THESIS

EVALUATION OF A NOVEL ROTATION OF ORGANICALLY PRODUCED FORAGE AND A SPRING PLANTED VEGETABLE CROP

Submitted by

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In partial fulfillment of the requirements

for the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2010

COLORADO STATE UNIVERSITY

July 7, 2010

WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY DANIEL GOLDHAMER ENTITLED EVALUATION OF A NOVEL ROTATION OF ORGANICALLY PRODUCED ANNUAL FORAGE AND A SPRING PLANTED VEGETABLE CROP AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

EVALUATION OF A NOVEL ROTATION OF ORGANICALLY PRODUCED FORAGE AND A SPRING PLANTED VEGETABLE CROP

There are a limited number of organic forage producers in Colorado, thus organic dairies are faced with a shortage of high-quality, locally-produced organic forage. This study was conducted to explore warm-season forage production in rotation with a spring vegetable as a viable cropping system. In addition, effect of raw and composted dairy manure on soil quality was evaluated within this system. In order to evaluate the usefulness of annual forage crops in rotation with an organic vegetable, tef (*Eragrostis tef* Zucc.) and German millet (*Setaria italica* (L.) P. Beauv.) were seeded in the summers of 2008 and 2009, either alone or in combination with forage soybean (*Glycine max* L.) or sesbania (*Sesbania macrocarpa* Muhl. ex Raf.). The viability of these forage crops was evaluated in terms of their yield, crude protein (CP) content, neutral detergent fiber (NDF), acid detergent fiber (ADF) and weed composition. Forage yields ranged from 3960 kg ha^{-1} for tef alone to 7040 kg ha^{-1} for German millet alone. There was high weed pressure and low legume establishment. When German millet was planted alone, plots contained significantly lower weed biomass (29.8% in 2008 and 7.5% in 2009) than the

other forage treatments which ranged between 26 and 60% weeds. Additionally, legume establishment in all plots was poor, accounting for at most 8.7% of the total yield by dry weight. Generally, tef had higher CP and NDF and ADF. Despite, the high concentration of weeds in the forage mixes, overall digestibility, as measured by a lower ADF content, was improved through the presence of weeds. Weed presence in forage has the potential to increase or decrease its quality depending on the weed species present and their concentration.

In order to explore the effect of this rotation and additions of raw and composted dairy manure on soil quality, these organic inputs were applied in conjunction with the forage treatments and a control that received no soil amendments. Overall, the pH increased from 8.0 to 8.2 between years. This may have influenced the availability of macro and micro nutrients. Soil N and P were influenced by the fertility treatment by year interaction. There was higher soil NO_3-N in 2008 in the manure treatment while there was no difference in soil NO_3-N between the manure and compost treatments in 2009. Available soil P was higher in the manure treatment in 2008. Soil organic matter and particulate organic matter decreased with depth and year. This was possibly due to twice-yearly tillage within this system. Soil aggregation increased with depth for the >1000 µm and 500-1000 µm size classes and decreased with depth for the 53-250 µm size class.

This warm-season forage production system may provide growers with an opportunity to expand their markets while also providing dairies with a local source of organic forage; however, the issues of weed control and legume establishment must be

rectified. Overall, the inclusion of manure or compost application can increase soil quality; however, tillage must be minimized in order for significant gains to be realized.

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ACKNOWLEDGEMENTS

I would like to thank Aurora Organic Dairy for so generously funding this research and supporting the organic program at Colorado State University. Without their support, this and other pressing organic-specific research could not have taken place. I would like to thank everyone who has supported me through these two and a half years. A special thanks goes to the amazing crew of work-study students who tirelessly helped me in the lab and the field. Thank you: Hanna Walters, Michael Herder, Dan McCue, and Soni Hueftle. You were all great to work with. I would also like to give special thanks to Andy Beahm and Matt Booher. As part of the forage team, I thank you so much for all the help, good conversation, and trail blazing. You have contributed so much to my experience here at CSU and to the greater community of aspiring forage scientists. I would also like to thank Dr. Maysoon Mikha for allowing me to work in her lab and teaching me about aggregate stability and soil carbon. Thanks must be given to the leader of the forage team and my committee member, Dr. Joe Brummer. Without his patience, guidance, support, and wisdom I would not have learned so much about what it takes to be a forage scientist and better scientific writer. Your contributions to this project were invaluable. I also want to thank Dr. Frank Stonaker for serving on my committee and dreaming up this project. It was his vision and guidance that started this entire project and his help in the field which allowed this research to become what it is. Finally, I would like to give my thanks and gratitude to Dr. Jessica Davis. As an advisor and mentor, I could not have been luckier. It was your patience, leadership and guidance that not only made these past two and a half years a joy but also gave me the support and freedom I

needed to begin my career as a scientist. You were there for me when I needed support and always encouraged me when plans changed. Thank you for the hours you have spent with me discussing, advising, and editing. To all of my committee, you have given me such an opportunity, thank you for putting your faith in me, and I have learned so much from all of you. It means the world to me that you took an interest in me and supported me through my development as a young scientist. Thank you.

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ABSTRACT

There are a limited number of organic forage producers in Colorado, thus, organic dairies are faced with a shortage of high-quality, locally-produced organic forage. This study was conducted to explore warm-season forage production in rotation with a spring vegetable as a viable cropping system. In order to evaluate the usefulness of annual forage crops in rotation with an organic vegetable, tef *(Eragrostis tef* Zucc.*)* and German millet (*Setaria italica* (L.) P. Beauv.) were seeded in the summers of 2008 and 2009, either alone or in combination with forage soybean (*Glycine max* L,) or sesbania (*Sesbania macrocarpa* Muhl. ex Raf.). The viability of these forage crops was evaluated in terms of their yield, crude protein content, neutral detergent fiber (NDF), acid detergent fiber (ADF_, and weed composition. Forage yields ranged from 3960 kg ha^{-1} for tef alone to 7040 kg ha^{-1} for German millet alone. There was high weed pressure and low legume establishment. When German millet was planted alone, plots contained significantly lower weed biomass (29.8% in 2008 and 7.5% in 2009) than the other forage treatments which ranged between 26 and 60% weeds. Additionally, legume establishment in all plots was poor with at most 8.7% by weight. Generally, tef had higher crude protein and lower NDF and acid detergent fiber ADF. This warm-season forage production system may provide growers with an opportunity to expand their market while also providing dairies with a local source of organic forage if the issues of weed control and legume establishment can be rectified.

INTRODUCTION

The organic dairy industry in Colorado is faced with a shortage of high quality, locally available forage. There is a clear demand for organic forage produced in Colorado; however, there are not enough hectares in organic production to meet the demand. This study was conducted to examine the feasibility of increasing organic forage production by incorporating annual warm-season forage grasses in rotation with a spring-planted vegetable crop, such as lettuce (*Lactuca sativa* L.). This production system would allow organic vegetable growers to incorporate a forage crop into their yearly crop rotation and increase profits on the farm while providing another local industry with necessary inputs.

Little previous research has been conducted to evaluate organic annual forages grown in rotation with vegetables. However, there are clear potential benefits to growing warm-season forage crops or green manures in rotation with vegetable crops. These include weed suppression (Brennan et al., 2009; Isik et al., 2009; Mennan et al., 2009; Wang et al., 2008), suppression of soil-borne diseases (Baysal et al., 2008), nitrogen fixation for subsequent crops (Fageria et al., 2005), capture of residual nitrogen that would otherwise be lost to leaching (Evanylo et al., 2008), and erosion control (Flach, 1990).

Organic production of high quality forage is possible, and multiple studies have demonstrated that there is either no difference in the quality of organic forage or increased quality as compared to conventional production systems (Doyle and Topp, 2004; Lestingi et al., 2009). The challenge is to develop a rotation that addresses regional and local production issues. Weed control is a challenge in organic forage production.

Since some forage crops are more efficient at controlling different weed species (Schoofs and Entz, 2000), appropriate forage species must be explored to ensure that they will be competitive with local weed pressure. Through the proper selection of both forage and vegetable crops, local farmers should be able to fulfill the demand for organic forage, while also increasing the diversity of their farming operations and reaping long-term benefits.

The objective of this study was to evaluate yield and quality of two warm-season forage grasses, tef (*Eragrostis tef* Zucc.) and German millet (*Setaria italica* (L.) P. Beauv.), grown alone or in combination with either forage soybean (*Glycine max* L.) or sesbania (*Sesbania macrocarpa* Muhl. ex Raf.) using organic production methods.

MATERIALS AND METHODS

The experiment was conducted at the Colorado State University (CSU) Horticulture Field Research Center located 10.9 km northeast of Fort Collins, Colorado (40°36’ N 104°59’ W, elevation 1524 meters). The mean annual precipitation is 33 cm, and the mean temperature is 29°C in the summer months and 5.6 °C in the winter months. The soil at the site is a fine, smectitic, mesic Aridic Argiustoll which is classified as a Nunn clay.

In order to evaluate the feasibility of incorporating warm-season forage grasses and cool-season legumes into an organic vegetable production rotation, tef and German millet were seeded in the summer of 2008 and 2009 and grown in rotation with a crop of spring-seeded lettuce. These grasses were seeded alone or in combination with either forage soybean or sesbania. Additionally, a single whole plot in each block was left fallow and weeded three times throughout the summer. Each whole plot of the forage treatments measured 2.44 by 12.84 m. Seeding of the German millet, sesbania, and forage soybean was conducted with a Kincaid plot drill (Kincaid Equipment Manufacturing, Haven, KS). The width of the seeder was 1.22 m and the spacing between rows was 15.24 cm. The tef was seeded with a Brillion seeder (Model SSP-8, Brillion, WI). Seeding rates were based on pure live seed (Table 1). When grasses were planted in combination with legumes, the recommended seeding rate for the grasses was reduced to 40% of the monoculture rate while the legume was planted at 60% of the monoculture rate. This approach was utilized to lessen competition between the grass and legume.

There was no specific variety for the German millet or sesbania. The German millet was purchased from Arkansas Valley Seed (Longmont, CO) and the sesbania from Peaceful Valley Farm Supply (Grass Valley, CA). The tef variety was 'Tiffany' produced by Target Seed Company (now Producer's Choice, Woodland, CA). The variety of the forage soybean was 'IA 1008' produced by Albert Lea Seed House (Albert Lea, MN). All seed was either untreated or certified organic.

Each whole plot was then divided into three subplots for fertility treatments to achieve a split-plot design. The fertility treatments were dairy cow manure or composted dairy cow manure and a check plot that received no added fertility. These fertility treatments were designed to explore the effect of dairy manure and composted dairy manure on soil quality. The manure and compost were applied to achieve 123 kg ha^{-1} of total N in the first year and 56 kg ha^{-1} of total N in the second year. The rate in 2008 was based on residual soil nitrate levels (Davis and Smith, 1996). In 2009 the application rate was based on soil, manure, and compost testing, including a credit of 34 kg ha^{-1} per percent organic matter present, and a credit of 20% of the total nitrogen applied in the first year of the fertility treatments expected to be available in the second year. The fertility treatments were randomly applied to the subplots which measured 2.44 by 4.28 m. Manure and compost were incorporated through rototilling to a depth of 15 cm. There were three replications of each forage mix/fertility treatment combination.

