4.14), and forage HEM (8.1 to 48.1 % of DM; SD = 7.25). The supplement intake metrics listed and their standard deviations of the complete, refined dataset include supplement DMI (0.00 to 7.42 kg x hd^{-1} x d^{-1}; SD=1.28), supplement HEMI (0.00 to 1.39 kg x hd^{-1} x d^{-1}; SD=0.24), supplement CPI (0.00 to 3.47 kg x hd^{-1} x d^{-1}; SD=0.43), and supplement NDFI (0.00 to 4.38 kg x hd^{-1} x d^{-1}; SD=0.60). All of the minimum supplement intake values in the development models were 0.00 due to the inclusion of data from non-supplemented control groups, which represented cattle that only consumed forage.

The aforementioned tables include data demonstrating the range and mean of metrics that were utilized in conducting this meta-analysis. The NASEM equations for net energy for maintenance (NE_m) intake of cows are not suggested to be used for forages with total digestible nutrients (TDN) levels outside of the 50-60% range (NASEM, 2016). Within this range, TDN possesses the capability to predict intake between both early gestating cows and lactating cows, but should not be utilized to estimate intake of gestating beef cows after the first trimester (NASEM, 2016). This is could be caused by an increase of space in the cows abdominal cavity and increasing nutrient requirements for maintenance through parturition and lactation. Precisely like the previously mentioned NASEM cow equation, the ranges reported herein provide information that establishes the parameters within which models should be expected to be accurate.

Model development

Explanatory variables that were considered to explain the greatest amount of variation for the response variables forage DMI and total DMI, their included number of treatment means, *P*-value, and adjusted R-squared in the complete preliminary dataset are summarized in Table 1.4. Model development requires inclusion of all response and explanatory variables in all treatment means, and excludes any treatment mean lacking a single variable. Thus, the metric with the least inclusion in a model is a major limiting factor to comprehensive model development. Categorical variables and their respective *P*-values included cattle breed (<0.0001), cattle production class (0.0016), cattle production stage (<0.0001), forage harvest method (0.0007), forage classification (<0.0001), forage stem length (<0.0001), and supplement feeding frequency (<0.0001).

The final modes that were developed utilized forage and total DMI expressed in kg x hd^{-1} x d^{-1} as the response variables. Distribution of metrics for total intake for the complete preliminary dataset as well as the model development and validation datasets can be found in Table 1.3. The Y-intercept for the forage and total DMI development models were 9.3712 and

9.3600, respectively. The Y-intercept adjustments for the categorical variable experiment production stage for forage and total DMI, respectively included calves (-0.7897, -0.7916), yearlings (-0.4317, -0.4337), early and middle gestation (-0.3873, -0.3898), late gestation and early lactation (1.6087, 1.6150). Calves and yearlings were separated into individual categorical variables in NASEM equations. This is likely due to the difference of plane of growth and nutrient requirements varying between the two categories. Dissimilar nutrient requirements between the two groups are caused by hyperplasia and hypertrophy of varying tissues such as visceral mass, bone mass, muscle adiposity, and fat adiposity requiring separate feeding strategies (Shahin and Berg, 1985). Calves, denoted in this experiment as cattle <250 kg are developing more neural tissue, visceral organ mass, and bone mass (Shahin and Berg, 1985), whereas yearlings (250-500 kg) have developed the majority of their mature bone mass, and have begun accumulating muscle mass at more accelerated rates (Owens et al., 1993). Due to these differences, calves and yearlings were separated as categorical variables in this experiment. Along the same lines, mature cows were further separated by production stage. This is due to the difference in nutrient requirements, predominately protein and energy, of early and middle gestating cows when compared to late gestating and early lactating cows.

The Y-intercept adjustments for forage harvest method for forage and total DMI, respectively were grazed (1.9311, 1.9305), harvested dry forage (-0.9703, -0.9778), and harvested haylage and silage (-0.9508, -0.9527). Depending on the time of year cattle might consume greater volumes of grazed forages than mechanically-harvested forages. This however is more than likely a function of the quality and availability of forage rather than the harvest method. However, haylage and silage generally possess greater levels of nutrient values than dry harvested or pasture forages, with the exception of some legumes.

The Y-intercept adjustments for each respective forage classification for forage and total DMI, respectively were cool season annual (-0.8185, -0.8200), cool season perennial (-0.2101, -0.2100), warm season annual (-0.1248, -0.1248), and warm season perennial forages (1.1571, 1.1549). As a causation of differences in cellular arrangement of cool season and warm season forages, cool season forages are generally more lush and palatable (Jones et al., 1988). The Y-intercept adjustments for forage stem length for forage and total DMI, respectively were grazed (-1.4158, -1.4168), long stem (0.5803, 0.5798), coarsely processed (0.1653, 0.1600), and finely processed (0.6701, 0.6770). The Y-intercept adjustments for supplement feeding frequency for forage and DMI, respectively were alternating days (-0.7366, -0.7385), not supplemented (0.4240, 0.4295), once daily (0.5401, 0.5413), and twice daily (-0.2275, -0.2322).

One specific factor with known effects on VFI is processing and the resulting forage stem length. Long-stem forages are more difficult for breakdown via mastication, resulting in reduced rate of passage (Judkins et al., 1991). Therefore, forage processing increases VFI, due to smaller particle size and an increased rate of digesta passage (Galyean and Goetsch, 1993). This implies that models should account for forage processing and stem length to predict VFI. Just as in other production classes, forage quality effects VFI, however forage quality causes greater variation between lactating and gestating cows, with greatest VFI differences amongst the two being found in lower quality forages (Lalman, 2004). Previous research suggests an increased intake of 0.2 kg x hd^{-1} x d^{-1} of forage DMI per kilogram of milk produced for cows in early lactation in order to account for added nutrient requirements by maintenance and milk production (Lalman, 2004; NASEM, 2016). This trend can result in a 28% increase of total DMI from gestation to lactation (Marston and Lusby, 1995). Data for the Y-intercept adjustments is summarized in Table 1.5.

Continuous explanatory variables and their coefficients for forage DMI were -2.1811, 2.4155, 1.3967, 0.1304, -0.0665, -0.0727, and 0.0081 for supplement NDFI, supplement HEMI, supplement CPI, forage CP content, forage NDF content, forage HEMI content, and average shrunk BW, respectively. Continuous explanatory variables and their coefficients for total DMI were -2.2143, 2.3970, 1.3771, 0.1347, -0.0663, -0.0729, and 0.0081 for supplement NDFI, supplement HEMI, supplement CPI, forage CP content, forage NDF content, forage HEM content, and average shrunk BW, respectively. Data for the aforementioned coefficients is summarized in Table 1.6. Hemicellulose and NDF were used in this experiment in order to also account for the highly digestible fiber fraction which is the difference between the NDF and hemicellulose portion. Another differing factor between NASEM models and models developed for this experiment is the inclusion of categorical variables such as forage classification, forage production stage, forage stem length, and supplement feeding frequency.

Calculated variance inflation factors (VIFs) were ≤9.50 for all continuous variables and ≤5.85 for all categorical data in the total DMI model. These low VIFs (<10) demonstrate a lack of collinearity amongst explanatory variables. The model that was developed to predict forage DMI expressed in kg x hd^{-1} x d^{-1} explained 70% of the variation in forage DMI ($P < 0.0001$; RMSE = 1.3056), while the model that was developed to predict total DMI expressed in kg x hd^{-1} x d^{-1} explained 77% of the variation in total DMI ($P < 0.0001$; RMSE = 1.3110). The aforementioned metrics are summarized in Table 1.7. The actual by predicted plot for the forage DMI and total DMI prediction models can be found in Figures 1.2 and 1.3, respectively. Similarly, albeit with slightly more precision, the total DMI prediction model explained approximately 7% more of the variation than the forage DMI model.

Equations that predict total DMI or NE_m intake (NE_mI) in growing and finishing cattle or gestating and lactating cows have previously been adopted by the NASEM (2016). However, due a lack of standardized equations used to calculate energy, calculated energy values could influence prediction model performance. Outcomes of prediction could vary depending on which energy calculations are used. Using methods to calculate fiber and protein are universally standardized procedures, promoting consistency among models utilizing those metrics.

One drawback to the previously developed models for predicting NE_m intake of beef cows is their lack of ability to predict intake in protein deficient forages. Models developed in this experiment did not dismiss low quality forages for intake prediction. In the model development portion, various methods of expression of BW were used to develop equations. Some of the different BW metrics included shrunk, un-shrunk, un-shrunk metabolic BW ($BW^{0.75}$), and shrunk $BW^{0.75}$. Shrunk BW explained 1.2% and 0.9% more variation in the forage DMI or total DMI, respectively when compared to un-shrunk BW. However, converting shrunk BW to $BW^{0.75}$ yielded no detectable advantage, therefore shrunk BW was selected as the most appropriate BW metric for use in model development, whereas previous models predicting NE_mI intake of growing-finishing cattle have used $BW^{0.75}$ (NASEM, 2016).

Model validation

As previously mentioned, distribution of metrics for forage intake for the complete dataset as well as the model development and validation datasets can be found in Table 1.3. The ranges in validation models included: forage CP (2.8-17.7), forage NDF (54-82.5), forage HEM (16.4-48.1) expressed as a % of DM. The forage intake metrics listed and their standard deviations (SD) for the development dataset include forage NDF % of DM (SD=6.46), forage CP % of DM (SD=9.64), forage hemicellulose % of DM (SD=7.20). Similar to the model development dataset, all of the minimum values of supplement nutrient intake metrics in the validation dataset were 0.00 due to the inclusion of data from non-supplemented cattle. The maximum supplement intake values for the validation dataset were 6.50, 0.76, 1.60, and 2.37 kg x hd^{-1} x d^{-1} for supplement DMI, HEMI, CPI, and NDFI, respectively.

The validation dataset was comprised of the remaining 30% of treatment data (n=62 treatments). When applied to the validation dataset, the total DMI prediction model explained approximately 72% of the variation in total DMI ($P < 0.0001$; RMSE = 1.3144), while the forage DMI model explained approximately 68% of the variation in forage DMI ($P < 0.0001$; RMSE = 1.3182). Actual vs. predicted plots for forage and total DMI within the validation dataset can be found in Figures 1.4 and 1.5, respectively. The average of residuals (0.03 and 0.03 for forage and total DMI, respectively) were incredibly low and suggest no slope bias. Similarly, due to the lack of significance ($P \geq 0.60$), it was concluded that the y-intercepts for each validation did not differ from 0, and therefore were un-biased.

