DIVERSIFICATION OF CURRENT OKLAHOMA NO-TILL CROPPING SYSTEMS USING COOL SEASON AND WARM SEASON COVER CROPS

By

KEVIN BRIAN MEEKS

Bachelor of Science in Animal Science
Texas Tech University
Lubbock, Texas
2007

Master of Science in Crop Science
Texas Tech University
Lubbock, Texas
2011

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
DOCTOR OF PHILOSOPHY
December, 2014

DIVERSIFICATION OF CURRENT OKLAHOMA NO-TILL CROPPING SYSTEMS USING COOL SEASON AND WARM SEASON COVER CROPS

Dissertation Approved:

Dr. Jason Warren

Dissertation Adviser

Dr. Jeff Edwards

Dr. Brian Arnall

Dr. David Porter

Dr. Michael Smith

ACKNOWLEDGEMENTS

First and foremost, I would like to thank my Lord and Savior, Jesus Christ, because without him none of this would have been possible. I would also like to express my deepest gratitude and appreciation to my wife, Katie, and the rest of my family for all the love and support throughout this process.

I would also like to thank my advisor, Dr. Jason Warren, for the willingness to provide support and guidance to me the last three years. Furthermore, I would like to express appreciation to the faculty who served on my committee and provided me the chance to obtain this degree from Oklahoma State University: Dr. Jeff Edwards, Dr. Brian Arnall, Dr. Mike Smith, Dr. David Porter, and Dr. Chad Godsey.

Lastly, I would like to thank Wendal Vaughan and all graduate students that have, at one time or another, helped or participated in my research. Without your help and involvement, this project would not have been possible.

Name: KEVIN BRIAN MEEKS

Date of Degree: DECEMBER, 2014

Title of Study: DIVERSIFICATION AND INTENSIFICATION OF COVER CROPS IN OKLAHOMA NO-TILL CROPPING SYSTEMS

Major Field: CROP SCIENCE

This study evaluated fall and summer cover crop performance from a forage production, forage quality and water use efficiency standpoint. Five fall cover crop mixtures, for three site years, and six summer cover crop mixtures, for five site years, were evaluated for yield, total nitrogen, nitrogen uptake, acid digestible fiber, neutral digestible fiber, and relative feed value. The six summer cover crop mixtures were evaluated for their potential role to be planted in place of a summer fallow period in a continuous wheat system from a soil moisture and water use standpoint. The results indicated that rye containing fall cover crop mixtures had the highest yields, but lowest relative feed value. Some of the non-rye containing mixtures had higher feed values than the control, but had less yield potential. Summer cover crop mixtures containing all or a portion of legumes produced intermediate yields combined with the highest forage quality. No significant differences in wheat grain yield were seen between cover crop treatments and fallow treatments. However, the fallow plots produced, on average, 161 kg ha^{-1} more grain yield. Grain yield reduction was presumably caused by less soil moisture content at the time of planting. However, in-season and post-wheat harvest soil moisture values in the cover crop treatments were equal to or greater than soil moisture in the fallow treatment. Utilization of the summer cover crops, as a forage, should be done in-order to offset the seed cost due to the lack of cash crop yield improvements.

TABLE OF CONTENTS

Chapter I Page

Chapter II Page

LIST OF TABLES

Table Page

LIST OF FIGURES

CHAPTER I

Cover Crops as Forage Sources

INTRODUCTION

Summary of Work

Cover crops, in Oklahoma, can be used as sources of low input, high productivity forages for grazing or hay production if forage needs are increased as a result of the onset of drought conditions. Although, historically utilizing cover crops for forage has been considered to be detrimental to their function, it may provide for increased resilience to drought stress for producers who own grazing animals. In this study, cool season, C3, and warm season, C4, cover crop species were evaluated for their ability to add value to current cropping systems in Oklahoma.

A study was conducted on commercially available cool season, C3 cover crops mixtures. These mixtures contain both C3 broadleaf and grass species. Crop species for these mixtures include barley (*Hordeum vulgare* L.), canola (*Brassica napus* L.), cereal rye (*Secale cereal* L.), oat (*Avena stirgo* Schreb.), radish (*Raphanus sativus* L.), triticale (x *Triticosecale*), wheat (*Triticum aestivum* L.). Mixtures were planted following the protocol of monoculture variety trials. After biomass harvest, dry matter yield and forage quality were evaluated for each mixture at each specific site. Crop species composition within each mixture varies to provide flexibility to the grower. This increase in flexibility will allow the grower to choose a mixture that will cater to the needs of the farming operation.

A study was also conducted on commercially available warm season, C4 cover crops mixtures. These mixtures contain C4 broadleaf, grass, and legume species. Warm season, C4 cover crop mixtures include buckwheat (*Fagopyrum esculentum* M.), corn (*Zea Mays* L.), cowpea (*Vigna unguiculata* L.), golden german millet (*Seraria italic* L.), mungbean (*Vigna radiata* L.), pearl millet (*Pennisetum americanum* L.), radish (*Raphanus sativus* L.), safflower (*Carthamus tinctorius* L.), sorghum sudangrass (*Sorghum biocolor x Sorghum biocolor var. Sudanese*), soybean (*Glycine max* L.), sunflower (*Helianthus annuus* L.), and sunn hemp (*Crotalaria juncea* L.). Planting these mixtures as an alternative to the traditional summer fallow period, might be a fit after winter wheat harvest in continuous wheat systems. These warm season cover crop mixtures produce large quantities of biomass and could serve as a high quality forage source during the summer months used for flash grazing program or hay production. These mixtures may provide a viable alternative summer grazing or hay source for livestock.

REVIEW OF LITERATURE

Current Cropping Systems

Stockpiling hay for winter feed is important and economical for Oklahoma producers. In Oklahoma, producers focus on winter wheat for grazing, grain, or both (Hossain et al., 2004). However, there is interest in diversifying current cropping systems using cover crop mixtures. Using winter wheat as a dual purpose crop requires removing the livestock from the field in a timely manner. The most common time for livestock removal is when the wheat is at “first hollow stem” or physiological growth stage of Feekes 5 (Large, 1954). Butchee and Edwards (2013) indicated that dual purpose wheat, at the time of grazing termination (Feekes 5), needs to have a 0.62 or greater fractional canopy closure in order for 95% of the yield goal to be achieved.

Acres that are strictly planted for grazing purposes only comprise about 10-20% of planted wheat acres in Oklahoma (True et al., 2001, and Hossain et al., 2004). The producers that use this "graze out" management practice are those most greatly affected by soil compaction, land degradation, runoff and erosion within their pastures. This is caused by excessive residue removal, conventional tillage, or over grazing. Furthermore, these producers are hesitant to change to a no-till management, which represents only 8.5% of the cropland statewide (Conservation Technology Information Center, 2004), after many years of conventional tillage because of concerns about decreased grazing potential due to the need to rotate crops in a no-till system. Utilization of a cover crop, or a cover crop mixture, could provide an alternative that provide the benefits of crop rotation, while maintaining, or even improving, overall forage and feed productivity.

There are other systems implemented in Oklahoma, in which cover crops can be a useful tool for producers. For traditional farmers that plant soybean, corn, sorghum, or cotton as a cash crop in late spring, fall-seeded cover crops like black oat (*Avena stirgos* Schreb), triticale (*Triticale hexaploide* Lart.), barley (*Hordeum vulgare* L.), radish (*Raphanus sativus* L.) and rye (*Secale cereale* L.) may be useful cover crops for winter grazing or hay production.

Cool Season Cover Crops

Cereal rye (*Secale cereale* L.), a winter cover crop, is often used as a grazing forage for livestock when rotated with a summer grain crop such as grain sorghum, or corn (Franzluebbers and Stuedemann, 2008). When planted as a monoculture in the fall, rye can produce up to 10 Mg ha^{-1} of biomass on a dry matter basis (Bugg et al., 1996). Rye is also thought to have allelopathic effects on weed suppression by the production of two hydroxamic acids (Chase et al., 1991). Rye is often included in fall planted mixtures to reduce nitrate losses as well (Feyereisen et al. 2006). Clarke et al., 1994, found that rye planted with broadleaves tended to dominate, and biomass yield was directly correlated with rye concentration. The inclusion of a brassica, such as canola or radish, with rye is shown to be able to break pest cycles in the soil and reduce parasitic nematodes (Gallandt et al., 1998)

Oat (*Avena sativa* L.) is a low cost, cool season cover crop species that has potential in Oklahoma cropping systems. Oats provide a palatable, high yielding forage (5500 kg ha^{-1}) that can be used as a forage or rotational crop that also has nutrient cycling capabilities (Welty, 1991, USDA ARS Fact Sheet, 2005, Parkin et al., 1997). Proper no-till management of oat residues may contribute in the addition of soil organic matter, and maintaining soil moisture (USDA ARS Fact Sheet, 2005, Zibilske and Makus, 2009).

Barley (*Hordeum vulgare* L.) is a commonly used cool season cover crop in the high plains. Winter barley is used for erosion control, nutrient cycling, weed suppression, and as a forage source (Canadian Organic Growers Inc. 1992, Meisinger et al., 1991, Creamer et al., 1996, Kobayashi et al., 2004, Hofstetter, B., 1988). Winter barley can help suppress summer annual weeds when incorporated into crop rotation (Creamer et al., 1996, Kobayashi et al., 2004). Barley is an excellent source of forage for lactating beef and dairy cows (Mustafa et al., 2000, Khorasani et al., 1996). When compared to oat, wheat, and triticale, winter barley can produce higher quality forage (Hofstetter, B., 1988).

Triticale (x *Triticosecale*) can be used as a cool season cover crop and has many similarities to the previously mentioned crops. Triticale is similar to cereal rye and winter wheat, because it is a cross between the two species. However, there are some differences. Triticale requires more growing degree days in order to reach physiological maturity, but forage biomass yields do not differ when compared to wheat (Rao et al., 2000). As a result of longer maturity, triticale could provide additional late season forage production which also reduces supplemental feed cost (Rao et al., 2000). Like barley, triticale is an excellent forage source for lactating beef and dairy cows (Khorasani et al., 1996).

Winter wheat is most commonly used as a cash, forage, or dual purpose crop in Oklahoma. Winter wheat has the potential to work well in mixtures that contain other grass or legume species (Blaser et al., 2006). Furthermore, winter wheat strictly as a forage cover crop, can be used to reduce erosion, promote weed suppression, and nutrient cycling (Delgado et al., 1999, Canadian Organic Growers Inc., 1992, Delgado 1998,)

Warm Season Cover Crops

The warm season cover crop grass species used in this experiment include sorghum sudangrass, german millet, pearl millet, and sterile corn. These cover crops are included in both grass only and grass/legume mixtures because these grasses have a tendency to produce higher yields, but lack in forage quality. However, the inclusion of a legume into an all grass mixture has been shown to improve forage quality (Brown and Munsell, 1943).

Sorghum sudangrass (*Sorghum bicolor x S. bicolor var. Sudanese*) is a summer annual, warm season, cover crop grass species that has many diverse benefits. Sorghum sudangrass is a cover crop that has a high yield potential due to its large primary and secondary root systems, and lower total leaf area; thus resulting in higher water use efficiencies in comparison to corn (McGuire, 2003, Sarrantonio, 1994). Studies show that sorghum sudangrass works well as a rotational crop in different cropping systems because of its ability to suppress weeds and increase nutrient uptake for the following crop (Forney and Chester, 1984, Delgado and Lemunyon, 2006).

German millet (*Setaria italic* L.) is a rapidly maturing, low input, warm season grass species. The inclusion of millet as a hay crop during the summer fallow period of a graze out, no-till system was shown to be an economical alternative to grain only and dual purpose wheat in Oklahoma (Decker et al., 2009). Golden german millet is desired in most summer cover crop mixtures because it performs well with other grass and legume plant species, has a maturity time of 75-90 days to grain, and can be used as a forage as early as 50 days after planting (Creamer and Baldwin, 1999, Barnhart, 2010). German millet's shallow root system and short stature, reduce the water requirement needed, making it a more desirable crop choice in water limited, rain-fed environments (Creamer and Baldwin, 1999).

Pearl millet (*Pennisetum glaucum* L.) is a warm season cover crop that is incorporated into the mixtures because of its rapid growth and productivity. Forage quality and yield improvements have been made by breeding later maturing cultivars (Burton et al., 1986, Rachie and Majmudar, 1980). This allows for forage quality to remain at high levels longer throughout the growing season, thus maintaining digestibility. Pearl millet has been included in commercially available mixtures because it can produce large amount of biomass and maintain forage quality throughout the majority of the season. (Burton et al., 1986).

