Drought-tolerant teff grass as an alternative forage for dairy cattle

by

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B.S., University of Arizona, 2015

A THESIS

submitted in partial fulfillment of the requirements for the degree

MASTER OF SCIENCE

Department of Animal Sciences and Industry
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2017

Approved by:

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Abstract

Declining ground water supplies are putting significant pressure on the dairy industry in the United States. The water needed for forage production represents the great majority of total water use on most dairy farms, posing a major challenge in the pursuit of improved drought resilience. Teff (*Eragrostis tef)*, a drought-tolerant annual grass (C4 physiology) native to Ethiopia, could prove an attractive alternative to traditional forage crops. While teff grass has potential to fit the needs for forage production in water-stressed regions, very little is currently known about its nutritional characteristics and whether it can support high levels of milk production by dairy cattle. An experiment was conducted to investigate the effects of variety and cutting age on dry matter yield, nutritive values, and digestibility of teff grass. Eighty pots were blocked by location in a greenhouse and randomly assigned to 4 teff varieties (Tiffany, Moxie, Corvallis, and Dessie) and to 5 cutting ages (40, 45, 50, 55, or 60 d after planting [DAP]). Results from this study indicate that, under greenhouse conditions, the first cutting of teff grass should be harvested at 45 to 50 DAP to optimize forage yield, quality, and digestibility in that cutting and in subsequent cuttings. A second experiment was conducted to assess the productivity of lactating dairy cows fed diets with teff hay as the sole forage. Nine multiparous Holstein cows were randomly assigned treatment sequence in a 3×3 Latin square design. Diets were either a control, where dietary forage consisted of a combination of corn silage, alfalfa hay, and prairie hay, or 1 of 2 teff diets, where teff hay was the sole forage. The teff diets maintained yields of milk and milk fat while increasing milk protein yield. Together, these two studies suggest that teff-based diets have potential to maintain high levels of milk production while improving the resilience of the dairy industry to future water shortages.

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Chapter 1 - Literature Review

FEEDING DAIRY CATTLE DURING DROUGHT

There are many issues threatening the sustainability of the U.S. dairy industry today. One of the most pressing issues is drought. It is well known that dairy farms have significant demands for water, both on the farm and in the field. For dairy producers threatened by drought, irrigation for growing feed presents the greatest water-utilization challenge. More than 90% of the water used to support a dairy farm is devoted to producing crops that feed the cattle (Innovation Center, 2013). If the dairy industry hopes to meet the needs of a growing population, a great deal of thought must go into how dairy cattle will be fed amid the threat of increasing water scarcity. This review of literature will address the current and projected drought situation in the United States, the effects of drought on traditional forage crops, and a variety of feeding programs that offer solutions to this threat moving forward.

The current and future water situation

It is a well-known fact that, in recent years, some of America's top dairy producing states have had to bear the weight of extreme water shortages. California, the nation's leading dairy state since 1993, has perhaps been the most effected by drought. In 2013 and 2014, 79% of the state was described as experiencing extreme to exceptional drought (Cross, 2015). Water shortages were the most severe in California's Central Valley. In February 2014, irrigation allocated to farmers was eliminated, leading to their inability to grow adequate supplies of alfalfa and other crops. The result was an increase in feed prices and transportation costs. During that time, scarce water resources were more likely to be allocated to "high value crops" like vegetables as well as fruit and nut trees (Cross, 2015). Drought, as well as other environmental concerns facing the Central Valley, prompted many of the region's dairies to relocate to areas

like Arizona, New Mexico, Idaho and Western Kansas over the past 20 years. Today, all of these areas are starting to experience similar water shortages. There is no doubt that the long-term sustainability of dairies in these areas is questionable.

Drought has also been a major problem in much of the Midwest. According to a 2014 survey, 90% of Wisconsin dairy farmers reported crop losses due to drought over the last five years (Cross, 2015). In the High Plains region of western Kansas and the Texas panhandle, where the dairy industry has seen incredible growth in recent years, farmers are threatened by water shortages due to decreased rainfall and excessive withdrawal of water from the Ogallala Aquifer (Cross, 2015). According to Famiglietti (2014), groundwater depletion is a global concern. In general, groundwater reserves receive significantly less management attention than more visible surface water supplies like rivers and reservoirs. As a result, in many of the world's major aquifers, groundwater is being pumped at a much faster rate than it can be restored naturally. As groundwater supplies across the western United States diminish and management strategies to maintain groundwater levels intensify, it will become increasingly difficult for dairies in drought prone areas to acquire locally-produced crops like alfalfa, a forage commonly fed to dairy cattle that has significant water demands.

Looking into the future, increasing temperatures and faster evaporation rates will only add more stress to these overtaxed resources. According to Cook et al. (2015), climate models show consistent drying during the latter half of the 21st century both in the American Southwest and the Central Plains. This trend, driven by increased greenhouse gas concentrations rather than shifts in ocean-atmosphere dynamics, can manifest itself as 1) a reduction in cold season precipitation and 2) an increase in evapotranspiration rates due to the high evaporative demand of a warmer atmosphere. The overall predicted result is a severe reduction in soil moisture. Cook

and his colleagues (2015) expect that the mean state of drought for the Southwest and Central Plains in the late 21st century will likely exceed even the most severe "megadrought periods" of the Medieval era.

Water needs of traditional forage crops

Approximately 70% of the world's freshwater withdrawals are used for agricultural purposes (FAO, 2010). It comes as no surprise, therefore, that the steps taken by the dairy industry toward enhanced stewardship of the world's water resources will have profound impacts on future water stresses. To enhance water stewardship, it is crucial to first address the dairy industry's water needs. According to Matlock et al. (2013), a dairy farmer's primary water use challenge is irrigation for growing feed rather than on farm use. In fact, reducing on-farm water use will have a relatively minor impact on overall water stresses. In most areas, on-farm dairy production water use is less than 0.5% of irrigation water use (Matlock et al., 2013).

Forages are key components of the diet for any dairy cow, and alfalfa and corn silage are the most commonly fed forages on dairy farms today. In addition to being high quality feedstuffs, alfalfa and corn silage are also significant water users. Saz et al. (2014) attempted to help alfalfa farmers better understand and manage their water resources by measuring the water use (evapotranspiration) of alfalfa in the Albuquerque, NM, South Valley region. Evapotranspiration (ET) was measured for alfalfa on two South Valley farms during the 2010 and 2011 growing seasons. Research sites were located 2 miles apart. Evapotranspiration was measured using energy budget and eddy covariance methods described by Brutseart (2005). Total alfalfa ET for the 2010 growing season (season = 274 days) was 1191 mm (3.91 acre-ft/acre) and 1187 mm (3.9 acre-ft/acre) for the 2011 growing season (294 d).

Howell et al. (1994) measured the mean seasonal ET for corn. The study was conducted at the USDA-ARS Laboratory at Bushland, TX, and ET was measured with weighing lysimeters during the 1989 and 1990 growing seasons. For the two seasons, the mean seasonal ET for corn was found to be 771 ± 53 mm (2.53 ± 0.17 acre-ft/acre). Given the high water demands of alfalfa and corn silage, water scarcity, at any level, can be detrimental to forage production.

Effects of water stress on maturation rate, yield, and quality of traditional forage crops

Drought can create numerous challenges on dairy farms, especially when trying to grow high quality forages that have significant water demands like alfalfa and corn silage. Management strategies meant to maintain groundwater levels will put increasing pressure on dairy farmers as they try to produce high yielding, high quality forages. Many farmers, in an attempt to reduce their water use during a drought year, will employ a strategy known as deficit irrigation. Deficit irrigation involves limiting water application to the drought-sensitive growth stages of a crop (Geerts and Raes, 2009). Outside of these growth stages, irrigation is either limited or unnecessary depending on the amount of water provided by rainfall. Generally, deficit irrigation works better for tree and vine crops because many fruit trees are not sensitive to water shortages at some stages of development (Fereres and Soriano, 2007).

Traditional forage crops have conflicting responses to water shortages. Drought has been shown to reduce yield and slow crop regrowth but improve forage quality. Peterson and others (1992) determined the effect of drought yield and quality of alfalfa as well as three other legumes. The experiment was conducted at the Sand Plains Experimental Station in Becker, MN. DK-120 Alfalfa stands were established in 1985 at seeding rates of 900 seeds/m^2 and utilized in 1987. Pure stands of '526' alfalfa were established in 1987 and used for experiments in 1988 and

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1989. Two soil water regimes supported either "droughted" or well-watered (control) plant growth. The well-watered control was maintained by sprinkler irrigation when 35% depletion of extractable soil water (ESW) occurred. The droughted regime received irrigation to maintain ESW between 50 and 75% depletion.

Researchers found that drought reduced both alfalfa height and herbage yield. When the well-watered control was harvested at 70 cm in July 1987 and June 1988, and 50 cm in July 1988, the droughted alfalfa was harvested at 45 cm in July 1987 and June 1988, and 25 cm in July 1988. Additionally, droughted alfalfa herbage yield averaged 33% of the control. Peterson et al. (1992) also found that drought delayed maturation in alfalfa. When well-watered plants were harvested at the late flower (July 1987), early bud (June 1988), or late bud stage (July 1988), droughted plants were found to be at the early flower stage in July 1987 and the late vegetative stage in June and July 1988.

Forage quality analysis showed that droughted alfalfa had a greater ($P < 0.05$) leaf:stem weight ratio (LSWR) than that of the control (1.47 ± 0.5 vs. 0.97 ± 0.21). Additionally, drought was shown to reduce concentrations (g/kg DM) of neutral detergent fiber (NDF) by 25%, and acid detergent fiber (ADF) and acid detergent lignin by 20%. Crude protein (CP) responses to drought were variable. In this case, the improved forage quality was believed to be associated with delayed maturity and the higher LSWR.

Corn silage yield can also be greatly affected by drought. Farré and Faci (2006) analyzed and compared the responses of corn and sorghum to deficit irrigation. This field experiment was conducted in Northeast Spain on a loam soil. Six irrigation treatments (T1-T6) were established using the sprinkler line-source technique which provides a continuous variable water gradient perpendicular to the sprinkler line so that water applied decreased linearly from the sprinkler line

(T1) to the end of the plot (T6). Researchers found that water deficit delayed maturity (136 days after sowing (DAS) for T1 and 148 DAS for T5) and flowering (66 DAS for T1 and 73 DAS for T5). Additionally, water deficits reduced the overall corn biomass (T1- 2140 g/m^2, T3- 1100 g/m^2, and T6- 357 g/m^2) and grain yield (T1- 1082 g/m2, T3- 480 g/m2, and T6-10 g/m2).

Drought can also affect perennial grass yield and quality. Shaeffer et al. (1992) determined the effect of water deficit on forage yield of reed canarygrass, orchardgrass, smooth bromegrass, and timothy. The experiment was conducted from 1987 to 1989 at the Sand Plains Experiment Station in Becker, MN. Pure stands of orchardgrass, reed canarygrass, smooth bromegrass, and timothy were established in 1986 at rate of 806.5 seeds/m^2. Grasses were subject to two soil water regimes: droughted and well-watered (control). Total season yields of reed canarygrass, orchardgrass, smooth bromegrass, and timothy exposed to a period of drought were 54, 60, 81, and 62%, respectively, of the irrigated controls. Additionally, drought during regrowth resulted in yields that were 33, 37, 24, and 34% of irrigated controls. Forage quality analysis showed that, across grass varieties, drought increased CP concentrations and decreased NDF and ADF concentrations in both the leaves and stems. Researchers concluded that the forage quality improvements were related to a greater proportion of leaves to stems and delayed maturation.

In addition to forage quality and yield, drought has been shown to affect plant nitrate concentrations to the point that commonly fed forages become toxic. Under normal growing conditions, nitrate nitrogen is taken up by plants and converted to amino acids and proteins. As a result, nitrate levels are not high enough to be toxic. During prolonged periods of drought stress, however, the plant's ability to convert nitrate to amino acids is reduced and nitrate accumulates

(Steinke, 2012). To avoid health problems associated with nitrate toxicity, it is recommended that drought stressed crops be tested for nitrate before being fed.

Short-term feeding strategies: Cover crops

Dairy producers, especially those located in areas threatened by drought, should be prepared for water shortages. To prevent financial losses due to decreased production and higher feed costs, it is vital that drought response strategies be discussed prior to a drought event. For producers who have experienced unexpected alfalfa and corn silage losses due to drought, there are 2 primary short-term solutions available to boost stores of high quality forage. First, multiple cover crops can be planted following a period of drought to provide producers with an emergency source of high quality forage. Second, non-forage fiber sources (NFFS) can be incorporated into dairy rations following a period of drought. To stretch forage stores, NFFS can help maintain a healthy rumen environment while incorporating smaller amounts of traditional forages into the diet.