Implications and limitations

Models developed during this experiment and reported herein can be deployed into the field for usage by producers and nutritionists. Going forward, greater research emphasis should be placed on reporting nutrient metrics such as forage EE, RDP, RUP, and starch content in order to continue working towards progressing the ability to accurately predict VFI of forage-fed cattle that are also supplemented with other sources of nutrients. Models from this experiment aid in the progress of the comprehension of how cattle specific information, forage intake and nutrient composition, and supplement nutrient composition influence VFI variation in supplement-based feeding systems. Prediction of VFI will continue to remain important to the production community, and therefore should remain an area of research.

Models developed in this experiment will not work with perfect accuracy every time, but possess the ability to accurately predict forage or total DMI. For this reason, these models can be deployed into field-based scenarios to aid in prediction of total DMI. However, caution should be exercised if using these models to predict forage or total DMI using parameters outside of the ranges reported herein. The ability to predict forage and total DMI possesses economic benefits as well as the ability to plan for the future. This information can be used to not only help producers or nutritionists predict intake levels, but also can be used to predict intake of stockpiled forage, harvested forage, or commodity feeds in order to last through feeding seasons without procuring more than needed.

Implications and future research

Nutrient intake of supplemented beef cattle is challenging to predict due to increasing or decreasing effects of voluntary forage intake (VFI) that are caused by a number of cattle-specific factors, forage nutrient composition, and supplement amount and nutrient composition. The ability to accurately predict VFI of beef cattle provides the beef cattle industry with the ability to accurately predict total nutrient intake in forage-based production systems where cattle are also supplemented with other sources of nutrients. Going forward, nutritionists can apply findings from this study directly to field-based production systems in order to aid producers in their quest to meet nutrient requirements in the most economical way possible.

Accurate prediction of VFI provides the ability to determine the appropriate level of supplementation necessary to meet the nutrient requirements of a group of cattle. An enhanced understanding of the factors that influence VFI will allow for the strategic refinement of supplementation protocols. This not only provides economic value in the form of cost savings, but also allows producers to better estimate their harvested forage, stockpiled forage, and supplementation needs.

Future research pertaining to prediction of VFI requires more in-depth research to report forage and supplement nutrient composition for utilization of determining factors that affect VFI. Data or descriptive information that was insufficiently reported or missing from many reports that could potentially influence VFI include ionophore usage, implant usage, rumen protein degradability, comprehensive forage and supplement nutrient composition, cattle production stage, and cattle breed. Very little to no information is currently available for growing or mature bulls, as well as cattle supplemented *ad libitum*. Discovery and inclusion of the aforementioned data will add power and predictive capability to previously developed models. If achieved, more applicable models will provide producers and nutritionists with a greater ability to predict VFI and accurately predict total nutrient intake.

Bibliography

Abe, A., and S. Horii. 1978. Application of the detergent analysis to the feed ingredients and to the various formula feeds. Jpn. J. Zootech. Sci. 49:733.

Adams, D. 1985. Effect of time of supplementation on performance, forage intake and grazing behavior of yearling beef steers grazing Russian wild ryegrass in the fall. J. Anim. Sci. 61(5):1037-1042. Doi: https://doi.org/10.2527/jas1985.6151037x

Adams, D. C. 1986. Getting the most out of grain supplements. Rangeland J. 8(1):27-28.

Adams, D. C., R. T. Clark, T. J. Klopfenstein, and J. D. Volesky. 1996. Matching the cow with forage resources. Rangeland J. 18(2):57-62.

Allen, M. S. 1996. Physical constraints on voluntary intake of forages by ruminants. J. Anim. Sci. 74(12):3063-3075. Doi: https://doi.org/10.2527/1996.74123063x

Anderson, S., J. Merrill, M. Mcdonnell, and T. Klopfenstein. 1988. Digestibility and utilization of mechanically processed soybean hulls by lambs and steers. J. Anim. Sci. 66(11):2965-2976. Doi: https://doi.org/10.2527/jas1988.66112965x

Atasoglu, C., C. J. Newbold, and R. J. Wallace. 2001. Incorporation of [15N] Ammonia by the Cellulolytic Ruminal Bacteria Fibrobacter succinogenesbl2, Ruminococcus albus SY3, and Ruminococcus flavefaciens 17. Appl. Environ. Microb. 67(6):2819-2822. Doi: DOI: 10.1128/AEM.67.6.2819-2822.2001

Ball, D., E. N. Ballard, M. Kennedy, G. D. Lacefield, and D. Undersander. 2009. Extending grazing and reducing stored feed needs.

Bandyk, C. A., R. C. Cochran, T. A. Wickersham, E. C. Titgemeyer, C. G. Farmer, and J. J. Higgins. 2001. Effect of ruminal vs postruminal administration of degradable protein on utilization of low-quality forage by beef steers. J. Anim. Sci 79(1):225-231. (Article) doi: https://doi.org/10.2527/2001.791225x

Barry, T. 2013. The feeding value of forage brassica plants for grazing ruminant livestock. Anim. Feed Sci. Tech. 181(1-4):15-25. Doi: https://doi.org/10.1016/j.anifeedsci.2013.01.012

Bartley, E. 1965. Bloat in cattle. 6. Prevention of legume bloat with a nonionic surfactant. J Dairy Sci. 48:102-104. Doi: http://dx.doi.org/10.3168/jds.S0022-0302(65)88170-X

Baumann, T., G. Lardy, J. Caton, and V. Anderson. 2004. Effect of energy source and ruminally degradable protein addition on performance of lactating beef cows and digestion characteristics of steers. J. Anim. Sci. 82(9):2667-2678. Doi: https://doi.org/10.2527/2004.8292667x

Bergen, W. G., and D. B. Bates. 1984. Ionophores: their effect on production efficiency and mode of action. J. Anim. Sci. 58(6):1465-1483.

Bodine, T. N., H. T. Purvis, and D. L. Lalman. 2001. Effects of supplement type on animal performance, forage intake, digestion, and ruminal measurements of growing beef cattle. J. Anim. Sci. 79(4):1041-1051. (Article) doi: https://doi.org/10.2527/2001.7941041x

Bouton, J. 2007. The economic benefits of forage improvement in the United States. Euphytica 154(3):263-270. Doi: https://doi.org/10.1007/s10681-006-9220-6

Bowman, J., B. Sowell, D. Boss, and H. Sherwood. 1999. Influence of liquid supplement delivery method on forage and supplement intake by grazing beef cows. Anim. Feed Sci. Tech. 78(3-4):273-285. Doi: https://doi.org/10.1016/S0377-8401(98)00279-X

Bradstreet, R. B. 1954. Kjeldahl method for organic nitrogen. Annu. Rev. Anal. Chem. 26(1):185-187. Doi: https://doi.org/10.1021/ac60085a028

Brake, A., A. Goetsch, L. Forster Jr, and K. Landis. 1989. Feed intake, digestion and digesta characteristics of cattle fed bermudagrass or orchardgrass alone or with ground barley or corn. J. Anim. Sci. 67(12):3425-3436. Doi: https://doi.org/10.2527/jas1989.67123425x

Brakenridge, D. 1956. Nitrate poisoning caused by turnips and redroot. New Zeal. Vet. J. 4(4):165-166. Doi: https://www.tandfonline.com/doi/pdf/10.1080/00480169.1956.33241

Brokaw, L., B. Hess, and D. Rule. 2001. Supplemental soybean oil or corn for beef heifers grazing summer pasture: Effects on forage intake, ruminal fermentation, and site and extent of digestion. J. Anim. Sci. 79(10):2704-2712. Doi: https://doi.org/10.2527/2001.79102704x

Burns, J., D. Fisher, and H. Mayland. 2007. Diurnal shifts in nutritive value of alfalfa harvested as hay and evaluated by animal intake and digestion. Crop Sci. 47(5):2190-2197. Doi: https://doi.org/10.2135/cropsci2007.02.0072

Carey, D. A., J. S. Caton, and M. Biondini. 1993. Influence of energy source on forage intake, digestibility, in situ forage degradation, and ruminal fermentation in beef steers fed medium-quality brome hay. J. Anim. Sci. 71(8):2260-2269. Doi: 10.2527/1993.7182260x

Chase Jr, C., and C. Hibberd. 1989. Effect of level and frequency of maize supplementation on the utilization of low-quality grass hay by beef cows. Anim. Feed Sci. Tech. 24(1-2):129-139. Doi: https://doi.org/10.1016/0377-8401(89)90026-6

Church, D., and A. Santos. 1981. Effect of graded levels of soybean meal and of a nonprotein nitrogen-molasses supplement on consumption and digestibility of wheat straw. J. Anim. Sci. 53(6):1609-1615. Doi: https://doi.org/10.2527/jas1982.5361609x

Dhuyvetter, J., K. Hoppe, and V. L. Anderson. 1999. Wheat middlings: A useful feed for cattle.

Drewnoski, M. E., and M. H. Poore. 2012. Effects of supplementation frequency on ruminal fermentation and digestion by steers fed medium-quality hay and supplemented with a soybean hull and corn gluten feed blend. J. Anim. Sci. 90(3):881-891. Doi: 10.2527/jas.2010-3807

Elrod, C., M. Van Amburgh, and W. Butler. 1993. Alterations of ph in response to increased dietary protein in cattle are unique to the uterus. J. Anim. Sci. 71(3):702-706. Doi: https://doi.org/10.2527/1993.713702x

Eversole, D. E., M. F. Browne, J. B. Hall, and R. E. Dietz. 2005. Body condition scoring beef cows.