Sterile corn (*Zea Mays* L.) incorporates a sterile cytoplasm which is substituted for the normal cytoplasm in fertile hybrids (Duvick, 1958). Today, sterile corn is used in cover crop mixtures because of it biomass producing capabilities. However, in rain-fed, drought stressed environments, the benefits of incorporating sterile corn into cover crop mixtures is unknown. Furthermore, the high water demand for corn may limit the growth and production of other plant species if planted in the same mixture.

Crop Livestock Integration

With proper management, cover crops may provide some improvement for the soil and some assistance for grazing or feeding livestock, but it does take some time to see the returns (Franzluebbers and Stuedemann, 2008).

Unlike much of the agriculture in the U.S., Oklahoma's agriculture historically includes the integration of livestock and crop production with the grazing of cattle on wheat pasture. Our challenge is to promote and improve diversification of the cropping systems that will allow for the adoption of successful no-till management that would reduce off-site impacts and provide opportunity for improved productivity if gains in soil conditions and soil moisture could be realized through the use of cover crops.

Objective and Hypothesis

The objective of this study was to evaluate fall and summer cover crops for their forage production potential in Oklahoma no-till production systems. Implementation of fall and summer cover crops could add value to a production system as a forage source.

. The hypothesis for the fall cover crop forage trial is as follows:

H_O: Implementation of a fall cover crop, for forage production, has no advantage over winter wheat used as forage only.

H_A: Fall cover crops exhibit greater forage production and quality than winter wheat used as forage only.

The hypothesis for the summer cover crop forage trial is as follows:

H_O: There are no differences in forage quality and quantity produced by the different cover crops when implemented in place of a fallow period in a continuous wheat system.

H_A: There is a difference in forage quality and quantity produced by the different cover crops when implemented in place of a fallow period in a continuous wheat system

METHODOLOGY

Fall Cover Crop Forage Trial

Field experiments for the fall planted cover crops were conducted from fall 2011 through spring 2014 in Geary, Oklahoma (35°37’14” N, 98°16’33” W) on a privately-owned producer farm. The experimental site consisted of a Norge silt loam (fine-silty, mixed, active, thermic Udic Paleustolls) soil that is well drained. The slope of experimental site ranged from 3 to 5% slope. The average annual precipitation is approximately 765 mm.

The fall cover crop forage experiment consisted of five different commercially available cover crop treatments and one winter wheat treatment serving as the check. The cover crop treatments are presented, in Table 1 and the species composition of each mixture is presented in Table 2. The cover crop mixtures were developed and purchased from Kauffman Seed in Haven, Kansas. The six treatments were laid out in a randomized complete block design with four replications. Individual plot size was approximately 1.52 by 9.14 m. Cover crops were planted 17 October 2011, 18 October 2012, and 10 October 2013 (Table 3) using a Great Plains no-till grain drill. The fall seeded cover crops were planted at approximately 2.54 cm in depth, each having six rows with 18.8 cm row spacing. The recommended seeding rate for these commercial cover crops was 67.2 kg ha^{-1}and was provided by the seed company.

No starter nitrogen fertilizer was applied prior to planting. Nitrogen fertilizer (urea) was applied by the cooperator broadcast in February of 2012, 2013, and 2014 at a rate of 44.8 kg ha^{-1}. No insecticides or fungicides were used. Glyphosate was applied to each plot post-harvest, in 2012, 2013, and 2014, at a rate of 4.68 kg ai ha^{-1}.

In 2012 and 2014, fall planted cover crop above ground biomass was harvested twice. In 2013, biomass was harvested once due to limited rainfall and drought conditions. Harvest dates are presented in Table 3. Cover crop biomass was harvested using a Chute Forage Harvester by Carter Manufacturing Company. Biomass was collected in the field by cutting a 0.91 by 9.14 m strip from the center of each plot. The total biomass field weight was determined by weighing the sample cut from this area. A representative subsample for each plot was collected, bagged and stored for moisture and forage quality analysis. Approximately 2.5-5.0 cm of standing above-ground biomass residue was left in each plot after each harvest. The variation of cutting height was due to unleveled ground within the plot area.

Sub-samples were weighed in the lab and then placed in a drying oven for 5 to 7 days. Once removed, sub-samples were again weighed and ground using a forage grinder. Samples were then submitted to the Oklahoma State University Soil, Water and Forage Analytical Laboratory for forage quality analysis. Dry matter (%), crude protein (%), total nitrogen (%), acid detergent fiber (%) and neutral detergent fiber (%) was determined for each submitted sample. Using the forage quality results for each sample, protein yield (kg ha^{-1}), and relative feed value index was calculated for each treatment.

Forage dry matter (%) was determined by the difference in moisture concentration after each sample was then dried at 85°C overnight then dried at 105°C overnight. Total nitrogen (%) for each sample was determined using a dry combustion LECO Truspec Carbon/Nitrogen Analyzer (NFTA, 1993). Total nitrogen uptake for each sample was then calculated by multiplying total nitrogen content by the amount of dry matter biomass produced. Acid detergent fiber and neutral detergent fiber content (%) for each sample was determined using the Ankom Fiber Analyzer (Ankom Technology, 2011).

Digestible dry matter (DDM) and dry matter intake (DMI) were determined for each sample by using ADF and NDF values, respectively (Jeranyama and Garcia, 2004). Digestible dry matter and dry matter intake formulas are expressed below:

$$DDM = 88.9 - (0.779\ x\ \%\ ADF)$$

$$DMI\ (\%\ of\ BW) = 120/(\%\ NDF)$$

Once DDM and DMI were calculated, relative feed value for each sample could then be determined by the formula below.

$$RFV = (DDM\ x\ DMI)/1.29$$

Fall cover crop biomass yield, total nitrogen, acid digestible fiber, neutral digestible fiber and relative feed value were analyzed by SAS software version 9.3 (SAS, Cary, NC). Fall cover crop biomass yields were analyzed in a split block design with individual harvest dates and season total analyzed separately. Analysis of variance was determined using general linear model (PROC GLM). Statistical differences between treatment means were determined by using Fisher's protected least significant difference test in which α=0.05.

Summer Cover Crop Forage Trial

Field experiments were conducted during the summers of 2012, and 2013 in Geary, Oklahoma (35°37’14” N, 98°16’33” W) on privately owned demonstration farms. The Demo experimental site (2012 and 2013) consisted of a Norge silt loam (fine-silty, mixed, active, thermic Udic Paleustolls) soil that is well drained. The slope of this experimental site ranged from 3 to 5%. The average annual precipitation is approximately 765 mm. The Lagoon experimental site (2012 only) consisted of a Bethany silt loam (fine-silty, mixed, active, thermic Udic Paleustolls) soil that is well drained. The slope of experimental site ranged from 0 to 1%.

The study was also conducted in 2013 and 2014 at the Oklahoma State University North Central Research Station (36°23’13”N, 98°6’39”W), one mile west of Lahoma, Oklahoma. The experimental site consisted of a Grant silt loam (fine-silty, mixed, superactive, thermic Udic Argiustolls) which is a deep, well drained, moderately permeable soil. The slope of the experimental site ranged from 1 to 3%. The average annual precipitation is approximately 863 mm.

The experiment consisted of 6 different cover crop treatments consisting of warm season grass, legume, and brassica mixtures (Table 5). The six treatments were laid out in a randomized complete block design with four replications. Individual plot size was approximately 3.05 by 9.14 m. Warm season cover crops were planted during June and July, as seen in Table 4, at a depth of approximately 2.54 cm using a Great Plains no-till grain drill. The drill planted the cover crops in six rows with 18.8 cm row spacing. The recommended seeding rate from the seed company was 33.6 kg ha^{-1}.

Unlike the fall cover crop trials, biomass was harvest once at the end of the growing season. Above-ground biomass was harvested using a Chute Forage Harvester by Carter

Manufacturing Company. Biomass was collected in the field by cutting a 0.91 by 9.14 m strip out of the center of each plot. A representative sub-sample of the whole plot was then collected, bagged and stored for moisture and forage quality analysis. There was approximately 5.08 to 10.46 cm of above ground residue left after harvest. Harvest dates are presented in Table 4.

Wet subsamples were weighed and then placed in the drying oven for 5 to 7 days. After drying, subsamples were weighed to determine moisture content and ground to pass through a 1 mm screen using the Forage Grinder (need Mfg info). Samples were then submitted to the Oklahoma State University Soil, Water and Forage Analytical Laboratory for forage quality analysis. Forage dry matter (%), protein content (%), total nitrogen (%), acid detergent fiber (%) and neutral detergent fiber (%) analysis was performed for each submitted sample.

Forage dry matter (%) was determined by the difference in moisture concentration after each sample was then dried at 85°C overnight then dried at 105°C overnight. Total nitrogen (%) for each sample was determined using a dry combustion LECO Truspec Carbon/Nitrogen Analyzer (NFTA, 1993). Total nitrogen uptake for each sample was then calculated by multiplying total nitrogen by the amount of dry matter biomass produced. Acid detergent fiber and neutral detergent fiber content (%) for each sample was determined using the Ankom Fiber Analyzer (Ankom Technology, 2011).

Digestible dry matter (DDM) and dry matter intake (DMI) were determined for each sample by using ADF and NDF values, respectively (Jeranyama and Garcia, 2004). Digestible dry matter and dry matter intake formulas are expressed below:

$$DDM = 88.9 - (0.779\ x\ \%\ ADF)$$

$$DMI\ (\%\ of\ BW) = 120/(\%\ NDF)$$

Once DDM and DMI were calculated, relative feed value for each sample could then be determined by the formula below.

$$RFV = (DDM\ x\ DMI)/1.29$$

Statistical Analysis

Summer cover crop biomass yield, protein content, total nitrogen, acid digestible fiber, neutral digestible fiber and relative feed value were analyzed by SAS software version 9.3 (SAS, Cary, NC). Analysis of variance was determined using general linear model (PROC GLM). Statistical differences between treatment means were determined by using Fisher's protected least significant difference test in which α=0.05.

RESULTS AND DISCUSSION

Fall Cover Crop Biomass Yield

There was no significant treatment by year interaction for biomass yield; therefore, the 3-year average total yield is presented in table 7. This analysis shows that treatments 3 and 4 produced significantly larger yields than remaining treatments. These treatments along with treatment 2 all produced significantly more forage yield that the winter wheat control treatment. Treatment 2 was a mixture of barley, oats, rye, triticale, and radish; treatment 3 was a mixture of canola, radish, barley, oats, and rye; and treatment 4 was a mixture of canola, radish, and rye. The canola and radish in these mixtures were a very minor component of the species composition for these treatments due to poor emergence and growth (Table 2). Poor emergence and growth of these brassicas are similar to Clarke et al. (1994) who found that when rye is mixed with other brassicas, the rye dominates and has higher yields than treatments not containing rye. Therefore, these treatments were dominated by the grass species listed. It is interesting to note that as the amount of rye in the mix increased the yield also increased. Treatments 2, 3 and 4 not only produced the largest average total yields, but also produced the largest fall and winter forage as indicated by yields collected during the first harvests in 2012 and 2014, with treatment 4 producing the largest fall and winter forage. Treatment 1 was the only treatment that produced total annual yields that were not significantly different than the control and treatment 5 yields were significantly lower than the winter wheat control. Treatment 1 consisted on barley, triticale, radish, and canola, whereas treatment 5 contained barley, oats, wheat, and radish. It should be noted that the wheat in treatment 5 was supplied by the seed company and therefore was not Duster which was planted in the control treatment.

Fall Cover Crop Nitrogen Concentration

As expected, total nitrogen concentrations were higher in the first harvest compared to the second harvest in 2012 (Table 8). However, significant differences among treatments were only observed in the April harvest in 2012, and May harvest in 2014. The nitrogen concentrations for treatments 1-4 were significantly higher than treatment 5 which was significantly higher than the control in the April harvest of 2012. In contrast, treatment 5 contained a significantly higher protein concentration when compared to remaining treatments in the May harvest of 2014. This inconsistency between harvests likely results from interactions between species composition, differences in maturity rate among species, differences in protein concentrations in each plant species and weather conditions.

Fall Cover Crop Total Nitrogen Uptake

Table 9 indicates that there were significant differences in treatment means for total nitrogen uptake in each site year. Total nitrogen uptake is dependent on biomass yield and total nitrogen concentration for each treatment. In 2012, total nitrogen uptake increased between the March and April harvest dates, as expected, due to higher biomass yields in April. In 2013, total nitrogen uptake was highest in the rye containing treatments also because they were the highest yielding. However, in 2014, total nitrogen uptake for rye containing treatments decreased from May to June because of a decrease in yields. The opposite was seen in the non-rye containing treatments and in the control. In May 2014, treatments 1, 5 and the control, had significantly lower total nitrogen uptake compared to the remaining treatments. However, in June 2014, treatment 3 had the lowest total nitrogen uptake which was significantly different than the remaining treatments.