Wheat

Belyea and others (1976) investigated wheat forage as a potential substitute for corn silage and legume haylages in dairy cow diets. Wheat was grown on four sites in northwest Missouri and harvested at 10 cutting ages. The interval between the cutting ages was approximately 7 days. Wheat harvested at the earliest cutting age was in the emerging stage of growth, while wheat harvested at the latest cutting age was in the ripe seed stage of growth.

Across the 10 cutting ages, crude protein (CP) ranged from 30.90 to 6.78% of dry matter (DM). Neutral detergent fiber (NDF) ranged from 46.10 to 59.79% of DM. Using the Goering and Van Soest (1970) method, it was determined that the 48 hour in-vitro dry matter digestibility

(IVDMD) of the wheat samples ranged from 90.59 to 71.22 %. Overall, Belyea and others (1976) concluded that the optimum cutting stages for wheat forage, to optimize both yield and quality, were boot to early head. Wheat forage harvested between the boot and early head stage proved an attractive alternative to drought stressed Missouri corn silage. In fact, the net energy for lactation (NE_L) content of wheat harvested between these two stages of growth ranged from 1.49 to 1.67 Mcal/kg DM and was comparable to drought-stressed corn silage but with lower NDF content. Additionally, the average CP concentration during this growth stage (20.87 to 15.31% of DM) was similar to that of many legumes. The authors did note that the calcium and phosphorus content of the wheat forage was significantly lower than the NRC recommendations for dairy cattle. As a result, feeding wheat forage requires Ca and P supplementation.

Wheat can also be harvested for silage well into the plant's reproductive phase. Wheat is unique in that total plant NDF remains nearly constant as the reproductive phase progresses (Weinberger et al., 1991). This phenomenon is potentially due to the fact that, as maturity increases, starch formation increases along with lignocellulose formation. Arieli and Adin (1994) analyzed the performance of dairy cows fed wheat silage cut at two different stages of maturity. Israeli-Friesian cows (n = 168) were evenly assigned to two dietary treatments according to initial milk yield, lactation number, and days in milk (DIM). Cows were assigned to dietary treatments for two months. The two diets contained wheat silage cut at two different stages of maturity: early and late. Forage for early cut silage was harvested at the middle flowering stage (129 days postemergence and wilted to 30% DM). Forage for late cut silage was harvested 11 days later (at the end of the milk stage) and wilted to 31.5% DM. There was very little difference in chemical composition between the early and late silage. Early silage contained (as % of DM)

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6.5% CP, 53.7% NDF, and 35.7% ADF. Late silage contained 6.4% CP, 53.0% NDF, and 35.5% ADF. NE_L was identical for the two silages (1.49 Mcal/kg).

Cows fed early cut silage (30.51% of diet DM) were 119 DIM and had a preliminary milk yield (PMY) of 31.2 kg of 3.5% FCM (SE = 0.7). Cows receiving late cut silage (33.17 % of diet DM) were 129 DIM and PMY = 31.8 kg (SE = 0.7). Cows were milked three times per day. After being assigned to dietary treatments for 2 months, milk production averaged 36.0 ± 0.80 kg/d for cows fed early cut silage and 32.8 ± 0.70 kg/d for cows fed late cut silage. The difference in milk yield ($P < 0.001$) was most likely due to the differences in fiber degradability between the two silages. Dietary NDF and NDF contributed by forage were nearly constant between the two treatments. Additionally, milk fat percentage was significantly greater ($P < 0.001$) in cows fed late cut silage than those fed early cut silage (2.79 vs. 2.45 ± 0.04%). There was no effect ($P > 0.05$) of treatment on milk protein percentage.

Barley, oat, and triticale silage

A variety of other cover crops have potential to boost forage stores following a period of drought. Khorasani and others (1996) examined the effect of whole-crop barley, oat, triticale, and alfalfa silage on milk production, ruminal digestion, and nutrient supply to the intestine in dairy cattle. Researchers used 8 lactating Holstein cows (21 ± 8 DIM) fitted with ruminal and duodenal cannulas. Cows were assigned to 4 dietary treatments in a 4×4 Latin square design. Treatment periods were 3 wk in length; 2 wk for adaptation and 1 wk for sample collection. Each treatment diet had a 50:50 forage:concentrate ratio. NDF content (as % of DM) of the 4 forages was: alfalfa silage (45.6 %), barley silage (50.6 %), oat silage (60.8 %), and triticale silage (54.3 %). Crude protein (CP) content of the 4 forages was: alfalfa silage (19.9 %), barley silage (12.4 %), oat silage (11.5 %), and triticale silage (12.7 %). Concentrates were based on barley, corn,

canola oil, canola meal, soybean meal, corn gluten meal, meat and bone meal, and fish meal and contained 23.2% CP. Cows were fed twice daily at 0800 and 1800 h.

Khorasani and others (1996) found that NDF intake was the same across all diets, due to differences in dry matter intake (DMI). Cows fed oat and triticale silage had significantly less ($P < 0.05$) DMI (16.7 and 17.2 ± 0.42 kg/d) than cows fed alfalfa or barley silage (19.6 and 18.6 ± 0.42 kg/d). Additionally, cows fed barley silage had higher forestomach DM digestibility ($P < 0.05$) than those fed triticale silage (40.6% vs. 32.8 ± 2.57%). Cows fed alfalfa or barley silage had higher ($P < 0.05$) whole tract DM digestibility (67.6 and 66.1 ± 0.76%) than those fed oat and triticale silage (64.6 and 63.6 ± 0.76%). Total VFA concentrations were higher ($P < 0.05$) for cows fed alfalfa silage than those fed the cereal silages. Researchers found no differences in yields of milk, 4% FCM, milk fat, protein, or lactose.

Another study by Khorasani et al. (1993) reported similar findings. Twenty early lactation Holstein cows and 24 midlactation Holstein cows were subjected to a 21-d covariate period where they were fed a TMR (50:50 forage:concentrate ratio) containing equal parts of alfalfa, barley, oat, and triticale silages. For 12 weeks after the covariate period, cows were fed diets that contained one of the four silages. DM, OM, CP, and ADF digestibilities were greatest for alfalfa silage, intermediate for barley silage, and least for diets containing oat and triticale silages. Feed intake was least for diets containing oat and triticale silages due to the high NDF content of those silages. Intriguingly, forage source had no significant effect on cow performance. Neither milk yield nor 4% FCM yield was affected by silage type. The results from these two studies by Khorasani indicate that barley, oat, and triticale silages harvested at an early stage of maturity have potential to replace alfalfa silage in dairy cow rations.

Grass-clover silage

Grass-clover silages have similar potential as high quality forage sources for dairy cattle. Alstrup and others (2016) examined the effects of maturity and season of harvest of grass-clover silages and forage:concentrate ratio on feed intake, milk production, chewing activity, digestibility, and fecal consistency of Holstein dairy cows. Twenty-four Holstein cows (104 ± DIM, 37.2 ± 6.4 kg ECM, 22.9 ± 2.8 kg DMI) were used in the study. Cows were fed diets containing perennial rye-grass-red clover silage cut at 4 different time points. Time points included an early spring cutting (ESP), a late spring cutting (LSP), an early summer cutting (ESU), and a late summer cutting (LSU). Experimental design was a 4 × 4 Latin square with 4 21-d periods and a 2 × 2 factorial arrangement of treatments with either high or low forage:concentrate ratio (HFCR or LFCR). The 8 rations were fed to 3 cows per ration per period. Forage consisted of two-thirds grass-clover silage and one-third corn silage, and were either fed as HFCR (80:20) or LFCR (50:50).

Of the 4 silages fed, ESP contained the lowest concentration (% of DM) of both total NDF (30.8 %) and indigestible NDF (3.0 %). The greatest concentrations of total NDF and indigestible NDF were found in LSP: 44.1 % NDF and 7.4 % indigestible NDF. ESU contained the greatest concentration of CP (27.7 % of DM) and LSP contained the least (15.3 %). The greatest milk yield was obtained with ESU for both HFCR and LFCR (33.8 ± 1.4 kg/d and 33.5 ± 1.1 kg/d). Milk yield responses to ESU were concluded to be the result of both high NDF digestibility (due to decreased forage maturity) and high CP (due to increased clover proportion in the silage and increased grass leaf:stem ratio).

Short-term feeding strategies: Nonforage fiber sources (NFFS)

Following a period of drought, NFFS can help stretch forage stores by partially replacing forages in lactation diets without compromising productivity or rumen health. Increasing biofuel production in the U.S. has led to increased supplies of high-fiber byproduct feeds. In the biofuel industry, as well as many other industries around the globe, crops are processed to recover particular plant fractions. In many cases, the fiber component of the crop is of little value. However, these high-fiber byproduct feeds are suitable as feedstuffs for ruminants. According to a review published by Bradford and Mullins (2012), dairy cattle nutritionists can use NFFS to partially replace both forages and concentrates in lactation rations without compromising health or productivity. Many high-fiber byproducts can be used in dairy diets including, but not limited to, brewers spent grains, corn gluten feed, distillers grains with solubles, soybean hulls, sugar beet pulp, and wheat middlings. This review will focus primarily on corn gluten feed, soy hulls, and beet pulp as replacements for traditional forages in lactation rations.

Wet corn gluten feed (WCGF)

Boddugari et al. (2001) attempted to determine the maximal amount of forage and concentrate that could be replaced by a wet corn milling product (CMP) similar to wet corn gluten feed (WGCF). In one study, 30 Holstein cows (10 primiparous) were assigned within parity at 1 d after parturition to one of two diets. The first diet acted as the control and contained no CMP. The second diet contained CMP in place of 50% of the concentrate and 30% of the forage (40% of total ration DM). The control diet contained 25.4% alfalfa silage and 25.4% corn silage, and the CMP diet contained 17.5% alfalfa silage and 17.5% corn silage. The diets were fed for 9 weeks and were designed to contain similar amounts of CP and RUP. Cows fed the diet with 40% CMP consumed less ($P < 0.05$) DM and more ($P < 0.05$) NDF. Additionally, CMP

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cows produced more ($P < 0.05$) milk, milk fat, and milk protein, and had a greater efficiency of FCM production than cows fed the control diet ($P < 0.05$). The experiment demonstrated that a properly formulated WCGF product could replace 50% of the concentrate and 30% of the forage in a lactation ration and maintain a high level of production.

Rezac et al. (2012) conducted a similar study with WCGF (Sweet Bran, Cargill Inc., Blair, NE). Diets containing varying amounts of tallgrass prairie hay (TPH, 67.4% NDF and 3.9% CP) and WCGF were fed in comparison to a control diet and production responses of lactating dairy cattle were measured. The control diet (CON) contained 17.6% corn silage, 17.6% alfalfa hay, and 33% WCFG as significant sources of fiber. The first treatment diet (TPH20) contained 19.2% TPH and 46.1% WCGF as significant sources of fiber without the addition of corn silage or alfalfa hay. The second treatment diet (TPH14) contained 13.8% TPH and 56.0% WCGF as sources of fiber without the addition of corn silage or alfalfa.

Least squares mean milk yields were 36.0 ± 1.1, 34.6 ± 1.1, and 35.2 ± 1.4 kg/d for CON, TPH20, and TPH14 respectively and were not significantly different ($P > 0.05$). Milk fat concentration was greater ($P < 0.05$) for CON and TPH20 than TPH14 (3.48 and 3.41 vs. 2.82%). Additionally, researchers found that cows fed TPH14 experienced a high prevalence of ruminal acidosis and diarrhea. Rezac and his colleagues concluded that, while TPH14 did not provide cattle with adequate amounts of physically effective NDF (peNDF), a diet containing 19.2% tallgrass prairie hay and 46.1% wet corn gluten feed (without the addition of corn silage or alfalfa hay) may be feasible.

Soybean hulls

Soybean hulls are another high-fiber byproduct feed that can be substituted for portions of forage or concentrate in dairy diets. Weidner and Grant (1993) evaluated soyhulls as a

replacement for forage fiber in the diets of lactating dairy cows. Thirty Holstein cows were grouped by stage of lactation and, for 12 wk, fed either a control diet (60% forage, 1:1 alfalfa:corn silages, wt/wt, DM basis) or 1 of 4 treatment diets in which soyhulls replaced either 25 or 42% of the forage mixture and coarsely chopped alfalfa hay replaced either 0 or 33% of the remaining forage in the diet (DM basis). All diets were isocaloric compared with the control diet. Researchers found that the high inclusion rate of soyhulls fed in combination with coarsely chopped hay increased ($P < 0.05$) DMI, NDF intake, and milk production by 14, 33, and 9%, respectively, compared with the control diet. The high soyhull diets also increased ($P < 0.05$) DM digestibility by 7% compared with the control diet.