Farmer, C., R. Cochran, D. Simms, J. Heldt, and C. Mathis. 2001. Impact of different wheat milling by-products in supplements on the forage use and performance of beef cattle consuming low-quality, tallgrass-prairie forage. J. Anim. Sci. 79(9):2472-2480. Doi: https://doi.org/10.2527/2001.7992472x

Farran, T., G. E. Erickson, T. Klopfenstein, C. Macken, and R. Lindquist. 2006. Wet corn gluten feed and alfalfa hay levels in dry-rolled corn finishing diets: Effects on finishing performance and feedlot nitrogen mass balance. J. Anim. Sci. 84(5):1205-1214. Doi: https://doi.org/10.2527/2006.8451205x

Fay, J., K.-J. Cheng, M. Hanna, R. Howarth, and J. Costerton. 1980. In vitro digestion of bloat-safe and bloat-causing legumes by rumen microorganisms: gas and foam production. J Dairy Sci. 63(8):1273-1281. Doi: https://doi.org/10.3168/jds.S0022-0302(80)83078-5

Fike, G. D., D. Simms, R. Cochran, E. Vanzant, G. Kuhl, and R. Brandt Jr. 1995. Protein supplementation of ammoniated wheat straw: effect on performance and forage utilization of beef cattle. J. Anim. Sci. 73(6):1595-1601. Doi: https://doi.org/10.2527/1995.7361595x

Fleck, A. T., K. S. Lusby, F. N. Owens, and F. T. Mccollum. 1988. Effects of corn gluten feed on forage intake, digestibility and ruminal parameters of cattle fed native grass hay. J. Anim. Sci. 66(3):750-757. Doi: 10.2527/jas1988.663750x

Freeman, A. S., M. L. Galyean, and J. S. Caton. 1992. Effects of supplemental protein percentage and feeding level on intake, ruminal fermentation, and digesta passage in beef steers fed prairie hay. J. Anim. Sci. 70(5):1562-1572. Doi: 10.2527/1992.7051562x

Funston, R. N., D. M. Larson, and K. Vonnahme. 2010. Effects of maternal nutrition on conceptus growth and offspring performance: implications for beef cattle production. J. Anim. Sci. 88(suppl_13):E205-E215. Doi: https://doi.org/10.2527/jas.2009-2351

Gai, G. P., L. Pötter, M. G. Da Rocha, M. J. De Oliveira Sichonany, P. R. Salvador, L. G. Do Amaral Neto, É. D. De Moura, and L. M. Cadó. 2018. Ingestive behavior and forage intake of heifers receiving corn grain with or without crude glycerin on italian ryegrass pasture. Biosci. J. 34(1)doi: https://doi.org/10.14393/BJ-v34n1a2018-35055

Galloway, D. L., Sr., A. L. Goetsch, L. A. Forster, Jr., A. R. Patil, W. Sun, and Z. B. Johnson. 1993. Feed intake and digestibility by cattle consuming bermudagrass or orchardgrass hay supplemented with soybean hulls and(or) corn. J. Anim. Sci. 71(11):3087-3095. Doi: 10.2527/1993.71113087x

Galloway Sr, D., A. Goetsch, L. Forster Jr, W. Sun, and Z. Johnson. 1991. Feed intake and digestion by Holstein steers fed warm or cool season grass hays with corn, dried molasses, or wheat middlings. J Dairy Sci. 74(3):1038-1046. Doi: https://doi.org/10.3168/jds.S0022-0302(91)78253-2

Galloway Sr, D., A. Goetsch, A. Patil, L. Forster Jr, and Z. Johnson. 1993. Feed intake and digestion by Holstein steer calves consuming low-quality grass supplemented with lasalocid or monensin. Can. J. of Anim, Sci. 73(4):869-879. Doi: https://doi.org/10.4141/cjas93-089

Galyean, M., and A. Goetsch. 1993. Utilization of forage fiber by ruminants. Forage cell wall structure and digestibility. 33-71. doi: https://doi.org/10.2134/1993.foragecellwall.c2

Garces-Yepez, P., W. Kunkle, D. Bates, J. Moore, W. Thatcher, and L. Sollenberger. 1997. Effects of supplemental energy source and amount on forage intake and performance by steers and intake and diet digestibility by sheep. J. Anim. Sci. 75(7):1918-1925. Doi: https://doi.org/10.2527/1997.7571918x

Gribbins, M. F. 1954. Ruminant feed composition. Google Patents, Wilmington, DE.

Gunn, P., J. Schoonmaker, R. Lemenager, and G. Bridges. 2014. Feeding excess crude protein to gestating and lactating beef heifers: Impact on parturition, milk composition, ovarian function, reproductive efficiency and pre-weaning progeny growth. Livest. Sci. 167:435-448. Doi: https://doi.org/10.1016/j.livsci.2014.05.010

Guthrie, M., and D. Wagner. 1988. Influence of protein or grain supplementation and increasing levels of soybean meal on intake, utilization and passage rate of prairie hay in beef steers and heifers. J. Anim. Sci. 66(6):1529-1537. Doi: https://doi.org/10.2527/jas1988.6661529x

Hall, K., A. Goetsch, and L. Forster Jr. 1990. Effects of buffer or DL-methionine with different amounts of supplemental corn on feed intake and nutrient digestion by Holstein steers consuming bermudagrass hay. J. Anim. Sci.68(6):1674-1682. Doi: https://doi.org/10.2527/1990.6861674x

Hall, M., and P. Kononoff. 2011. Feed ingredients feed concentrates: Co-product feeds. 978-0-12-374407-4

Hannah, S. M., R. C. Cochran, E. S. Vanzant, and D. L. Harmon. 1991. Influence of protein supplementation on site and extent of digestion, forage intake, and nutrient flow characteristics in steers consuming dormant bluestem-range forage. J. Anim. Sci. 69(6):2624-2633. (Article) doi: https://doi.org/10.2527/1991.6962624x

Haramoto, E. R., and E. R. Gallandt. 2005. Brassica cover cropping: I. Effects on weed and crop establishment. Weed Sci. 53(5):695-701. Doi: https://doi.org/10.1614/WS-04-162R.1

Hardin, A., A. Goetsch, K. Landis, G. Murphy, Z. Johnson, and K. Hall. 1989. Intake, digestion and daily gain by cattle consuming bermudagrass (Cynodon dactylon) and supplemented with different combinations of ground corn, vegetable oil, urea, and corn gluten and blood meals. Anim. Feed Sci. Tech. 25(1-2):99-110. Doi: https://doi.org/10.1016/0377-8401(89)90111-9

Hart, R., J. Bissio, M. Samuel, and J. Waggoner Jr. 1993. Grazing systems, pasture size, and cattle grazing behavior, distribution and gains. Rangeland J. 81-87. Doi: 10.2307/4002452

Hatch, M., and C. Slack. 1968. A new enzyme for the interconversion of pyruvate and phosphopyruvate and its role in the C4 dicarboxylic acid pathway of photosynthesis. Biochem. J. 106(1):141-146. Doi: https://doi.org/10.1042/bj1060141

Henning, J., G. Lacefield, M. Rasnake, R. Burris, J. Johns, K. Johnson, and L. Turner. 2000. Rotational grazing. University of Kentucky Cooperative Extension Service ID-143. Available at: www. Caf. Wvu. Edu/~ Forage/ukpdf/id143. Pdf (accessed 24 June 2013)

Hepworth, K., P. Test, R. Hart, J. Waggoner, and M. Smith. 1991. Grazing systems, stocking rates, and cattle behavior in southeastern Wyoming. Rangeland Ecology & Management/Journal of Range Management Archives 44(3):259-262.

Hess, B. W., K. K. Park, L. J. Krysl, M. B. Judkins, B. A. Mccracken, and D. R. Hanks. 1994. Supplemental protein for beef cattle grazing dormant intermediate wheatgrass pasture: effects on nutrient quality, forage intake, digesta kinetics, grazing behavior, ruminal fermentation, and digestion. J. Anim. Sci. 72(8):2113-2123. Doi: 10.2527/1994.7282113x

Hitz, A. C., J. R. Russell, D. R. Maxwell, and L. Secor. 1997. Efficacy of Grazing Stockpiled Perennial Forages for Winter Maintenance of Beef Cows. Doi: ASL R1350

Hoover, W. 1986. Chemical factors involved in ruminal fiber digestion. J. Dairy Sci. 69(10):2755-2766. Doi: https://doi.org/10.3168/jds.S0022-0302(86)80724-X

Horton, G. 1978. The intake and digestibility of ammoniated cereal straws by cattle. Can. J. Anim. Sci. 58(3):471-478. Doi: https://doi.org/10.4141/cjas78-060

Houghton, P., R. Lemenager, K. Hendrix, G. Moss, and T. Stewart. 1990. Effects of body composition, pre-and postpartum energy intake and stage of production of energy utilization by beef cows. J. Anim. Sci. 68(5):1447-1456. Doi: https://doi.org/10.2527/1990.6851447x

Hoveland, C. S. 1986. Beef-forage systems for the southeastern United States. J. Anim. Sci. 63(3):978-985. Doi: https://doi.org/10.2527/jas1986.633978x

Hume, I., R. Moir, and M. Somers. 1970. Synthesis of microbial protein in the rumen. I. Influence of the level of nitrogen intake. Aust. J. of Agr. Res. 21(2):283-296. Doi: https://doi.org/10.1071/AR9700283

Hussein, H., N. R. Merchen, and G. Fahey Jr. 1995. Composition of ruminal bacteria harvested from steers as influenced by dietary forage level and fat supplementation. J. Anim. Sci. 73(8):2469-2473. Doi: https://doi.org/10.2527/1995.7382469x

Huston, J., H. Lippke, T. Forbes, J. Holloway, and R. Machen. 1999. Effects of supplemental feeding interval on adult cows in western Texas. J. Anim. Sci. 77(11):3057-3067. Doi: https://doi.org/10.2527/1999.77113057x

Islas, A., T. Gilbery, R. Goulart, C. Dahlen, M. Bauer, and K. Swanson. 2014. Influence of supplementation with corn dried distillers grains plus solubles to growing calves fed medium-quality hay on growth performance and feeding behavior. J. Anim. Sci. 92(2):705-711. Doi: https://doi.org/10.2527/jas.2013-7067

Islas, A., and S. A. Soto-Navarro. 2011. Effect of supplementation of dried distillers grains with solubles on forage intake and characteristics of digestion of beef heifers grazing small-grain pasture. J. Anim. Sci. 89(4):1229-1237. Doi: 10.2527/jas.2009-2757

Jenkins, T., R. Wallace, P. Moate, and E. Mosley. 2008. Board-invited review: Recent advances in biohydrogenation of unsaturated fatty acids within the rumen microbial ecosystem. J. Anim. Sci. 86(2):397-412. Doi: https://doi.org/10.2527/jas.2007-0588

Johnson, C. R., D. L. Lalman, M. A. Brown, L. A. Appeddu, D. S. Buchanan, and R. P. Wettemann. 2003. Influence of milk production potential on forage dry matter intake by multiparous and primiparous Brangus females. J. Anim. Sci. 81(7):1837-1846. (Article) doi: https://doi.org/10.2527/2003.8171837x

Johnson, R., and K. Mcclure. 1972. High fat rations for ruminants. I. The addition of saturated and unsaturated fats to high roughage and high concentrate rations. J. Anim. Sci. 34(3):501-509. Doi: https://doi.org/10.2527/jas1972.343501x