Differences in nitrogen uptake may be attributed to plant maturity and days after planting (DAP) harvest time. In 2012, cover crop biomass was harvested 149 DAP and then again 36 days later (185 DAP). At 149 DAP the all wheat control was between Feekes growth stage 7-8. At 185 DAP sufficient rainfall was received and the wheat control had reached the heading stage (Feekes growth stage 10.1). In 2013, due to low fall rainfall, biomass was harvested once at 201

DAP. At the time of harvest, the wheat control had reached the heading stage (Feekes growth stage 10.1). In 2014, due to extreme fall and spring drought, cover crop biomass was harvested 211 DAP and then again 28 days later (239 DAP). At the time of the first harvest, the winter wheat control was at Feekes growth stage 6-7, but the lack of rainfall limited vegetative growth. 239 DAP, the wheat control had reached the heading stage (Feekes growth stage 10.1), but wheat production was low due to limited early season growth and tillering. In summary, nitrogen uptake was much higher in 2012 and 2013 due to higher yields and nitrogen concentrations. In 2014, harvest dates were delayed due to limited rainfall and biomass production. Plant maturities were not the same across harvest dates, but they were very similar.

Fall Cover Crop ADF

Table 10 shows documentation that no significant differences were observed among treatment means for ADF, except in 2013. Here the rye containing treatments (2, 3 and 4) had the highest ADF. The ADF concentration is an integral part of forage digestibility, with lower ADF having higher forage digestibility. Therefore, although treatments 2, 3 and 4 produced consistently higher forage yield, than remaining treatments, the quality of this forage can be significantly lower than that found in the winter wheat control and treatments 1 and 5. In fact, despite the lack of significance in the remaining harvests, the ADF in treatments 3 and 4 was consistently higher than the winter wheat control and treatments 1 and 5.

Fall Cover Crop NDF

Significant differences among treatments were seen in 2013 and 2014 for neutral digestible fiber (NDF) concentrations (Table 11). Treatments 2, 3 and 4 contained the highest NDF and were significantly higher than treatment 5 in each of these harvests. In 2013, treatments 3 and 4 were also significantly higher than all remaining treatments. In 2013, the winter wheat control resulted in an intermediate NDF of 46.3. The NDF of forage is inversely proportional to the estimated dry matter intake (Oba and Allen, 1999) Therefore, it becomes apparent that the larger yields produced by treatments 2, 3 and 4 may be consumed at a greater rate than treatments 1 and 5, thereby potentially offsetting the benefits of the larger yields (Bates, 1999). Rye containing mixtures mature more rapidly in the spring than wheat, allowing for more rapid growth of the rye mixtures. However, because NDF increases as forage matures, this rapid growth comes with the cost of increased intake by grazing animals (Briceno et al., 1987).

Fall Cover Crop Relative Feed Value

Table 12 shows that there were significant treatment differences in relative feed value in 2013 and 2014. In 2013, the relative feed value was directly proportional to harvested yield, again suggesting that maximum yields are realized at the expense of forage quality (Rohweder et al., 1978). In 2014, differences in relative feed value were much less pronounced with treatment 3 having a significantly lower value than remaining treatments.

Summer Cover Crop Biomass Yield

There was no significant treatment by year interaction for biomass yield. Therefore, the five year average yield is presented in table 13. This analysis shows that yields from treatment 4 were significantly lower than remaining treatments and that treatment 3 was significantly lower than treatments 1, 2, 5 and 6 which were not significantly different from each other. Treatment 4 consistently performed poorly due to the fact that the mixture contained 60% broadleaves and 40% grasses. The safflower generally did not emerge in this treatment. The radish and buckwheat generally emerged but simply did not produce significant biomass. The limited growth of the broadleaves also resulted in a more weed infested plot area. Treatment 3 consisted of mungbean, cowpea, sunn hemp and Laredo soybean which had reduced yields compared to remaining treatments that contained mixtures of legumes and grasses or grasses only. These results are similar to the studies conducted by Wortman et al. (2011) and Teasdale and Abdul-Baki (1998) which indicate higher yields when comparing grass, and grass-legume cover crop mixtures to all legume mixtures. It is noteworthy, that when sudangrass was planted with a mixture of broadleaves, early season growth allowed it to out complete the other species, despite the fact that in these mixes, it represented less than 20% of the species composition by weight of seed. A representation of average plant stand count by species in one square meter can be seen in Table 27 in the appendices. In addition to its rapid growth, the small seed size allowed it to be over represented after emergence. This data confirms that maximization of forage yield is realized with mixtures containing grass species with high forage production potential such as pearl millet, sterile corn or sorghum sudangrass. Rachie and Majmudar (1980), Duvick (1958), and McGuire (2003) all indicated that the inclusion of pearl millet, sterile corn, or sorghum sudangrass in a crop mixture will maximize biomass yields. German millet is excluded from this list due to limited forage yield potential. The lack of significant yield differences among treatments, suggest that selection of grass species to include in a cover crop mixture can be based on factors other than forage yield.

Summer Cover Crop Nitrogen Concentration

There was a significant year by treatment interaction for nitrogen concentration. Furthermore, there were significant treatment differences in 2013 at the Demo farm and Lahoma and 2014 at Lahoma (Table 14). No treatment differences were seen in 2012, in both locations, due to the lack of in-season rainfall and severe drought. In 2013, lower treatment means for N concentration, in both locations, were observed due to higher forage biomass yields relative to other site years. Treatment differences in 2013, at the Demo farm, were seen due to high weed pressure from crabgrass which prevented full establishment and production of the cover crops. However, N concentration for treatment 4 was lower because the german millet, present in the treatment had senesced prior to harvest.

Treatment differences occurred in 2013 at Lahoma in which treatments 2 and 3 had the highest nitrogen concentrations (1.27 and 1.21%), and treatment 5 had the lowest concentration

(0.83%). The low nitrogen content found in treatment 5 is expected because it contained only grasses, and the high nitrogen content found in treatment 2 resulted from the fact that this treatment consisted of only legumes. The nitrogen concentration in treatment 3 was low in 2013, compared to published values for these legumes because they were harvest after flowering. Furthermore, in 2013 the mungbeans were fully mature at harvest. In addition, the mungbean did not nodulate in 2013, further reducing the capacity for this treatment to fix nitrogen. The mungbean was a dominate species in treatment 3 in 2013, this explains the issue that the nitrogen concentrations are similar for treatments 2 and 3 because the mungbean diluted the treatment 3 nitrogen concentration in the same way that the non-legumes diluted the nitrogen concentrations of treatments 1, 2, and 6.

In 2014, the differences among treatments were more pronounced because the mungbean nodulated in 2014. This resulted in the nitrogen concentration for treatment 3 to be significantly greater than that found in all remaining treatments. The nitrogen concentrations in treatment 1 were significantly greater than remaining treatments because unlike the other site years, the german millet was not as prominent in this year as it was in all other years. A 38 mm rainfall event occurring 3 days after planting stimulated optimum emergence of the broadleaves in this treatment. As a result, stunted emergence of the small seeded german millet occurred due to crusting. Again in 2014, treatment 5, which was comprised mostly of grass species, had the lowest nitrogen concentration. Similarly to 2013, treatments 4 and 6 had intermediate nitrogen concentrations as would be expected from grass/legume mixtures.

Summer Cover Crop Total Nitrogen Uptake

There was a significant year by treatment interaction for total nitrogen uptake (Table 15). Furthermore, there were significant treatment differences across all site years. Treatment differences were seen in 2012, followed the same trend as was seen in forage yield, with treatment 4 having significantly lower total nitrogen uptake than all remaining treatments. Treatment differences were seen in 2013 Demo, in which treatments 2, 5 and 6 had the highest total nitrogen uptake which was significantly greater than treatments 1 and 3 which was significantly greater than treatment 4. Treatment differences occurred in 2013, at Lahoma, in which treatments 1, 2, and 3 had significantly higher total nitrogen uptake than all remaining treatments. In 2014, at Lahoma, treatments 1 and 3 had the highest total nitrogen uptake, 57 and 69 kg ha^{-1}, which were significantly different than treatment 2, 43 kg ha^{-1}, which was significantly different than the remaining treatments.

These results indicate that the inclusion of a legume may increase total nitrogen uptake in summer cover crops. However, the inconsistency in total nitrogen uptake illustrates the difficulty in evaluating cover crop mixtures. Specifically, each site year can produce different results due to differences in environmental and management factors that can impact differences in species establishment, legume nodulation, species growth and maturity rate. These results are consistent with Ledgard and Steele (1992), which indicated that grasses and legumes, when planted together, legumes out compete grasses for the uptake of nitrogen.

Summer Cover Crop ADF

There was a significant year by treatment interaction for average acid digestible fiber concentration. Furthermore, there were significant treatment differences across all site years, except 2013 Demo (Table 16). In 2012, in both locations, treatment 1 resulted in the highest average ADF, which was not significantly differently than the ADF in treatments 3 and 4, which were significantly different than the remaining treatments. The ADF in treatment 2 were significantly high than that found in treatments 5 and 6. Treatments 5 and 6 were dominated by sudangrass in 2012. In contrast, treatments 1 and 4 were dominated by german millet which matures more rapidly in comparison to sorghum sudangrass (Table 6). In fact, in 2012, the german millet had senesced prior to harvest. Furthermore, in 2012, treatment 3 had significantly higher ADF due to environmental stresses and weed pressure from crabgrass resulting in poor plant establishment, growth and performance.

There were no differences in ADF at the demo farm in 2013 due to weed pressure from crabgrass. However, treatment 4 had the highest ADF (40.6%) due to the presence of german millet, which competed with the crabgrass, but had senesced prior to harvest, thus resulting in a higher ADF value. At the lahoma location, in 2013, ADF was significantly lower in treatments 5 and 6 than remaining treatments, which followed the trends from data collected from 2012. In contrast, treatment 3 had the lowest ADF at lahoma in 2014. This is likely due to the excellent crop growth and performance of this legume treatment observed in 2013.

ADF concentration is an integral part of forage digestibility, with lower ADF having higher forage digestibility. Therefore, based on forage biomass yields and ADF values, treatments 5 and 6 would contribute greater amounts of higher quality forage with respect to ADF.

Summer Cover Crop NDF

There was a significant year by treatment interaction for neutral digestible fiber concentration. In 2012 for both locations, no treatment differences were seen (Table 17). In 2013, at the Demo farm, treatment 4 had the highest NDF content (60.4%) which was statistically different than all other treatments. This is likely due to the fact that at this location, crabgrass contaminated all the treatments. However, the german millet in this treatment did compete well with it. Furthermore, the german millet had senesced prior to harvest making the NDF higher for this treatment. On the other hand, despite the crabgrass, some cowpeas were present in treatment 3 which is likely responsible for the lower NDF value for this treatment. In 2013 at Lahoma, treatment 3 has the lowest NDF content (51.4%) which was statistically different than all other treatments. This illustrates, that at this location, all treatments except for treatment 3, were dominated by grass species of moderate to low quality at harvest. In 2014, treatment 5 resulted in the highest average NDF, but was not significantly differently than the NDF in treatments 2 and 6, which were significantly different that the remaining treatments. The similarity of these treatments, with respect to NDF, is likely due to the fact that the sorghum sudangrass was responsible for most of the dry matter produced. Similarly to data collected in 2013, treatment 3 contained the lowest NDF (33.3%). However, unlike the data collected in 2013, where treatment 4 had a NDF concentration that was above the site average, this treatment provided an intermediate NDF. This resulted from the fact that the german millet did not mature as rapidly in 2014, and this treatment contained more buckwheat and safflower than observed in previous years. Similarly, treatment 1 was not dominated by german millet in 2014, as was the case in prior site years. Therefore, the prevalence of the broadleaves causes a relatively lower NDF for this treatment, in this site year, compared to previous years.

Neutral digestible fiber is another integral part of forage digestibility, with lower NDF having higher forage digestibility. Therefore, based on NDF alone, treatment 3 would contribute the highest digestibility across all site years.

Summer Cover Crop Relative Feed Value

There was a significant year by treatment interaction for relative feed value. No treatment differences were seen in 2012 (Table 18). No significant treatment differences were seen in 2013, in all locations. In 2013, at the Demo farm, relative feed values were much lower due to much higher weed pressure than the year before. An infestation of crabgrass and other grassy weeds reduced crop growth and performance even greater. The results indicate that the presence of crabgrass and other grassy weeds can reduce relative feed value.