In 2008, the forages were seeded on June 10 and harvested on August 18. The crop of lettuce between the forage crops was planted on March 13, 2009 and harvested on June 5, 2009. In 2009, the forages were seeded on June 24 and harvested on August 20.

Irrigation was provided by an overhead sprinkler system, and the forage received a total of 2.54 cm of water per week in two applications. The lettuce crop was not irrigated.

Harvest was performed using a walk-behind sicklebar mower (Model 34034, Troy-Bilt, Cleveland, OH). The width of the mower was 104 cm, and the height of cutting was 6.4 cm. The forage was harvested from the middle of each plot, and the entire cutting was then raked and weighed. Two sub-samples of approximately 500 g were taken. The first was weighed fresh, dried, and then used for quality analysis as a representation of the entire forage mix. This sample was also utilized to determine percent dry matter of the forage mix so that yields and forage quality parameters could be expressed on a dry matter basis. A second sample was taken and frozen. This sub-sample was used to determine the composition of forage. This sample was sorted by hand and divided into grass, legume, and weed fractions prior to drying and weighing.

Samples were dried at 55°C for at least 72 hr until no change in weight was detected. Grinding for both samples was a two step process. The first was through a sheer mill (Wiley Model 4, Arthur H. Thomas Co., Philadelphia, PA) equipped with a 2 mm screen. The second was through a cyclone mill (Cyclotec Model 1093, Foss Corp., Eden Prairie, MN) also equipped with a 2 mm screen. Grinding through the cyclone mill was done to ensure a higher degree of uniformity of particle size of the ground forage.

Forage quality was evaluated by determining neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein (CP), and relative feed value (RFV). All 4 variables were measured in the bulk forage samples while only NDF and ADF analyses were performed on the grass and weed separations due to the limited amount of legume present in the forage.

NDF and ADF analyses were performed using an ANKOM Fiber Analyzer (Model No: ANKOM 200, Ankom Technology, Macedon, NY), utilizing filter bags and the ANKOM methodology (ANKOM, 2006a; ANKOM, 2006b) which is a modification of the procedure outlined by (Vansoest et al., 1991). For both NDF and ADF, ground forage (approximately 0.5 g) was placed into filter bags which were digested in either neutral detergent or acidic detergent solution, respectively. The samples were then dried at 100 C° for at least 24 hours. The samples were then weighed and NDF and ADF were calculated as a percent of total dry matter.

From NDF and ADF, the relative feed value (RFV) was calculated. RFV provides a composite picture of the digestible dry matter and dry matter intake potential of forages. An RFV value of 100 is comparable to full-bloom alfalfa with an ADF of 41% and NDF of 53% (Rohweder et al., 1978). RFV was calculated using Eq [1]:

$$RFV = \frac{\frac{120}{NDF\,\%} * (88.9 - (0.779 * ADF\%))}{1.29} \qquad [1]$$

Crude protein of the forage was determined using a LECO CN autoanalyzer (Model CN 2000, Leco Corp., St. Joseph, MI). Ground forage (approximately 0.1 g) was combusted and analyzed for total C and N content according to the Dumas combustion procedure (Etheridge et al., 1998). Crude protein was extrapolated from total N content through multiplication by 6.25 and expressed as a percentage of forage dry matter.

Statistical analyses were performed using the PROC GLMMIX procedure in SAS 9.2 (SAS Institute, 2009). For yields and the quality analyses of the bulk samples, the class variables were blocks (3), forage treatments (6), fertility treatments (3), and years (2). Block, block by forage, and block by forage by fertility interactions were considered random effects. For the data dealing with the separations, the class variables were blocks (3), forage treatments (6), fertility treatments (3), years (2), and fractions (3). Block, block by forage, block by forage by fertility, and block by forage by fertility by year interactions were considered random effects. The degrees of freedom were determined utilizing the Kenward-Rogers method (Kenward and Roger, 1997). When the F-test for a given factor was significant, means were separated based on least square means utilizing Tukey's adjustment to compensate for multiple comparisons (Tukey, 1953). Statistical significance was set at $p \leq 0.05$.

RESULTS AND DISCUSSION

Yield

German millet planted alone had the highest yield when averaged over years and was significantly different from all the tef treatments (Figure 1). Additionally, tef planted alone yielded significantly less than all of the German millet treatments, both alone and in combination with sesbania and forage soybean. There were no observed fertility treatment effects on forage yield (p=0.3101) or year (p=0.0564).

The average yield of e German millet planted alone was 7040 kg ha^{-1} which is equal to or higher than what is typically expected from conventional irrigated production of this species for forage. Yields of German millet grown for forage in Saskatchewan, Canada have been reported to range from 2360 to 10520 kg ha^{-1} with an average of 5360 kg ha^{-1} (May et al., 2007). Additionally, in another study in Manitoba, Canada that took place over four years, German millet grown for forage yielded between 7270 and 8860 kg ha^{-1} (McCaughey et al., 2002). In a study conducted near Beltsville, MD, yield of German millet for forage was 6350 kg ha^{-1} when grown alone (AbdulBaki et al., 1997). Although this study was not irrigated, water was not limited due to ample precipitation.

In addition to climatic variations, these differences could also be attributed to differences in seeding rate and fertility management. The seeding rate in the Beltsville study (AbdulBaki et al., 1997) for German millet when planted alone was 40 kg ha^{-1} compared to 22.4 kg ha^{-1} in this study while the seeding rate for the soybean and German millet combination was 60 and 27 kg ha^{-1}, respectively, compared to 56 and 9 kg ha^{-1}, respectively. The seeding rate of German millet when planted alone was almost double the rate used in this study while the rate of German millet when planted in combination with forage soybean was triple the rate used in this study. This difference could help explain the yield differences due to excessive planting density and competition among plants (Carberry et al., 1985). Additionally, in the Beltsville study, N fertilizer was applied as granular urea at a rate of 56 kg ha^{-1} for the plots of German millet alone, while the plots of German millet and forage soybean received no N inputs. In this study, compost and manure were applied at rates of 123 kg ha^{-1} of total N in the first year and 56 kg ha^{-1} in the second to all forage combinations. Despite these differences, the yield of German millet when grown alone or in combination with legumes in this organically managed study was comparable to conventional production.

The yield of tef when planted alone (3960 kg ha^{-1}) and the average yield of tef when planted with sesbania or forage soybean (4750 kg ha^{-1}) was also within expected values. In South Dakota over two years, the average yield of tef when planted alone was 4290 kg ha^{-1} (Boe et al., 1991). In New York, the observed yield of tef for forage was 11210 kg ha^{-1} when cut three times over a season and the average yield per cutting was 3720 kg ha^{-1} (Hunter, 2008). In Michigan, tef under full irrigation yielded 2400 kg ha^{-1} (Peck et al., 2009). In 2008, under conventional production in western Colorado, tef yielded on average 4035 kg ha^{-1} for the first cutting and 2690 kg ha^{-1} for the second cutting. Total yields averaged 5600 kg ha^{-1} when no additional N was applied and 7620 kg ha^{-1} when 45 kg $ha^{-1}$of N was applied (Pearson and Brummer, 2008). When comparing this multiple cutting data to what was found in New York, it appears that tef as a forage crop grown in Colorado has a similar potential for increased yields with multiple cuttings. Compared to this study, the first cutting yield in the conventionally managed system in western Colorado was higher than what was observed in the organic system by only 70 kg ha^{-1}. Since there was only one cutting taken in this study, it is unknown if there would have been comparable yields for a second cutting.In future studies of the viability of tef as a forage crop both under conventional and organic production, it would be useful to utilize multiple cuttings to maximize yields. At this point, it appears that the tef grown in this study was comparable in yield to other single cutting trials of tef.

There was no effect of fertility (p=0.0812) or forage treatment (p=0.0709) on the yield of lettuce. The average yield was 6000 kg m^{-2}. This is less than a third of reported organic leaf lettuce yield which ranged from 13000 to 28000 kg m^{-2} (Ribeiro et al., 2010). However, Ribeiro et al. (2010) conducted their experiment in a controlled greenhouse setting where soil moisture and temperature were controlled. Additionally, the amount of N applied ranged from 69 to 590 kg ha^{-1}. These production method differences could explain why there was such a drastic yield difference. Overall, implementing a spring crop like lettuce is feasible; however, precise timing of lettuce planting is necessary to ensure adequate vegetable crop yield and allow for appropriate timing of planting the forage crop.

Bulk Forage Quality

There was an effect of forage treatment on NDF (p=0.0040, Table 2). Overall, the forages with tef in the mix tended to have lower NDF compared to the treatments with German millet in the mix. The average value for the tef mixes was 55.2%, and the average value for the German millet treatments was 58.3%. That is a difference of 3.1 percentage points (p=0.0075). The values of NDF for all forage treatments were above the recommended maximum percent for lactating dairy cows which ranges from 25-33% depending on particle size and non-fiber carbohydrate (NFC) content of the forage (NRC, 2001). Although the NDF of these warm-season forages was too high for feeding to lactating dairy cows, this assumes they would be the main forage in the diet. By diluting with other feeds, they could be fed as part of a total mixed ration (TMR).

Overall, both the German millet and tef treatments contained NDF values comparable to conventional production systems. For the German millet, NDF averaged

58.3% compared to values from other studies that have been reported between 59.5 (May et al., 2007) and 68.8% (Svirskis, 2009). For tef, NDF averaged 55.2% compared to other reported NDF values of 53.8 (Nsahlai et al., 1998), 59.5 (Rosenberg et al., 2005), 60.3 (Hunter, 2008), and 70.9% (Pearson and Brummer, 2009).

There was also an effect of forage treatment on ADF (p=0.0005, Table 2). The tef mixes had lower ADF values than the mixes with German millet. The average value for the tef treatments was 31.2%, and the average value for treatments with German millet was 33.1%. That is a difference of 2.0 percentage points (p<.0001). Like NDF, the ADF of all forage treatments were above the maximum recommended ADF content of 17-21%, which may be too high for some lactating dairy cows depending on their intake needs (NRC, 2001). When compared to other reported values of ADF, both the German millet and tef treatments possessed similar ADF values. The average ADF value for plots containing German millet was almost identical compared to another reported value of 33.2% (May et al., 2007). The average ADF value of the tef treatments fell on the lower end of other values reported in the literature such as 28.3 (Nsahlai et al., 1998), 34.1 (Pearson and Brummer, 2009), 35.2 (Rosenberg et al., 2005), and 37.7% (Hunter, 2008).