Jones, A., A. Goetsch, S. Stokes, and M. Colberg. 1988. Intake and digestion in cattle fed warm- or cool-season grass hay with or without supplemental grain. J. Anim. Sci. 66(1):194-203. Doi: https://doi.org/10.2527/jas1988.661194x

Judkins, M. B., D. H. Shain, and H. D. Radloff. 1991. Effects of supplemental corn vs corn fortified with soybean-meal or urea fed with low-quality mixed grass hay on forage intake, particulate passage rate and neutral detergent fiber digestion in beef heifers. Anim. Feed Sci. Tech. 33(3-4):323-329. (Article) doi: 10.1016/0377-8401(91)90070-9

Jung, H., and M. Allen. 1995. Characteristics of plant cell walls affecting intake and digestibility of forages by ruminants. J. Anim. Sci. 73(9):2774-2790. Doi: https://doi.org/10.2527/1995.7392774x

Jung, H., and K. P. Vogel. 1986. Influence of lignin on digestibility of forage cell wall material. J. Anim. Sci. 62(6):1703-1712. Doi: https://doi.org/10.2527/jas1986.6261703x

Kennedy, V. C., B. R. Mordhorst, J. J. Gaspers, M. L. Bauer, K. C. Swanson, C. O. Lemley, and K. A. Vonnahme. 2016. Supplementation of corn dried distillers' grains plus solubles to gestating beef cows fed low-quality forage: II. Impacts on uterine blood flow, circulating estradiol-17 beta and progesterone, and hepatic steroid metabolizing enzyme activity. J. Anim. Sci. 94(11):4619-4628. (Article) doi: 10.2527/jas2016-0400

Keunen, J., J. Plaizier, I. Kyriazakis, T. Duffield, T. Widowski, M. Lindinger, and B. Mcbride. 2003. Effects of subacute ruminal acidosis on free-choice intake of sodium bicarbonate in lactating dairy cows. J. Dairy Sci. 86(3):954-957. Doi: https://doi.org/10.3168/jds.S0022-0302(03)73678-9

Kim, S. A., J. M. Gillespie, and K. P. Paudel. 2008. Rotational grazing adoption in cattle production under a cost-share agreement: does uncertainty have a role in conservation technology adoption? Aust. J. Agr. Res. Econ. 52(3):235-252. Doi: https://doi.org/10.1111/j.1467-8489.2007.00434.x

Kirk, P. L. 1950. Kjeldahl method for total nitrogen. Annu. Rev. Anal. Chem. 22(2):354-358. Doi: 10.1021/ac60038a038

Kocoloski, M., W. M. Griffin, and H. S. Matthews. 2011. Impacts of facility size and location decisions on ethanol production cost. Energ. Policy 39(1):47-56. Doi: https://doi.org/10.1016/j.enpol.2010.09.003

Kononoff, P., and A. J. Heinrichs. 2003. The effect of corn silage particle size and cottonseed hulls on cows in early lactation. J. Dairy Sci. 86(7):2438-2451. doi: https://doi.org/10.3168/jds.S0022-0302(03)73838-7

Kononoff, P. J., S. Ivan, and T. J. Klopfenstein. 2007. Estimation of the proportion of feed protein digested in the small intestine of cattle consuming wet corn gluten feed. J. Dairy Sci. 90(5):2377-2385. Doi: https://doi.org/10.3168/jds.2006-552

Koster, H. H., R. C. Cochran, E. C. Titgemeyer, E. S. Vanzant, I. Abdelgadir, and G. Stjean. 1996. Effect of increasing degradable intake protein on intake and digestion of low-quality, tallgrass-prairie forage by beef cows. J. Anim. Sci. 74(10):2473-2481. (Article) doi: https://doi.org/10.2527/1996.74102473x

Kouakou, B., A. L. Goetsch, A. R. Patil, D. L. Galloway, Z. B. Johnson, and K. K. Park. 1994. Voluntary intake and digestibility by mature beef cattle and holstein steer calves consuming alfalfa or orchardgrass hay supplemented with soybean oil and(or) corn. Archiv für Tierernaehrung 47(2):131-151. Doi: 10.1080/17450399409381801

Kunkle, W., J. Johns, M. Poore, and D. Herd. 2000. Designing supplementation programs for beef cattle fed forage-based diets. J. Anim. Sci. 77:1-11.

Lagasse, M., A. Goetsch, K. Landis, and L. Forster Jr. 1990. Effects of supplemental alfalfa hay on feed intake and digestion by Holstein steers consuming high-quality bermudagrass or orchardgrass hay. J. Anim. Sci. 68(9):2839-2847. Doi: https://doi.org/10.2527/1990.6892839x

Lalman, D. 2004. Supplementing beef cows. Oklahoma Cooperative Extension Fact Sheet (ANSI-3010). doi: http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Version-6172/ANSI-3010web.pdf

Leupp, J. L., G. P. Lardy, K. K. Karges, M. L. Gibson, and J. S. Caton. 2009. Effects of increasing levels of corn distillers dried grains with solubles to steers offered moderate-quality forage. J. Anim. Sci. 87(12):4064-4072. Doi: 10.2527/jas.2008-1711

Lewis, D. 1957. Blood-urea concentration in relation to protein utilization in the ruminant. The J. Agr. Sci. 48(4):438-446. Doi: https://doi.org/10.1017/S0021859600032962

Linden, D., E. Titgemeyer, K. Olson, and D. Anderson. 2014. Effects of gestation and lactation on forage intake, digestion, and passage rates of primiparous beef heifers and multiparous beef cows. J. Anim. Sci. 92(5):2141-2151. Doi: https://doi.org/10.2527/jas.2013-6813

Lintzenich, B., E. Vanzant, R. Cochran, J. Beaty, R. Brandt Jr, and G. St Jean. 1995. Influence of processing supplemental alfalfa on intake and digestion of dormant bluestem-range forage by steers. J. Anim. Sci. 73(4):1187-1195. Doi: https://doi.org/10.2527/1995.7341187x

Liu, R., H. Yu, and Y. Huang. 2005. Structure and morphology of cellulose in wheat straw. Cellulose 12(1):25-34. Doi: https://doi.org/10.1007/s10570-004-0955-8

Löest, C., E. Titgemeyer, J. Drouillard, D. Blasi, and D. Bindel. 2001. Soybean hulls as a primary ingredient in forage-free diets for limit-fed growing cattle. J. Anim. Sci. 79(3):766-774. Doi: https://doi.org/10.2527/2001.793766x

Loy, T. W., T. J. Klopfenstein, G. E. Erickson, C. N. Macken, and J. C. Macdonald. 2008. Effect of supplemental energy source and frequency on growing calf performance. J. Anim. Sci. 86(12):3504-3510. Doi: 10.2527/jas.2008-0924

Loy, T. W., J. C. Macdonald, T. J. Klopfenstein, and G. E. Erickson. 2007. Effect of distillers grains or corn supplementation frequency on forage intake and digestibility. J. Anim. Sci. 85(10):2625-2630. (Article) doi: 10.2527/jas.2005-750

Majak, W., J. Hall, and W. Mccaughey. 1995. Pasture management strategies for reducing the risk of legume bloat in cattle. J. Anim. Sci. 73(5):1493-1498. Doi: https://doi.org/10.2527/1995.7351493x

Marston, T. T., and K. S. Lusby. 1995. Effects of energy or protein supplements and stage of production on intake and digestibility of hay by beef cows. J. Anim. Sci. 73(3):651-656. Doi: 10.2527/1995.733651x

Martin, S., and C. Hibberd. 1990. Intake and digestibility of low-quality native grass hay by beef cows supplemented with graded levels of soybean hulls. J. Anim. Sci. 68(12):4319-4325.

Mathis, C., R. Cochran, J. Heldt, B. Woods, I. O. Abdelgadir, K. Olson, E. Titgemeyer, and E. Vanzant. 2000. Effects of supplemental degradable intake protein on utilization of medium-to low-quality forages. J. Anim. Sci. 78(1):224-232. Doi: https://doi.org/10.2527/2000.781224x

Mcallister, T., H. Bae, G. Jones, and K.-J. Cheng. 1994. Microbial attachment and feed digestion in the rumen. J. Anim. Sci. 72(11):3004-3018. Doi: https://doi.org/10.2527/1994.72113004x

Mcaloon, A., F. Taylor, W. Yee, K. Ibsen, and R. Wooley. 2000. Determining the cost of producing ethanol from corn starch and lignocellulosic feedstocks, National Renewable Energy Lab., Golden, CO (US).

Mccollum, F., and M. Galyean. 1985. Influence of cottonseed meal supplementation on voluntary intake, rumen fermentation and rate of passage of prairie hay in beef steers. J. Anim. Sci. 60(2):570-577. Doi: https://doi.org/10.2527/jas1985.602570x

Mckey, D. 1994. Legumes and nitrogen: the evolutionary ecology of a nitrogen-demanding lifestyle. Advances in legume systematics 5:211-228.

Mertens, D. 1987. Predicting intake and digestibility using mathematical models of ruminal function. J. Anim. Sci. 64(5):1548-1558. Doi: https://doi.org/10.2527/jas1987.6451548x

Moore, J. E., W. E. Kunkle, and W. F. Brown. 1991. Forage quality and the need for protein and energy supplements. Florida Beef Cattle Short Course 40

Moore, J., M. Brant, W. Kunkle, and D. Hopkins. 1999. Effects of supplementation on voluntary forage intake, diet digestibility, and animal performance. J. Anim. Sci. 77(suppl_2):122-135. doi: https://doi.org/10.2527/1999.77suppl_2122x

Morgan, S.E. Gossypol as a toxicant in livestock. In Burrows GE (ed): The Veterinary Clinics of North America: Food Animal Practice. Philadelphia. W.B. Saunders, 1989, pp 251-263.

Moser, L. E., B. L. Burson, and L. E. Sollenberger. 2004. Warm-season (C4) grass overview. Warm-season (C4) grasses 45:1-14. Doi: https://doi.org/10.2134/agronmonogr45.c1

NASEM. 2016. Nutrient requirements of beef cattle. The National Academies Press Washington, DC.

NASS, N. A. S. S. 2020. Agricultural Statistics Board, United States Department of Agriculture (USDA). Doi: https://doi.org/10.3329/ujzru.v31i0.15403

Oltjen, J., and J. Beckett. 1996. Role of ruminant livestock in sustainable agricultural systems. J. Anim. Sci. 74(6):1406-1409. Doi: https://doi.org/10.2527/1996.7461406x

Ovenell, K., K. Lusby, G. Horn, and R. Mcnew. 1991. Effects of lactational status on forage intake, digestibility, and particulate passage rate of beef cows supplemented with soybean meal, wheat middlings, and corn and soybean meal. J. Anim. Sci. 69(6):2617-2623. Doi: Doi:10.2527/1991.6962617x

Owens, F., R. Zinn, and Y. Kim. 1986. Limits to starch digestion in the ruminant small intestine. J. Anim. Sci. 63(5):1634-1648. Doi: https://doi.org/10.2527/jas1986.6351634x

Pathak, A. 2008. Various factors affecting microbial protein synthesis in the rumen. Veterinary World 1(6):186.