In 2013, at Lahoma, relative feed values were much higher than recorded at the Demo farm. There were no significant treatment differences seen in 2013 at Lahoma. However, treatment 3, which is comprised of 100% legume species, had the highest relative feed value. In this site year, very little weed pressure was present, allowing for more normal growing conditions. This provided a more accurate picture of plant productivity.

In 2014, at Lahoma, there were treatment differences seen in which treatment 3 had the highest relative feed value (187), which was statistically different than the remaining treatments. In 2014, an earlier planting date could be the cause for such wide variability of relative feed values between treatments. At the time of harvest, in 2014, treatment 3 had not yet reached physiological maturity resulting in a much higher relative feed value. However, all remaining treatments had reached physiological maturity and had begun to senesce at the time of harvest.

CONCLUSIONS

Fall Cover Crops

Fall cover crop forage performance was dependent on rainfall distribution and species composition which affects crop production as well as forage quality. Treatments that included rye, tended to have greater yields across the three site years. However, forage quality for these rye containing treatments were consistently lower when compared with the other treatments. Reduced forage quality for these rye treatments affects forage intake when feeding animals. Therefore, more feed and other supplements are required to meet the animal's nutritional requirements.

Treatments without rye had improved forage quality traits and higher feed values. Forage quality and feed values of these treatments (1 and 5) were similar, if not better, than the wheat control. However, they did result in lower yields compared to wheat

Fall cover crop yields and forage quality values were fairly consistent between treatments across site years. During the time of this trial, there were three very different growing seasons (see rainfall distribution graphs in appendices). However, despite these differences in growing conditions, similar treatment responses were observed in each season.

In the 2011-2012 growing season, there was a dry fall and a wet spring compared to normal seasonal averages for this site. Early spring rains, coupled with mild temperatures, resulted in a high yielding environment for the cover crops. In the 2012-2013 growing season, there was a semi-wet fall and a wet spring. More uniform rainfall distribution in the fall and spring also resulted in a high yielding environment for theses cover crop mixtures. The 2013-2014 growing season, there was a very dry fall and dry spring. As a result, cover crop yields were significantly lower than previous years.

In summary, there are a few fall cover crop alternatives that performed as well or better than the all winter wheat control. The recommendation for choosing a fall cover crop mixture is highly dependent on the needs of the individual. If a producer has a market for hay production, then choosing a heavily concentrated rye based mixture is encouraged. However, if a producer is feeding cattle with these heavy rye mixtures, intake efficiency will be lower and more forage will be consumed. If a producer wants to stockpile forage for feed, then choosing a mixture (non-rye) that combines forage quality and yield potential to the highest degree is encouraged.

Summer Cover Crops

Growth, productivity, and forage quality of summer cover crops was highly dependent on environmental stresses, such as temperature and rainfall. Furthermore, weed pressure contributed to limited crop growth and forage quality of summer cover crops. Timely establishment is an important consideration that may impact the capacity of these cover crops to control weed pressure. Herbicide termination of weeds, at the time of planting, could also be considered.

Species composition of summer cover crop mixtures should also be considered with respect to producing high quality forage used for feeding. In these site years, cover crop mixtures containing 100% legume plant species produce the highest quality forage with intermediate production, while mixtures containing grasses maximize production but have reduced quality.

Treatment 3 (legume mixture) consisting of cowpea, mungbean, sunn hemp, and Laredo soybean had the highest average nitrogen concentration (1.91%) across all site years and locations. Treatment 3 also had the highest forage quality as shown by the lowest neutral digestible fiber content (37.2%), and highest average relative feed value (143.1). Treatment 3 was the only treatment consistently capable of feeding dairy cows, young heifers (3-12 months) and stocker cattle (Undersander, 2003).

In summary, species composition of summer cover crops affected crop yield and forage quality. Like the fall cover crops, the recommendation for choosing a summer cover crop mixture is highly dependent on the needs of the individual. If a producer has a market for hay production, then choosing a grass based mixture may be encouraged, realizing forage quality and intake efficiency will be lower. However, if a producer aims to graze or use forage as hay, then choosing a mixture, with different legumes, that combines forage quality and yield potential to the highest degree is encouraged.

REFERENCES

Abel, G.H. 1976. Effects of irrigation regimes, planting dates, nitrogen levels, and row spacing on safflower cultivars. Agron. J. 68:448-451

Akemo, M.C., E.E. Regnier, and M.A. Bennett. 2000. Weed suppression in spring-sown rye (Secale cereal)-pea (Pisum sativum) cover crop mixes. Weed Technology. 14:545-549.

Anderson, R.L., 2008. Growth and yield of winter wheat as affected by preceding crop and crop management. Agron J. 100:977-980.

Andraski, T.W. and L.G. Bundy. 2005. Cover crops effects on corn yield response on nitrogen on an irrigated sandy soil. Agron. J. 97:1239-1244.

ANKOM Technology. 2011. Method for determining acid detergent fiber. https://www.ankom.com/procedures.aspx.

Balkom, K.S. and D.W. Reeves. 2005. Sunn-hemp utilized as a legume cover crop for corn production. Agron. J. 97:26-31.

Barnes, J.P., A.R. Putnam, B.A. Burke., and A.J. Aasen. 1987. Isolation and characterization of allelochemicals in rye herbage. Phytochemistry 26:1385-1390.

Barnhart, S.K. 2010. Forage and cover crop considerations for delayed planting and flooded sites. Iowa State University Cooperative Extension Fact Sheet. Available at http://www.extension.iastate.edu/CropNews/2010/0629barnhart.htm.

Bates, G. 1999. Small grains, ryegrass and clovers for forage. The University of Tennessee Agricultural Extension Service Fact Sheet SP 434-A.

Berglund, D.B., N. Riveland, and J. Bergman. 1998. Safflower production. NDSU Ext. Circ. A-870 (revised). North Dakota Agric. Exp. Stn., North Dakota State Univ., Fargo

Biederbeck, V.O., and O.T. Bouman. 1994. Water use by annual green manure legumes in dryland cropping systems. Agron. J. 86:543-549.

Briceno, J.V., H.H Van Horn, B. Harris Jr., C.J. Wilcox. 1987. Effects of neutral detergent fiber and roughage source on dry matter intake and milk yield and composition of dairy cows. J. of Dairy Sci. 70:298-308.

Brown, B.A., and R.I. Munsell. 1943. Grasses fertilized with nitrogen compared with legumes for hay and pasture. Agron. J. 35:811-816.

Bugg, R.L., G. McGourty, M. Sarrantonio, W.T. Lanini, and R. Bartolucci. 1996. Comparision of 32 cover crops in an organic vineyard on the north coast of California. Biol. Agric. Hortic. 13:63-81.

Burton, G.W., A.T. Primo, and R.S. Lowrey. 1986. Effect of clipping frequency and maturity on the yield and quality of four pearl millets. Crop Sci. 26:79-81.

Butchee, J.D. and J.T. Edwards. 2013. Dual-purpose wheat grain yield as affected by growth habit and simulated grazing intensity. Crop Sci. 53:1686-1692.

Canadian Organic Growers Inc. 1992. Organic field crop handbook. Anne Macey (ed.). Canadian Organic Growers Inc., Ottawa, Ontario.

Carrera. L.M., A.A. Abdul-Baki, and J.R. Teasdale. 2004. Cover crop management and weed suppression in no-tillage sweet corn production. Hort. Sci. 39(6): 1262-1266.

Chase, W.R., M.G. Nair, and A.R. Putnam. 1991. 2,2’-OXO,1’-Azobenzene: Selective toxicity of rye (*Secale cereale* L.) allelochemicals to weed and crop species:II. J. of Chem. Ecology. 17:9-19.

Clark, A.J., A.M. Decker, and J.J. Meisinger. 1994. Seeding rate and kill date effects on hairy vetch-cereal rye cover crop mixtures for corn production. Agron. J. 86:1065-1070.

Conservation Technology Information Center. 2004. National survey of conservation tillage practices. Available at http://www.ctic.purdue.edu/CTIC%20HOME/. CTIC, West Lafayette, IN.

Creamer, N.G. and K.R. Baldwin. 1999. Summer Cover Crops. North Carolina State University Cooperative Extension Fact Sheet HIL-37.

Creamer, N.G, M.A. Bennett, B.R. Stinner, J. Cardina, and E.E. Regnier. 1996. Mechanisms of weed suppression in cover crop based production systems. Hort. Sci. 31:410-413.

Dadashi, N. and M.R. Khajehpour. 2004. Effects of planting date and cultivar on growth, yield components and seed yield of safflower in Isfahan. JWSS. 8:95-112.

Decker, J.E., F.M. Epplin, D.L. Morley, and T.F. Peeper. 2009. Economics of five wheat production systems with no-till and conventional tillage. Agron. J. 101:364-372.

Delgado, J.A. 1998. Sequential NLEAP simulations to examine effect of early and late planted winter cover crops on nitrogen dynamics. J. Soil Water Conserv. 53:241-244.

Delgado, J.A. and J. Lemunyon. 2006. Nutrient Management. Pp. 1557-1160. In R. Lal (ed.). Encyclopedia Soil Sci. Markel and Decker, New York, pp 1924. NY.

Delgado, J.A., R.T. Sparks, R.F. Follett, J.L. Sharkoff, and R.R. Riggenbach. 1999. Use of winter cover crops to conserve soil and water quality in the San Luis Valley of South Central

Colorado. Pp 125-142. In R. Lal (ed.). Soil Quality and Soil Erosion. CRC Press, Boca Raton, FL.

Duvick, D.D. 1958. Yields and other agronomic characteristics of ytoplasmically pollen sterile corn hybrids, compared to their normal counterparts. Agron. J. 1958. p:121-125.

Emami, T., R. Naseri, H. Falahi, and E. Kazemi. 2011. Response of yield, yield component and oil content of safflower (*cv*. Sina) to planting date and plant spacing on row in rainfed conditions of western Iran. American-Eurasion J. Agric. &Environ. Sci., 10 (6):947-953.

Feyereisen, G.W., B.N. Wilson, G.R. Sands, J.S. Strock, and P.M. Porter. 2006. Potential for a rye cover crop to reduce nitrate loss in southwestern Minnesota. Agron. J. 98:1416-1426.

Forney, D.R. and L.F. Chester. 1984. Phytotoxicity of products from rhizospheres of a sorghum-sudangrass hybrid. Weed Sci. 33:597-604.

Francois, L.E., and L. Berstein. 1964. Salt tolerance of safflower. Agron. J. 56: 38-40.

Franzluebbers, A.J., 2007. Integrated Crop-Livestock Systems in the Southeastern USA. Agron. J. 99:361-372.

Franzluebbers, A.J., and J.A. Stuedemann. 2008. Soil physical responses to cattle grazing cover crops under conventional and no tillage in the Southern Piedmont USA. Soil Tillage Res., 100: 141-153.

French, R.J. 1978. The effect of fallowing on the yield of wheat. II. The effect of grain yield. Aust. J. Agric. Res. 29: 669-684.

Gallandt, E.R. M. Liebman, S. Corson, G.A. Porter, and S.D. Uhllrich. 1998. Effects of pest and soil management systems on weed dynamic potatoes. Weed Sci. 46:238-248.

Henderson, C. W. 1989. Lupin as a biological plough: evidence for, and effects on wheat growth and yield. Austr. J. of Exp. Ag. 29:99-102.

Hofstetter, B. 1998. The new farm's cover crop guide: 53 legumes, grasses and legume-grass mixes you can use to save soil and money. The New Farm 10:17-31.

Hossain, I., F.M. Epplin, G.W. Horn, and E.G. Krenzer, Jr. 2004. Wheat production and management practices used by Oklahoma grain and livestock producers. Bull. B-818. Oklahoma Agric. Exp. Stn., Stillwater.

Irving, D.W., M.C. Shannon, V.A. Breda and B.E. Mackey. 1988. Salinity effects on yield and oil quality of high-linoleate and high-oleate cultivars of safflower (*Carthamus tinctorious* L.) J. Agric. Food Chem. 36: 37-42.

Jajarmi, V., M. Azizi, A. Shadlu, and A.H. Omidy Tabrizi. 2005. The effect of density, variety, and planting date on yield and yield components of safflower. 7th International Safflower Conference, Wagga Wagga, Australia.

Jeranyama, P. and A.D. Garcia. 2004. Understanding relative feed value (RFV) and relative forage quality (RFQ). South Dakota State University Cooperative Extension Service Extension Extra ExEx8149.