Ipharraguerre et al. (2002) evaluated the performance of dairy cows fed varying amounts of soyhulls as a replacement for corn grain. Fifteen multiparous Holstein cows were fed 5 diets in a 5×5 Latin square design. Diets contained 23% alfalfa silage, 23% corn silage, and 54% concentrate (DM basis). Soyhulls replaced corn to supply 0, 10, 20, 30, or 40% of the DM in the diet. Researchers found that DMI tended to decrease linearly ($P = 0.06$) as soyhull inclusion rate increased. Milk production tended to decrease ($P = 0.07$) when soyhulls supplied 40% of the dietary DM, but 3.5% fat-corrected milk yield as well as milk protein concentration and yield were unaffected by treatment ($P > 0.10$). Increasing the inclusion rate of soyhulls in the diet resulted in a linear increase in milk fat content and yield ($P < 0.01$). Ipharraguerre and others (2002) concluded that soyhulls can supply up to 30% of dietary DM without affecting performance. Soyhulls could prove especially useful in situations where milk fat prices are high and soyhulls are priced more competitively than corn grain.

Beet pulp

Beet pulp, a byproduct of the sugar beet industry, is another NFFS that can be fed to dairy cattle to reduce traditional forage use. As a feed high in NDF, especially pectins, beet pulp has potential to reduce the risk of rumen disorders compared to high-starch feedstuffs (Boguhn et al., 2010). Voelker and Allen (2003) examined the effects of feeding varying levels of dry, pelleted beet pulp substituted for high-moisture corn on intake and milk production. In a duplicated 4×4 Latin square, 8 ruminally and duodenally cannulated Holstein cows (79 ± 17 DIM) were fed diets containing pelleted beet pulp at 0, 6, 12, and 24% substituted for high-moisture corn (DM basis). Volker and Allen (2003) found that increasing the inclusion rate of beet pulp decreased DMI linearly ($P < 0.05$). Additionally, increasing levels of beet pulp had a quadratic effect on milk fat yield ($P = 0.03$) and tended to have a similar effect on 3.5% FCM yield ($P = 0.07$), with the most milk fat and 3.5% FCM yielded at 6% beet pulp. Increasing beet pulp inclusion rate had no effect ($P < 0.10$) on protein or lactose yield.

In addition to dried, pelleted beet pulp, there is also potential to feed ensiled beet pulp. Boguhn and others (2010) conducted a study to examine the effects of pressed beet pulp silage included in corn silage-based rations of high yielding dairy cows. Sixty-three multiparous Holstein and Holstein $\times$ Brown Swiss cows were placed into one of two groups. The first group (n = 39) was fed the control diet where corn silage, grass silage, alfalfa silage, and corn cob silage were the primary sources of forage. The second group (n = 39) was fed a treatment diet containing 20.8% (of DM) beet pulp silage. The beet pulp silage mainly replaced the corn and corn cob silages. Cows were evenly distributed into treatment groups on the basis of previous lactation milk yield, body weight, and days in milk. Cows were milked 3 times per day. Researchers found no significant difference ($P > 0.05$) in milk yield or component concentrations

between the two treatments. Feed intake was significantly decreased ($P < 0.01$) in cows fed the TMR containing beet pulp silage compared to those fed the control diet (23.0 vs 24.5 ± 0.4 kg/d). Digestibility of organic matter, however, increased ($P < 0.05$) in cows fed beet pulp. Conclusions from this study indicate that beet pulp silage has specific effects on ruminal fermentation that have the potential to depress feed intake but improve digestibility (Boguhn et al., 2010). Including beet pulp silage in lactation rations at a rate of 20% of DM is possible without affecting milk yield or component concentrations.

Limitations of NFFS

Although high-fiber byproduct feeds can be incorporated successfully into lactation rations as sources of nonforage fiber, there are some potential limitations. In their review on NFFS, Bradford and Mullins (2012) outline a few of these limitations. The first is physically effective NDF (peNDF). Physically effective NDF incorporates information on particle length and chemical composition of a diet to determine its ability to stimulate chewing and maintain milk fat concentration and production (Bradford and Mullins, 2012). Nutritionists need to consider peNDF when formulating diets with NFFS because substitution of NFFS for forage can greatly reduce the mean particle size of the TMR and decrease the physical effectiveness of NDF. NFFS are unique in that they are high in fiber like forages but are passed rapidly out of the rumen like concentrates. This can have a significant effect on chewing activity, ruminal retention, overall rumen health, and milk fat production (Allen and Grant, 2000). A second limitation is variability. Unfortunately, the chemical and physical composition of NFFS can vary dramatically across batches. One approach to minimize this risk is to work with a sole supplier who has demonstrated product consistency. Another approach is to mix different NFFS to minimize the risk posed by individual ingredients (Bradford and Mullins, 2012).

A third limitation pertains to stability. For NFFS added to rations at low inclusion rates, product stability can be limited. To minimize this risk, dry products are often the best option. Additionally, other feed preservation strategies, like ensiling, do exist. Finally, byproducts have the potential to contain abnormally high concentrations of minerals. The reason for this lies in the fact that, during plant processing, the most valuable plant fractions are removed, thus concentrating the minerals in the waste product. Before feeding a byproduct feedstuff, mineral levels should definitely be tested.

Dealing with drought: long-term solutions

One of the most effective ways for producers to respond to long-term water stresses is through the incorporation of drought-tolerant forage crops into the feeding program. A variety of drought-tolerant forage crops have potential to meet the high nutrient demands of lactating dairy cattle while simultaneously reducing a dairy's water footprint.

Physiology of drought-tolerant crops

Before a discussion of potential drought-tolerant forages can begin, it is first necessary to address the physiology of drought-tolerant crops and how it differs from that of forage crops that have higher demands for water. One of the most significant physiological differences between drought-tolerant crops and those crops that have higher water demands relates to how photosynthesis is accomplished. Most drought-tolerant crops utilize what is known as C_4 photosynthesis, while those that have higher water demands utilize C_3 photosynthesis. According to Gowik and Westhoff (2011), C_4 physiology evolved as an adaptation to high light intensities, high temperatures, and dryness.

In all plants, CO_2 fixation occurs via the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco). Rubisco catalyzes the carboxylation of ribulose-1,5-

bisphosphate yielding two molecules of 3-phosphoglycerate. In addition to this pathway, Rubisco can also add oxygen to ribulose-1,5-bisphosphate yielding one molecule each of 3-phosphoglycerate and 2-phosphoglycolate. 2-phosphoglycolate has no known purpose and, in high enough concentrations, can be toxic to the plant (Gowik and Westhoff, 2011). Therefore, 2-phosphoglycolate has to be processed in a pathway called photorespiration. The process of photorespiration demands energy and leads to a net loss of CO_2, ultimately decreasing the efficiency of photosynthesis. This oxygenase reaction is increased under stressful conditions like high temperatures and dryness.

C_4 plants have developed a way to cope with this problem. Through a variety of biochemical and anatomical modifications, C_4 plants are able to concentrate CO_2 at the site of Rubisco, thereby repressing the oxygenase reaction and the subsequent photorespiratory pathway. The result is increased photosynthetic efficiency under hot and water-stressed conditions. Additionally, C_4 plants exhibit better water-use efficiency. Because CO_2 can be concentrated at the site of Rubisco in C_4 plants, they are able to acquire sufficient CO_2 while keeping their stomata more closed, ultimately reducing water loss by transpiration.

Forage sorghum

Sorghum (*Sorghum bicolor* (L.) Moench) is a drought-tolerant C_4 crop that has been investigated extensively for its ability to be used as a forage source for dairy cattle. Sorghum has been shown to be significantly more drought tolerant than corn. In the previously mentioned deficit irrigation study by Farré and Faci (2006), sorghum yield was superior to corn yield under moderate to severe water deficits. Under water application treatment T-4 (representing a moderate to severe water deficit), sorghum averaged 1073 g/m^2 of above-ground biomass while corn averaged 700 g/m^2. Under the same water application treatment, sorghum also maintained

higher grain yields than corn (489 vs. 195 g/m^2). The ability of drought-stressed sorghum to outperform similarly drought-stressed corn has been attributed to a variety of factors including a greater ability to extract water from deep soil layers, shorter growth duration, and more efficient use of irrigation water (Farré and Faci, 2006).

While sorghum has an advantage over corn with regard to drought tolerance, DM digestibility is typically greater for corn than sorghum (Aydin et al., 1999). Lignin, the indigestible component of plant cell walls, forms a complex matrix with cell wall carbohydrates ultimately inhibiting the digestibility of those carbohydrates in the rumen. Because corn contains less lignin than traditional sorghum, feeding traditional sorghum to dairy cattle poses a potential threat to DMI and milk production (Aydin et al., 1999). In order to improve fiber digestibility of forages, chemical and genetic approaches have been used to reduce forage lignin content. Brown midrib (BMR) forage genotypes generally contain less lignin than traditional forages (Aydin et al., 1999). Additionally, the chemical composition of lignin present in BMR forages is altered. These modifications have resulted in improved fiber digestibility in BMR forage sorghum.

In a series of experiments, Lusk et al. (1984) assessed the differences in dry matter digestibility and milk production between dairy cows fed a diet containing BMR sorghum silage and one containing corn silage. For both of their digestibility experiments, researchers found no significant difference ($P > 0.05$) between the dry matter digestibility of BMR sorghum silage and corn silage. Additionally, Lusk et al. (1984) found no significant differences in milk and fat-corrected milk (FCM) production between cows fed corn silage and those fed BMR sorghum silage.

Oliver et al. (2004) reported similar findings. In their experiment, 16 multiparous Holstein cows (124 ± 28 DIM) were used in a replicated Latin square design with 28-d periods.

Diets contained 40% of a test silage (conventional forage sorghum, bmr-6 forage sorghum, bmr-18 forage sorghum, or a dual-purpose corn hybrid), 10% alfalfa silage, 3.7% whole cottonseed, 22.7% wet corn gluten feed, and 23.6% of a concentrate mix. Diets contained similar amounts of CP and RUP but different amounts of NDF and lignin due to the different sources of silage. Researchers found that DMI was unaffected by the diet ($P > 0.05$). Cows fed the bmr-6 sorghum silage and corn silage had similar milk yields ($P > 0.05$). Cows fed the conventional forage sorghum had the least milk production while those fed the bmr-18 forage sorghum did not show any differences ($P > 0.05$) in milk production compared with cows fed the other diets. While Oliver and others (2004) found a similar pattern for milk fat production, there were no significant effects of silage source on milk protein or lactose production. Together, literature shows that BMR sorghum silage has potential to be an effective alternative to corn silage in lactating dairy cow diets.

BMR sorghum silage has also shown potential to replace alfalfa silage in the diets of lactating dairy cattle. In a study by Aydin and others (1999), similar DMI and milk production ($P > 0.05$) was reported for cows fed alfalfa silage and those fed BMR sorghum silage. Both diets contained 65% silage and 35% of a concentrate mixture (soybean meal, dry-rolled corn, vitamin and mineral premix). Diets were isonitrogenous with similar RUP. Because of the similarities in DMI and FCM, the efficiency of FCM production was also similar for the BMR and alfalfa silage diets.

Sorghum-sudangrass

Sorghum-sudangrass is another water-efficient forage crop that could prove an attractive alternative to traditional forages during times of drought. A C_4 summer annual, sorghum-sudangrass is finer stemmed than forage sorghum and, like a grass, it will regrow after each

harvest. Dann and others (2008) attempted to determine the effect of substituting a bmr-6

sorghum-sudangrass silage hybrid for a dual-purpose corn silage hybrid on lactational

performance in dairy cattle. In this study, 12 Holstein dairy cows (4 primiparous, 8 multiparous)

were assigned randomly within parity to 1 of 4 diets in a replicated 4×4 Latin square with 21-d

periods. Cows averaged 81 ± 31 DIM. Diets contained either bmr sorghum-sudangrass (bmrSS)

or corn silage (CS) at two inclusion levels (35% or 45% of dietary DM).

Dann and others (2008) found that DMI was greatest when cows were fed the 35 and

45% CS diets, intermediate when fed the 35% bmrSS diet, and least when fed the 45% bmrSS

diet. Despite the fact that diet significantly affected DMI ($P < 0.001$), 3.5% FCM and solids-

corrected milk (SCM) yields were similar among the 4 diets ($P > 0.10$). Whereas milk fat yield

was unaffected by dietary treatment ($P = 0.69$), milk fat percentage tended to be decreased for

cows fed CS diets ($P = 0.11$). Milk protein yield, however, was the least ($P < 0.001$) when cows

were fed the 45% bmrSS diet. With that being said, Dann and colleagues (2008) found the

efficiency of milk production (3.5% FCM or SCM per kg DMI) to be 28% greater when cows

were fed the bmr sorghum-sudangrass diets than when they were fed the CS diets. Overall, this

study shows that, like forage sorghum, bmr-6 sorghum sudangrass has potential to compete with

corn silage in dairy diets.