There were also differences between the forage treatments regarding CP (p=0.0129, Table 2). On average, the tef treatments had a CP concentration of 13.4% while the German millet treatments averaged 12.0%. That is a difference of 1.4 percentage points (p=0.0003). The overall yield of CP for tef was 573 kg ha^{-1} and compared to 731 kg ha^{-1} for German millet. There was not a significant difference between the two (p=0.1383). The CP of German millet compared favorably to other reported values of 9.7 (May et al., 2007) and 9.5% (Svirskis, 2009). For tef, CP averaged

13.4%. Unlike the German millet, the CP for tef in this study was similar to values reported in Colorado but lower than values reported outside of Colorado. Other CP values that have been reported for tef include 11.1 (Pearson and Brummer 2009), 16.6 (Nsahlai et al., 1998), and 17.2% (Hunter, 2008). This lower CP could be due to multiple factors including differences in climate affecting morphological traits of the tef which can in turn affect CP content (Boe et al., 1991). Another possibility is the difference in soil N available between synthetic fertilizers, which were utilized in the other studies, and the N availability of dairy manure and composed dairy manure (Habteselassie et al., 2006). If N from the manure or compost was not as readily available, the lower levels of soil N could have caused lower CP levels in the tef (Rosenberg et al., 2005). All forage treatment combinations would only supply adequate CP for cows weighing up to 454 kg, in mid-lactation, and producing up to10 kg of milk per day (NRC, 2001). If the cow is larger in size, producing more milk per day, or in early lactation, the CP of these forages would not be sufficient without supplementation.

There was a significant forage treatment effect for RFV (p=0.0006, Table 2). Overall, the treatments with tef had an RFV of 197.5, and the treatments with German millet had an RFV 178.1. That is a difference of 19.4 (p=0.0011). This difference indicates that the tef treatments were of overall higher quality then the German millet treatments. Specifically, the tef treatments contained fewer structural carbohydrates (cellulose, hemicellulose, and lignin) and, therefore, were more easily digestible (NRC, 2001).

In the end, quality of the bulk forage samples was adequate in NDF and ADF for incorporation into the diet of a dairy cow; however, each forage would have to be mixed with a higher quality forage to ensure adequate intake and digestibility (NRC, 2001). On average, the tef treatments had lower NDF and ADF than the German millet. For both the tef and German millet, the values of NDF and ADF were close to other observed values in conventional systems. Since the tef treatments contained lower NDF and ADF, this led to a higher RFV value compared to German millet. This result in combination with a higher average CP content would make tef a more nutritious and better forage choice for organic dairy operations. However, all German millet and tef forage treatments could only provide enough CP for smaller and lower-producing dairy cows in the middle of their lactation cycle. Supplemental protein could easily be provided to satisfy a larger range of dairy cows.

These nutritional characteristics should be taken into account along with total yields of the forages when making annual warm-season forage management decisions. The German millet had a lower nutritional profile; however, it yielded significantly more than the tef which could lead to a higher yield of nutrients per hectare. In the end, both German millet and tef can be utilized for forage in an organic dairy setting; however, considerations of yield, intake, digestibility, and CP must be taken into account to ensure proper animal nutrition and overall profitability of the dairy. Knowing the quality of a forage can greatly aid in determining the need for supplementation with other feedstuffs.

Forage Composition

There was an interaction between forage type and year on forage composition (p=0.0001, Table 4). The biggest difference in this interaction was that the 2009 German millet possessed a significantly higher grass percentage compared to all other treatments. Also, the 2008 German millet contained a higher grass percent than all other treatments except the 2009 tef plots and the 2009 German millet and sesbania plots. Finally, the 2008 tef and the 2008 and 2009 tef and sesbania plots all possessed the lowest grass percentages and were significantly lower than all other treatments, but not different from one another. When comparing forage treatments that contain tef to treatments containing German millet, the treatments with tef possessed on average 43.8% grass and 54.5% weed while the treatments with German millet contained on average 68.8% grass and 30.5% weed (p=<.0001). In general, the German millet treatments contained a higher grass biomass percentage than the tef treatments. Legume biomass ranged from 0% to 8.9%. There were no effects on overall legume composition, and the average percent legume was 2.2%.

From the forage composition data, two clear challenges have emerged in this production system. The first is legume establishment, and the second is weed control. The legumes did not contribute a large portion to the forage mix. With at most 8.9% of the mix being legume, it is critical to achieve better establishment. The low degree of establishment does not fit with other published results for German millet seeded with soybean where the mix was 50% soybean (AbdulBaki et al., 1997). However, Abdul-Baki et al. (1997) utilized herbicides for weed control. Therefore, one must use caution when comparing the two studies because of differences in production systems. There are no known studies which incorporated forage soybean and sesbania with German millet or tef and studied the resulting forage composition under organic production.

Possible problems with legume establishment could stem from both the soil structure and chemistry of the research site. The soil is high in clay which might impact establishment through crusting. Also, legume establishment may have been inhibited by the high pH (7.99-8.02) (Rogovska et al., 2009).

In the future, it will be necessary to increase legume establishment if this rotation is to be viable. Both forage soybean (Rao et al., 2005) and sesbania (Abbas et al., 2001; Osuji and Odenyo, 1997) possess favorable forage qualities and are able to improve a forage's nutritional value when incorporated into a warm-season forage mix. There are soybean varieties being developed specifically for forage production (Darmosarkoro et al., 2001; Devine et al., 1998); however, there has yet to be a specific focus on developing a high pH tolerant forage soybean which also performs well in soils with high clay content. If such a forage soybean were developed, it should be evaluated in this forage rotation. Until then, additional forage soybean varieties should be tested in order to fully understand how to integrate them as forage with warm-season grasses in heavy soils with high pH. For sesbania, another approach to increasing establishment is to explore other species. One study found that *Sesbania macrantha* Muhl. ex Raf. performed better than three other sesbania species (*S. rostrata* Muhl. ex Raf., *S quadrata* Muhl. ex Raf. and *S. sesban* Muhl. ex Raf.), especially in a heavy Vertisol (Mengistu et al., 2002). If the issue of legume establishment can be solved in this organic system in high clay soils, then perhaps the issue of low CP could also be solved, and these forage mixes could satisfy the protein demand of larger cows, producing more milk, and throughout all stages of lactation. This would significantly increase the viability of these forage mixes for use in organic and conventional dairies.

In contrast to the low establishment of legumes, weed growth was great in this annual forage production system. Weeds consisted of just over half of the forage in tef and nearly a third in German millet plots. The treatment where weed pressure was lowest was where German millet was seeded alone. In this forage treatment, weed composition averaged 18.4%. This degree of weed presence was higher than other published work on German millet planted alone with the use of herbicides. However, in that study, 14% of the biomass was weeds (AbdulBaki et al., 1997), only a slight difference of 4.4 percentage points. This difference was small compared to differences measured between the German millet planted with forage soybean in this study, 37.1% weed, versus 8% weed in the conventionally produced German millet and forage soybean study by (AbdulBaki et al., 1997) This lower total weed biomass in the conventional system is to be expected due to the use of herbicides.

Differences in seeding rate might explain some of the observed differences in weed composition in the pure stand of German millet versus the German millet forage soybean combination. In this study, German millet planted as a pure stand was seeded at a higher rate compared to German millet planted with forage soybean. The higher seeding rate of 22.4 kg ha^{-1} compared to 9.0 kg ha^{-1} could help explain why German millet was better able to compete with the weeds when planted alone. In other organic forage production systems, a higher seeding rate increased forage competitiveness with weeds while not decreasing total yields due to competition with itself (Brennan et al., 2009). However, as seen in the conventionally produced German millet and German millet-forage soybean study (AbdulBaki et al., 1997), the higher seeding rate of 40 kg ha^{-1} in addition to the lower N applied could have contributed to lower total observed yield. Therefore, there might be an upper limit to the benefits of increasing seeding rate and its effect on total yield and competition with weeds. Thus, it is important to test a range of seeding rates for specific species of organic forages in the future, including German millet and tef when planted alone or in combination with legumes. Perhaps by increasing the seeding rate of forages in future organic production studies, there could be greater forage competition with weeds.

Quality of Forage Components

When looking at the grass separations, there was an interaction between grass species and year for NDF ($p=0.0035$), ADF ($p=0.016$), and RFV ($p=<.0001$, Table 5). Tef was higher in NDF in 2008 than all the other grass species by year combinations which were not different from each other. The 2008 tef contained the highest ADF, and there was a difference between the 2008 and 2009 tef plots of 3.2 percentage points ($p=<.0001$) with 2008 possessing the higher ADF. Unlike NDF, there was no difference between 2008 tef and German millet in ADF. For RFV, there was again a difference of 22.2 ($p=<.0001$) between the 2008 and 2009 tef plots with the 2009 plots having the higher RFV. Like ADF, there was no difference between 2008 tef and the other grass samples for RFV.

There was an effect of year on NDF of the weed samples ($p=0.0118$, Table 6). The NDF of the 2009 weed samples averaged 3.4 percentage points higher than in 2008. However, there were no effects on weed sample ADF which averaged 28.4%. There were also no significant effects on the RFV of the weed component which averaged 222 points.

There was an interaction between year and separation type (grass, legume, and weeds) and the bulk samples in terms of NDF ($p<.0001$, Table 7). There was a difference between all years and all separation types. When comparing quality of the weeds to quality of the bulk and grass samples, the weeds had lowest NDF, the grass samples had the highest NDF, while the bulk samples contained NDF values between the grass and the weed samples. Thus, weeds possessed a higher forage quality than bulk or grass samples.

Among the weed, grass, and bulk separations, there was also an interaction of grass species by year on ADF (p=0.0006) and RFV (p=0.0008) (Table 8). There were no effects for NDF (p=0.38). This interaction illustrates the beneficial effect of weed presence in these forage treatments by lowering ADF and increasing RFV when weed percentage is high. Overall, weeds had the lowest ADF and highest RFV with the bulk tef sample from 2008 also possessing similarly low NDF and high RFV. Another important difference is that the grass fraction from the tef plots in 2008 (the tef grass itself without any weeds present) had the highest ADF and lowest RFV of all the grass species alone in both years.

It is interesting that the bulk tef in 2008 possessed the highest RFV and lowest ADF of all the treatments while at the same time, the grass itself within the 2008 tef possessed the highest ADF and lowest RFV. The 2008 tef also had an NDF that was significantly higher than all the other grasses (Table 5). There was no difference between the ADF and RFV of the weeds in those plots compared to the weeds in other plots. There was a slight difference between weed NDF in 2008 and 2009 with the 2008 weeds having a slightly lower NDF (Table 6). This small difference in weed quality did not impact the RFV. Since there was not a large difference in weeds in the plots between the two years, the observed higher quality in bulk 2008 tef plots compared to the rest of the bulk plots was most likely due to the increased presence of weeds in 2008. The 2008 tef plots contained 60.0% weeds which is significantly higher than all plots except for the 2009 tef plots which had 49.2% weeds (p=0.17). Thus, since the 2008 tef plot contained a higher percentage of weeds and the weeds in 2008 contained a low ADF and RFV, the higher weed composition of the 2008 tef plots elevated the RFV and by lowering the ADF. Additionally, the treatment with the lowest percent of weeds in its composition was the 2009 German millet with 7.5% of the dry weight biomass being weeds. The 2009 German millet plot, also had the highest NDF and ADF and the lowest CP and RFV when compared to the other plots with higher weed biomass (Table 3). This provides more evidence in favor of higher weed biomass increasing forage quality. Yet quality of weeds as forage varies significantly among weed species and specific weeds can detrimentally impact overall forage quality (Temme et al., 1979).