Johnson, A.M., D.L. Tanaka, P.R. Miller, S.A. Brandt, D.C. Nielsen, G.P. Lafond and N.R. Riveland. 2002. Oilseed crops for semiarid cropping systems in the northern great plains. Agron. J. 94: 231-240.

Kaffka, S.R. and T.E. Kearney. 1998. Safflower production in California. UCANR Publications. Vol. 21565.

Khoransani, G.R., E.K. Okine, and J.J Kennelly. 1996. Forage source alters nutrient supply to the intestine without influencing milk yield. J. of Dairy Sci.79:862-872.

Kihimba, F.C., Ranjan, R.S., Froese, J., Entz, M., and Nason, R. 2008. Cover crop effects on infiltration, soil temperature, and soil moisture distribution. Applied Engineering in Ag. 24:321-333.

Knowles, P.F. 1958. Safflower. Adv. Agron. 10:289-323.

Kobayashi, H., S. Miura, and A. Oyanagi. 2004. Effects of winter barley as a cover crop on the weed vegetation in a no-tillage soybean. Weed Biology and Management. 4:195-205.

Kuo, S., and Jellum, E.J. 2000. Long-term winter cover cropping effects on corn (*Zea mays* L.) production and soil nitrogen availability. Biol. Fertil. Soils 31:470-477.

Large, E.C. 1954. Growth stages in cereals: Illustrations of the Feekes scale. Plant Pathol. 3:128-129.

Lawley, Y., R. Weil, J.R. Teasdale. 2011. Forage radish winter cover crops suppress winter annual weeds in fall and prior to corn planting. Agron. J. 103:137–144.

Lal, R., 1984. Mechanized tillage systems effects on soil erosion from an alfisol in watersheds cropped to maize. Soil Tillage Res., 4:349-360.

Lipman, J.G. 1912. The associative growth of legumes and nonlegumes. Bull. No. 253. N.J. Agr. Exp. Sta., New Brunswick. 48 pp.

Long, D.S., Wraith, J.M., and Kegel, G. 2002. A heavy-duty time domain reflectometry soil moisture probe for use in intensive field sampling. Soil Sci. Soc. Am. J. 66:396-401.

McGuire, A. 2003. Sudangrass and sorghum-sudangrass hybrids. Washington State University Cooperative Extension Factsheet EB1950E.

Meisinger, J.J., Hargrove, W.L., Mikkelson, R.L., Williams, J.R., and Benson, V.W., 1991. Effects of cover crops on groundwater quality. P. 57-68. In W.L. Hargrove (ed.) Cover crops for clean water. Proc. Int. Conf., Jackson, TN. 9-11 April. 1991. Soil and Water Conservation Society., Ankeny, IA.

Mulla, D.J. 1988. Estimating spatial patterns in water content, matric suction, and hydraulic conductivity. Soil Sci. Am. J. 52:1547-1553.

Mustafa, A.F., D.A. Christensen, and J.J McKinnon. 2000. Effects of pea, barley, and alfalfa silage on ruminal nutrient degradability and performance of dairy cows. J. of Dairy Sci. 83:2859-2865.

National Forage Testing Association. 1993 Forage Analysis Procedures. http://www.foragetesting.org/index.php?page=lab_procedures.

Norwood, C. 1994. Profile water distribution and grain yield as affected by cropping system and tillage. Agron. J. 86:558-563.

Odhiambo, J.J and Bomke, A.A. 2007 Cover crop effects on spring soil water content and the implications for cover crop management in south coastal British Columbia. Agricultural Water Management. 88:92-98.

Oelke, E.A., E.S. Oplinger, H. Bahri, B.R. Durgan, D.H. Putnam, J.D. Doll, and K.A. Kelling. 1990. Rye. Alternative Field Crops Manual. University of Wisconsin Cooperative Extension. University of Minnesota. Available at http://www.hort.purdue.edu/newcrop/afcm/.

Parkin, T.B., T.C. Kaspar and C.A. Cambardella. 1997. Small grain cover crops to manage nitrogen in the Midwest. Cover Crops, Soil Quality, and Ecosystems Conference. California Soil and Water Conservation Society, Ankeny, Iowa.

Peterson, R.G. and Calvin, L.D. 1986. Sampling, p.33-52. In A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison. WI.

Pieters, A.J., 1927. Green manuring principles John Wiley & Sons, Inc., New York, N.Y. 356 pp.

Rachie, K.O., and J.V. Majmudar. 1980. Pearl millet. The Pennsylvania State University Press, University Park, PA.

Rao, S.C., S.W. Coleman, and J.D. Volesky. 2000. Yield and quality of wheat, triticale, and elytricum forage in the southern plains. Crop Sci. 40:1308-1312.

Rohweder, D.A., R.F. Barnes and N. Jorgensen. 1978. Proposed hay grading standards based on laboratory analysis for evaluating quality. J. Anim. Sci. 47:747-759.

Sabbe, W.E. and Marx, D.B. 1987. Soil sampling: spatial and temporal variability. p.1-14. In J.R. Brown (ed.) Soil testing: Sampling, correlation, calibration, and interpretation. SSSA Spec. Publ. 21. SSSA, Madison, WI.

Samanci, B. and Ozkaynak, E. 2003. Effect of planting date on seed yield, oil content, and fatty acid composition of safflower (Carthamus tinctorius) cultivars grown in the Mediterranean region of Turkey. J. Agron. Crop Science. 189: 359-360.

Seadh, S.E., A.N Attia, M.A. Badawi, and S.M. El-Hety. 2012. Response of seed yield and its components of safflower to sowing dates, nitrogen fertilizer levels and times of foliar application with milagrow. Journal of Biological Sciences, 12: 342-348.

Shira, N., Soleymani, A., Shams, M. 2013 Effect of sowing date and different planting management, on seed yield and yield components of Safflower in Isfahan Region. Intl. J. of Agric. and Crop Sci. Vol., 5 (9): 911-913.

Smith, E.G., Heigh, L., Klein, K.K., Moyer, J.R., Blackshaw, R.E. 2001. Economic analysis of cover crops in summer fallow-crop systems. J. of Soil and Water Cons. 56:315-321.

Smith, J.R. Safflower. Amer Oil Chemists Society, 1996.

Snapp, S.S., Swinton, S.M., Labarta, R., Mutch, D., Black, J.R., Leep, R., Nyiraneza, J., and O'neil, K. 2005. Evaluating cover crops for benefits, costs and performance within cropping system niches. Agron. J. 97:322-332.

Teasdale, J.R., A.A. Abdul-Baki. 1996. Comparison of mixtures vs. monocultures of cover crops for fresh-market tomato production with and without herbicide. Hort. Sci. 33:1163-1166.

True, R.R., F.M. Epplin, E.G, Krenzer, Jr., and G.W. Horn. 2001. A survey of wheat production and wheat forage use practices in Oklahoma. Bulletin B-815. Oklahoma Agric. Exp. Stn., Stillwater.

Undersander, D. 2003. The new relative forage quality index- concept and use. World's forage superbowl contest, UWEX.

Unger, P.W. and T.C. Kaspar, 1994. Soil compaction and root growth: A review. Agron. J. 86:759-766.

USDA ARS Fact Sheet. 2005. SoilSaver- a black oat winter cover crop for the lower southeastern coastal plain. Conservation Systems Fact Sheet No. 01.

Wagner, R.E. 1954. Legume nitrogen versus fertilizer nitrogen in protein production of forage. Agron. J. 46:232-237.

Welty, L., 1991. Effect of harvest management and nurse crop on production of five small-seeded legumes. Monatana Ag Research 8:11-14.

Williams, S.M and R.R. Weil, 2004. Cover crop root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. 68:1403-1409.

Wortman, S.E., C.A. Francis, and J.L. Lindquist. 2011. Cover crop mixture for the western corn belt: opportunities for increased productivity and stability. Agron J. 104:699-705.

Table 1. Treatments, crop species and seeding rates for fall planted cover crops from 2011-2014. Species in each treatment are abbreviated as follows: Barley (B), Canola (C), Oat (O), Radish (R), Rye (Ry), Triticale (T), Wheat (W).

Treatment	Crop Species	Seeding Rate
		----kg ha^{-1}----
Trt 1 (BCRT)	Barley, Canola, Radish, Triticale	67
Trt 2 (BORRyT)	Barley, Oat, Radish, Rye, Triticale	67
Trt 3 (BCORRy)	Barley, Canola, Oat, Radish, Rye	67
Trt 4 (CRRy)	Canola, Radish, Rye	67
Trt 5 (BORW)	Barley, Oat, Radish, Wheat	67
Trt 6 (W)	Wheat (Duster)	67

Table 2. Treatments, and crop species as a percentage of weight for fall planted cover crops from 2011-2014.

Crops Species	Trt 1	Trt 2	Trt 3	Trt 4	Trt 5	Control
			% Species in each treatment			
Barley	47	24	31	-	32	-
Oats	-	24	31	-	32	-
Rye	-	24	31	92	-	-
Tritcale	47	24	-	-	-	-
Wheat	-	-	-	-	32	100
Radish	4	4	5	4	4	-
Canola	2	-	2	4	-	-

Table 3. Planting and forage biomass harvest dates for fall planted cover crops from 2011-2014.

Planting Date	Harvest Date(s)
17 October 2011	14 March 2012, 19 April 2012
18 October 2012	7 May 2013
10 October 2013	9 May 2014, 6 June 2014

Table 4. Planting and forage biomass harvest dates for summer cover crops from 2012-present at Geary (Demo and Lagoon) and Lahoma, OK.

Location	Planting Date	Harvest Date(s)
Demo	11 June 2012	2 October 2012
	28 June 2013	20 September 2013
Lagoon	11 June 2012	2 October 2012
Lahoma	1 July 2013	5 September 2013
	20 June 2014	3 September 2014

Table 5. Treatments, crop species and seeding rates for summer cover crops from 2012-present at Geary (Demo and Lagoon) and Lahoma, OK. Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

Treatment	Crop Species	Seeding Rate
		--kg ha^{-1}--
Trt 1 (ShRCwGm)	Sunn Hemp, Radish, Cowpea, German Millet	33
Trt 2 (CnSsSuCw Sh)	Corn, Sorghum Sudan, Sunflower, Cowpea, Sunn Hemp	33
Trt 3 (MCwShLs)	Mungbean, Cowpea, Sunn Hemp, Laredo Soybean	33
Trt 4 (SfBGmR)	Safflower, Buckwheat, German Millet, Radish	33
Trt 5 (PmGmSs)	Pearl Millet, German Millet, Sorghum Sudan	33
Trt 6 (CwPmSsMLs)	Cowpea, Pearl Millet, Sorghum Sudan, Mungbean, Laredo Soybean	33

Table 6. Treatments, crop species composition (% of weight planted), and estimated days to maturity for summer planted cover crops from 2011-present at Geary (Demo and Lagoon) and Lahoma, OK.

Crops Species	Trt 1	Trt 2	Trt 3	Trt 4	Trt 5	Trt 6	Days to Maturity
			% Species in each treatment				
Cowpea	40	36	35	-	-	22	60-90
Mungbean	-	-	35	-	-	21	90-120
Laredo Soybean	-	-	17	-	-	21	90-120
Sunn Hemp	20	16	13	-	-	-	60-90
S. Sudan	-	16	-	-	33	18	65-90
Corn	-	16	-	-	-	-	90-120
P. Millet	-	-	-	-	33	18	90-100
G. Millet	33	-	-	40	34	-	75-90
Sunflower	-	16	-	-	-	-	90-100
Radish	7	-	-	8	-	-	45-70
Buckwheat	-	-	-	12	-	-	70-90
Safflower	-	-	-	40	-	-	110-140

Table 7. Average biomass yield kg ha^{-1} for four site years of fall planted cover crops in Geary, Oklahoma. Species in each treatment are abbreviated as follows: Barley (B), Canola (C), Oat (O), Radish (R), Rye (Ry), Triticale (T), Wheat (W).

	March 2012	April 2012	2012 Total	2013 Total	May 2014	June 2014	2014 Total	3 Year Total Ave.
				------------------DM kg ha^{-1}---------------				
Trt 1 (BCRT)	1896 b†	5844	7740	5657 d†	562 c†	2105	2668 b†	5355 c†
Trt 2 (BORRyT)	2496 a	5608	8105	7498 c	1381 b	1772	3151 b	6253 b
Trt 3 (BCORRy)	2125 a	6306	8432	8958 b	2208 a	1651	3447 b	6946 a
Trt 4 (CRRy)	2582 a	5964	8546	10610 a	2844 a	1952	4797 a	7985 a
Trt 5 (BORW)	2125 c	5980	7490	3991 e	300 c	1785	2085 c	4522 d
Control (W)	2410 a	5728	8138	6282d	863 b	1745	2608 b	5677 c

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

Table 8. Average nitrogen concentration for three site years of fall planted cover crops in Geary, Oklahoma. Species in each treatment are abbreviated as follows: Barley (B), Canola (C), Oat (O), Radish (R), Rye (Ry), Triticale (T), Wheat (W).