Poore, M., and M. Drewnoski. 2010. Utilization of stockpiled tall fescue in winter grazing systems for beef cattle. The Professional Animal Scientist 26(2):142-149. Doi: https://doi.org/10.15232/S1080-7446(15)30573-8

Prigge, E., B. Stuthers, and N. Jacquemet. 1990. Influence of forage diets on ruminal particle size, passage of digesta, feed intake and digestibility by steers. J. Anim. Sci. 68(12):4352-4360. Doi: https://doi.org/10.2527/1990.68124352x

Raboisson, D., A. Ferrières, P. Cousinié, and F. Schelcher. 2013. Clinical and biochemical consequences of soybean meal intoxication in cattle. Veterinary Record:vetrec-2012-101468. Doi: doi: 10.1136/vr.101468

Ramsey, R., D. Doye, C. Ward, J. Mcgrann, L. Falconer, and S. Bevers. 2005. Factors affecting beef cow-herd costs, production, and profits. J. Agric. Econ. 37(1):91-99. Doi: https://doi.org/10.1017/S1074070800007124

Reed, J. J., M. R. O'Neil, G. P. Lardy, K. A. Vonnahme, L. P. Reynolds, and J. S. Caton. 2007. Effect of undegradable intake protein supplementation on intake, digestion, microbial efficiency, in situ disappearance, and plasma hormones and metabolites in steers fed low-quality grass hay. J. Anim. Sci. 85(4):1092-1101. Doi: 10.2527/jas.2006-619

Riesterer, J. L., D. Undersander, M. D. Casler, and D. K. Combs. 2000. Forage yield of stockpiled perennial grasses in the Upper Midwest USA. Agronomy Journal 92(4):740-747.

Roberts, S. D., C. R. Kerth, K. W. Braden, D. L. Rankins, Jr., L. Kriese-Anderson, and J. W. Prevatt. 2009. Finishing steers on winter annual ryegrass (Lolium multiflorum Lam.) With varied levels of corn supplementation I: effects on animal performance, carcass traits, and forage quality. J. Anim. Sci. 87(8):2690-2699. Doi: 10.2527/jas.2008-1704

Rude, B., K. Hanson, and W. Tucker. 2002. Effect of supplementing corn or hay to beef cattle consuming annual ryegrass (Lolium multiflorum) on performance and nutrient utilization. J. App. Anim. Res. 21(1):35-48. Doi: https://doi.org/10.1080/09712119.2002.9706355

Russell, J. B., and H. Strobel. 1989. Effect of ionophores on ruminal fermentation. App. Environ. Microbiol. 55(1):1.

Salisbury, F., and C. Ross. 1985. Plant Physiology. Wadsworth. Inc, USA doi: https://doi.org/10.1042/bj1060141

Satter, L., and L. Slyter. 1974. Effect of ammonia concentration on rumen microbial protein production in vitro. Br. J. N. 32(2):199-208. Doi: https://doi.org/10.1079/BJN19740073

Sawyer, J., J. Mulliniks, R. Waterman, and M. Petersen. 2012. Influence of protein type and level on nitrogen and forage use in cows consuming low-quality forage. J. Anim. Sci. 90(7):2324-2330. Doi: https://doi.org/10.2527/jas.2011-4782

Scholljegerdes, E. J., and S. L. Kronberg. 2010. Effect of supplemental ground flaxseed fed to beef cattle grazing summer native range on the northern Great Plains. J. Anim. Sci. 88(6):2108-2121. Doi: 10.2527/jas.2009-2535

Sewell, B. 1993. Urea supplements for beef cattle. University of Missouri. Department of Animal Sciences. Missouri extension press.

Shahin, K. A., and R. Berg. 1985. Growth patterns of muscle, fat and bone, and carcass composition of double muscled and normal cattle. Can. J. Anim. Sci. 65(2):279-293. doi: https://doi.org/10.4141/cjas85-035

Shaikat, A. H., M. M. Hasan, S. A. Hasan, S. A. Khan, M. A. Haque, M. N. Islam, and M. B. Hossain. 2012. Non-protein nitrogen compound poisoning in cattle. University Journal of Zoology, Rajshahi University 31:65-68. Doi: https://doi.org/10.3329/ujzru.v31i0.15403

Shike, D. W. 2013. Beef cattle feed efficiency.

Shull, L., and P. Cheeke. 1983. Effects of synthetic and natural toxicants on livestock. J. Anim. Sci. 57(suppl_2):330-354. doi: https://doi.org/10.2527/animalsci1983.57Supplement_2330x

Sprott, L., T. Goehring, J. Beverly, and L. Corah. 1988. Effects of ionophores on cow herd production: A review. J. Anim. Sci. 66(6):1340-1346. Doi: https://doi.org/10.2527/jas1988.6661340x

Stock, R. A., M. H. Sindt, J. C. Parrott, and F. K. Goedeken. 1990. Effects of grain type, roughage level and monensin level on finishing cattle performance. J. Anim. Sci. 68(10):3441-3455. (Article) doi: https://doi.org/10.2527/1990.68103441xd

Stokes, S., A. Goetsch, A. Jones, and K. Landis. 1988a. Feed intake and digestion by beef cows fed prairie hay with different levels of soybean meal and receiving postruminal administration of antibiotics. J. Anim. Sci. 66(7):1778-1789. Doi: https://doi.org/10.2527/jas1988.6671778x

Stokes, S., A. Goetsch, and K. Landis. 1988b. Feed intake and digestion by beef steers consuming and receiving ruminal insertions of prairie hay differing in level and particle size. J. Anim. Sci. 66(5):1267-1274. Doi: https://doi.org/10.2527/jas1988.6651267x

Sunvold, G., R. Cochran, and E. Vanzant. 1991. Evaluation of wheat middlings as a supplement for beef cattle consuming dormant bluestem-range forage. J. Anim. Sci. 69(7):3044-3054. Doi: https://doi.org/10.2527/1991.6973044x

Thomas, M. V., M. J. Hersom, T. A. Thrift, and J. V. Yelich. 2017. Comparison of wet brewers' grains or dried distillers' grains as supplements to conserved bermudagrass forage as winter feeding options for beef cows. J. Anim. Sci. 95(1)doi: 10.2527/jas2016.0781

Tjardes, K., D. Buskirk, M. Allen, R. Tempelman, L. Bourquin, and S. Rust. 2002. Neutral detergent fiber concentration in corn silage influences dry matter intake, diet digestibility, and performance of Angus and Holstein steers. J. Anim. Sci. 80(3):841-846. Doi: https://doi.org/10.2527/2002.803841x

Van der Kolk, J. H., J. J. Gross, V. Gerber, and R. Bruckmaier. 2017. Disturbed bovine mitochondrial lipid metabolism: A review. Veterinary quarterly 37(1):262-273. Doi: https://doi.org/10.1080/01652176.2017.1354561

Van Soest, P. J. 1982. Nutritional ecology of the ruminant. O & B Books. Inc., Corvallis, OR 374

Walton, P., R. Martinez, and A. Bailey. 1981. A comparison of continuous and rotational grazing. Rangeland Ecology & Management/Journal of Range Management Archives 34(1):19-21.

Weder, C., T. Delcurto, T. Svejcar, J. Jaeger, and R. Bailey. 1999. Influence of supplemental alfalfa quality on the intake, use, and subsequent performance of beef cattle consuming low-quality roughages. J. Anim. Sci. 77(5):1266-1276. Doi: https://doi.org/10.2527/1999.7751266x

Whetsell, M., E. Prigge, and E. Nestor. 2004. Influence of mass of ruminal contents on voluntary intake and digesta passage in steers fed a forage and a concentrate diet. J. Anim. Sci. 82(6):1806-1817. Doi: https://doi.org/10.2527/2004.8261806x

Wilson, J. 1993. Organization of forage plant tissues. Forage cell wall structure and digestibility:1-32. Doi: doi:10.1017/S0021859600087347

Winterholler, S., C. Mcmurphy, G. Mourer, C. Krehbiel, G. Horn, and D. Lalman. 2012. Supplementation of dried distillers grains with solubles to beef cows consuming low-quality forage during late gestation and early lactation. J. Anim. Sci. 90(6):2014-2025. Doi: https://doi.org/10.2527/jas.2011-4152

Xu, L., Y. Jin, M. L. He, C. Li, T. A. Mcallister, and W. Z. Yang. 2013. Effects of increasing levels of corn dried distillers grains with solubles and monensin on intake, digestion, and ruminal fermentation in beef heifers fed high-barley grain diets. J. Anim. Sci. 91(11):5390-5398. (Article) doi: 10.2527/jas.2013-6456

Zinn, R., and J. Borques. 1993. Influence of sodium bicarbonate and monensin on utilization of a fat-supplemented, high-energy growing-finishing diet by feedlot steers. J. Anim. Sci. 71(1):18-25. Doi: https://doi.org/10.2527/1993.71118x

Appendix A: tables

Table 1.1. Number of publications per journal that were used to populate the complete dataset

Journal[1]	Number of publications
Animal Feed Science and Technology	9
Annals of Animal Science	1
Archives of Animal Nutrition	3
Asian-Australasian Journal of Animal Science	2
Brazilian Journal of Veterinary and Animal Science	1
Canadian Journal of Animal Science	3
Journal of Animal Science	95
Journal of Applied Animal Research	1
Journal of Dairy Science	3
Journal of Livestock Science	6
Journal of Tropical Animal Health and Production	1
Nebraska Beef Report	3
Oklahoma State University Animal Science Research Report	1
Translational Animal Science	2

[1]Publications were found by performing searches using the Journal of Animal Science, Google Scholar, and the Web of Science database

Table 1.2. Frequencies of categorical data in the complete, development, and validation datasets