In fact, it has been shown that weeds can improve forage quality despite their negative connotation in a production system (Bosworth et al., 1986; Moyer and Hironaka, 1993). The primary concerns when considering weeds as part of the forage are their digestibility, protein content, and palatability. Many species of both annual (Marten and Andersen, 1975) and perennial weeds (Marten et al., 1987) have adequate digestibility, mineral nutrition, and protein to sustain desirable weight gains in both sheep and cattle (Bosworth et al., 1986).

Overall, the impact of weed species on a forage mix is variable to such a degree that weed control should be handled on a species specific basis. Depending on the weed species present, weed control can be necessary in order to maintain or elevate forage quality. At other times, the weed species present could contribute to total quality and yield of the forage, thus, weed control through herbicides or other methods would prove detrimental. There is far from an exhaustive inventory of the forage quality of annual and perennial weeds, thus, production decisions should utilize all available information. However, lack of information may hinder effective decision-making in terms of weed control.

Another major concern with the feeding of weeds is potential nitrate toxicity. In the United States, some of the weed species related to possible nitrate poisoning include: kochia (*Kochia scoparia* L.) (Rankins et al., 1991), lambsquarters (*Chenopodium album* L.) (Ozmen et al., 2003), and redroot pigweed (*Amaranthus retroflexus* L.) (Aslani and Vojdani, 2007). Care must be taken when grazing pastures that contain high concentrations of these weed species or feeding hay with these species present.

While some weeds are able to increase the overall feed value of a pasture or forage mix, others can detrimentally impact yields, quality, and feed value. In this system, the two weed species that dominated the forage stand were redroot pigweed and Canada thistle (*Cirsium arvense* L.). These two species provide an example of a weed beneficial to the quality of the forage and a weed potentially detrimental to the quality of the forage, respectively.

Forage quality of redroot pigweed is comparable to alfalfa (Lestingi et al., 2009). Pigweed has been found to have an ADF content ranging from 15.9 (Temme et al., 1979) to 23.7% dry weight (Marten and Andersen, 1975). For CP, estimated values range from 25.0 (Marten and Andersen, 1975) to 18.0% (Marten and Andersen, 1975) to as low as 11.5% (Moyer and Hironaka, 1993). Additionally, digestibility of the protein in redroot pigweed is higher than brome grass, but not as high as pure alfalfa (Lestingi et al., 2009). Redroot pigweed also has high concentrations of Mg, P, Ca, and K (Marten and

Andersen, 1975). Finally, redroot pigweed has good palatability (Marten and Andersen, 1975). The one concern with feeding forage high in redroot pigweed is nitrate poisoning (Aslani and Vojdani, 2007). It appears that the leaves contain the highest concentration of nitrate, and cows fed stem material were not adversely affected (Casteel et al., 1994). In order to avoid nitrate poisoning due to redroot pigweed, care should be taken when grazing cows in a new pasture of relatively poor quality with a large amount of redroot pigweed present. If the pasture is of poor quality and the cows are allowed to graze, then the probability of the cows selecting and consuming redroot pigweed at dangerous concentrations is increased (Kerr and Kelch, 1998). If feeding hay with a high concentration of redroot pigweed, then forage nitrate testing should be implemented before feeding. Overall, in moderation, redroot pigweed can improve or at least not decrease forage quality.

Like redroot pigweed, Canada thistle can theoretically increase or at least not decrease the quality of forage in terms of NDF, ADF, and CP. The NDF of Canada thistle has been measured at 50.4%, and its crude protein ranges from 27.6% in May to 14.7% at the end of June (Marten et al., 1987). However, it has low palatability due to spines on the leaves which can prevent such gains from being realized. The potential does exist for reducing Canada thistle populations by grazing it with sheep (Marten et al., 1987) or cattle (De Bruijn and Bork, 2006). Overall, it is a matter of availability of other forages and stocking density which will determine if grazers consume Canada thistle (De Bruijn and Bork, 2006).

Organic producers are limited in their options for weed control, especially after the crop has emerged. Due to this limitation, special considerations should be taken when growing organic forage. These considerations include the amount and species of weeds present, the potential impact of the weeds present on quality of the forage and the possibility of nitrate toxicity. Overall, when growing annual warm-season forage, producers should consider the appropriate forage species and varieties that will work within their local system and be highly competitive with local weed pressure, possibly increasing the seeding rate to assist with competition with weeds, and the impact the weeds will have on forage quality.

A possible method for addressing the presence of weeds in the forage mix and to increase the overall forage quality, would be to change the rotation to an annual cool-season forage grown in rotation with a summer vegetable. This rotation could prove advantageous because, in general, annual cool-season forages can better outcompete weeds during spring than warm-season forages (Schoofs and Entz, 2000), and they are often of higher overall quality then warm-season forages (Mengistu et al., 2002). Additionally, producing a vegetable crop during the summer would allow for mechanical weed control during the summer when weed emergence is often occurring at the greatest rate (Forcella et al., 1997). This rotation should be explored because it may address the major issues that lessened the viability of the rotation explored in this study.

Overall, this novel rotation of an annual forage with a spring vegetable provided an organically-produced forage crop that yielded comparably to conventional production. The quality was also comparable to conventional production. The issues of poor legume establishment and high weed presence were of concern. However, the high presence of weeds increased the RFV of the forage. With further work this rotation could become a viable option for satisfying local demand for organic forage and incorporating an additional crop into organic vegetable producers' rotations.

TABLES

Table 1. Seeding rates.

	----kg ha^{-1}----
Tef alone	6.7
Tef with legumes	2.7
German millet alone	22.4
German Millet with legumes	9.0
Forage soybean	56.0
Sesbania	28.0

Table 2. Forage quality analysis of neutral detergent fiber (NDF), acid detergent fiber (ADF), crude protein (CP), and relative feed value (RFV) as affected by forage type.

Forage type	NDF	ADF	CP	RFV
	--------------------%---------------------			
tef	56.7 ab†	30.6 b	14.6 a	110.3 ab
tef and sesbania	51.7 b	30.5 b	13.1 ab	119.4 a
tef and forage soybean	56 ab	31.5 b	13.3 ab	108.3 abc
German millet	59.1 a	34.0 a	11.4 b	99.0 c
German millet and sesbania	58.3 a	32.6 ab	11.8 b	102.8 bc
German millet and forage soybean	57.5 a	32.8 ab	11.6 b	103.9 bc
Standard error	1.7	0.6	0.73	5.4

† Differing letters within the same column signify statistical differences at $p \leq 0.05$ according to least square means utilizing the Tukey adjustment.

Table 3. Forage composition as determined through dry weight separations of bulk forage samples as affected by forage type and year.

Forage type	Year	Grass	Weed	Legume
		---------------------------%---------------------------		
tef	2008	40.0 d†	60.03 ab	
tef	2009	69.1 bc	31.0 bcd	
tef and sesbania	2008	32.9 d	66.9 ab	0.2 a
tef and sesbania	2009	31.6 d	68.4 a	0 a
tef and forage soybean	2008	44.5 cd	54.4 ab	1.1a
tef and forage soybean	2009	43.0 cd	48.2 bcd	8.9 a
German millet	2008	73.4 b	29.3 cd	
German millet	2009	92.6 a	7.5 d	
German millet and sesbania	2008	54.6 cd	45.3 bc	0.1 a
German millet and sesbania	2009	73.9 b	26.1 c	0 a
German millet and forage soybean	2008	50.9 cd	48.0 bcd	1.1 a
German millet and forage soybean	2009	67.9 cd	26.1 c	6.0 a
Standard error		0.05	0.05	0.05

† Differing letters within the same column signify statistical differences at $p \leq 0.05$ according to least square means utilizing the Tukey adjustment.

Table 4. Forage quality analysis of neutral detergent fiber (NDF), acid detergent fiber (ADF), and relative feed value (RFV) of the grass separation fraction by grass species and year.

Separation fraction	Grass species	Year	NDF	ADF	RFV
			--------------%-------------		
Grass	tef	2008	68.1 a†	35.9 a	83.4 c
Grass	tef	2009	63.8 b	32.7 c	92.6 ab
Grass	German millet	2008	63.6 b	35.5 ab	89.7 bc
Grass	German millet	2009	62.4 b	34.2 abc	93.3 a
	SE		0.8	0.7	1.7

† Differing letters within the same column signify statistical differences at p≤0.05 according to least square means utilizing the Tukey adjustment.

Table 5. Forage quality analysis of the weed fraction for content of neutral detergent fiber (NDF) affected by year.

Year	NDF	SE
	--------------------------------%---------------------------------	
2008	44.7 b†	1.3
2009	48.1 a	1.3

† Differing letters within the same column signify statistical differences at p≤0.05 according to least square means utilizing the Tukey adjustment.

Table 6. Comparison of the forage quality analysis of neutral detergent fiber (NDF) of the separation fractions by year.

Separation fraction	Year	NDF
		------%-----
Bulk	2008	52.4 d†
Bulk	2009	60.6 c
Grass	2008	65.9 a
Grass	2009	63.1 b
Weed	2008	44.7 f
Weed	2009	48.1 e
SE		0.9

† Differing letters within the same column signify statistical differences at p≤0.05 according to least square means utilizing the Tukey adjustment.

Table 7. Comparison of the forage quality analysis of acid detergent fiber (ADF) and relative feed value (RFV) of the separation fractions by grass species and year.

Separation fraction	Grass species	Year	ADF	RFV
			-----%-----	
Weed	tef	2008	28.4 c†	138.6 a
Weed	tef	2009	28.3 c	138.3 a
Weed	German millet	2008	27.7 c	143.0 a
Weed	German millet	2009	29.4 c	127.4 a
Grass	tef	2008	35.9 a	83.4 c
Grass	tef	2009	32.7 b	92.6bc
Grass	German millet	2008	35.5 a	89.7 bc
Grass	German millet	2009	34.2 ab	93.32 bc
Bulk	tef	2008	29.5 c	121.8 a
Bulk	tef	2009	32.4 b	102.6 b
Bulk	German millet	2008	32.5 b	110.0 b
Bulk	German millet	2009	33.7 ab	93.9 bc
SE			0.6	3.3

† Differing letters within the same column signify statistical differences at $p \leq 0.05$ according to least square means utilizing the Tukey adjustment.