	March 2012	April 2012	2013	May 2014	June 2014
			---------------------Nitrogen Concentration %---------------		
Trt 1 (BCRT)	4.16	2.65 a†	2.23	1.49 b†	2.44
Trt 2 (BORRyT)	4.04	2.96 a	2.12	1.53 b	2.14
Trt 3 (BCORRy)	4.07	2.88 a	2.48	1.26 b	2.06
Trt 4 (CRRy)	4.26	2.63 a	2.07	1.52 b	2.15
Trt 5 (BORW)	4.21	2.56 b	2.47	1.93 a	2.54
Control (W)	3.84	2.36 c	2.49	1.54 b	2.23

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

Table 9. Average total nitrogen uptake kg ha^{-1} for three site years of fall planted cover crops in Geary, Oklahoma. Species in each treatment are abbreviated as follows: Barley (B), Canola (C), Oat (O), Radish (R), Rye (Ry), Triticale (T), Wheat (W).

	March 2012	April 2012	2013	May 2014	June 2014
	---------------------Nitrogen Uptake kg ha^{-1}---------------				
Trt 1 (BCRT)	79 b†	154 a†	126 b†	19 c†	30 a†
Trt 2 (BORRyT)	100 a	165 a	158 b	36 b	26 a
Trt 3 (BCORRy)	87 a	183 a	221 a	59 a	20 b
Trt 4 (CRRy)	109 a	159 a	219 a	80 a	30 a
Trt 5 (BORW)	62 c	154 a	98 c	10 c	33 a
Control (W)	92 a	135 b	157 b	26 c	26 a

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

Table 10. Average acid digestible fiber concentration for three site years of fall planted cover crops in Geary, Oklahoma. Species in each treatment are abbreviated as follows: Barley (B), Canola (C), Oat (O), Radish (R), Rye (Ry), Triticale (T), Wheat (W).

	March 2012	April 2012	2013	May 2014	June 2014
	----------------------------% ADF-------------------------				
Trt 1 (BCRT)	33.5	38.8	32.8 b†	31.7	36.4
Trt 2 (BORRyT)	32.9	37.1	35.3 a	33.8	38.6
Trt 3 (BCORRy)	31.6	36.4	36.3 a	35.1	40.1
Trt 4 (CRRy)	34.4	39.1	38.2 a	35.1	39.9
Trt 5 (BORW)	33.7	38.3	33.1 b	31.3	36.8
Control (W)	30.9	35.3	31.9 b	32.8	37.9

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

Table 11. Average neutral digestible fiber concentration for three site years of fall planted cover crops in Geary, Oklahoma. Species in each treatment are abbreviated as follows: Barley (B), Canola (C), Oat (O), Radish (R), Rye (Ry), Triticale (T), Wheat (W).

	March 2012	April 2012	2013	May 2014	June 2014
	-----------------------------% NDF			--------------------------	
Trt 1 (BCRT)	48.9	56.0	47.9 c†	48.6 a†	52.3 a†
Trt 2 (BORRyT)	45.8	51.2	52.0 b	49.5 a	54.2 a
Trt 3 (BCORRy)	46.3	50.3	53.6 a	51.7 a	57.2 a
Trt 4 (CRRy)	50.9	55.4	55.6 a	48.7 a	54.8 a
Trt 5 (BORW)	48.6	54.0	43.5 d	44.9 b	50.2 b
Control (W)	46.4	51.3	46.3 c	49.5 a	53.8 a

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

Table 12. Average relative feed value Index for three site years of fall planted cover crops in Geary, Oklahoma. Species in each treatment are abbreviated as follows: Barley (B), Canola (C), Oat (O), Radish (R), Rye (Ry), Triticale (T), Wheat (W).

	March 2012	April 2012	2013	May 2014	June 2014
	----------------------------	-Relative Feed Value		--------------------------	
Trt 1 (BCRT)	120.7	97.8	123.1 b†	125.5 a†	107.6 a†
Trt 2 (BORRyT)	130.9	110.6	109.9 c	117.8 a	101.1 a
Trt 3 (BCORRy)	130.4	112.6	105.2 c	110.7 b	93.8 b
Trt 4 (CRRy)	114.2	98.7	99.0 d	119.5 a	99.4 a
Trt 5 (BORW)	120.3	102.0	135.2 a	134.3 a	112.1 a
Control (W)	131.2	112.0	128.9 a	120.4 a	103.1 a

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

Table 13.Average biomass yield kg ha^{-1} for five site years of summer planted cover crops at Geary (Demo and Lagoon) and Lahoma, OK. Crop type for each treatment is abbreviated: Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

	2012 Demo	2012 Lagoon	2013 Demo	2013 Lahoma	2014 Lahoma	5 Yr Ave.
	-----------------DM Yield kg ha^{-1}---------------					
Trt 1 (ShRCwGm)	2584 a†	2913 a†	2757	3881	2657	2959 a†
Trt 2 (CnSsSuCw Sh)	2903 a	3415 a	3899	3830	2833	3376 a
Trt 3 (MCwShLs)	2550 a	2935 a	2398	3272	2312	2694 b
Trt 4 (SfBGmR)	652 b	980 b	2587	2078	2028	1665 c
Trt 5 (PmGmSs)	2604 a	3034 a	3465	3034	2992	3026 a
Trt 6 (CwPmSsMLs)	2290 a	2610 a	3069	3704	2928	2920 a

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

Table 14. Average nitrogen concentration % for five site years of summer planted cover crops at Geary (Demo and Lagoon) and Lahoma, OK. Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

	2012 Demo	2012 Lagoon	2013 Demo	2013 Lahoma	2014 Lahoma
	-----------------Nitrogen Concentration %---------------				
Trt 1 (ShRCwGm)	1.94	1.94	1.07 a†	1.06 b†	2.17 b†
Trt 2 (CnSsSuCw Sh)	2.17	2.18	1.14 a	1.27 a	1.51 c
Trt 3 (MCwShLs)	2.13	2.14	1.09 a	1.21 a	3.00 a
Trt 4 (SfBGmR)	2.04	2.04	0.85 b	0.99 c	1.54 c
Trt 5 (PmGmSs)	2.36	2.37	0.98 a	0.83 d	1.05 d
Trt 6 (CwPmSsMLs)	2.35	2.36	1.17 a	0.88 c	1.28 c

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

Table 15. Average total nitrogen uptake kg ha^{-1} for five site years of summer planted cover crops at Geary (Demo and Lagoon) and Lahoma, OK. Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

	2012 Demo	2012 Lagoon	2013 Demo	2013 Lahoma	2014 Lahoma
	-----------------Total Nitrogen Uptake kg ha^{-1}---------------				
Trt 1 (ShRCwGm)	46 a†	53 a†	29 b†	40 a†	57 a†
Trt 2 (CnSsSuCw Sh)	66 a	78 a	45 a	47 a	43 b
Trt 3 (MCwShLs)	53 a	61 a	26 b	39 a	69 a
Trt 4 (SfBGmR)	13 b	19 b	21 c	20 d	30 c
Trt 5 (PmGmSs)	61 a	71 a	34 a	24 c	31 c
Trt 6 (CwPmSsMLs)	51 a	58 a	35 a	33 b	37 c

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

Table 16. Average acid digestible fiber percentage for five site years of summer planted cover crops at Geary (Demo and Lagoon) and Lahoma, OK. Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

	2012 Demo	2012 Lagoon	2013 Demo	2013 Lahoma	2014 Lahoma
			-----------------% ADF---------------		
Trt 1 (ShRCwGm)	41.7 a†	42.4 a†	39.6	36.6 a†	36.9 a†
Trt 2 (CnSsSuCw Sh)	34.9 b	35.7 b	38.0	36.7 a	36.1 b
Trt 3 (MCwShLs)	40.3 a	40.6 a	38.2	36.9 a	29.3 c
Trt 4 (SfBGmR)	40.5 a	40.9 a	40.6	33.8 a	38.2 a
Trt 5 (PmGmSs)	32.3 c	33.3 c	38.1	32.3 b	37.7 a
Trt 6 (CwPmSsMLs)	34.3 c	32.7 c	36.6	31.2 b	37.2 a

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

Table 17. Average neutral digestable fiber percentage for five site years of summer planted cover crops at Geary (Demo and Lagoon) and Lahoma, OK. Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

	2012 Demo	2012 Lagoon	2013 Demo	2013 Lahoma	2014 Lahoma
	-----------------% NDF---------------				
Trt 1 (ShRCwGm)	50.9	51.5	54.4 b†	51.1 a†	48.7 c†
Trt 2 (CnSsSuCw Sh)	52.9	53.6	54.3 b	50.8 a	54.0 a
Trt 3 (MCwShLs)	45.5	48.3	51.4 c	43.7 b	33.3 d
Trt 4 (SfBGmR)	55.8	56.0	60.4 a	50.4 a	52.1 b
Trt 5 (PmGmSs)	54.0	54.0	56.2 b	54.9 a	60.6 a
Trt 6 (CwPmSsMLs)	53.8	53.6	55.6 b	51.4 a	56.8 a

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

Table 18. Average relative feed value Index for five site years of summer planted cover crops at Geary (Demo and Lagoon) and Lahoma, OK. Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

	2012 Demo	2012 Lagoon	2013 Demo	2013 Lahoma	2014 Lahoma
			-----------------Relative Feed Value--------------		
Trt 1 (ShRCwGm)	104.2	101.9	99.8	110.3	114.9 b†
Trt 2 (CnSsSuCw Sh)	108.8	106.1	101.8	111.1	105.3 b
Trt 3 (MCwShLs)	123.8	111.6	108.1	130.1	187.3 a
Trt 4 (SfBGmR)	96.1	95.2	88.3	115.4	106.7 b
Trt 5 (PmGmSs)	110.3	108.7	98.1	109.9	91.5 b
Trt 6 (CwPmSsMLs)	107.7	110.1	100.9	116.9	98.4 b

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

1

CHAPTER II

Impact of Cover Crops on Soil Moisture.

INTRODUCTION

Soil moisture is an integral component of crop production and productivity in Oklahoma dry-land cropping systems. In rain-fed, non-irrigated environments, soil moisture is a valued commodity for crop production during the growing season. Continuous wheat systems in Oklahoma incorporate a fallow period during the summer months to accumulate rainfall to restore the water deficit in the soil profile.

Incorporating a cover crop during the summer fallow period, between wheat crops, has been proposed as an alternative method to increase diversity of the crop system, as well as improve soil health indicators such as improve water infiltration, microbial activity, soil organic carbon, nutrient uptake, biological nitrogen fixation and decrease compaction, soil erosion and runoff. However, inclusion of a cover crop in place of a fallow period may result in a water deficit at the end of the growing season. Choosing cover crops that have lower water requirements and higher water use efficiencies may not have a detrimental effect on soil moisture. Using crop species that are easily established and quick to reach physiological maturity may result in greater soil moisture content when compared to those that are still growing in the late summer months (Robins, 1956).

REVIEW OF LITERATURE

The effects of summer cover crop mixtures on soil moisture and grain yield, planted in a continuous wheat system, have not been widely researched in Oklahoma. However, in the high plains, there is interest in diversifying continuous wheat production systems through the use of cover crops and specifically, cover crop mixtures. Most recent research explores the benefits of cover crop monocultures, in rotation with winter wheat or other cash crops. However, no research has evaluated these specific cover crop mixtures and their effects on soil moisture and subsequent winter wheat grain yields.

Inclusion of Cover Crops in a Cash Crop Rotation

Decker et al. (2009) indicated that double cropping millet with early season no-till winter wheat for forage production, in Oklahoma, resulted in small positive net returns in both small (200 ha) and large (>1000 ha) farm sizes. Andrews et al. (2009) indicated that the inclusion of a summer cover crop (sorghum-sudangrass, pearl millet, cowpea) instead of a summer fallow period into Oklahoma no-till continuous winter wheat systems caused a reduction in subsequent wheat grain yield. However, Blanco-Canqui (2012), in Kansas, reported that, with the inclusion of a nitrogen application, winter wheat grain yields following sunn hemp, or late maturating soybean, were greater than or equal to those following a fallow period. Blanco-Canqui (2011) indicated that greater wheat yields, when double cropped with sunn hemp can be attributed to greater water infiltration and soil organic carbon concentration. Abreu et al. (2011) also indicated incorporating cover crops (radish, Austrian winter pea, cowpea, sunn hemp, and pigeon pea) in a Oklahoma continuous winter wheat system had no negative effects on subsequent grain yields in Oklahoma.