Category	Item	Complete dataset (no.)[1]	Complete dataset (%)[2]	Model development dataset (no.)[1]	Model development dataset (%)[2]	Model validation dataset (no.)[1]	Model validation dataset (%)[2]
Breed	Bos Indicus and Bos indicus X Bos taurus	85	13.97	23	16.08	11	17.74
	Bos taurus beef	413	67.81	80	55.94	37	59.68
	Bos taurus dairy	111	18.22	40	27.97	14	22.58
Production stage[3]	Calves	198	32.50	48	33.57	18	29.03
	Early and middle gestation	110	18.07	30	20.98	15	24.19
	Late gestation and early lactation	41	6.73	15	10.48	7	11.29
	Yearlings	260	42.70	50	35.97	22	35.48
Forage harvest method	Grazed	55	9.02	11	7.69	6	9.68
	Harvested dry	495	81.29	124	86.71	52	83.87
	Harvested haylage/silage	59	9.69	8	5.94	4	6.45
Forage classification	Warm season perennial	294	48.28	74	51.75	34	54.84
	Warm season annual	37	6.07	3	2.10	1	1.61
	Cool season perennial	176	28.90	45	31.47	19	30.65
	Cool season annual	102	16.75	21	14.69	8	12.90
Forage stem length	Finely processed	160	26.27	32	22.38	12	19.35
	Coarsely processed	118	19.38	16	11.19	5	8.06
	Long stem	266	43.68	80	55.94	39	62.90
	Grazed	65	10.67	15	10.49	6	9.68
Supplementation frequency	Alternating days	46	7.55	6	4.20	4	6.54
	Not supplemented	92	15.11	44	30.77	20	32.26
	Once daily	339	55.67	53	37.06	23	37.10
	Twice daily	113	18.56	40	27.97	15	24.19

[1]Number of treatments that were defined using this designation within the respective category

[2]Percentage of treatments that were defined using this designation within the respective category

3Mature steers and heifers >30 months were classified as early and middle gestation

Table 1.3. Distribution of continuous data in the complete, development, and validation datasets

	Complete dataset				Model development dataset				Model validation dataset			
Item[1]	Mean	Min	Max	Std Dev	Mean	Min	Max	Std Dev	Mean	Min	Max	Std Dev
Experiment year published	1999	1979	2019	10.55	1999	1987	2019	10	2000	1984	2019	11
Average shrunk BW, kg	344.51	96.96	758.40	127.56	341.40	102.72	702.28	128.32	348.97	102.72	604.80	122.80
Forage OM, % of DM	91.45	81.17	96.20	2.68	91.06	82.90	96.15	2.84	91.41	83.70	96.15	2.50
Forage TDN % DM	53.63	34.70	68.70	6.29	54.15	34.7	64.60	5.59	54.53	40.97	63.80	4.61
Forage NEm, Mcal x kg^{-1} of DM	1.46	0.29	3.25	0.81	1.69	0.29	2.88	0.80	1.85	0.51	2.99	0.83
Forage CP, % of DM	8.85	1.94	19.10	4.14	9.46	1.94	17.7	4.06	9.64	2.80	17.70	3.80
Forage RDP, % of DM	3.85	1.66	6.21	1.41	3.99	1.87	5.63	1.38	4.08	1.91	5.53	1.24
Forage RUP, % of DM	2.90	0.89	6.60	1.50	3.84	1.14	6.60	2.12	3.63	1.24	6.60	2.06
Forage NDF, % of DM	70.10	42.60	86.40	8.65	70.14	48.90	86.40	8.02	71.49	54.00	82.50	6.46
Forage ADF, % of DM	41.84	17.40	69.40	7.53	40.57	25.70	61.10	6.54	41.33	29.20	57.20	5.84
Forage ADL, % DM	6.52	0.80	12.80	1.87	6.37	0.80	12.80	2.35	6.51	2.50	12.80	2.05
Forage HEM, % of DM	29.08	8.10	48.10	7.25	29.61	8.10	48.10	7.81	30.35	16.40	48.10	7.20
Forage cellulose, % of DM	35.23	12.80	56.00	7.63	33.16	22.10	56	6.89	33.80	24.7	51	5.95
Supp DMI, kg x hd^{-1} x d^{-1}	1.40	0.00	7.42	1.28	1.05	0.00	6.40	1.31	0.94	0.00	6.50	1.13
Supp DMI, % of BW	0.44	0.00	2.00	0.39	0.32	0.00	2.00	0.36	0.27	0.00	1.40	0.29

Supp TDNI, kg x hd^{-1} x d^{-1}	0.90	0.00	4.76	0.96	0.74	0.00	4.29	0.94	0.67	0.00	4.13	0.89
Supp NEmI, Mcal x kg^{-1} of DM	0.51	0.00	1.93	0.39	1.09	0.00	2.49	0.93	1.05	0.00	2.47	0.96
Supp CPI, kg x hd^{-1} x d^{-1}	0.33	0.00	3.47	0.44	0.23	0.00	1.60	0.31	0.22	0.00	1.60	0.31
Supp OMI, kg x hd^{-1} x d^{-1}	1.23	0.00	7.03	1.25	1.00	0.00	6.09	1.24	0.89	0.00	6.19	1.07
Supp RDPI, kg x hd^{-1} x d^{-1}	0.16	0.00	1.91	0.29	0.11	0.00	0.92	0.18	0.11	0.00	0.92	0.19
Supp RUPI, kg x hd^{-1} x d^{-1}	0.13	0.00	1.12	0.18	0.09	0.00	0.68	0.14	0.12	0.00	0.68	0.17
Supp NDFI, kg x hd^{-1} x d^{-1}	0.43	0.00	4.38	0.60	0.36	0.00	2.92	0.55	0.30	0.00	2.37	0.43
Supp ADFI, kg x hd^{-1} x d^{-1}	0.24	0.00	2.99	0.40	0.21	0.00	2.32	0.40	0.17	0.00	1.90	0.30
Supp HEM, kg x hd^{-1} x d^{-1}	0.18	0.00	1.39	0.22	0.14	0.00	0.95	0.21	0.13	0.00	0.76	0.17
Supp cellulose I, kg x hd^{-1} x d^{-1}	0.17	0.00	1.39	0.22	0.13	0.00	0.92	0.20	0.12	0.00	0.60	0.16
Supp ADLI, kg x hd^{-1} x d^{-1}	0.07	0.00	1.44	0.19	0.07	0.00	1.42	0.23	0.05	0.00	1.44	0.20
Supp EEI, kg x hd^{-1} x d^{-1}	0.05	0.00	0.43	0.07	0.04	0.00	0.29	0.06	0.04	0.00	0.34	0.06
Supp Starch I, kg x hd^{-1} x d^{-1}	0.21	0.00	2.03	0.43	0.14	0.00	1.85	0.37	0.12	0.00	1.46	0.34

Shrunk body weight (BW) was calculated as 96 % of un-shrunk BW; OM = organic matter; DM = dry matter; TDN = total digestible nutrients; CP = crude protein; RDP = rumen degradable protein; RUP = rumen undegradable protein; NDF = neutral detergent fiber; ADF = acid detergent fiber; ADL = acid detergent lignin; HEM = hemicellulose; EE = ether extract; I denotes intake in kg x hd^{-1} x d^{-1} for specific nutrient metrics; NEm = net energy for maintenance; Supp = supplement

Table 1.4. Statistically significant (*P* < 0.05) explanatory variables identified from the complete dataset

Explanatory variable	*P* - value	Adjusted R^2	Number of observations
Average Initial BW, kg	<.0001	0.187851	489
Forage NDF, % of DM	<.0001	0.103008	394
Forage Ash, % of DM	<.0001	0.080682	370
Forage OM, % of DM	<.0001	0.069472	370
Supp DMI, % BW	<.0001	0.048487	489
Supp DMI, g x kg^{-1} $BW^{0.75}$	<.0001	0.036022	489
Supp Cellulose, % BW	0.0002	0.040904	301
Supp OMI, % BW	0.0002	0.034437	369
Forage Hemicellulose, % of DM	0.0004	0.033878	339
Supp TDNI, % BW	0.0006	0.041054	258
Supp cellulose, g x kg^{-1} $BW^{0.75}$	0.0008	0.033563	301
Supp OMI, g x kg^{-1} $BW^{0.75}$	0.0011	0.026115	369
Forage ADF, % of DM	0.0016	0.025031	358
Forage ADL, % of DM	0.002	0.040815	207
Supp TDN, g x kg^{-1} $BW^{0.75}$	0.0023	0.03201	258
Supp Avg ADFI, % BW	0.003	0.024142	323
Supp Avg NDFI, % BW	0.0036	0.019718	377
Forage DM % AF	0.0039	0.033461	218
Supp Ash, % of BW	0.0056	0.018042	369
Forage Starch, % of DM	0.00664	0.086789	29
Supp ADFI, g x kg^{-1} $BW^{0.75}$	0.0068	0.019583	323
Supp ADLI, g x kg^{-1} $BW^{0.75}$	0.00785	0.00884	242
Supp NDFI, g x kg^{-1} $BW^{0.75}$	0.0102	0.014861	377
Supp Starch, % of BW	0.01051	0.010061	164
Forage TDN, % of DM	0.01064	0.010664	153
Supp CPI, % of BW	0.0132	0.011719	439
Supp Ash, g x kg^{-1} $BW^{0.75}$	0.0154	0.013208	369
Supp Cellulose kg^{-1} x d^{-1}	0.0179	0.015333	301
Forage RDP, % of CP	0.0245	0.065099	63
Forage RUP % of CP	0.0245	0.065099	63
Supp CP % DM	0.027	0.008881	439
Supp CPI g x kg^{-1} $BW^{0.75}$	0.0385	0.007495	439
Supp Starch kg^{-1} x d^{-1}	0.0417	0.019329	164

BW = body weight; DM = dry matter; OM = organic matter; NDF = neutral detergent fiber; TDN = total digestible nutrients; CP = crude protein; RDP = rumen degradable protein; RUP = rumen undegradable protein; ADF = acid detergent fiber; ADL = acid detergent lignin; HEM = hemicellulose; EE = ether extract; I denotes intake in kilograms x hd^{-1} x d^{-1} for specific nutrient metrics; NEm = net energy for maintenance; Supp = supplement

Table 1.5. Y-intercept adjustments for categorical designations in forage and total DMI prediction models