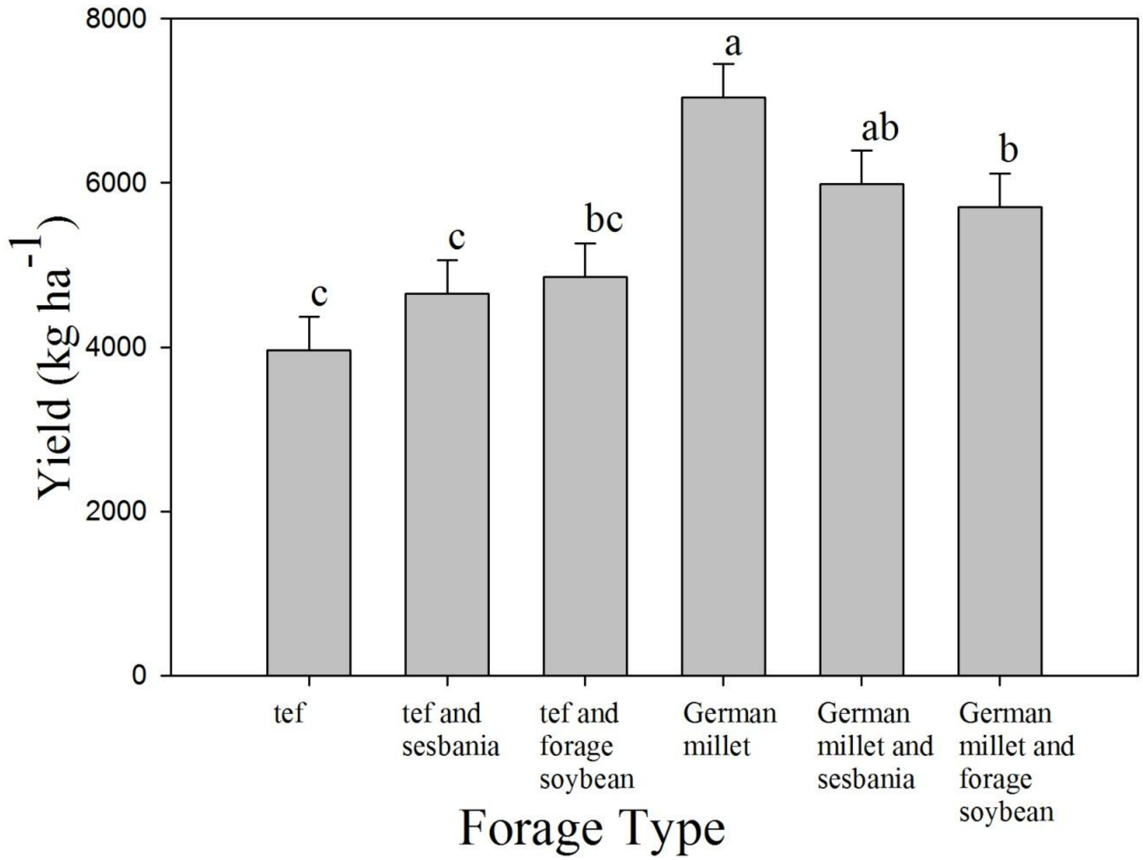

Figure 1. Total yields of six different forage mixes averaged over the 2008 and 2009 growing seasons. Differing letters signify statistical differences at p=0.05 according to least square means utilizing the Tukey adjustment.

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CHAPTER 2: EFFECT OF MANURE AND COMPOST APPLICATION ON SOIL QUALITY IN A NOVEL ORGANIC FORAGE ROTATION

ABSTRACT

Raw and composted dairy manure were applied assoil amendments on a N basis in an organically produced annual warm-season grass and legume forage mix in a two-year study conducted in 2008 and 2009. The manure and compost were applied at similar total N rates, and the forage grasses evaluated were tef (*Eragrostis tef* Zucc.) and German millet (*Setaria italica* (L.) P. Beauv.) seeded either alone or in combination with forage soybean (*Glycine max* L.) or sesbania (*Sesbania macrocarpa* Muhl. ex Raf.). Overall, the pH increased from 8.0 to 8.2 between the two years which influenced the availability of macro and micro nutrients. Soil N and P were influenced by the fertility treatment by year interaction. There was higher soil NO_3-N in 2008 with the manure treatment while there was no difference in soil N between the manure and compost treatments in 2009. Available soil P was higher in the manure treatment in 2008. Soil organic matter and particulate organic matter decreased with depth and year. This was possibly due to twice-yearly tillage within this system. Soil aggregation increased with depth for the >1000 µm and 500-1000 µm size classes and decreased with depth for the 53-250 µm size class. Overall, the inclusion of manure or compost application can increase soil quality; however, tillage must be minimized in order for significant gains to be realized.

INTRODUCTION

The organic dairy industry is faced with the dual problem of lack of enough high quality organic forage and then, once the forage is consumed, the removal and utilization of dairy manure. The lack of high quality organic forage can be addressed through incorporating annual forages into an organic vegetable production system. The production of forages has been associated with increases in soil quality. Specific influences of forage production in a vegetable system include increased organic matter (Buschiazzo et al., 1999; Min et al., 2003), conservation of soil moisture (Fageria et al., 2005), decreased erosion (Lu et al., 2000), and increased soil aggregation (Gulser, 2006; Tisdall and Oades, 1979). Thus, by incorporating organic forage into a vegetable rotation, organic vegetable producers can not only increase profits in the short-term through diversifying their production, but also increase the quality of their soil over the long-term.

After the forage has been utilized, the waste product of manure must be dealt with. Since dairy manure is rich in plant available nutrients, it is often applied to agricultural soils. Organic vegetable production systems often rely on manures as their primary fertility source. In addition to applying raw manures, vegetable producers often utilize composted manures. Composted manures possess significant advantages over raw manures, including the reduction of mass and volume of the manure, decreased weed seed viability, and odor reduction (Rynk et al., 1992). Composting also provides an agronomic benefit through the slower release of both N (Eghball, 2000) and P (Habteselassie et al., 2006). For nitrogen, this slower release may coincide better with the time of plant nutrient demand and/or not be lost to leaching (Shi et al., 2004). Compost has also been shown to increase soil C levels more than the application of manure due to the stabilization of C through the composting process (Eghball, 2002).

Applications of both raw and composted dairy manure have been shown to increase overall soil quality. Specifically, the application of manure and compost have been shown to decrease bulk density (Lynch et al., 2005), increase soil carbon stocks (Min et al., 2003), increase water holding capacity (Fares et al., 2008), improve aggregation (Min et al., 2003), and reduce erosion (Olson et al., 2005).

There has been little research on the combined effect of annual forage production and the application of manure and compost on soil quality, although there are numerous studies that provide information on the separate practices. In one long-term study, no differences were measured between organic and conventional production methods relative to their impact on soil quality (Schjonning et al., 2002). The reduction of tillage caused by implementation of no-till or reduced-till practices yielded the greatest gains in soil quality (Hansen, 1996; Malhi et al., 2009; Milne and Haynes, 2004).

The objective of this study was to evaluate the effect of manure and compost application on soil quality in a warm-season annual forage- vegetable crop rotation system.

MATERIALS AND METHODS

The experiment was conducted at the Colorado State University (CSU) Horticulture Field Research Center located 10.9 km northeast of Fort Collins, Colorado (40°36’ N 104°59’ W, elevation 1524 meters). The mean annual precipitation is 33 cm, and the mean temperature is 29°C in the summer months and 5.6 °C in the winter months

(NCWCD, 2010). The soil type is a fine, smectitic, mesic Aridic Argiustoll which is classified as a Nunn clay.

In order to evaluate the feasibility of incorporating warm-season forages into an organic vegetable production rotation, tef (*Eragrostis tef* Zucc.) and German millet (*Setaria italica* (L.) P. Beauv.) were seeded in the summer of 2008 and 2009 and grown in rotation with a crop of spring-seeded lettuce (*Lactuca satica* L.). These grasses were seeded alone or in combination with either forage soybean (*Glycine max* L.) or sesbania (*Sesbania macrocarpa* Muhl. ex Raf.). Additionally, a single whole plot in each block was left fallow and weeded three times throughout the summer. Each whole plot of the forage treatments measured 2.44 by 12.84 m. Seeding of the German millet, sesbania, and forage soybean was conducted with a Kincaid plot drill (Kincaid Equipment Manufacturing, Haven, KS). The width of the seeder was 1.22 m and the spacing between rows was 15.24 cm. The tef was seeded with a Brillion seeder (Model SSP-8, Brillion, WI). Seeding rates were based on pure live seed (Table 8). When grasses were planted in combination with legumes, the recommended seeding rate for the grasses was reduced to 40% of the monoculture rate while the legume was planted at 60% of the monoculture rate. These seeding rates were utilized to lessen competition between the grass and legume.

There was no specific variety for the German millet or sesbania. The German millet was purchased from Arkansas Valley Seed (Longmont, CO) and the sesbania from Peaceful Valley Farm Supply (Grass Valley, CA). The tef variety was ‘Tiffany’ produced by Target Seed Company now (Producer’s Choice, Woodland, CA). The variety of the forage soybean was ‘IA 1008’ produced by Albert Lea Seed House (Albert Lea, MN). All seed was either untreated or certified organic.

To explore the effect of organic fertility treatments on soil quality, each whole plot was then divided randomly into three subplots to achieve a split plot design. The fertility treatments were dairy cattle manure or composted dairy cattle manure and a check plot that received no fertility treatment. The subplots of the fertility treatments measured 2.44 by 4.28 m.

The manure and compost was applied to achieve 123 kg ha^{-1} of total N in the first year and 56 kg ha^{-1} in the second year. The rate of application was determined based on soil tests performed by Ward Laboratories in Kearney, Nebraska and manure and compost analysis performed by Colorado Analytical Laboratory in Brighton, Colorado. The rate in 2008 was based on residual soil nitrate levels (Davis and Smith, 1996). In 2009 the application rate was based on soil, manure, and compost testing, including a credit of 34 kg ha^{-1} per percent organic matter present, and a credit of 20% of the nitrogen applied in the first year of the fertility treatments expected to be available in the second year. These calculations were performed before treatment application in the spring of 2008 and again in the fall of 2008. For the spring 2008 application, the rate was 51.8 Mg ha^{-1} for the manure and 11.4 Mg ha^{-1} for the compost. For the fall 2008 application, the rate was 14.6 Mg ha^{-1} for the manure and 19.3 Mg ha^{-1} for the compost. There were three replications of each forage mix/fertility treatment combination. Both treatments were incorporated through rototilling to a depth of 15 cm. The N and P composition of the manure and compost is listed in Table 9, the actual N and P application rates in Table 10, and the differences in applied N and P in Table 11.

Irrigation was applied by an overhead sprinkler system, with the forage receiving 1.27 cm of water twice per week. The lettuce crop was not irrigated.