Pearl Millet

Pearl millet [*Pennisetum glaucum* (L.) R.] is another forage crop that may potentially

provide dairy producers with a long-term solution to drought. Pearl millet is a tropical plant that

utilizes the C_4 photosynthetic pathway, thus increasing its tolerance to drought and heat (Maiti

and Wesche-Ebeling, 1997). New forage millet hybrids have been shown to produce 9.5 to 10.9

tons of DM/ha under nonirrigated conditions (AERC, 2007). Amer and Mustafa (2010)

conducted an experiment to determine the feeding value of pearl millet silage relative to corn silage. The forage millet used in the experiment (hybrid CSPM 7) was harvested at the heading stage. Due to wilting difficulties, the millet was ensiled at a lower DM content than the corn (26.9 vs. 37.3%).

For this study, 20 lactating Holstein cows (139 ± 63.5 DIM) were blocked by parity and DIM and randomly divided into 2 groups. Two isonitrogenous diets were fed with a 53:47 forage:concentrate ratio. The forage portion of the diet consisted of 66% pearl millet or corn silage. Alfalfa silage and grass hay made up the rest of the forage portion. Fermentation data suggested that the millet silage was ensiled properly, indicated by a low pH and high lactic acid content (Amer and Mustafa, 2010). Pearl millet silage contained greater concentrations of CP, NDF, and ADF but less starch and NE_L than the corn silage. Amer and Mustafa (2010) attributed these differences to the advanced grain development in the corn silage compared to the millet silage.

DMI was not affected by silage type ($P = 0.81$). However, cows fed the millet silage consumed more NDF ($P < 0.05$) than those fed the corn silage. This was most likely due to the higher NDF content of the millet silage relative to corn silage. There was no significant difference in milk yield between treatments (mean = 38 kg/d). ECM, SCM, and 4% FCM, however, were all greater ($P < 0.05$) for cows fed the millet silage compared to those fed the corn silage. This increase in ECM, SCM, and 4% FCM was due to the increase in fat concentration in the milk of cows fed the millet silage, as concentrations of all other milk components were similar across diets. This study demonstrates that pearl millet silage has potential to replace corn silage in the diets of lactating dairy cows.

Not only can pearl millet be used as a forage source, new pearl millet hybrids bred for grain production have been shown to produce 3 to 3.5 Mg/ha of grain under nonirrigated and drought conditions (AERC, 2005). Relative to corn, pearl millet grain contains greater concentrations of CP but less starch (Hill and Hanna, 1990). Mustafa (2010) found that pearl millet grain can replace corn in dairy diets up to 30% of the diet DM. Fifteen multiparous cows (DIM = 76 ± 24) were used in a 3 × 3 Latin square experiment with 24-d periods. Three isonitrogenous diets were fed, all with a 57:43 forage:concentrate ratio. Ground corn in the first diet (30% of diet DM) was replaced by 50% and 100% (wt/wt) of ground pearl millet grain (hybrid CGPMH 60) in diets 2 and 3, respectively. Mustafa (2010) found that grain type had no effect on milk yield ($P = 0.99$) or ECM ($P = 0.98$). Additionally, yields of milk fat ($P = 0.86$), protein ($P = 0.99$), and lactose ($P = 0.49$) were unaffected by grain type. Pearl millet can be a viable replacement for corn in the diets of lactating dairy cows without affecting milk yield or milk components. Furthermore, due to the higher CP content of pearl millet grain relative to corn, feeding pearl millet grain may reduce the need for a supplemental protein source (Mustafa, 2010).

Teff grass

Teff grass (*Eragrostis tef*) is another drought-tolerant forage crop that may have potential to replace traditional forages on dairy farms. Teff is a warm season annual grass that can be harvested multiple times during the growing season (Miller, 2011). Native to Ethiopia, Africa, teff has been used as a grain crop for human consumption since 4000 B.C. (Miller, 2011). Once introduced to the United States, researchers began evaluating the ability of teff to be used as a forage crop. The CP content of teff can range from 8.5 to 21.5% (Miller, 2011; Roseberg et al., 2005 and 2006; Young et al., 2014). NDF content can range from 53 to 73% (Miller, 2011;

Rosenberg et al., 2005; Young et al., 2014). The forage quality of teff grass is highly dependent on the N application rate, stage of growth at harvest, and cutting number.

Currently there is very little known about the feeding value of teff grass and its ability to be used as an alternative forage source for lactating dairy cattle. Young and others (2014) conducted a study at Utah State University to determine the feeding value of teff hay as a forage source for growing beef steers and dairy heifers. Twelve beef steers and 12 dairy heifers (mean BW = 181 kg) were used in a 12-wk feeding study comparing rations containing alfalfa hay with those containing teff hay. The rations were formulated to meet the nutrient requirements of the animals on the study. The beef steer diets contained (as a % of diet DM) 21% alfalfa hay and 43% corn silage for the alfalfa-based diet, and 44% teff hay and 21% corn silage for the teff-based diet. The dairy heifer diets contained (as a % of diet DM) 54% alfalfa hay and 25% corn silage for the alfalfa-based diet, and 8.5% alfalfa hay, 42% teff hay, and 11% corn silage for the teff-based diet. DMI was significantly increased with the teff-based diet for beef steers and dairy heifers ($P = 0.01$). Whereas dietary treatment did not affect BW gain or ADG of the beef steers, feeding teff grass to dairy heifers increased both BW gain and ADG ($P = 0.02$). Efficiency was unaffected by dietary treatment (Young at al., 2014).

A substantial amount of work still needs done before drought-tolerant forages like teff can be implemented into feeding programs on commercial dairy farms. First, as was previously mentioned, reported forage quality values for teff vary greatly (Roseberg et al., 2005 and 2006; Miller, 2011; Young et al., 2014). Given that dairy cow productivity is highly dependent on forage quality and digestibility (Allen, 1996), standardized quality and digestibility values for teff, and any novel forages like it, must be established before the productivity of cows fed teff grass can be predicted with confidence. Additionally, recommended harvest ages for these novel

forages must be standardized, considering plant age at harvest is one of the most important factors influencing forage quality and digestibility (Van Soest, 1982). While informal industry publications addressing harvest timing do exist, these recommendations need to be confirmed by peer-reviewed research. Next, additional feeding trials need to be conducted to assess the productivity of high-producing dairy cows fed drought-tolerant forage crops like teff. Currently, feeding trials involving teff hay have been limited to horses (Staniar et al., 2010) and growing cattle (Young et al., 2014). Before a commercial farm can adopt a novel forage crop, expected production responses should be understood. Similarly, there is also a need to investigate the quality and feeding value of ensiled teff. Other ensiled grasses are commonly fed to lactating dairy cows (Cherney et al., 2004) so there is reason to believe that ensiled teff would perform similarly. Finally, additional research needs to be done to further understand the exact water demands of these drought-tolerant crops, as well as the economic feasibility of a nutrition program utilizing these novel forages.

Conclusions

Water shortages pose a significant threat to the U.S. dairy industry. For dairy producers threatened by drought, irrigation for growing feed presents the greatest water-utilization challenge because more than 90% of the water used to support a dairy farm is devoted to producing crops that feed the cattle (Innovation Center, 2013). For producers experiencing significant yield losses due to drought, and for those who may facing water shortages in the future, there are a variety of short and long-term solutions to drought, including cover crops, NFFS, and drought-tolerant forage crops.

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Chapter 2 - Effect of seed variety and cutting age on dry matter yield, nutritive values, and in vitro digestibility of teff grass

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ABSTRACT

Declining groundwater supplies are among the most pressing issues facing the dairy industry today. The water needed for forage production represents the great majority of total water use on most dairy farms, posing a major challenge in the pursuit of improved drought resilience. The objective of this experiment was to investigate the effect of variety and cutting maturity on dry matter yield, nutritive values, and digestibility of teff grass (*Eragrostis tef*), a warm-season annual grass native to Ethiopia that is well adapted to drought conditions. Eighty pots were blocked by location in a greenhouse and randomly assigned to 4 teff varieties (Tiffany, Moxie, Corvallis, and Dessie) and to 5 cutting ages (40, 45, 50, 55, or 60 d after planting [DAP]). Harvested samples were dried, weighed, and analyzed for crude protein (CP), neutral detergent fiber (aNDFom), and 24 h *in vitro* NDF digestibility (IVNDFD). It was found that seed variety had no effect on dry matter (DM) yield, CP, aNDFom, or IVNDFD. DM yield increased linearly from 4.1 to 26.4 ± 0.45 g/pot as cutting age increased from 40 to 60 DAP. Similarly, aNDFom concentration increased quadratically from 51.7 to 63.5 ± 0.81% of DM with increasing cutting age. CP decreased linearly from 28.7 to 11.2 ± 0.49% of DM and IVNDFD decreased linearly from 60.8 to 41.2 ± 1.0% as cutting age increased from 40 to 60 DAP. To assess carryover effects of cutting age on nutritive values, two additional cuttings were taken from each pot. It was found that increasing the age at first cutting from 40 to 60 DAP significantly decreased CP concentration in the second cutting. Additionally, increasing DAP significantly reduced DM yield in the subsequent cuttings. Across all varieties and cutting ages, CP decreased and aNDFom increased linearly with each additional cutting. Results indicate that, under greenhouse conditions, the first cutting of teff grass should be taken between 45 and 50

DAP to optimize nutritive values and digestibility in that cutting and any additional cuttings.

Key words: drought, teff grass, dry matter yield, nutritive value, dairy cattle

INTRODUCTION

One of the most pressing issues facing the dairy industry is drought. In the Southwestern and High Plains regions of the United States, where annual precipitation is low, irrigation for growing feed presents the greatest water-utilization challenge for dairy producers. More than 90% of the water used to support a dairy farm is devoted to producing crops that feed the cattle (Innovation Center, 2013). While the dairy industry has seen impressive growth in states like Kansas, New Mexico, and Texas, ground water levels in these areas have been decreasing at an alarming rate (Cross, 2015). As ground water levels drop, some wells are no longer able to provide fields with the intended volume of water. Given the high water demands of crops like alfalfa and corn, and that alfalfa hay and corn silage are the most commonly fed forages in the dairy industry, the sustainability of the dairy industry in the Southwest and High Plains is questionable without an intentional shift toward water conservation.

While there is substantial ongoing work to improve the drought tolerance of grain crops, less effort has been made to decrease the water needs for forage crops. Water-efficient warm-season forage crops, with acceptable nutritional value, could prove an attractive alternative to traditional forages like alfalfa and corn silage. Teff (*Eragrostis tef)* is a warm-season annual grass (C4 physiology) native to Ethiopia that is well-adapted to arid conditions. For thousands of years, teff has been used as a grain crop for human consumption (Mengesha, 1966). Once introduced to the United States, however, researchers began evaluating teff as a forage crop (Miller, 2011).

While teff grass has potential to fit the needs for forage production in water-stressed regions, very little is currently known about its nutritional characteristics and whether it can support high levels of milk production by dairy cattle. In Ethiopia, because teff is primarily

grown as a grain crop, most feeding trials have aimed at improving the nutritive value of low-quality teff straw (Bonsi et al., 1995 and 1996; Mesfin and Ledin, 2004). Additionally, studies that have investigated the quality of teff grass before it reaches full maturity have reported nutritive values that are highly variable. The crude protein (CP) concentration of teff has been reported to range anywhere from 8.5 to 21.5% (Roseberg et al., 2005 and 2006; Miller, 2011; Young et al., 2014). The neutral detergent fiber (NDF) concentration, a predictor of intake in ruminants, has been reported to range from 52.5 to 72.5% (Roseberg et al., 2005; Miller, 2011; Young et al., 2014). Due to the extreme variation in reported nutritive values for teff, it is difficult to know at this point if teff grass is a suitable forage source for high producing dairy cows. Given that the productivity of a dairy cow is highly dependent on forage quality and digestibility (Allen, 1996), standardized quality and digestibility values for teff must be established before the productivity of cows fed teff grass can be investigated. Because both variety and age at harvest play a crucial role in dictating the quality of a given forage, the objective of this study was to investigate the effect of variety and cutting age on dry matter yield, nutritive values, and *in vitro* digestibility of teff grass.