		Forage DMI[1]			Total DMI[2]		
Category	Item	kg x hd^{-1} x d^{-1}	% of BW x d^{-1}	g x kg^{-1} of $BW^{0.75}$	kg x hd^{-1} x d^{-1}	% of BW x d^{-1}	g x kg^{-1} of $BW^{0.75}$
Production stage	Calves[4]	-0.7897	-0.2732	-11.1708	-0.7916	-0.1675	-7.8140
	Early and middle gestation[4]	-0.3873	-0.0244	-0.0590	-0.3898	-0.0599	-3.6266
	Late gestation and early lactation[4]	1.6087	0.5025	18.9378	1.6151	0.4563	18.6125
	Yearlings[4]	-0.4317	-0.2049	-7.7081	-0.4337	-0.2288	-7.1717
Forage harvest method	Grazed[5]	1.9311	0.6156	25.3284	1.9305	0.5970	25.6989
	Harvested[5]	-0.9703	-0.4191	-15.1818	-0.9778	-0.3357	14.1236
	Harvested haylage/silage[5]	-0.9508	-0.1965	-10.1466	-0.9527	-0.2613	-11.5753
Forage classification	Warm season perennial[6]	1.1571	0.2353	11.5793	1.1549	0.2131	11.1713
	Warm season annual[6]	-0.1284	0.0260	-2.7095	-0.1248	0.0510	0.2047
	Cool season perennial[6]	-0.2101	0.0846	-2.2222	-0.2100	-0.1103	-3.8199
	Cool season annual[6]	-0.8185	-0.1767	-6.647	-0.8200	-0.1628	-7.5561
Forage stem length	Finely processed[7]	0.6701	0.1653	8.0816	0.6770	0.1490	6.7847
	Coarsely processed[7]	0.1653	0.2434	7.4798	0.1600	0.2454	7.6404
	Long stem[7]	0.5803	0.1927	7.7328	0.5798	0.1471	6.7482
	Grazed[7]	-1.4158	-0.6015	-23.2940	-1.4168	-0.5415	-21.1733
Supplementation frequency	Alternating days[8]	-0.7366	--	-9.7459	-0.7385	--	--
	Not supplemented[8]	0.4240	--	4.6182	0.4295	--	--
	Once daily[8]	0.5401	--	7.3462	0.5413	--	--
	Twice daily[8]	-0.2275	--	-2.2185	-0.2323	--	--

[1]Y-intercept adjustments for models that predict forage dry matter intake (DMI)
[2]Y-intercept adjustments for models that predict total DMI
-- indicates that a variable was removed from the model due to lack of significance ($P \geq 0.05$).

Table 1.6. Regression coefficients of continuous explanatory variables used in forage and total DMI prediction models

Item[3]	Forage DMI[1]			Total DMI[2]		
	$kg \times hd^{-1} \times d^{-1}$	% of $BW \times d^{-1}$	$g \times kg^{-1}$ of $BW^{0.75}$	$kg \times hd^{-1} \times d^{-1}$	% of $BW \times d^{-1}$	$g \times kg^{-1}$ of $BW^{0.75}$
Forage NDF, % of DM	-0.0665	-0.0219	-0.9388	-0.0663	-0.0213	-0.8618
Forage CP, % of DM	0.1341	0.0383	1.6072	0.1347	0.0442	1.7048
Forage HEM, % of DM	-0.0727	-0.0177	-0.6160	-0.0729	-0.0188	-0.8266
Supplement DMI, $kg \times hd^{-1} \times d^{-1}$	--	--	--	1.0210	--	9.8294
Supplement HEMI, $kg \times hd^{-1} \times d^{-1}$	2.4155	--	--	2.3970	0.6052	28.5203
Supplement CPI, $kg \times hd^{-1} \times d^{-1}$	1.3967	0.3516	15.5895	1.3771	0.4397	19.0357
Supplement NDFI, $kg \times hd^{-1} \times d^{-1}$	-2.1812	-0.4223	-16.2117	-2.2143	-0.6249	-26.6131
Average shrunk BW, kg	0.0082	-0.0217	-0.0992	0.0081	-0.0039	-0.0953

[1]Coefficients for models predicting forage dry matter intake (DMI)

[2]Coefficients for developed models predicting total DMI

[3]SBW = average shrunk BW, calculated as 96% of un-shrunk BW

DM = dry matter, NDF = neutral detergent fiber, CP = crude protein, HEM = hemicellulose, I denotes intake in kilograms $\times hd^{-1} \times d^{-1}$ for specific nutrient metrics

-- denotes that a respective variable was removed from the model due to lack of significance ($P \geq 0.05$)

Table 1.7. Regression summary statistics for forage and total DMI prediction models

	Development[1]				Validation[2]					
Response variable	Regression descriptor	R^2	*P*-value	RMSE	R^2	*P*-value	RMSE	Y-intercept bias	Y-intercept *P*-value	Sum of residuals
Forage DMI, kg x hd^{-1} x d^{-1}	SBW[5]	0.70	< 0.0001	1.31	0.68	< 0.0001	1.32	0.07	0.9041	0.03
Forage DMI, % of BW x d^{-1}	SBW[5]	0.61	< 0.0001	0.39	0.56	< 0.0001	0.40	0.13	0.5298	0.01
Forage, g x kg^{-1} of $BW^{0.75}$	SBW[5]	0.52	< 0.0001	15.89	0.47	< 0.0001	16.01	4.78	0.5997	0.52
Total DMI, kg x hd^{-1} x d^{-1}	SBW[5]	0.77	< 0.0001	1.31	0.72	< 0.0001	1.31	0.31	0.5997	0.03
Total DMI, % of BW x d^{-1}	SBW[5]	0.64	< 0.0001	0.38	0.56	< 0.0001	0.40	0.24	0.3043	0.01
Total DMI, g x kg^{-1} of $BW^{0.75}$	SBW[5]	0.54	< 0.0001	15.94	0.41	< 0.0001	16.73	14.59	0.2314	0.25

[1]Summary statistics of prediction models produced during the development stage

[2]Summary statistics of the prediction models once applied to the independent validation dataset

BW = average un-shrunk body weight; SBW = average shrunk BW, calculated as 96% of un-shrunk BW

Appendix B: Figures

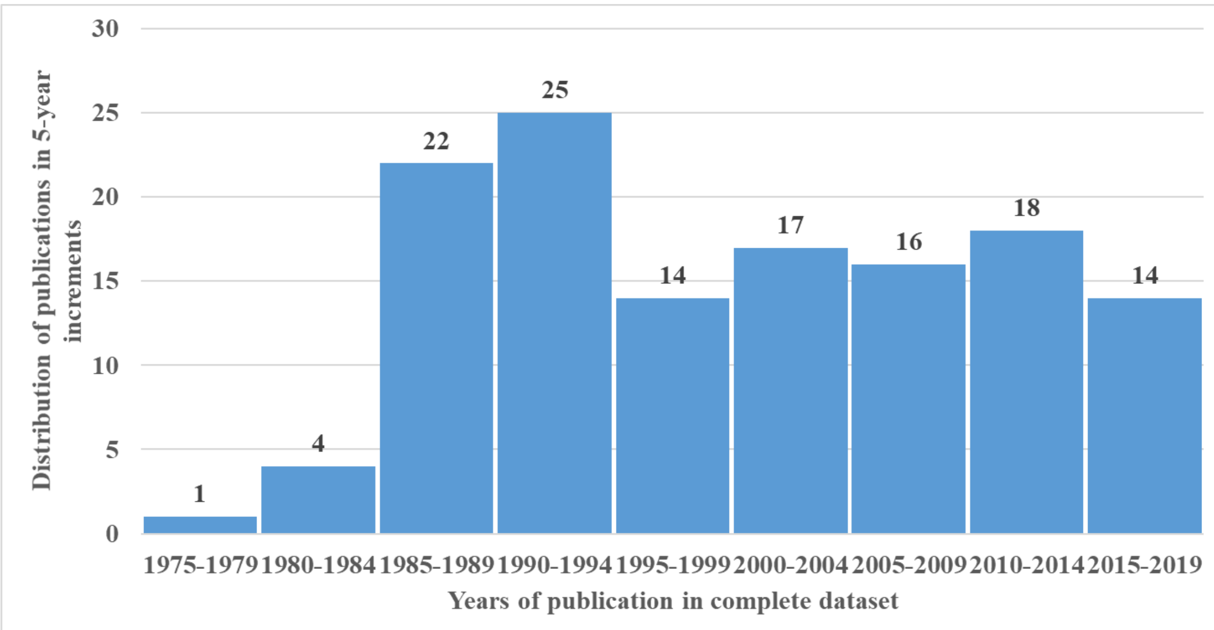

Figure 1.1: Distribution of year of publication for publications included in the complete dataset, listed in five year increments.

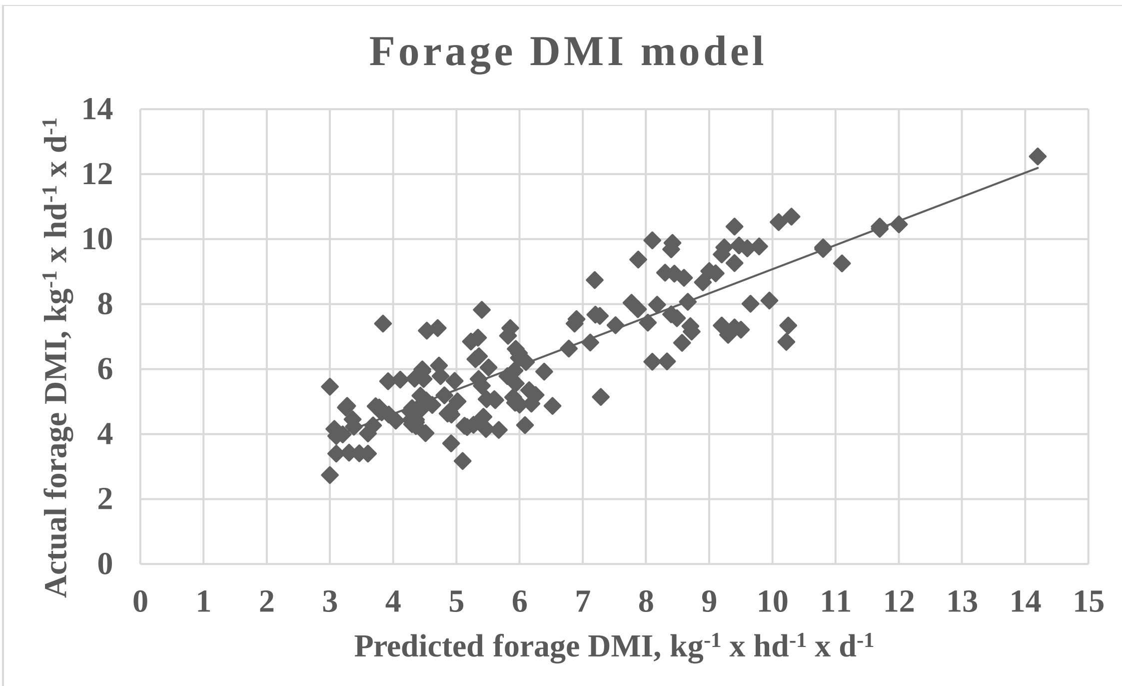

Figure 1.2: Actual vs. predicted plot for the forage DMI prediction model, expressed in kg x hd^{-1} x d^{-1}