The effect of manure and compost on soil quality is defined in this work as the effect of these treatments on the macro and micro nutrient status, electrical conductivity (EC), pH, organic matter content, bulk density, distribution of the organic and inorganic carbon (C) fractions, and the size distribution of water stable aggregates.

To determine the macro and micro nutrient status, organic matter content, pH, and EC of the soil after application of manure and compost, 6 cores 2 cm in diameter were taken to a 20 cm depth from each sub-plot following harvest and composited for analysis. These cores were then air dried for at least 1 week at 23°C, ground, sieved to pass a 2 mm screen, and sent to Ward Laboratory in Kearney, Nebraska for analysis. Available K, Ca, Mg, and Na were determined through ammonium acetate extraction (Sparks, 1996) while available Zn, Fe, Mn and Cu were determined through DTPA extraction (Sparks, 1996). In 2009, some of the soil samples were contaminated when they were unintentionally ground through a Retsch plant tissue grinder (Model SM 2000, Haan, Germany). The blades used in the machine were composed of 82% Fe and could have increased apparent soil Fe.

For further analysis of the effect of manure and compost on soil quality, soil C, aggregate stability, and bulk density were measured. However, not all forage treatments were examined for these properties. Rather, the plots of German millet, German millet with sesbania, and fallow were examined for these indicators of soil quality.

To determine organic and inorganic C, total soil C was determined with a LECO CHN-1000 autoanalyzer (LECO Corporation, St. Joseph, MI, USA). Inorganic C analysis was performed utilizing a modified pressure-calcimeter (Sherrod et al., 2002). Organic C was then determined through subtraction of inorganic C from total C.

Aggregate stability was determined through wet sieving (Mikha et al., 2005). Soil was sampled in 2008 in two depth increments: 0-5 and 5-10 cm. Four cores were taken from each plot by hand using 2 - 4.8 by 5 cm rings that were taped together and pounded into the soil with a plank of wood and rubber mallet. The rings were then separated, and the soil was sieved through a 6 mm screen and air dried. In 2009, 4 cores 4.8 cm in diameter were taken from each plot using a truck mounted Giddings soil probe (Giddings Machine Company, Windsor, CO). The cores were then extracted from the probe and cut into 0-5 and 5-10 cm depth increments. As in 2008, the samples were sieved through a 6 mm screen and air dried. Samples (100 g) from both years were sieved through stacked 1000 µm, 500 µm, and 250 µm sieves using distilled water and a custom sieving apparatus for 10 min (Mikha et al., 2005). The solution was collected and poured through a 53 µm sieve to determine the final fraction. The individual fractions were dried at 50°C and weighed to determine size distribution of water stable aggregates.

Bulk density was determined using intact soil cores. In 2009, samples 4.8 cm in diameter were taken using a truck mounted Giddings soil probe (Giddings Machine Company, Windsor, CO). Samples were then frozen and stored at 30 ºC until they were trimmed to the 0-5 cm depth and dried at 100 ºC for at least 72 hours. After drying, the samples were weighed, and bulk density was determined by dividing the weight over the volume of the cores (97.03 cm^3) (Blake and Hartge, 1986).

Statistical analyses were performed using the PROC GLMMIX procedure in SAS 9.2 (SAS Institute, 2009). For macro and micro nutrient concentrations, EC, pH, soil organic matter content, and distribution of the organic and inorganic C fractions, the class variables were blocks (3), forage treatments (6), fertility treatments (3), and years (2). Block, block by forage, and block by forage by fertility interactions were considered random effects. For the data dealing with the distribution of water stable aggregates, the class variables were blocks (3), forage treatments (6), fertility treatments (3), years (2), and size classes (4). Block, block by forage, block by forage by fertility, and block by forage by fertility by year interactions were considered random effects. The degrees of freedom were determined utilizing the Kenward-Rogers method (Kenward and Roger, 1997). When the F-test for a given factor was significant, means were separated based on least square means utilizing Tukey's adjustment to compensate for multiple comparisons (Tukey, 1953). Statistical significance was set at $p \leq 0.05$. Data were not included in analyses for plots with missing or outlying observations. Data points were deemed outliers if the point was four or more standard deviations from the mean and the data were normally distributed. There were never more than two missing/outlying data points per estimate. The harmonic mean was used to calculate standard error of estimates.

RESULTS AND DISCUSSION

pH

In 2008 the pH was 8.01 and in 2009 the pH was 8.20, a significant difference of 0.2 units ($p<.0001$) between years (Table 12). There was no significant fertility treatment ($p=0.3849$) or fertility treatment by year interaction ($p=0.9040$). The application of dairy manure has been shown to increase soil pH as application rate and frequency increase in soils with an initial pH around 6 (Min et al., 2003), but not in soils with a pH of 8 (Habteselassie et al., 2006). In a field trial with a soil pH of 8.4, there were no observed differences among plots receiving either dairy manure or composted dairy manure annually for six years, or control plots (Habteselassie et al., 2006). This lack of change was suggested to be due to high carbonate concentration in the soil which buffers pH. It is currently unknown if German millet or tef planted for forage alone or in combination with sesbania or forage soybean has any effect on pH of soils with a reading of 8 or higher. Grasses, legumes, manures and irrigation strategies can be used to decrease soil pH in calcareous soils if properly managed (Murtaza et al., 2009; Qadir et al., 2002). Though none of the forages or soil amendments utilized in this study were evaluated in these trials.

The explanation for the increase in pH between the two years in this study could be related to the interaction between the forage and fertility treatments which was significant (p=0.0231). However, within this interaction, there were only 3 significant differences and only two of those provide insight. The first was between the tef/forage soybean plots that received compost (8.21) and the control tef/forage soybean plots (8.05) (p=0.0182). The second difference was between the tef/forage soybean plots that received compost (8.21) and the German millet plots that received compost (8.05) (p=0.0182). The final difference was between the tef/forage soybean plots that received compost (8.21) and the German millet plots that received manure (8.03) (p=0.0057). The first two differences perhaps point to the combination of both compost and tef/forage soybean. There have been no reported cases of pH effects of tef, forage soybean, or tef and forage soybean grown together on increasing soil pH. Dairy manure compost has been shown to increase soil pH from 6.7 to 7.5 after one year of application at 70 Mg ha^{-1} and to 8.0 after three years (Butler et al., 2009). No explanation for this increase in pH was given. Perhaps if continued, this study would provide additional information on the effect of German millet or tef forage production and manure or compost application on pH of calcareous soils.

Soil Nitrate

Soil NO_3-N concentrations affected by the interaction of fertility treatment and year (p=0.0025, Table 13). Differences between the manure treatment in 2008 compared to the compost and control treatments amounted to 2.0 (p=0.0003) and 1.3 mg kg^{-1} respectively (p=0.0254). In 2009, there were no statistical differences among the fertility treatments.

This difference in residual NO_3-N may be attributed to different rates of N mineralization between raw and composted manure. The composting process can lead to volatilization of much of the readily available N in dairy manure (Michel et al., 2004; Pattey et al., 2005; Shi et al., 2004) and provide a more stable supply of N that is not as readily available compared to raw manure (Habteselassie et al., 2006; Hadas et al., 1996). In 2008 the manure treatments had higher residual NO_3-N than the compost or control treatments. Since the plots received the same amount of total N, this suggests that more of the N from the manure was available in the 2008 growing season or the rate of N mineralization in the manure treatments was greater than the compost treatments.

In 2009 there were no differences among the fertility treatments which suggest that by the second year, either a greater percent of the N from the compost was available or less of the N from the manure was available. However, timing of application of the compost and manure between the two years was different and this could have affected availability of N in the second year. Since the manure and compost were applied in the fall of 2008 for the 2009 season, the N in both treatments would have had more time to mineralize during the fall, winter, and spring. Although not much N mineralization is expected form either dairy manure (Gupta et al., 2004) or composted dairy manure (Watts et al., 2010) throughout the winter when freezing temperatures are experienced, mineralization can occur throughout the early fall and spring when temperatures are above 10 ºC (Gupta et al., 2004; Watts et al., 2010). Therefore, increased N mineralization of the fall applied manure or compost could have contributed to the lack of differences in soil NO_3-N levels in 2009. Additionally, less N was applied in the second year. N mineralization from dairy manure (Shi et al., 2004) and composted dairy manure (Hadas et al., 1996) can behave with first order kinetics and thus the lower the amount of N applied, the lower the rate of N mineralization. Thus a lower rate of mineralization combined with a longer period of mineralization could have accounted for the lack any of difference between the manure and compost treatments.

Another scenario is that the N from the manure was not as available in 2009 as it was in 2008 due to differences in percent of organic N. In 2008, the compost had more organic N (94.13%) than the manure (83.61%), while in 2009 the opposite was true, with the compost possessing less organic N (88.66 %) compared to the manure (92.47%). The percent organic N is an important factor in determining N availability and mineralization rates. The greater the percent organic N, the less total N is immediately plant available (Dao and Cavigelli, 2003). Theoretically, in 2009 there would have been less N available in manure plots than in the compost and manure plots in 2008. However, much of the data supporting mineralization rates has been conducted through soil incubation under controlled environments, and on a field scale other factors such as soil moisture, temperature, and soil biological, chemical and physical properties can influence mineralization rates of manure (Eghball, 2000). These other factors could have also contributed to the observed differences in 2008 and the lack of differences in 2009.

Soil Phosphorus

The fertility by year interaction affected Olsen P (p=<0.0001) and Mehlich-3 P (p= 0.0324, Table 13). All treatments in 2008 had different Olsen P levels. The difference between the manure and compost treatments was 4.1 mg kg^{-1} (p=<0.0001) with the manure having the higher Olsen P. In 2008, the control was lower than the compost by 2.0 mg kg^{-1} (p=<0.0001) and the manure by 6.1 mg kg^{-1} (p=<0.0001). In 2009, there was no difference between the compost and manure treatments. However, the compost treatment was higher than the control by 1.8 mg kg^{-1} (p=0.011) and the manure treatment was higher than the control by 1.3 mg kg^{-1} (p=0.0063). All 2009 treatments were lower in Olsen P than the 2008 treatments. For Mehlich-3 P in 2008, there was a difference between the manure and control plots of 5.9 mg kg^{-1} (p=<0.0001), and between the compost and control plots of 5.9 mg kg^{-1} (p=<0.0001). In 2009, the only difference was between the compost and control. The difference was 5.2 mg kg^{-1} (p=<.0001) with the compost having the higher Mehlich-3 P.