Planting cover crops, or green manures, in place of fallow periods can reduce soil moisture through plant transpiration and cause a yield reduction to the subsequent crop in other parts of the U.S. as well. In Colorado, cover crops planted in place of a fallow period, resulted in a reduction of soil water available to wheat crop by 55 to 104 mm (Nielson and Vigil, 2005). Vigil and Nielson 1998, also reported that wheat yields were reduced by 400 to 1050 kg ha^{-1}, when planted after a legume green manure. In Kansas, Aiken et al., 2013, reported that replacing the fallow period with an "oilseed" component (i.e. spring canola, soybean, or sunflower) resulted in a reduction of wheat yields from 18 to 56%. Other studies, in the Northwest U.S., report similar findings. In most normal years, yield reductions occur, but greater yield reductions occur during droughts (Miller and Holmes, 2005).

Impacts on Soil Moisture

The importance of a three month fallow period, in a semi-arid, dryland, continuous winter wheat system, is to capture as much precipitation as possible and replenish the soil moisture deficit after wheat has been harvested. The amount and efficiency of captured precipitation can be influenced by management practices and the use of cover crops.

The addition of a cover crop into a rotation can increase soil quality, soil organic matter, soil structure, and water infiltration (Frye et al. 1988, Gulick et al., 1994) through the breakdown of the residues. Residue management is an important component in no-till systems and can have an effect on soil moisture content and other soil properties. Through the use of no-till, crop residues reduce erosion and runoff, allow for increased water infiltration, reduce soil temperatures, and improve soil quality (Karlen et al., 1994). Zibilske and Makus, 2009 indicated that soil water content was maintained as a result of less evaporation and lower soil temperatures from proper residue management when compared to a three month summer fallow.

Some studies have suggested that cover crops, when combined with no-till, can improve soil moisture conditions by increasing surface residues that reduce evaporation and that this combined with the improved structure, which allow for improved infiltration is thought to offset the water used by the cover crops and improve cash crop performance. Tillage and residues from grass/legume cover crop rotations are key factors that influence soil quality, surface runoff, sediment losses, weed suppression, plant available water, and crop performance (Munkholm et al., 2012, Blevins et al., 1990, Lawley et al. 2012, Frye et al., 1988, Blanco-Canqui et al., 2012).

Although, there is data evaluating wheat yields in Oklahoma following certain cover crops, there is very little data evaluating the impact of cover crops on soil moisture. Currently, there is no data available that evaluates the impact of summer cover crop mixtures, in no-till, on soil water status in Oklahoma.

Objective and Hypothesis

The objective of this study is to evaluate the effects of cover crops on soil moisture when planted in a continuous winter wheat system. Inclusion of a summer cover crop, in a no-till system, may influence the soil water status after cover crops are harvested. Our research will test to see if there are any differences between cover crop mixtures with respect to soil moisture content as well as wheat yields. The hypothesis for the study is as follows:

H_O: Inclusion of a summer cover crop treatment has no effect on soil moisture content and subsequent winter wheat grain yield in a continuous wheat system.

H_A: Inclusion of a summer cover crop treatment has an effect on soil moisture content and subsequent winter wheat grain yield in a continuous wheat system.

METHODOLOGY

Field experiments were conducted during the summers of 2012, and 2013 in Geary, Oklahoma (35°37’14” N, 98°16’33” W) on privately owned demonstration farms (Demo). The experimental site consisted of a Norge silt loam (fine-silty, mixed, active, thermic Udic Paleustolls) soil that is well drained. The slope of experimental site ranged from 3 to 5%. The average annual precipitation is approximately 765 mm.

The study was also conducted in 2013 and 2014 at the North Central Research Station (36°23’13”N, 98°6’39”W), one mile west of Lahoma, Oklahoma (Lahoma). The experimental site consisted of a Grant silt loam (fine-silty, mixed, superactive, thermic Udic Argiustolls) which is a deep, well drained, moderately permeable soil. The slope of the experimental site ranged from 1 to 3%. The average annual precipitation is approximately 863 mm.

Warm season cover crops were planted during June and July, as seen in Table 20, with a Great Plains no-till grain drill. The experiment consisted of six different cover crop treatments consisting of warm season grass, brassica, and legume mixtures as seen in Table 21. Species composition of the treatments used is presented in Table 22. The six treatments were laid out in a randomized complete block design with four replications. Individual plot size was approximately 3.05 by 9.14 m. The drill planted the cover crops in six rows with 18.8 cm row spacings. The seeding rate used recommended by the seed company was 33.6 kg ha^{-1}.

Cover crop biomass was harvested using a Chute Forage Harvester by Carter Manufacturing Company. Biomass was collected in the field by cutting a 0.91 by 9.14 m strip out of the center of each plot after this data collection remaining biomass was removed with the same carter harvester. This biomass data is presented in Chapter 1. Soil samples were collected after cover crop forage harvest. Soil samples were collected using a tractor mounted hydraulic driven soil probe. For each plot, one soil core of 3.96 cm in diameter was collected to a depth of 110 cm. Each soil core was divided into segments for the following depths: 0-15, 15-30, 30-60, 60-80, 80-110 cm. After the core was divided, each core segment was packaged in a plastic bag and placed in a cooler for transport.

Wet soil core segments were then weighed in the bag and the weight for each was recorded. Soil samples were then taken out of the plastic bag and placed in a paper bag. Each sample was then weighed and recorded. They were then dried at 105°C for 24 hours. The soil segments were then weighed to determine gravimetric water content. The wet bulk density was determined using the weight of the soil segment as determined in the plastic bag. This was then converted to dry bulk density based on the gravimetric water content and then used to determine the volumetric water content. .

Gravimetric water content for a mass of soil can be expressed by the following formula:

$$Grav = \frac{(mass\ wet - Paper\ bag) - (mass\ dry - Paper\ bag)}{(mass\ dry - Paper\ bag)}$$

or

$$u = \frac{mwet\ (g) - mdry\ (g)}{mdry\ (g)}$$

mwet is the mass of the wet soil expressed in grams. Mdry is the mass of the dry soil expressed in grams.

Soil bulk density (ρ_b) can be expressed by the following formula:

$$\rho_b = \frac{mdry\ (g)}{V\ (cm-3)}$$

Mdry is the mass of dry soil expressed in grams. As measured in this study the mdry was the dry soil in the plastic bag as determined by subtracting the water mass from the wet soil mass. The volume of the core segment (V) is expressed in cubic centimeters and is represented by the formula:

$$V = \pi r^2 h$$

Once gravimetric water content and soil bulk density is calculated, volumetric water content (Θ) can then be calculated by using the following formula:

$$\Theta = \text{Gravimetric water content x Bulk Density}$$

Once all moisture calculations were made for each segment depth and cover crop blend, the data was compiled and water content in the soil profile (0-110 cm) was calculated and averaged for each treatment as well as the control. The differences in soil moisture between the fallow treatment and cover crop treatments can be calculated by the following formula:

$$\text{Soil Moisture Difference} = \theta_{\text{fallow}} - \theta_{\text{treatment}}$$

The (BMD) biomass produced per cm of soil moisture depletion (kg ha^{-1} cm^{-1}) for each cover crop mixture can then be calculated by using the following formula:

$$\text{BMD} = \frac{\text{Yield (kg ha} - 1)}{\text{Soil Moisture Difference (cm)}}$$

Statistical Analysis

Soil moisture concentration at each depth and the profile water content for cover crop treatments were analyzed using SAS software version 9.3 (SAS, Cary, NC). Analysis of variance was determined using general linear model (PROC GLM). Statistical differences between treatment means were determined by using the Fisher's protected least significant difference test in which $\alpha=0.05$.

RESULTS AND DISCUSSION

Winter Wheat Grain Yield Lahoma 2014

There were no significant treatment differences in winter wheat grain yields at Lahoma in 2014 (Table 22). However, the winter wheat grain yield following standard fallow treatment produced 161 kg ha^{-1} more grain than the wheat yields averaged across all cover crop treatments. Differences in grain yields following cover crop treatments ranged from 3 to 263 kg ha^{-1} compared to fallow. The results are similar to Andrews et al. (2009) which found that planting a summer cover crop caused a reduction in subsequent wheat grain yield compared to fallow; except for in this current study the differences were not significant. .

Treatment and Sampling Date Soil Water Content

There was a significant treatment by sample date interaction for soil water content to a depth of 110 cm (Table 23). As expected, soil moisture changed as a function of time in the cover crop treatments. The soil water content of treatments 1 -3 was significantly lower after both summer seasons as compared to the 28 Feb. 2014 and 20 June 2014 sampling dates. In Contrast, there was no difference in soil moisture in Treatments 4-6 when comparing sample dates 5 Sept. 2013, 28 Feb. 2014 and 20 June 2014, which all had significantly higher soil moisture than the 3 Sept. 2014 sampling. No significant differences among sample dates were seen for the fallow treatments. The lower soil moisture observed in 3 Sept. 2014 as compared to 5 Sept. 2013 is a result of lower rainfall experiences in the 2014 spring and summer months compared to that experienced in 2013 (Figures 10 and 11).

In summary, total soil water volumes for treatments 1-6 were lower after cover crop harvest than recorded in-season or post-wheat harvest in 2014. Total soil water volume in the fallow plots, were the highest in September 2013, and declined through the wheat growing season, and 2014 summer fallow period. In contrast, the soil moisture in the cover crop treatments increased during the wheat growing season and then declined after cover crop termination in 2014. These soil water dynamics in which the soil moisture in Feb. 2014 increased after cover crops to a level greater than that found in the Fallow treatment in the instance of treatments 1, 2, 4, and 5 shows that inclusion of cover crops can increase soil water status in a wheat crop. This is further supported by the significantly higher soil water content as measured in June 2014 in the cover crop treatments compared to the fallow treatment.

Soil Profile Moisture Content September 2013

The profile water contents in treatment 5 and the fallow treatment were statistically higher than all remaining treatments (Table 24). Treatment 3 had the lowest profile water content of 18.6 cm which was significantly lower than all remaining treatments. Soil moisture differences between the fallow plots and treatments 5 and 3, ranged from 2.7 cm to 6.7 cm, respectively (Table 24). This data shows that soil profile water depletion was greatest for treatment 3, 100% legumes, yet minimized in treatment 5, 100% grasses, with the mixtures of grasses and broadleaves having intermediate soil profile moisture contents. No significant treatment differences for biomass yield occurred.

Due to the lack differences in forage yield, the biomass produced per cm of soil moisture depletion (BMD) (kg ha^{-1} cm^{-1}) followed a similar trend as the profile water content. Treatments 1 and 5 had the highest water use efficiencies (946 and 1123 kg cm-1) which were significantly higher than all remaining treatments. Furthermore, treatment 3 had the lowest BMD. It is also notable that the low yield observed for treatment 4 resulted in the second lowest BMD, despite the fact that this treatment had the second highest soil profile water content.

This data shows that grass mixtures can provide an optimum balance between biomass production and soil water use. However, it is apparent that utilization of legumes to biologically fix nitrogen in a legume only mix, will most effectively deplete soil moisture. Furthermore, the inclusion of grass/legume mixtures (treatments 1, 2, and 6) resulted in intermediate impacts on soil moisture, yet biomass production was maximized with the inclusion of a legume. These results are similar to Karpenstein and Stuelpnagel (2000) which indicated that inclusion of a legume into a grass legume mixture can improve yields when compared to an all grass cover crop.

Volumetric Moisture Content September 2013

Figure 1 shows statistical significance for volumetric water content by depth for Lahoma. Significance is seen for each individual depth with the exception of 80-110 cm. Moisture measurements were taken following cover crop harvest in summer of 2013.

Treatment differences were seen at 0-15 cm depth in which treatment 7 (Fallow) had the highest moisture content, 0.16 cm cm^{-1}, which were statistically different than the remaining treatments. Treatment differences were seen at 15-30 cm depth between treatment 7 (Fallow) and treatment 1, but there were no differences between treatment 1 and the remaining treatments. Treatment differences were seen at 30-60 cm depth in which the soil moisture in treatment 7 (Fallow) was significantly higher than all remaining treatments. Also, at this depth treatments 3 and 6 had the lowest moisture content which were statistically different than remaining treatments. Treatment differences were also seen at 60-80 cm depth in which treatment 7 (Fallow), 4, and 5 had the highest moisture content which were statistically different than remaining treatments. There were no differences seen at 80-110 cm but moisture content ranged from 0.203 cm cm^{-1} (treatment 3) to 0.265 cm cm^{-1} (treatment 1).