MATERIALS AND METHODS

Design and Treatments

This experiment was conducted in a climate-controlled greenhouse space at Kansas State University (Manhattan, KS). The designated space averaged 24.6°C with 14 h of light/d as a combination of both natural and artificial light. Eighty plastic pots (3.78 L) were blocked by location and randomly assigned to 4 teff varieties and 5 cutting ages. The 20 treatment combinations were assigned in replicates of 4. The 4 varieties of teff seed used in this study were Corvallis, Dessie, Moxie, and Tiffany. All 4 varieties were commercially available at the start of

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the study and coated. Although the exact coating used on the seeds is proprietary, most seed coatings consist of a combination of lime to regulate soil pH, fertilizer to direct specific nutrients to the site of seed-soil contact, as well as insecticides and fungicides, all held together by a binding agent. Coating grass seeds can both enhance germination and add weight to the seeds for easier and more uniform sowing (Burns et al., 2002).

Seeds were planted in Metro Mix 360 (Sungro Horticulture, Agawam, MA) at a rate of 30 seeds per pot (equivalent to 16.81 kg/ha) and to an average depth of 0.48 cm. At planting, 0.15 g of urea (equivalent to 56 kg N/ha) was applied to each pot and the pots were lightly watered with a spray bottle. Pots were watered with a spray bottle until the seedlings were strong enough to withstand watering with a hose. Mature plants were watered to maintain "well-watered" conditions. An additional 0.15 g of urea (equivalent to 56 kg N/ha) was applied to all pots at d 60 after planting. The 5 cutting ages were 40, 45, 50, 55, and 60 d after planting (DAP).

Data and Sample Collection

Each pot was harvested at the assigned cutting age. Entire plants were cut with gardening clippers to a height of 10 cm and top biomass was collected and weighed. To assess the carryover effects of first-cutting harvest age on nutritive values, a second cutting was taken from each pot 30 d after the first cutting. A third cutting was taken 30 d after the second cutting. After the third cutting, regrowth was insufficient to justify a fourth cutting.

Analytical Techniques

Harvested samples were placed in paper bags and dried at 55°C in a forced-air oven for 72 h. After 24 h of air equilibration, dried samples were weighed to determine dry matter (DM) yield. Samples were then ground through a 1-mm screen using a Cyclone Sample Mill (UDY Corporation, Fort Collins, CO). Concentrations of amylase-treated, ash-free neutral detergent

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fiber (aNDFom) were determined in the presence of sodium sulfite (Van Soest et al., 1991) using

an Ankom Fiber Analyzer (ANKOM Technology, Macedon, NY). Crude protein (CP) was

determined by oxidation and detection of N_2 (LECO Analyzer, LECO Corp., St. Joseph, MI),

multiplied by 6.25. Concentrations of all nutrients except for DM were expressed as percentages

of DM determined by drying at 105°C in a forced-air oven for more than 8 h. *In vitro* NDF

digestibility (IVNDFD) was analyzed using a DAISY Incubator (ANKOM Technology,

Macedon, NY). Ground grass samples were placed in filter bags with 25 µm porosity (ANKOM

Technology, Macedon, NY) and incubated for 24 h in rumen fluid collected from a mature

Holstein steer fed a 50:50 forage:concentrate diet. Once removed from incubation, samples were

dried at 55°C and transferred to an Ankom apparatus to determine NDF concentration of the

residue. Second- and third-cutting samples were analyzed by Dairy One Forage Testing

Laboratory (Dairy One Inc., Ithaca, NY) using identical analytical techniques.

Statistical Analysis

The data were analyzed using JMP (version 10.0, SAS Institute, Cary, NC). An analysis

of variance was conducted to analyze how the fixed effects of teff seed variety, cutting age, and

their interaction influenced dependent variables. Independent variables were declared significant

at $P < 0.05$ and means were separated by Tukey's HSD test.

RESULTS AND DISCUSSION

Cutting 1

Plant maturity at harvest is one of the principal factors influencing forage quality and

digestibility (Van Soest, 1982). With the development of higher quality and more digestible

varieties, however, plant genetics are playing an increasingly crucial role in determining the

overall quality of a given forage. Researchers worldwide have investigated the effect of seed

variety on the quality and digestibility of a number of forage types including alfalfa (Guo et al., 2001), corn silage (Ballard et al., 2001), sorghum (Carmi et al., 2006), tall fescue (Chen et al., 2003), oats, and vetch (Assefa and Ledin, 2001) to name a few. There are multiple varieties of teff seed on the market today; some are better for grain production, others for forage production. Grain types tend to mature earlier than forage types, resulting in lower DM yields and forage quality (Miller, 2011). In this experiment, all 4 teff varieties evaluated were bred for forage production. In Cutting 1, seed variety had no effect ($P > 0.30$) on DM yield, aNDFom, CP, or IVNDFD (Table 2.1).

Cutting age, however, had significant impacts on first cutting forage yield, quality, and digestibility (Figure 2.1). As expected, DM yield increased linearly ($P < 0.001$) from 4.1 to 26.4 $\pm$ 0.45 g/pot as cutting age increased from 40 to 60 DAP. Additionally, aNDFom concentration increased ($P < 0.001$) from 51.7 to 63.5 $\pm$ 0.81% of DM with increasing DAP and CP decreased linearly ($P < 0.001$) from 28.7 to 11.2 $\pm$ 0.49% of DM. As forages mature, quality decreases as photosynthetic products are converted to fibrous, structural components (Van Soest, 1982). Grasses like teff, as opposed to legumes, have structural components in both their leaves and stems. Therefore, the forage quality of grasses tends to decline more rapidly with age than that of legumes (Van Soest, 1982). In this study, the CP concentration of first cutting teff decreased linearly at a rate of 0.88% per d (Figure 2.1). Similar trends have been seen with bromegrass (Kilcher and Troelsen, 1973) and sorghum-sudangrass (Ademosum et al., 1968). The average greenhouse temperature could explain the higher-than-expected CP concentration of teff cut at 40 and 45 DAP. Lower temperatures slow the maturation process and the subsequent production of fibrous structural compounds thus improving CP concentration and overall forage quality (Van Soest, 1982).

Cutting age also had a significant effect on the IVNDFD of first-cutting teff (Figure 2.1). As cutting age increased from 40 to 60 DAP, IVNDFD decreased linearly ($P < 0.001$) at a rate of 0.95% per day (60.8 to $41.2 \pm 1.0\%$). The NDF component of teff, like all forages, is composed primarily of cellulose, hemicellulose and lignin. Lignin represents the indigestible fraction of NDF (Van Soest, 1982). As a plant ages, lignin concentration increases, ultimately decreasing the overall digestibility of the fiber (Jung, 1987). Other studies have confirmed this trend (Ademosum et al., 1968; Kilcher and Troelsen, 1973). While the nutrient composition and digestibility of forages grown in a greenhouse are not always the same as those grown in the field, other studies (including Mir et al., 1997 and Guo et al., 2001) have used quality and digestibility values of greenhouse grown forages as initial estimates of what could be expected in a more practical cultivation scenario.

Cuttings 2 and 3

In Cutting 2, teff variety had no effect ($P = 0.47$) on DM yield, aNDFom concentration ($P = 0.13$), or CP concentration ($P = 0.84$, Table 2.1). Additionally, there was no effect ($P = 0.30$) of variety on the cumulative DM yielded from the 2 cuttings. First-cutting harvest age had a significant effect ($P < 0.001$) on second-cutting DM yield as well as second-cutting aNDFom and CP concentrations (Figure 2.2). Dry matter yield from Cutting 2 decreased from 23.68 to 11.59 ± 0.91 g/pot when first-cutting harvest age increased from 40 to 60 DAP. We found that second-cutting aNDFom concentration was greatest ($P < 0.001$) in those samples that were first cut at 45 and 50 DAP. Crude protein concentration of the second-cutting teff decreased dramatically, from 11.94 to $6.43 \pm 0.32\%$ of DM, when first-cutting harvest age was increased from 40 to 60 DAP.

In Cutting 3, again, teff variety had no effect ($P = 0.40$) on DM yield, aNDFom concentration ($P = 0.10$), or CP concentration ($P = 0.48$, Table 2.1). Additionally, seed variety had no effect ($P = 0.49$) on the cumulative DM yielded from the 3 cuttings. Like what was seen with Cutting 2, first-cutting harvest age had a significant effect ($P < 0.001$) on third-cutting DM yield, aNDFom concentration, and CP concentration (Figure 2.2). DM yield decreased from 18.70 to 5.24 ± 0.30 g/pot when first-cutting harvest age increased from 40 to 60 DAP. Third-cutting aNDFom concentration was greatest in samples originally cut at 45 DAP and least in those cut at 55 DAP ($P < 0.001$). CP was greatest in samples originally cut at 45 DAP and least in those cut at 55 DAP.

Whereas seed variety had no effect on the agronomic characteristics of teff, first-cutting harvest age played a critical role in influencing yield and nutritive values in Cuttings 2 and 3. According to Van Soest (1982), photosynthetic compounds are either stored or converted to structural material in plants. In a young plant, most of these photosynthetic compounds are stored. Stored nutrients are crucial for regrowth. When grasses are harvested during the late vegetative to early boot stage (40 to 45 DAP), these stored nutrients assist in the regrowth process and improve overall nutritive values. Grasses harvested during the boot to early heading stage (55 to 60 DAP), however, have already converted a large portion of these photosynthetic compounds to structural compounds. These structural compounds are mostly unavailable to the plant (Van Soest, 1982). Therefore, after harvesting, mature plants have less nutrients available for regrowth, ultimately reducing subsequent yield and protein concentration while increasing the fiber concentration.

Delaying the first cutting from 40 to 60 DAP had a significant impact on the cumulative DM yielded over the course of the trial (Figure 2.3). After 2 cuttings, delaying the first cutting

from 40 to 60 DAP significantly increased ($P < 0.001$) total DM yield from 25.76 to 38.00 ± 1.11 g/pot. This was most likely due to the fact that the first-cutting yield from plants harvested at 40 and 45 DAP was so low that the cumulative yield for the early-cut plants was still less than that of the late-cut plants after 2 cuttings, despite having a relatively higher second-cutting yield. After 3 cuttings, however, an initial cutting age of 40 DAP yielded significantly more ($P < 0.01$) DM than an initial cutting age of 45 DAP (44.47 vs. 38.15 ± 1.29 g/pot, or roughly 26 vs. 22 tons DM/ha) and numerically more DM than original cutting ages of 50, 55, and 60 DAP. After 3 cuttings, the advantage of harvesting a plant at an earlier maturity at Cutting 1 significantly outweighed the greater first cutting yield of a more mature plant. It is important to note that, although yield data collected from the greenhouse is useful for detecting differences among seed varieties and first-cutting harvest dates, yields observed in field trials do not typically match those observed in a controlled greenhouse setting.

Finally, across all teff varieties and cutting ages, Cutting 2 yielded significantly more DM ($P < 0.01$) than Cuttings 1 and 3 and Cutting 1 yielded significantly more DM ($P < 0.001$) than Cutting 3 (Table 2.2). Additionally, aNDFom concentration increased ($P = 0.01$) and CP decreased ($P < 0.001$) when cutting number increased from 1 to 3. Van Soest (1982) describes lignification as one of a plant's protective mechanisms against predatory attack or, in this case, a harvest event. As cutting number increases, then, it is expected that the concentration of the protective, fibrous component of teff would increase. This is supported by the fact that, as cutting number increased from 1 to 3, forage DM concentration, at harvest, increased ($P < 0.001$) from 19.96 to 31.37 ± 0.92% (Table 2.2). Reid et al. (1962) reported a similar trend with smooth bromegrass. As cutting number increased from 1 to 4, yield and digestibility tended to decrease while lignin concentration increased. The decrease in the CP concentration as cutting number

increased could be due to both the increase in the fiber portion of the plant as well as the overall depletion of N and other key nutrients from the soil over time. While additional N (0.15 g of urea) was applied at d 60, N was not applied between Cuttings 2 and 3.

CONCLUSIONS

Results from this study indicate that, under greenhouse conditions, the first cutting of teff grass should be harvested at 45 to 50 DAP to optimize forage yield, quality, and digestibility in that cutting and in subsequent cuttings. For best results, N should be applied at planting and at every cutting to optimize regrowth and CP concentration. Overall, the agronomic characteristics and nutrient profile of teff grass are similar those of other commonly fed forages like timothy (Miller, 2011), smooth bromegrass, and sorghum-sudangrass. To use teff grass in the diets of a high producing dairy cow, maturity at first cutting and soil fertility must be well managed to ensure that the forage provided in the diet is of the highest quality and as valuable as possible to the animal.