The differences in observed Olsen P and Mehlich-3 P levels between fertility treatments can be explained by the effect of composting on P availability. Despite the fact that the manure treatment in 2008 received 24.1 kg ha^{-1} less P than the compost treatment

(Table 11), the manured soil had significantly higher P after harvest. Most of the P in manure is inorganic and should be available for plant uptake (Eghball et al., 2002). Inorganic P in dairy cow manure can range from 50 to 87% of total P (Barnett, 1994), while inorganic P in compost has been reported at 92% (Sharpley and Moyer, 2000). Despite this high percent of inorganic P in compost, the biological and chemical processes that occur during composting stabilizes the P and can make it less readily available (Dao and Cavigelli, 2003). However, P mineralization in the field is also driven by various factors such as soil moisture content, temperature, and sorption dissolution equilibrium (Dao and Cavigelli, 2003; Eghball, 2002). Thus, it is difficult to explain why the manure plots had higher residual P at the end of the season despite applying less P in 2008.

Unlike Olsen-P, the Mehlich-3 test did not show a difference between the manure and compost treatments. Compared to the Olsen test, the Mehlich-3 has been shown to extract more P from high pH, calcareous, and manured soils. This is primarily due to the fact that the Mechlich-3 extract is acidic and the Olsen is buffered at a pH of 8.5 (Kumaragamage et al., 2007). This explains why there is higher P in the Mehlich-3 results compared to Olsen P and could explain why there was no difference between the fertility treatments if more P was extracted.

Soil K

Soil K was also affected by the interaction of fertility treatment and year (p=0.0365, Table 14). The compost and manure treatments had higher soil K than the control, except for the 2009 manure plots. Additionally, the 2009 manure plots were significantly lower than the 2008 compost and manure plots. Thus, soil K availability in manure plots could be decreasing as pH increases.

Mn, Zn, and Cu

Soil Mn concentration was only affected by year ($p<0.0001$, Table 12). This difference can be explained by the increase in pH over the two years which can reduce Mn availability (Marschner, 1995).

Both Zn and Cu were also affected by year (Table 12). Soil Zn decreased 0.4 mg kg^{-1} ($p<0.0001$) from 2008 to 2009 while soil Cu increased by 0.2 mg kg^{-1} ($p<0.0001$) in the same period. The observed increase in soil pH between years can explain the decrease in available Zn. As pH increases, in general, the availability of Zn decreases (Marschner, 1995). For Cu, the increase cannot be explained by pH, but rather through the fertility treatments.

Both Zn ($p<0.0001$) and Cu ($p=0.0123$) were also affected by fertility treatment (Table 15). For both elements, the order of concentration from highest to lowest was manure, compost, and then control. For Zn, all fertility treatments were different from one another. For Cu, the difference between the manure and control plots was 0.14 mg kg^{-1} ($p=0.0143$). There were no significant differences between the manure and compost treatments ($p=0.0566$) or the compost and control treatments ($p=0.85$). Overall, the year-to-year increase in available Cu, despite the increase in pH, could be due to the effect of soil biology, chemistry, and physical properties on the availability and mineralization rates of Cu when applied using manure or compost (Eghball et al., 2002). Testing the Cu or Zn content of the manure was not implemented. Future studies should test the manure and compost for all macro and micro nutrients in order to explain possible observed differences.

Bulk Density

Bulk density was affected by fertility treatment (p=0.0066, Table 16). The manure treatment had higher bulk density than the control. This was unexpected due to the fact that the addition of manure is typically associated with a reduction of bulk density in both conventional and organic systems (Schjonning et al., 2002; Williams and Petticrew, 2009). However, the impact of tillage on increasing bulk density despite manure and compost applications has been shown to occur in an organic dairy pasture (Hansen, 1996) Since this system was tilled twice per forage crop produced, the increase in bulk density could be related to tillage.

Soil Carbon

There were no effects of year, forage treatment, or fertility treatment on soil inorganic carbon. Average values were 1.01 g hg^{-1} soil of inorganic carbon and 8.39 g hg^{-1} soil of $CaCO_3$.

However, year (p<0.0001, Table 17) and depth (p=0.0002, Table 18) significantly affected soil organic C (SOC). Overall, 2008 had higher soil organic C and the 0-5 cm depth had the higher amount of SOC.

Soil organic matter (SOM) was affected by the interaction of forage treatment and year (p=0.0090); all the treatments had higher organic matter in 2008 than in 2009. There were no differences among the 2008 forage treatments. In 2009, there was a difference between tef/forage soybean and German millet/forage soybean of 0.34 g hg^{-1} soil (p=0.0068), with German millet/forage soybean having the higher organic matter content. This single difference in 2009 does not provide much insight into the SOM dynamics within this system. Thus, the amount of SOM can be simplified in that there was also an effect of year on the organic matter content of the soil (p=<0.0001, Table 17), with 2008 having the higher soil organic matter.

There was also an effect of year (Table 17) and depth (Table 18) on the amount of POM in the soil. In 2008, there was a greater concentration of POM. There was also a greater concentration of POM at the 0-5 compared to 5-10 cm depth.

Since all the observed differences in SOC, SOM, and POM demonstrated a decrease from 2008 to 2009, it would appear that this production system was ineffective at improving these parameters of soil quality over two years. This decline could be caused by the twice yearly tillage. Decreases in SOC, SOM, and POM in forage systems that received dairy manure or composted manure have been observed with yearly tillage (Milne and Haynes, 2004). However, increases in SOC and POM were observed as manure application rates increased (Lynch et al., 2005; Min et al., 2003). Most annual forage systems do not experience primary tillage events twice per production cycle. However, to incorporate a vegetable crop into this rotation, the additional primary tillage was implemented to prepare the field. This is a likely cause of the yearly decrease in SOC, SOM, and POM. Perhaps by increasing the application rate of manure or compost, a decrease of SOC, SOM, and POM could be avoided. However, by increasing the rate of manure or compost application, there is a higher risk of N or P pollution, the possibility of less effective nutrient utilization, and compaction.

Additionally, another option would be to explore other forage species. German millet production has been shown to decrease SOC, SOM, and POM compared to maize and sorghum when grown for grain after 27 years (Buschiazzo et al., 1999). This comparative decrease in SOC, SOM, and POM may also occur when German millet is grown for forage. If decreases in SOC, SOM and POM did occur in part to the growing of German millet for forage, then this could help explain the decrease in SOC, SOM, and POM in the two years. In the future, different forage crops should be evaluated to see if they are able to maintain or increase SOC, SOM, and/or POM in order to avoid possible soil degradation associated with German millet. Furthermore, when incorporating a vegetable crop into this rotation, perhaps minimum tillage could be implemented in order to lessen the impact on SOC, SOM, and POM. Minimum tillage vegetable production in rotation with annual cover crops has resulted in increases in SOM (Malhi et al., 2009).

Distribution of sand free aggregates

The distribution of sand free aggregates was effected by depth for the >1000 µm (p=0.0451), 500-1000 µm (p=0.0383), and 53-250 µm (p=0.0014) size classes (Table 19). There were no effects on the 250-500 µm (p=0.3392) size class. For the >1000 µm and 500-1000 µm size classes, the weight of aggregates decreased with depth. While for the 53-250 µm size class, the weight of the aggregates increased with depth. The increase in the weight of the 53-250 µm size class aggregates at the 0-5 cm depth suggests increased stabilization of the smallest aggregate size class, but not the larger aggregate size classes. Stabilization of the smallest aggregate size class could be due to higher levels of both POM and SOC in the 0-5 compared to5-10 cm depth (Table 18). The higher the amount of POM and SOC, the greater the degree of aggregate stabilization

(Cambardella and Elliott, 1993). Though there were no forage or fertility treatment effects on aggregate size class distribution, the initial increase of the smallest size class could indicate the beginning of increased soil aggregation.

Over time, forages can increase soil aggregation by stabilizing larger sized aggregates through increased rhizosphere C, microbial activity, and root growth (Cambardella and Elliott, 1993; Gulser, 2006; Haynes and Beare, 1997). Similarly, the application of dairy manure in forage systems has been shown to increase aggregate stability (Min et al., 2003). However, the increase in macroaggregates took place over five years of continuous application of manure and compost (Min et al., 2003). Thus, if this study was to continue, there might be an observed effect of forage treatments, manure, and/or compost application in the future.

Producers can combine annual forages with the application of dairy manure and compost to increase soil quality. However, in this study, multiple issues arose which could impact long term soil quality. The first was the increase of soil pH over the two years. If this increase continues, then there could be issues with Fe, Zn, and P availability as well as Boron toxicity as soil pH approaches 8.5 (Marschner, 1995). Additionally, the increase in bulk density in the manure treatments is of concern due to the fact that increased bulk density can negatively impact desirable soil physical qualities such as the amount of plant available water (Fernandez-Ugalde et al., 2009). Finally, the decrease of SOC, SOM, and POM over the two years indicates that this system was not being managed to increase soil organic matter. However, with the increased aggregation of the smallest size class, there is the possibility that, if continued, there would be further increases in aggregation which would increase soil quality. In order to achieve maximum gains in soil quality in an organically produced system, special considerations must be taken into account. These include selecting appropriate crops that will encourage increases in soil quality, applying manure or compost at a rate that will supply enough nutrients for healthy crop growth and increase soil quality while not contaminating ground or surface water with excessive N or P, and reducing tillage when possible to achieve the greatest gains in soil quality.

TABLES

Table 8. Seeding rates.

	----kg ha^{-1}----
Tef alone	6.7
Tef with legumes	2.7
German millet alone	22.4
German Millet with legumes	9.0
Forage soybean	56.0
Sesbania	28.0

Table 9. Nutrient composition of dairy manure and compost utilized in organic forage study.

Year	Fertility treatment	Total N	Organic N	NH_3-N	NO_3-N	P	P_2O_5
		-----------------	-----------------	---------%	-----------------	-----------------	-----------------
2008	Manure	0.238	0.199	0.0361	0.0031	0.065	0.15
2008	Compost	1.074	1.011	0.0127	0.0503	0.505	1.162
2009	Manure	0.385	0.356	0.0283	0.0003	0.085	0.197
2009	Compost	0.291	0.258	0.0325	0.0007	0.107	0.245

Table 10. Application rates of N and P from the compost and manure treatments.

Year	Fertility treatment	Total N	Organic N	NH_3-N	NO_3-N	P	P_2O_5
		-----------------	-----------------	---------kg ha^{-1}	-----------------	-----------------	-----------------
2008	Manure	123.2	103.0	18.7	1.6	33.7	77.7
2008	Compost	122.8	115.6	1.5	5.8	57.7	132.8
2009	Manure	56.1	51.9	4.1	0.0	12.4	28.7
2009	Compost	56.1	49.7	6.3	0.1	20.6	47.2

Table 11. Differences in application rates of N and P from the compost and manure treatments.

Year	Total N	Organic N	NH_3-N	NO_3-N	P	P_2O_5
	----------------------------------kg ha^{-1}-----------------------------------					
2008	0.48†	-12.5	17.2	-4.1	-24.1	-55.2
2009	-0.01	2.1	-2.2	0.1	-8.3	-18.5
Total	.47	-10.4	15.1	-4.1	-32.3	-73.7

† Differences are based on subtracting amount of N or P applied in the manure treatment from the compost treatment. Positive values indicate the manure treatment received more N or P while negative values indicate the manure treatments received less N or P.