RMSE = 1.3056; Adjusted R^2 = 0.70; $P < 0.0001$
DMI = dry matter intake

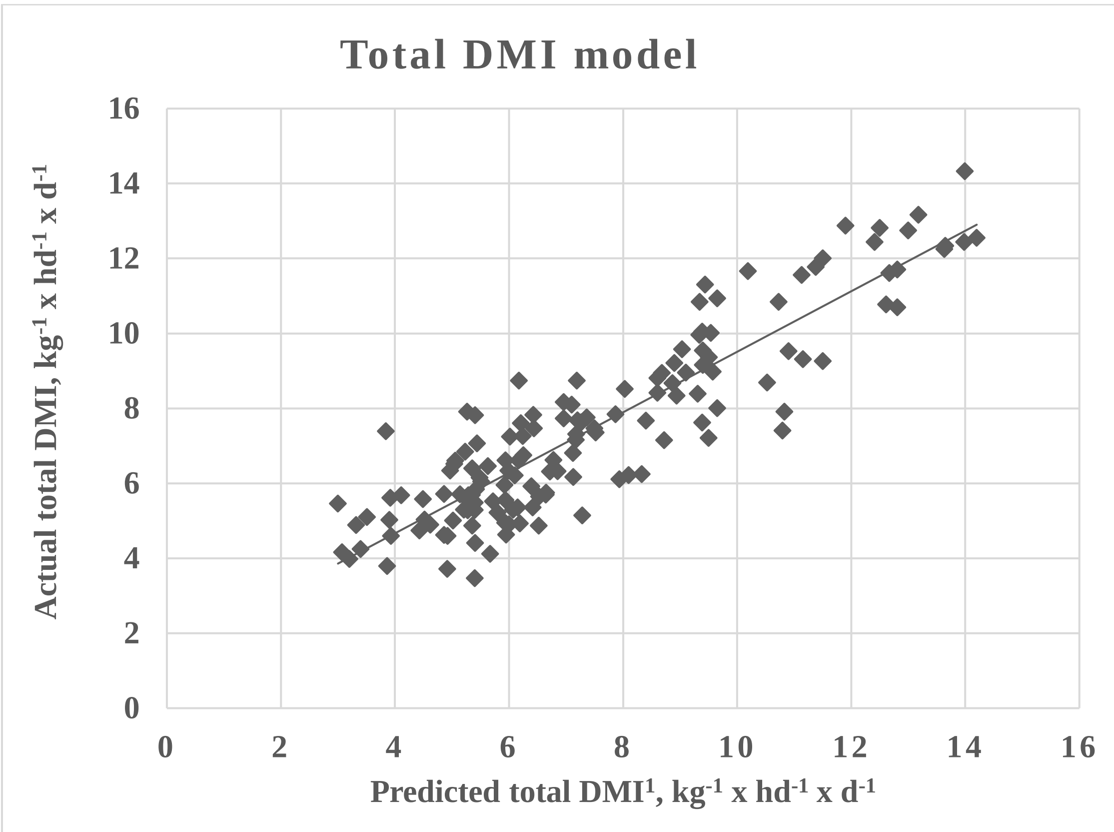

Figure 1.3: Actual vs. predicted plot for the total DMI prediction model, expressed in kg x hd^{-1} x d^{-1}

RMSE = 1.3109; Adjusted R^2 = 0.77; $P < 0.0001$
DMI = dry matter intake

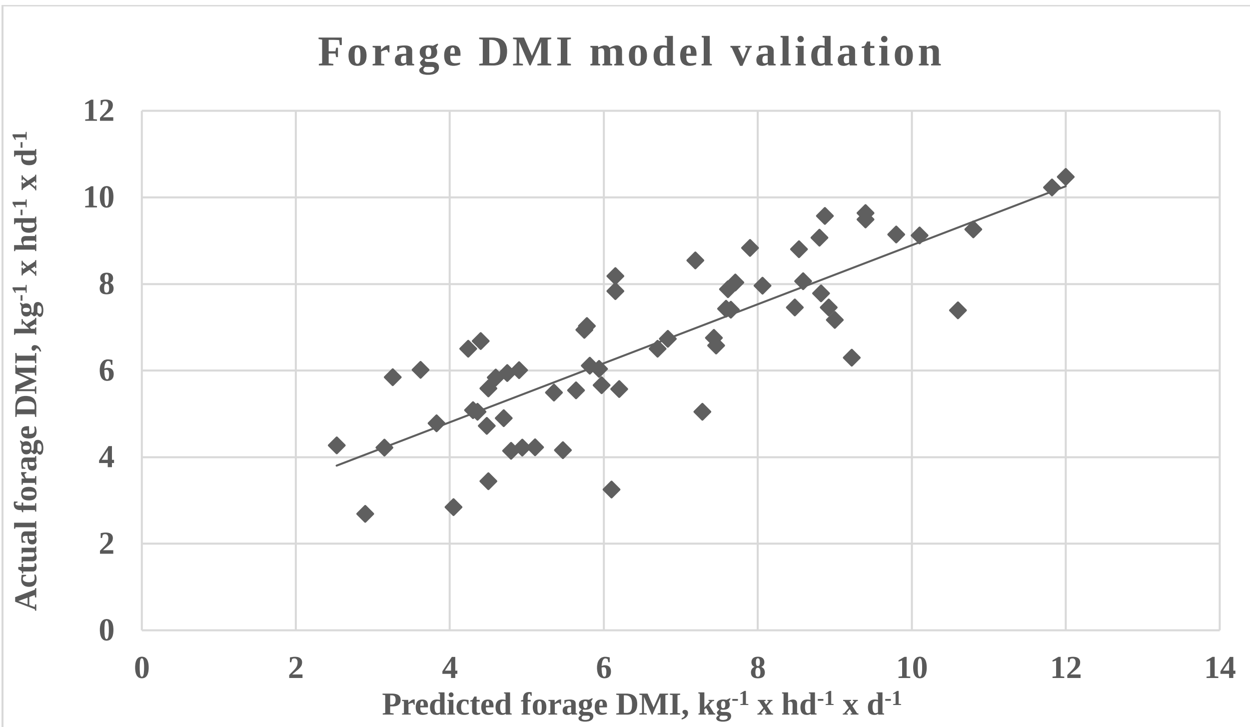

Figure 1.4: Actual vs. predicted plot of the forage DMI prediction model after being applied to the validation dataset, expressed in kg x hd^{-1} x d^{-1}

RMSE = 1.3182; Adjusted R^2 = 0.68; $P < 0.0001$

DMI = dry matter intake

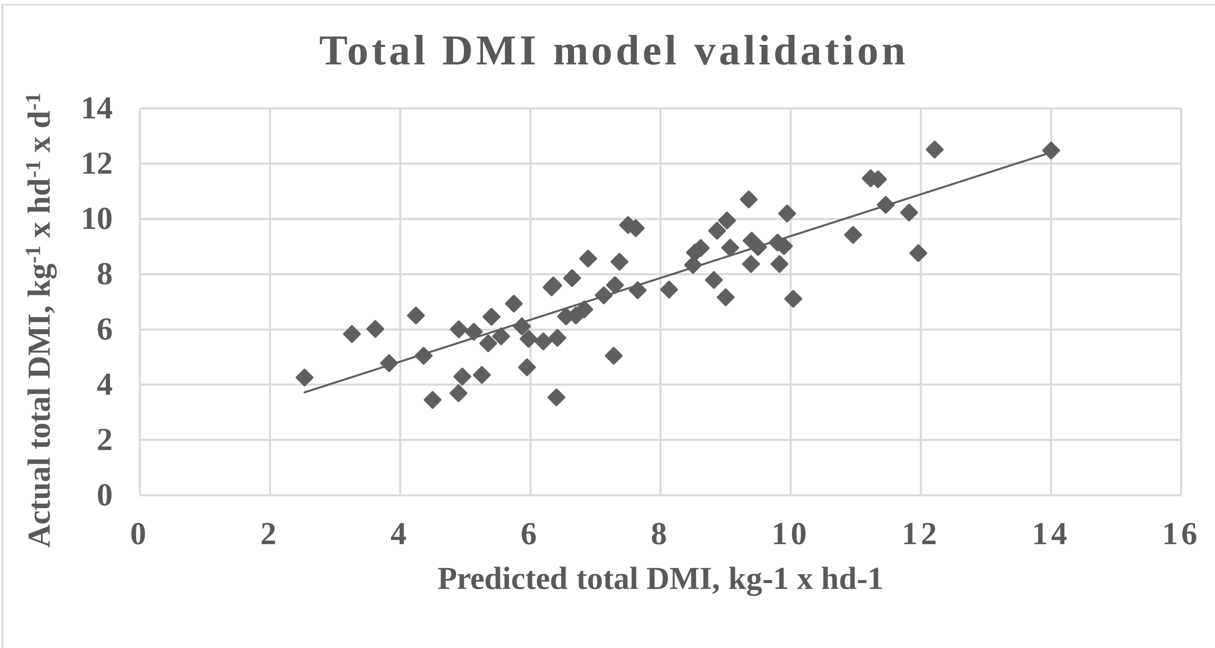

Figure 1.5: Actual vs. predicted plot of the total DMI prediction model after being applied to the validation dataset, expressed in kg x hd^{-1} x d^{-1}

RMSE=1.3144; Adjusted R^2 = 0.72; $P < 0.0001$
DMI = dry matter intake

VITA

Connor Kristopher Biehler was born in Shelbyville, IL on December 20, 1993 to Randy and Marilyn Biehler. Connor's mother was a 4-H leader which led to his involvement in the club and early passion for youth livestock projects. These early interests and family backing led him to pursue his Associates of Science degree in Agriculture at Lake Land College in Mattoon, Illinois. This knowledge base along with family ties to the feedlot industry led him to pursue a Bachelor of Science degree in Animal Sciences from Oklahoma State University in Stillwater, Oklahoma. This led him to take a job as a salesman for a feed company in Guthrie, Oklahoma. While there he developed an appreciation for applied animal nutrition and elected to pursue his Master of Science degree in Applied Ruminant Nutrition from the University of Tennessee, with a particular focus in Beef Cattle Nutrition.