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Table 2.1 Effect of teff variety on yield, nutritive values, and in vitro digestibility of teff grass

Item	Variety				SEM	P-value
	Tiffany	Moxie	Corvallis	Dessie		
Cutting 1						
DM[1] yield, g/pot	14.77	14.56	14.48	13.83	0.40	0.38
aNDFom[2,3]	60.27	58.61	59.13	59.13	0.73	0.43
CP[2,4]	20.39	19.89	19.58	20.63	0.44	0.32
IVNDFD[5], %	51.21	49.66	50.39	51.81	0.85	0.32
Cutting 2						
DM yield, g/pot	19.48	20.12	19.12	18.30	0.82	0.47
aNDFom	62.70	63.33	64.21	63.37	0.44	0.13
CP	7.99	8.27	8.23	8.44	0.35	0.84
Cumulative DM yield (g/pot)	34.26	34.68	33.60	32.13	0.99	0.30
Cutting 3						
DM yield, g/pot	8.35	8.38	7.97	8.63	0.27	0.40
aNDFom	63.82	64.44	63.68	63.66	0.24	0.10
CP	5.87	5.83	5.96	5.98	0.08	0.48
Cumulative DM yield (g/pot)	42.61	43.06	41.57	40.76	1.15	0.49

[1]Dry matter
[2]Nutrients expressed as a percent of DM
[3]Ash-free neutral detergent fiber with amylase
[4]Crude protein
[5]In-vitro neutral detergent fiber digestibility

Table 2.2 Effect of cutting number on yield and nutritive values of teff across all varieties and first-cutting harvest ages

	Cutting Number				
Item	1	2	3	SEM	P-values
DM yield, g/pot	14.58[b]	19.26[a]	8.33[c]	0.72	0.001
DM %	19.96[c]	26.72[b]	31.37[a]	0.92	< 0.001
aNDFom[1]	59.40[b]	63.40[a]	63.80[a]	0.40	< 0.001
CP[1]	19.97[a]	8.23[b]	5.90[b]	0.45	< 0.001

[1]Expressed as a percent of DM
[a,b]Means with different superscripts are significantly different ($P < 0.05$)

Figure 2.1 Effect of cutting age on yield, nutritive values, and digestibility of first-cutting teff grass. Increasing cutting age from 40 to 60 DAP significantly increased DM yield and aNDFom concentration ($P < 0.001$) but significantly decreased CP concentration and IVNDFD ($P < 0.001$).

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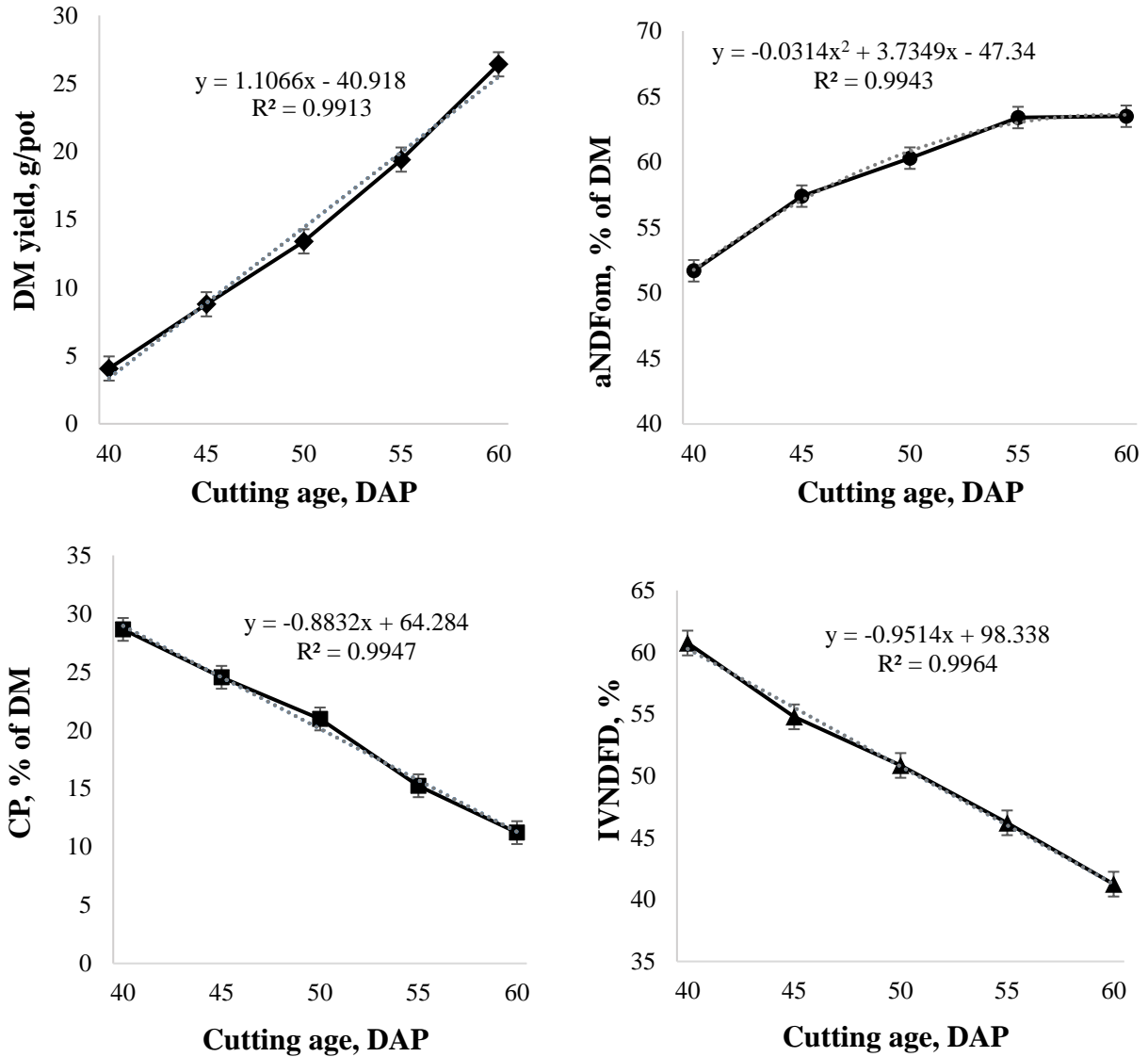
Figure 2.2 Effect of first-cutting harvest age on yield, nutritive values and digestibility of second- and third-cutting teff grass. For all pots, Cutting 2 was taken 30 d after Cutting 1. Cutting 3 was taken 30 d after Cutting 2. For Cuttings 2 and 3, first-cutting harvest age was a significant predictor ($P < 0.001$) of DM yield and concentrations of aNDFom and CP.
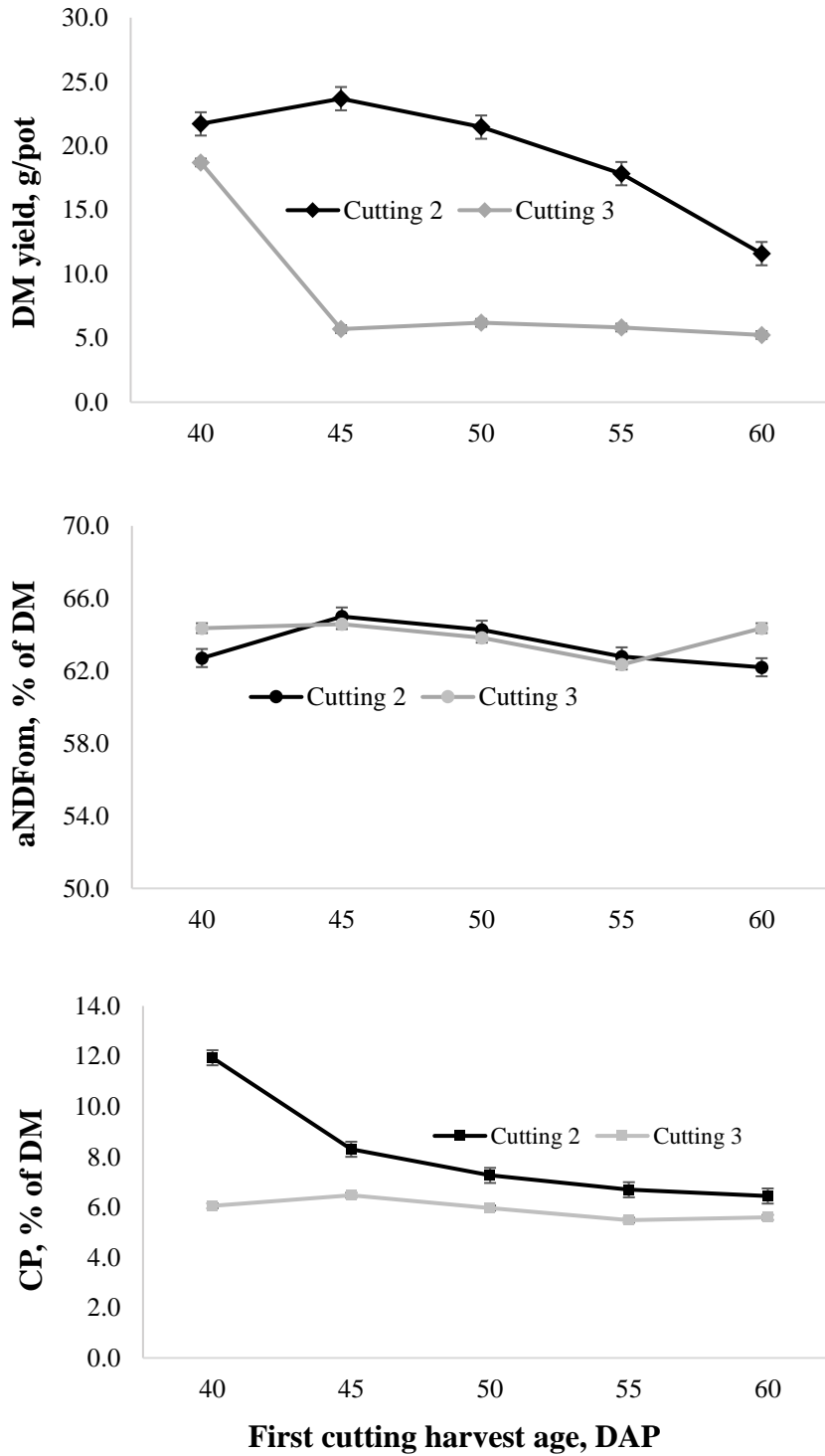
Figure 2.3 Effect of first-cutting harvest age on cumulative DM yielded from 3 cuttings
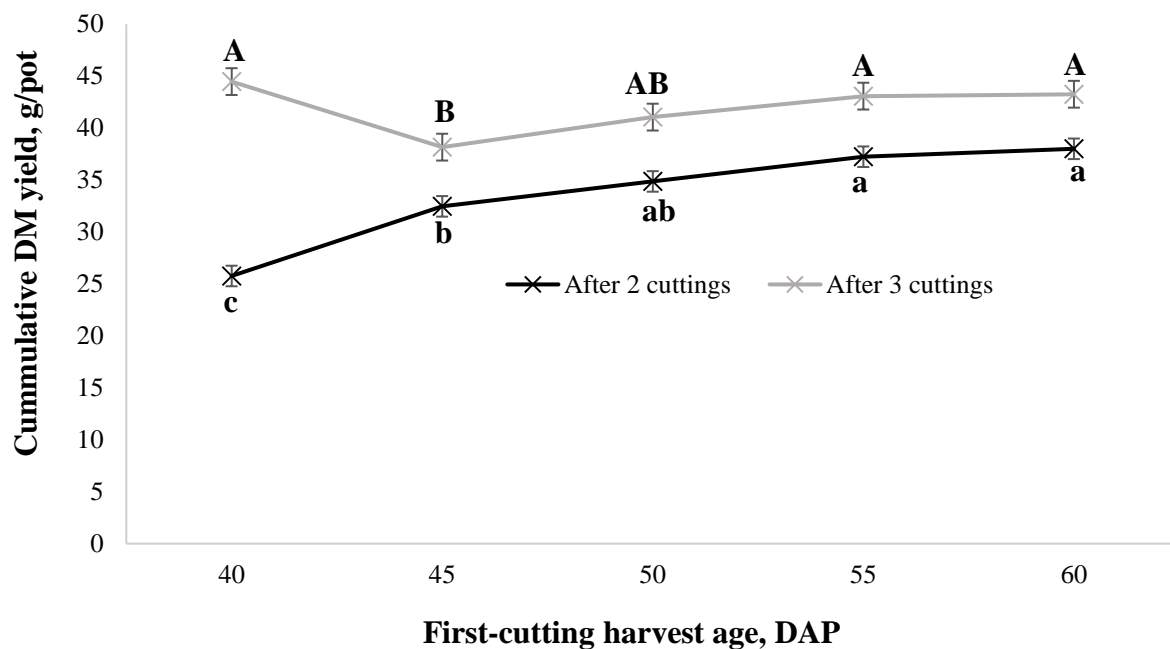
a,bMeans with different superscripts differ ($P < 0.05$)
A,BMeans with different superscripts differ ($P < 0.05$)