Table 12. Soil levels of pH and DTPA extractable iron, zinc, manganese, and copper as affected by year.

Nutrient	Unit	2008	2009	SE
pH	1:1	8.0 b†	8.2 a	0.03
Fe‡	mg kg^{-1}	6.7 b	8.3 a	0.7
Zn	mg kg^{-1}	1.45 a	1.07 b	0.03
Mn	mg kg^{-1}	7.4 a	4.3 b	0.3
Cu	mg kg^{-1}	1.08 b	1.26 a	0.06

† Differing lowercase letters signify statistical differences between years at $p \leq 0.05$ 0.05 according to least square means utilizing the Tukey adjustment.
‡ Statistical differences observed in Fe concentration could be due to contamination of soil samples through the grinding process.

Table 13. Soil concentrations of NO_3-N and phosphorus for the fertility treatment by year interaction.

Nutrient	Year	Compost	Manure	Control	Yearly average	SE
		-------------------------mg kg^{-1}	-------------------------	-------------------------		
NO_3-N	2008	4.7 c	6.7 a	5.4 bc	5.8 A‡	0.4
NO_3-N	2009	6.1 ab	6.4 ab	6.4 ab	6.5 B	0.4
Average NO_3-N		5.5 y §	6.8 z	6.1 z		
Olsen P	2008	19.7 b	23.8 a	17.7 c	19.7A	0.6
Olsen P	2009	11.9 d	11.4 d	10.1 e	11.1B	0.6
Average Olsen P		15.7 y	17.7 z	13.9 x		
Mehlich-3 P	2008	46.3 a	47.8 a	40.5 c	44.9 A	1.1
Mehlich-3 P	2009	44.9 ab	42.3 bc	39.7 c	42.3 B	1.1
Average Mehlich 3-P		45.6 z	45.3 z	40.1 y		

† Differing lowercase letters signify statistical differences among the interactions of fertility treatment by year at $p \leq 0.05$ according to least square means utilizing the Tukey adjustment.

‡ Differing uppercase letters signify statistical differences among fertility treatments averaged within year at $p \leq 0.05$ according to least square means utilizing the Tukey adjustment.

§ Differing lowercase letters at the end of the alphabet signify statistical differences among fertility treatments averaged over year at $p \leq 0.05$ according to least square means utilizing the Tukey adjustment.

Table 14. Available K as affected by the interaction of the fertility treatment with year.

Fertility Treatment	Year	Concentration
		---mg kg^{-1}---
Compost	2008	46 a†
Compost	2009	45 ab
Manure	2008	48 a
Manure	2009	42 bc
Control	2008	41 c
Control	2009	40 c
SE		1

† Differing lowercase letters within the same column signify statistical differences at $p \leq 0.05$ according to least square means utilizing the Tukey adjustment.

Table 15. Available Zn and Cu as affected by fertility treatment.

Element	Fertility treatment	Concentration	SE
		--------mg kg^{-1}--------	
Zn	Compost	1.26 b†	0.03
Zn	Manure	1.37 a	0.03
Zn	Control	1.16 c	0.03
Cu	Compost	1.14 ab	0.07
Cu	Manure	1.25a	0.07
Cu	Control	1.11 b	0.07

† Differing lowercase letters within the same column signify statistical differences at $p \leq 0.05$ according to least square means utilizing the Tukey adjustment.

Table 16. Bulk density as affected by fertility treatment.

Fertility treatment	Bulk density
	-------------g cm^{-3}-------------
Compost	1.25 ab†
Manure	1.28 a
Control	1.21 b
SE	0.03

† Differing lowercase letters within the same column signify statistical differences at $p \leq 0.05$ according to least square means utilizing the Tukey adjustment.

Table 17. Soil organic carbon (SOC), particulate organic matter (POM) and organic matter levels as affected by year.

ear	Soil organic carbon	POM	Soil organic matter
	----------------------------g hg^{-1}	----------------------------	
2008	2.30 a†	0.75 a	3.13 a
2009	2.25 b	0.52 b	2.56 b
SE	0.013	0.1	0.05

† Differing lowercase letters within the same column signify statistical differences at p≤0.05 according to least square means utilizing the Tukey adjustment.

Table 18. Soil organic carbon (SOC) and particulate organic matter (POM) as affected by depth.

Depth	Soil organic carbon	POM
	---------------------g hg^{-1} soil	---------------------
0-5 cm	2.29 a†	0.67 a
5-10 cm	2.25 b	0.60 b
SE	0.017	0.1

† Differing lowercase letters within the same column signify statistical differences at p≤0.05 according to least square means utilizing the Tukey adjustment.

Table 19. Aggregate size distribution as affected by depth.

	Depth		
Aggregate Size Class	0-5 cm	5-10 cm	SE
	-----------g	-----------	
>1000 µm	10.06 b†	11.73 a	1.07
500-1000 µm	13.69 b	15.43 a	0.82
250-500 µm	14.93 a	15.38 a	0.37
53-250 µm	24.93 a	21.31 b	1.68

† Differing lowercase letters within the same row signify statistical differences at p≤0.05 according to least square means utilizing the Tukey adjustment.

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APPENDIX A: SUPPLEMENTARY SOIL FERTILITY INFORMATION

Soil nutrients affected by forage treatment and year

There was an interaction of forage treatment and year on soil Ca (p=0.0153, Table 20). The Ca concentration in the German millet treatment in 2009 was higher than all of the other treatments in 2008. In addition, the 2009 tef /sesbania treatment was significantly higher in soil Ca than the 2008 tef/sesbania treatment (p=0.0383). Soil Ca was not affected by forage treatment (p=0.3177), fertility treatment (p=0.5419), or the fertility treatment by year interaction (p=0.9268).

Soil Na was significantly affected by the interaction of forage treatment and year (p=0.0193, Table 20). The only significant difference in the interaction was that the 2009 German millet had a higher soil Na concentration than the 2009 German millet and forage soybean. The difference was 35 mg kg^{-1}. Since there was no effect of the fertility treatment (p=0.6388) or the fertility treatment by year interaction (p=0.1216), the increase of available Na in the 2009 German millet plots compared to the 2009 German millet and forage soybean plots could be due to the presence of forage soybean in the forage mix and the increased seeding rate of the German millet when seeded alone. In the 2009 German millet and forage soybean plots, there was 6% forage soybean, 67% German millet, and 26% weeds by dry weight (Table 4). The low forage soybean presence makes it unlikely that the observed effect was due to its presence. It is also clear that the effect of seeding rate was not entirely responsible for the observed differences. There was no difference between the German millet and German millet plus sesbania treatments in 2009. The German millet in the German millet and sesbania was seeded at the same rate as the German millet in the German millet and forage soybean plots..

Soil Fe was significantly affected by the forage treatment by year interaction (p=0.0308, Table 20). Soil Fe was higher in 2009 than in 2008 in the German millet, specifically, and also when averaged across treatments (p=0.0007, Table 12). However, these differences are suspected to be due to contamination during improper grinding in 2009 leading to chipped stainless steel blades.

Mg was only affected by the interaction of forage treatment and year (p=0.0025, Table 20). The German millet plots had greater soil Mg in 2009 than the tef treatment and the German millet plus forage soybean treatment in 2009.

Soil sum of cations was significantly affected by the interaction of forage treatment and year (p=0.0057, Table 20). There was one difference of interest and that was between the 2009 tef and 2009 tef/forage soybean. The difference was 39 meq kg^{-1} (p=0.0043) with the 2009 tef having the higher sum of cations. Since there was no effect of fertility (p=0.7310) or fertility by forage treatment interaction (p=0.9121), this observed difference could have been due to the combined effect of the higher seeding rate of the 2009 tef compared to the tef/forage soybean and the presence of forage soybean. Since there was no difference between the 2009 tef and 2009 tef plus sesbania treatments, seeding rate alone cannot explain the above effect. Since Na is one of the cations contributing to the sum of cations, this is probably a reflection of the effect on Na.

Soluble salts were significantly affected by the interaction of forage treatment and year (p=0.0132, Table 20). Within the interaction, the only statistical difference was in 2008 between the German millet plus forage soybean and the tef plus forage soybean. The difference was 0.22 dS m^{-1} (p=0.0414) with the German millet plus forage soybean having higher total soluble salts. There was no effect of fertility (p=0.3876) or fertility by year interaction (p=0.4465). There was also no difference in total dry matter yield between the two plots. The observed levels of soluble salts are below what would cause yield reduction to most crops except the most salt sensitive (Marschner, 1995).

Table 20. Available soil concentrations of potassium, calcium, sodium, magnesium, sum of cations and total soluble salts for the forage treatment by year interaction.

Nutrient	Year	tef	tef and sesbania	tef and forage soybean	German millet	German millet and sesbania	German millet and forage soybean	Yearly average	SE
					----------mg kg^{-1}----------				
K	2008	547 a†	508 ab	508 ab	491 ab	488 ab	500 ab	507 A‡	19
K	2009	498 ab	504 ab	475 ab	511 ab	453 b	459 b	484 B	19
Ca	2008	5679 bc	5586 c	5578 c	5665 bc	5514 c	5674 bc	5616 B	109
Ca	2009	5741 abc	5952 ab	5824 abc	6195 a	5789 abc	5723 abc	5871 A	109
Na	2008	164 ab	166 ab	164 ab	179 ab	179 ab	180 ab	--	8
Na	2009	167 ab	182 ab	179 ab	197 a	180 ab	162 b	--	8
Fe	2008	7.1 ab	7.4 ab	6.4 ab	6.6 b	6.9 ab	6.1 ab	6.7 B	1.2
Fe	2009	8.9 ab	9.3 ab	8.0 ab	11.1 a	6.0 ab	6.7 ab	8.3 A	1.2
Mg	2008	993 ab	986 ab	979 ab	990 ab	976 ab	1012 ab	--	28.22
Mg	2009	959 b	1028 ab	982 ab	1093 a	971 ab	941 b	--	28.22
					----------meq kg^{-1}----------				
Sum of cations	2008	386 ab	377 b	389 ab	388 ab	382 b	381 b	384 B	8
Sum of cations	2009	423 a	390 ab	386 b	387 ab	404 ab	393 ab	397 A	8
					----------dS m^{-1}----------				
Soluble salts	2008	1.16 ab	1.12 ab	1.09 b	1.29 ab	1.28 ab	1.31 a	--	0.007
Soluble salts	2009	1.18 ab	1.17 ab	1.17 ab	1.22 ab	1.21 ab	1.13 ab	--	0.007

† Differing lowercase letters within the same nutrient signify statistical differences at $p \leq 0.05$ according to least square means utilizing the Tukey adjustment.

‡ Differing uppercase letters within the same nutrient signify statistical differences at $p \leq 0.05$ according to least square means utilizing the Tukey adjustment.

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