Chapter 3 - Productivity of lactating dairy cows fed diets with teff hay as the sole forage

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ABSTRACT

Groundwater depletion is one of the most pressing issues facing the dairy industry today. One strategy to improve the industry's drought resilience involves feeding drought-tolerant forage crops in place of traditional forage crops like alfalfa and corn silage. The objective of this study was to assess the productivity of lactating dairy cows fed diets with teff hay (*Eragrostis tef*) as the sole forage. Teff is a warm-season annual grass native to Ethiopia that is well adapted to drought conditions. Nine multiparous Holstein cows (185 ± 31 d in milk; mean $\pm$ SD) were randomly assigned to 1 of 3 diets in a 3×3 Latin square design with 18-d periods (14 d acclimation and 4 d sampling). Diets were either control (CON), where dietary forage consisted of a combination of corn silage, alfalfa hay, and prairie hay, or 1 of 2 teff diets (TEFF-A and TEFF-B), where teff hay ($13.97 \pm 0.32\%$ CP, DM basis) was the sole forage. All 3 diets were formulated for similar dry matter (DM), crude protein (CP) and starch concentrations. CON and TEFF-A were matched for concentrations of neutral detergent fiber (NDF) from forage ($18.23 \pm 0.15\%$ of DM), and TEFF-B included slightly less, providing 16.63% NDF from forage. Dry matter intake (DMI), milk and component production, body weight (BW), body condition score (BCS), as well as DM and NDF digestibility (DMD and NDFD) were monitored and assessed using mixed model analysis. Treatment had no effect on DMI (28.14 ± 0.75 kg/d). Similarly, treatment had no effect on milk production (40.68 ± 1.79 kg/d). Concentrations of milk fat ($3.90 \pm 0.16\%$) and lactose ($4.68 \pm 0.07\%$) were also unaffected by treatment. TEFF-A and TEFF-B increased milk protein concentration compared to CON (3.07 vs. $3.16 \pm 0.09\%$). Treatment had no effect on energy-corrected milk (ECM) yield (43.37 ± 1.26 kg/d), BW, or BCS change. Additionally, treatment had no effect on total-tract DM or NDF digestibility. Results from this

study indicate that teff hay has potential to replace alfalfa and corn silage in the diets of lactating dairy cattle without loss of productivity.

Key words: drought, teff hay, dairy cattle

INTRODUCTION

Drought is one of the most significant issues threatening the dairy industry today. For producers located in arid regions of the United States, irrigation for growing feed presents the greatest water-utilization challenge. In fact, irrigation used for growing the crops that feed cattle accounts for more than 90% of the water used on a dairy farm (Innovation Center, 2013). Declining ground water levels across the country are making it more difficult to produce feed locally (Cross, 2015). Management strategies intended to maintain surface water levels will only put more stress on groundwater reserves (Famiglietti, 2014). As groundwater levels decrease, wells will no longer be able to support the production of alfalfa and corn silage, forage crops with significant water demands. Without an industry-wide shift toward water conservation, the sustainability of the dairy industry in areas prone to drought is questionable.

Water-efficient forage crops, with acceptable nutritional value could prove an attractive alternative to traditional forage crops. Teff (*Eragrostis tef)* is a warm-season annual grass (C4 physiology) native to Ethiopia that is well-adapted to arid conditions. Since 4000 B.C., teff has been used as a grain crop for human consumption. Upon its introduction to the United States, however, researchers have begun evaluating teff as a forage crop (Miller, 2011). While teff grass has potential to fit the needs for forage production in areas threatened by drought, very little is currently known about how dairy cows might perform when fed a teff-based diet.

Because teff is primarily a grain crop in Ethiopia (Mengesha, 1966), a number of Ethiopian studies have investigated opportunities to improve the feeding value of teff straw (Bonsi et al., 1995 and 1996; Mesfin and Ledin, 2004). To optimize the quality of teff grass, however, harvest should occur well before the development of seedheads. As forages mature, quality decreases as photosynthetic products are converted to fibrous, structural components

(Van Soest, 1982). In a recent study completed by our group (B. Saylor, unpublished data), greenhouse-grown teff grass cut well before seedhead development (45 d after planting) contained an average of $24.6 \pm 0.49\%$ crude protein. Additionally, the 24 h in vitro NDF digestibility averaged $54.8 \pm 0.95\%$. These results show that, if cut at an early stage of maturity, teff grass has potential to be a highly nutritious forage. Still, very little work has been done to assess the effects of feeding high quality teff grass to dairy cattle. Several studies have evaluated responses to teff hay in growing cattle and horses (Stainiar et al., 2010; Young et al., 2014). Although studies like these are certainly valuable, the true test for teff grass will be in maintaining production in high producing dairy cows due to their immense nutrient demands. The objective of this study was to assess the productivity of high producing dairy cows fed diets with teff hay as the sole forage.

MATERIALS AND METHODS

Experimental procedures were approved by the Institutional Animal Care and Use Committee at Kansas State University.

Design and Treatments

Nine multiparous Holstein cows (185 ± 31 d in milk; mean $\pm$ SD) from the Kansas State University Dairy Cattle Teaching and Research Unit were randomly assigned to treatment sequence in a replicated 3×3 Latin square design. Treatment periods were 18 d, with the final 4 d used for data and sample collection. At the beginning of the experiment, body weight (BW) of cows were 694 ± 50 kg with a body condition score (BCS) of 3.18 ± 0.24.

Cows were offered 1 of 3 diets. Diets were either control (CON), where dietary forage consisted of a combination of corn silage, alfalfa hay, and prairie hay, or 1 of 2 teff diets (TEFF-A and TEFF-B), where teff hay was the sole forage. Chemical composition of the forages used in

this study is shown in Table 3.1. All 3 diets were formulated for similar dry matter (DM), crude protein (CP) and non-fiber carbohydrate (NFC) concentrations. CON and TEFF-A were matched for concentrations of neutral detergent fiber (NDF) from forage (fNDF), and TEFF-B included slightly less fNDF (Table 3.2).

Data and Sample Collection

Throughout the experiment, cows were fed twice daily for daily refusals of 2.27 kg as-fed. On d 15 to 18 of each treatment period, the amount of feed offered and refused was recorded to determine dry matter intake (DMI). Samples of all dietary ingredients were collected during the sampling period. Grab samples of the TMR, as well as all forage and wet corn gluten feed (WCGF) samples were collected at feeding on d 15 to 18. Concentrate samples were collected on d 16 and 18. Representative orts were collected 23.5 h post-feeding. Feed samples were composited into one sample per period. Fecal samples were collected approximately every 16 h from d 15 to 18 so that 6 samples were taken from each cow each period. Undigested NDF (uNDF, 240 h) was used as an internal marker to determine apparent total-tract digestibility of DM and NDF (Lee and Hristov, 2013).

Cows were milked 2 times daily (0400 and 1600 h) in a milking parlor, and milk was sampled and yield was recorded for every milking on d 15 to 18 of each period. Body weight and BCS were measured on d 1 of each period and d 18 of the last period. Body condition score was measured on a scale of 1 to 5 according to Wildman et al. (1982).

Nutrient and Milk Analyses

The Penn State Particle Separator was used to measure particle size for both TMR and orts (Lammers et al., 1996). Diet ingredients were sent frozen to Dairy One Forage Testing Laboratory (Dairy One Inc., Ithaca, NY) and analyzed for DM, CP, amylase-treated, ash-free

NDF (aNDFom), acid detergent fiber (ADF), ether extract (EE), ash, and uNDF. Fecal samples were dried for 72 h in a 55°C forced-air oven, ground to pass through a 1-mm screen using a Wiley mill (Arthur H. Thomas, Philadelphia, PA), then sent to Dairy One Forage Testing Laboratory (Ithaca, NY) to be analyzed for DM, aNDFom, and uNDF. DM was determined by drying samples for 16 to 24 h in a 55°C forced-air oven. CP was determined by oxidation and detection of N_2 (Leco Analyzer, Leco Corp., St. Joseph, MI). Concentrations of aNDFom (Van Soest et al., 1991) and ADF were determined using an Ankom Fiber Analyzer (ANKOM Technology, Macedon, NY). Crude fat was determined by ether extraction (AOAC 2003.05). Ash concentration was determined using AOAC method 942.05. Undigested NDF concentration was defined as the amount of NDF present after 240 h incubation (Raffrenato and Van Amburgh, 2010) in the DaisyII Incubator (ANKOM Technology Method 3, ANKOM Technology). Concentrations of all nutrients except DM were expressed as percentages of DM determined by drying at 105°C in a forced-air oven for 3 h.

Milk samples were analyzed for concentrations of fat, true protein, lactose (B-2000 Infrared Analyzer; Bentley Instruments, Chaska, MN), MUN (MUN spectrophotometer, Bentley Instruments), and somatic cells (SCC 500, Bentley Instruments) by MQT Lab Services (Kansas City, MO). Energy-corrected milk (ECM; $0.327 \times$ milk yield $+ 12.86 \times$ fat yield $+ 7.65 \times$ protein yield; DHI glossary, Dairy Record Management Systems, 2009) was calculated.

Statistical Analysis

Data were analyzed according to the following model using JMP (version 10.0, SAS Institute, Cary, NC):

$$Y_{ijk} = \mu + T_i + P_j + C_k + e_{ijk}$$

where μ = overall mean, T_i = fixed effect of treatment (j = 1 to 3), P_j = random effect of period (I = 1 to 3), C_k = random effect of cow (k = 1 to 9), e_{ijk} = residual error. Treatment effects were declared significant at $P < 0.05$ and tendencies for treatment effects were declared at $P < 0.10$. When significant treatment effects were observed, means were separated by Tukey's HSD test.

RESULTS AND DISCUSSION

Diet Composition and Particle Size

Diets were formulated to meet or exceed NRC (2001) requirements for a Holstein cow producing 43.1 kg/d of milk; diet ingredient and nutrient analyses are shown in Table 3.2. The teff hay used in this study was supplied from a single source (Marc Oster, La Salle, CO) and nutrient variability of this product, across the 3 collection periods, was relatively low (Table 3.1). Table 3.5 shows particle size analysis and sorting index for the treatments. Compared to CON, TEFF-A and TEFF-B contained a greater proportion of particles longer than 19 mm ($P < 0.001$) but a lesser proportion of particles between 8 and 19 mm ($P < 0.001$). Additionally, TEFF-A and TEFF-B contained a greater proportion ($P < 0.001$) of particles smaller than 8 mm compared to CON. An adequate supply of long particles is necessary to maintain rumen function (Lammers et al., 1996). While there was no effect ($P > 0.05$) of diet on sorting of particles greater than 19 mm and less than 8 mm, diet had a significant effect on sorting of particles between 8 and 19 mm ($P = 0.04$, Table 3.5).

DMI and Performance

The teff-based diets fed in this study were designed in such a way as to test 2 different strategies for formulating a diet containing teff hay as the sole forage. TEFF-A was designed to be a slightly more conservative diet than TEFF-B. TEFF-A and CON were formulated to contain similar concentrations of NDF from forage (fNDF, Table 3.2). Average fNDF for the 2 diets was

18.2% of DM. TEFF-B was formulated to contain slightly less fNDF (16.65% of DM) and to match the level of 'expected effective fiber' found in CON. Expected effective fiber levels were calculated using the following equation: (fNDF $\times$ 2) + NDF (Bradford and Mullins, 2012).

There was no significant effect of diet on DMI ($P = 0.76$). Across all three diets, DMI averaged 28.1 ± 0.76 kg/d (Table 3.3) According to Van Soest (1982), plant cell wall is the primary restriction on feed intake in high-forage diets. Osbourne et al. (1974) found that increasing forage cell wall content significantly decreased organic matter intake. While the NDF content of teff hay is much higher than that of corn silage and alfalfa hay (56.1 vs. 40.9 and 35.3% of DM respectively), the total inclusion rate of forage in the teff diets was lower than that in the control diet (28.5 vs 44.9% of DM). The low inclusion rate of teff in TEFF-A and TEFF-B likely explains the similarities in DMI between the 3 treatments. Rezac et al. (2012) reported similar findings. A diet containing only 19.2% tallgrass prairie hay (NDF= 67.5 ± 5.3% of DM) as the sole forage resulted in intakes similar to a control diet that contained corn silage and alfalfa hay.

There was no apparent difference in dry matter digestibility (DMD) or NDF digestibility (NDFD) between the 3 diets ($P > 0.10$). Across the 3 diets, DMD averaged 65.8 ± 3.2% and NDFD averaged 52.4 ± 5.4%. Digestibility is inherently complex in that it is dependent on a number of factors, including the amount and composition of fiber in the diet, intake level, passage rate, and particle size (Van Soest, 1982). In this case, the similarities in DMD and NDFD may be due to differences in retention time of the forage portion of the diet. Compared to grasses like teff, alfalfa particles are more fragile and have a shorter period of buoyancy in the rumen (Allen, 2000). These factors alone could increase the retention time of teff while decreasing the retention time of alfalfa. The result would be similar digestibilities between teff-

based and traditional diets. The particle size distribution of TEFF-A and TEFF-B compared to CON (Table 3.5) would also support increased ruminal retention time with the teff diet.

Milk yield averaged 40.7 ± 1.8 kg/d and was not significantly altered by treatment ($P > 0.10$, Table 3.3). Likewise, milk fat concentration and yield were unaffected by diet ($P > 0.10$, Table 3.4). Milk protein concentration was significantly greater in cows fed TEFF-A and TEFF-B than in those fed CON ($P < 0.001$, Table 3.4). Due to the similarities in milk production and differences in milk protein concentration, milk protein yield tended to be greater in the teff diets compared to the control ($P = 0.06$, Table 3.4). Despite the differences in protein concentration and yield, there was no significant effect of diet on ECM yield ($P = 0.80$, Table 3.3). Likewise, no treatment effects on production efficiency (calculated as ECM/DMI) were detected ($P = 0.75$). Additionally, lactose concentration and yield were unaffected by diet ($P > 0.10$, Table 3.4). There was a tendency ($P = 0.06$, Table 3.4) for greater MUN concentrations with TEFF-A compared to TEFF-B and control. Somatic cell linear score was unaffected by diet ($P = 0.82$, Table 3.4).

The milk protein response seen with TEFF-A and TEFF-B is consistent with protein responses associated with increases in overall diet fermentability. In a meta-analysis completed by Ferraretto et al. (2013), increasing diet fermentability by increasing concentrations of dietary starch resulted in greater milk protein concentrations. Ferraretto et al. (2013) also showed that increasing concentrations of dietary starch resulted in decreased milk fat concentrations. In this study, however, no such milk fat response was seen. Considering that, compared to the control, the teff-based diets contained a significantly greater proportion of long particles (> 19 mm), we expected to see increased concentrations of milk fat in cows fed TEFF-A and TEFF-B. Diets lacking long particles are generally more fermentable (Grant et al., 1990), which can lead to

greater acid production and a decrease in rumen pH (Mullins et al., 2010). Ruminal acidosis often results in a drop in milk fat concentration (Enjalbert et al., 2008). Yang and Beauchemin (2007) found the proportion of particles longer than 8 mm to be a useful predictor of ruminal pH dynamics as well. In this case, compared to TEFF-A and TEFF-B, CON contained a significantly greater proportion (P <0.001) of particles longer than 8 mm (34.0 vs 25.0 and 23.8%). This could explain why a difference in milk protein concentration between the treatments was found. Finally, we found no evidence that similar milk yields were maintained through differences in mobilization of body reserves as there was no effect of diet on 18 d body weight or body condition score change (P > 0.10).

It is important to note that, although this study shows that a diet containing teff has potential to maintain milk and component production, there are many practical questions that still need to be answered prior to adoption of this forage on commercial dairy farms. One of the first factors that needs to be addressed is yield potential. In an area like Kansas, annual corn silage and alfalfa yields average 6.5 and 4.0 tons of DM, respectively (USDA 2015). Although published data are limited, teff yields have potential to average 5.5 tons of DM per year (Roseberg et al., 2005 and 2006; Miller, 2011).

In order to gain a more complete understanding of teff's competitiveness relative to traditional forage crops, it may be helpful to provide a practical example. Annual forage needs were estimated for a hypothetical dairy milking 100 cows with the diets used in this study. If this dairy were to feed CON, annual forage needs would be approximately 455 tons of DM. If this same dairy were to feed TEFF-B, however, annual forage needs would drop to approximately 282 tons of DM. The advantage of feeding a high-NDF forage is that it can potentially be included in the diet at much lower rates than traditional forages. In the case of this study, 17.6%

less DM was contributed by forages in TEFF-B compared to CONT. The empty space was filled with dry ground corn, soybean meal, and soyhulls (Table 3.2). Such a strategy could allow for greater scale to be achieved when either land or water are limiting factors at a location, by importing more nutrients in the form of purchased concentrates, presuming that concentrates could be cost-effectively imported from areas with greater water resources.

There is also a need to investigate ensiled teff. Other ensiled grasses are commonly fed to lactating dairy cows, so there is reason to believe that ensiled teff would offer similar benefits. Cherney et al. (2004), investigated the lactation performance of cows fed diets based on enisled fescue, orghardgrass, and alfalfa and concluded that, with the help of additional concentrate, cows consuming first-cutting fescue and orchardgrass silage-based diets performed as well as those consuming alfalfa silage-based diets. Amer and Mustafa (2010) found that cows fed pearl millet silage, another drought-tolerant forage crop, produced more ECM than cows fed corn silage. Additionally, with advancements in silage inoculants and additives, the potential for producing high quality silage from high-NDF grasses is increased (Khota et al., 2016). Finally, there is a need for studies investigating the effects of a teff-based diet on the performance of early lactation cows. It is still uncertain at this point whether a teff-based diet can provide the energy and fermentability needed to meet the nutrient demands of an early lactation cow in a state of negative energy balance.

CONCLUSIONS

Results from this study indicate that teff grass has potential to be used as an alternative forage source for lactating dairy cows without negatively impacting DMI or milk and component production. A high-NDF forage like teff can be incorporated into the diet at a lower inclusion rate and, by filling space with additional concentrate, diet fermentability and rumen stability can be maintained. Feeding teff has potential to improve the resilience of the dairy industry to future water shortages.

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Table 3.1 Nutrient composition of forages used in experiment[1]
[1]Acquired from samples taken on d 15 to 18 of all 4 periods

Nutrients[2]	Teff hay		Corn silage		Alfalfa hay		Prairie hay	
	% of DM	Std. Dev.	% of DM	Std. Dev.	% of DM	Std. Dev.	% of DM	Std. Dev.
DM, % as-fed	92.3	0.3	33.6	2.0	90.4	0.5	93.9	0.6
CP	12.9	0.4	8.4	0.4	19.9	1.0	5.1	0.1
aNDFom[3]	56.1	1.9	40.9	2.5	35.3	2.3	63.4	1.2
ADF	29.8	0.8	24.2	2.3	29.2	1.2	40.3	0.5
NFC	12.2	2.1	40.5	3.2	21.1	0.4	12.8	0.5
EE	1.9	0.1	3.4	0.4	1.8	0.3	2.2	0.1
Ash	8.0	0.3	5.3	0.3	10.1	0.9	8.9	1.2
uNDF[4]	12.4	5.5	10.9	1.6	20.3	1.5	13.0	4.6

[2]All nutrients, except DM, are reported on a DM-basis
[3]Amylase-treated, ash-free neutral detergent fiber
[4]240 h undigested neutral detergent fiber

Table 3.2 Ingredient and nutrient composition of dietary treatments

		Diet		
		TEFF-A	TEFF-B	CON
% DM	Teff hay	29.6	27.3	-
	Corn silage	-	-	23.9
	Alfalfa hay	-	-	19.4
	Prairie hay	-	-	1.6
	Wet corn gluten feed[1]	23.2	23.2	23.2
	TEFF grain mix[2]	36.7	36.7	-
	CON grain mix[3]	-	-	27.9
	Ground corn	7.0	7.1	-
	Soybean hulls	-	2.2	-
	Cottonseed	3.5	3.5	4.0
	Water, % as-fed	26.2	26.2	-
Nutrients[4]	Dry matter, % as-fed	60.0	60.0	59.6
	Crude protein	17.1	17.1	16.8
	Neutral detergent fiber	33.6	33.6	31.7
	Acid detergent fiber	16.7	17.0	18.6
	Non-fiber carbohydrates[5]	35.3	35.5	36.7
	Ether extract	3.7	3.7	4.1
	Ash	8.8	8.7	9.1
	Undigested NDF (240 h)	5.8	5.5	9.0
	NDF from forage	18.1	16.6	18.3

[1]Sweet Bran, Cargill, Inc.

[2]TEFF grain mix consists of 56.88% ground corn, 15.68% soybean meal, 10.93% soy hulls, 4.84% Soy Best (Soy Best, West Point, NE), 3.5% limestone, 3.04% sodium bicarbonate, 2.17% Megalac R (Arm & Hammer Animal Nutrition, Princeton, NJ), 0.7 % magnesium oxide, 0.43% stock salt, 0.43% trace mineral salt, 0.43% Vit E premix (20 kIU/g), 0.43% potassium chloride, 0.27% Biotin 100 (ADM Alliance Nutrition, Quincy, IL), 0.07% Zinpro 4-Plex (Zinpro Corp., Eden Prairie, MN), 0.07% selenium 0.06%, 0.04% Vit A premix (30 kIU/g), 0.03% Zinpro 120 (Zinpro Corp., Eden Prairie, MN), 0.02% Rumensin 90 (Elanco Animal Health, Greenfield, IN), 0.01% Vit D premix (30 kIU/g), and 0.002% ethylenediamine dihyriodide premix.

[3]CON grain mix consists of 62.22% ground corn, 22.62% Soy Best (Soy Best, West Point, NE), 4.52% limestone, 3.96% sodium bicarbonate, 2.83% Megalac R (Arm & Hammer Animal Nutrition, Princeton, NJ), 0.91% magnesium oxide, 0.57% stock salt, 0.57% trace mineral salt, 0.57% Vit E premix (20 kIU/g), 0.57% potassium chloride, 0.35% Biotin 100 (ADM Alliance Nutrition, Quincy, IL), 0.10% selenium 0.06%, 0.09% Zinpro 4-Plex (Zinpro Corp., Eden Prairie, MN), 0.06% Vit A premix (30 kIU/g), 0.05% Zinpro 120 (Zinpro Corp., Eden Prairie, MN), 0.02% Vit D premix (30 kIU/g), 0.02% Rumensin 90 (Elanco Animal Health, Greenfield, IN), and 0.002% ethylenediamine dihyriodide premix.

[4]Nutrients other than DM expressed as a percentage of diet DM

[5]Calculated as DM – (CP + NDF + EE + ash)

Table 3.3 Effects of treatments on performance of lactating cows

Item	Diet			SEM	*P*-value
	TEFF-A	TEFF-B	CON		
DMI, kg/d	28.0	28.4	28.0	0.75	0.76
Milk, kg/d	40.6	41.0	40.4	1.79	0.65
ECM, kg/d	42.9	43.5	43.4	1.26	0.80
ECM/DMI	1.5	1.5	1.6	0.04	0.75
Apparent total-tract DM digestibility, %	65.4	67.7	64.3	3.18	0.47
Apparent total-tract NDF digestibility, %	52.2	54.9	50.0	5.42	0.58
Body weight change, kg/18 d	-2.3	-0.7	-4.4	15.2	0.91
BCS change/18 d	0.11	-0.03	0.06	0.12	0.48

Table 3.4 Effects of treatments on milk components

	Diet			SEM	*P*-value
	TEFF-A	TEFF-B	CON		
Milk fat, %	3.83	3.84	4.03	0.16	0.19
Milk protein, %	3.14[a]	3.18[a]	3.07[b]	0.09	< 0.001
Lactose, %	4.68	4.70	4.66	0.07	0.53
SCLS[1]	2.43	2.51	2.29	0.81	0.82
MUN, mg/dL	12.08	11.63	11.53	0.53	0.06
Yield, kg/d					
Milk fat	1.55	1.56	1.61	0.05	0.43
Milk protein	1.27	1.30	1.23	0.03	0.06
Milk lactose	1.91	1.93	1.88	0.10	0.60

[ab]Means with different superscripts are significantly different by Tukey's HSD ($P < 0.05$)
[1]Somatic cell linear score. Calculated as described by Schukken et al. (2003):
$\log_2$(somatic cell count/100) + 3.

Table 3.5 Particle size separation data (% as-fed basis)[1]

		Diet		
		TEFF-A	TEFF-B	CON
TMR	> 19 mm	13.5[a]	12.0[a]	4.0[b]
	19 to 8 mm	11.5[b]	11.7[b]	30.1[a]
	> 8 mm	25.0[b]	23.8[b]	34.0[a]
	< 8 mm	75.0[a]	76.2[a]	66.0[b]
Sorting index[2]	> 19 mm	1.37	1.07	1.03
	19 to 8 mm	0.88[ab]	0.82[b]	1.07[a]
	< 8 mm	0.99	1.06	0.99

[1]Measured using a 3 compartment Penn State Particle Size Separator (Lammers et al., 1996)
[2]Calculated as proportion in TMR/proportion in refusals. SI > 1.0 means preferential sorting occurred for a given particle size
[ab]Means with different superscripts are significantly different by Tukey's HSD ($P < 0.05$)