This assessment shows that soil water depletions in cover crop treatments relative to the fallow control, are most pronounced in the 15-80 cm depths of the soil profile. Furthermore, there were limited differences in soil moisture among the cover crop treatments in the 0-15, and 15-30 cm depths. In contrast, separation of treatment means effects among cover crop treatments were most extensive at the 30-60, and 60-80 cm depths. This suggests that differences in profile moisture are dependent on the cover crop treatments ability to extract moisture from the subsoil.

Volumetric Moisture Content February 2014.

Figure 2 shows statistical significance for volumetric water content by depth for Lahoma in February of 2014. Statistical significance was seen for the 30-60 and 60-80 cm depths. Soil moisture measurements were taken in-season during winter wheat production.

At the 30-60 cm depth, treatment 6 was significantly lower than treatment 5. No significant differences were seen between any other treatments. At the 60-80 cm depth, treatment 3 contained the lowest moisture content (0.20 cm cm^{-1}) which was significantly lower than treatments 1, 2, and 5. There were no significant treatment differences seen at 80-110 cm, but soil moisture content ranged from 0.21 cm cm^{-1} (treatment 3) to 0.25 cm cm^{-1} (treatment 1).

Treatments 3 and 6 had the lowest profile water content on September 5 (Figure 1). This soil moisture data collected in February, shows that soil moisture had recharged in these treatments to levels equivalent to the fallow control from the surface to 30 cm, but that the residual effects of the summer season depletion is still present. However, the soil moisture content remaining in the cover crop treatments, which experienced less soil moisture depletion such as treatments 1, 2, and 5 had fully recovered.

Volumetric Moisture Content June 2014

Figure 3 shows statistical significance for volumetric water content by depth for Lahoma in June of 2014, after winter wheat harvest. Statistical significance was seen for the 30-60 and 60-80 cm depths. Moisture measurements were taken following winter wheat harvest.

Differences between subsoil moisture values had shifted such that the fallow treatments contained significantly lower soil moisture content than some cover crop treatments.

Specifically, at the 30-60 cm depth, treatment 2 was statistically higher than treatment 7 (Fallow), but not statistically different from the remaining treatments. Treatment differences were also seen at 60-80 cm depth, in which treatment 7 (Fallow) had the lowest soil moisture content (0.13 cm cm^{-1}), which was statistically different than treatment 6, which was statistically different than the remaining treatments. Furthermore, treatment 6 had low subsoil moisture concentration among cover crop treatments, suggesting that the level of soil water depletion experienced by this treatment in the previous summer had caused a moisture deficiency that was not fully removed during the wheat growing season.

The mechanisms responsible for the lower soil moisture in the fallow treatment compared to cover crop treatments are difficult to isolate. However, two explanations could be responsible. First, the fallow treatment produced the highest average grain yield of 2163 kg ha^{-1} compared to the average yield of 2002 produced in the cover crop treatments (Table 22). Although these differences in grain yield were not significant, they could indicate greater levels of transpiration in the fallow treatment that depleted soil moisture. A second explanation is that the cover crop treatments provided increased water infiltration from rainfall received during the winter wheat growing season. Despite the uncertainty related to these mechanisms, it is clear that the soil moisture content in the cover crop treatments recovered.

Soil Profile Moisture Content September 2014

Treatment differences were not seen in profile water content at the 3 Sept. 2014 sampling date (Table 25). Soil moisture differences between the fallow plots and cover crop treatments ranged from 1.4 cm to 2.7 cm. Treatment differences in biomass yields were not seen, but average yields ranged from 2028 (treatment 4) to 2992 (treatment 5) kg ha^{-1}. However, significant treatment differences for BMD were observed. Treatments 1 and 3 had the lowest BMD, 856 and 978 kg cm^{-1} respectively, which were statistically different than the remaining treatments. These treatments had the lowest soil moisture content. Unlike the data collected in 2013, treatment 4 had the highest BMD because it had the highest profile water content among cover crop treatments. It is also important to note that the BMD was higher in all treatments in 2014 compared to 2013. The apparent differences in BMD depletion among years is due to differences in the amount of rainfall received during the summer growing season. In 2013, Lahoma received approximately 281 mm of rainfall during the summer growing season. In 2014, Lahoma received approximately 211 mm of precipitation during the summer growing season. The lower rainfall in 2014, resulted in reduced recharge of the fallow treatment, yet provided sufficient moisture for cover crop growth. In addition, the relatively low wheat yields harvested in 2013 provided limited residue in the fallow treatment which may have allowed for greater evaporation in this treatment as compared to 2013. However, residue cover and evaporation were not measured in this study.

Volumetric Moisture Content September 2014

Figure 4 shows that the soil moisture content depletion in the cover crop treatments relative to the fallow treatment was only significant at the 60-80 cm depth. At this depth, all cover crop treatments, except treatment 4, contained significantly less soil moisture than the fallow treatment. There was no significant treatment difference seen at 80+ cm but moisture content ranged from 0.157 cm cm^{-1} (treatment 1) to 0.192 cm cm^{-1} (Fallow treatment 7).

The lack of significant differences in the volumetric water content observed in the 0-60 cm depths among cover crop treatments and the fallow treatment in 2014, demonstrated that during drier years, the reduced soil evaporation in the cover crop treatments can offset transpiration water use especially when residue coverage is limited in the standard fallow treatment as a result of low yielding wheat production as was observed in 2014. These results are similar to Unger and Vigil (1998), which indicated that summer cover crop residues may offset transpirational water use in drier climates by reducing evaporation.

CONCLUSIONS

Winter wheat grain yields were not significantly different following standard fallow management vs cover crop treatments. However, grain yields following a fallow period averaged 161 kg ha^{-1} more than yields following the cover crops. Furthermore, there was a significant treatment by sampling date interaction for profile water content. Although the cover crop treatments reduced soil moisture at the end of the summer growing season as observed in September 2013 and 2014, this difference was removed for all treatments when moisture was assessed in February 2014 and June 2014. Furthermore, the moisture content of the fallow treatment in February was equal to or less than that found in all the cover crop treatments, indicating that the moisture deficient was removed prior to the onset of reproductive growth in the spring. Furthermore, in June 2014 after wheat harvest the fallow treatment contain significantly lower soil moisture than all cover crop treatments.

This research shows including cover crops in a wheat production system changes the soil water dynamics by depleting soil water during the summer fallow period. This depletion did not significantly decrease yield apparently due to the fact soil water status of the cover crop treatments was replenished prior to vegetative growth of the wheat. Therefore, cover crops can be grown in rotation with wheat. However, this short term assessment shows that there is no benefit to the wheat crop. Long-term assessment of including a cover crop in the summer fallow period are needed to determine if soil health improvements often cited by other research can be realized in this system.

REFERENCES

Abreu, S.L., J.T. Edwards, C.B. Godsey, A.R. Klatt, J.G. Warren, and A.K. Tyagi. 2011. Increasing crop rotation and intensity in central Oklahoma. Available at http://usi.earth.ac.cr/glas/sp/Dr%20Abreu%20PhD%20dissertation.pdf

Aiken, R.M., D.M. O'Brien, B.L. Olson, and L. Murray. 2013. Replacing fallow with continuous cropping reduces crop water productivity of semiarid wheat. Agron. J. 105:199-207.

Alvarez, R., R.A. Diaz, N. Barbero, O.J. Santanotoglia, L. Biotta. 1995. Soil organic carbon, microbial biomass and CO_2-C production from three tillage systems. Soil and Tillage Research. 33:17-28.

Andrews, C.J., J.T. Edwards, C.B. Godsey, K.L. Giles, and S.A. Tucker. 2009. Influence of warm-season cover crops on no-till winter wheat (*Triticum aestivum* L.). available at https://shareok.org/bitstream/handle/11244/9297/Andrews_okstate_0664M_11873.pdf?sequence=1.

Bailey, V.C, J.L. Smith, H. Bolton. 2002. Fungal-to-bacteria ratios in soils investigated for enhanced C sequestration. Soil Biol. Biochem. 34:997-1007.

Blanco-Canqui, H., Claassen, M.M., and D.R. Presley. 2011. Addition of cover crops enahances no-till production for improving soil physical properties. Soil Sci. Soc. Am. J. 75: 1471-1482.

Blanco-Canqui, H., Claassen, M.M., and D.R. Presley. 2012. Summer cover crops fix nitrogen, increase crop yield, and improve soil-crop relationships. Agron. J. 104: 137-147.

Blaser, B.C., L.R. Gibson, J.W. Singer, and J.L. Jannink. 2006. Optimizing seeding rates for winter cereal grains and frost-seeded red clover intercrops. Agron. J. 98:1041-1049.

Blevins, R.L, W.W. Frye, P.L. Baldwin, and S.D. Robertson. 1990. Tillage effects on sediment and soluble nutrient losses from a maury silt loam soil. J. Environ. Qual. 19:683-686.

Decker, J.E., F.M. Epplin, D.L. Morley, and T.F. Peeper. 2009. Economics of five wheat production systems with no-till and conventional tillage. Agron. J. 101:364-372.

Frye, W.W., R.L. Blevins, M.S. Smith, S.J. Corak, and J.J. Varco. 1988. Role of annual legume cover crops in efficient use of water and nitrogen. Cropping Stragies for Efficient Use of Water and Nitrogen (ASAspecialpub):129-154.

Fuentes, J.P., D.F. Bezdicek, M. Flury, S. Albrecht, J.L. Smith. 2006. Microbial activity affected by lime in long-term no till soil. Soil and Tillage Research. 88:123-131.Gulick, S.H, Grimes, D.W., Munk, D.S. and D.A. Goldhamer. 1994. Cover crop enhanced water infiltration of a slowly permeable fine sandy loam. Soil Sci. Soc. of America J. 58 (5): 1539-1546.

Karlen, D.L, N.C. Wollenhaupt, D.C Erbach, E.C. Berry, J.B. Swan, N.S. Eash, J.L. Jordahl. 1994. Long term effects on soil quality. Soil and Tillage Research. 32:313-327.

Karpenstein-Machan, M., and R. Stuelpnagel. 2000. Biomass yield and nitrogen fixation of legumes monocropped and intercropped with rye and rotation effects on a subsequent maize crop. Plant and Soil 218: 215-232.

Lawley, Y.E., Teasdale, J.R., Weil, R.R. 2012. The mechanism for weed suppression by a forage radish cover crop. Agron. J. 104:205-214.

Miller, P.R. and J.A. Holmes. 2005. Cropping sequence effects of four broadleaf crops and four cereal crops in the Northern Great Plains. Agron. J. 97:189-200.

Munkholm, L.J., Heck, R.J., and Deen, B. 2012. Long-term rotation and tillage effects on soil structure and crop yield. Soil Tillage Res. 3008.

Nielsen, D.C. and M.F. Vigil. 2005. Legume green fallow effect on soil water content at wheat planting and wheat yield. Agron. J. 97:684-689.

Nielsen, D.C., and M.F. Vigil. 2010. Precipitation storage efficiency during fallow in wheat-fallow systems. Agron. J. 102:537-543.

Qingie, W., L. Caiyun, L. Hongwen, H. Jin, K.K. Sarker, R.G. Rasaily, L. Zonghui, Q. Xiaodong, L. Hui, A.D. Jack.2014. The effects of no-tillage with subsoiling on soil properties and maize yield: 12-year experiment on alkaline soils of Northeast China. Soil and Tillage Research. 137:43-49.

Robins, J.S., C.E. Domingo. 1956. Moisture deficits in relation to the growth and development of dry beans. Agron. J. 48:67-70.

Vigil, M.F and D.C. Nielsen. 1998. Winter wheat yield depression from legume green fallow. Agron. J. 90:727-734.

Unger, P.W. and M.F. Vigil, 1998. Cover crop effects on soil water relationships. J. of Soil and Water Cons. 53(3):200-207.

Zibilske, L.M., and D.J. Makus, 2009. Black oat cover crop management effects on soil temperature and biological properties on a mollisol in Texas, USA. Geoderma. 149:3-4.

Table 19. Planting and forage biomass harvest dates for summer cover crops from 2012-present

Location	Planting Date	Soil Sampling Date(s)
Demo	11 June 2012	2 October 2012
	28 June 2013	20 September 2013
Lahoma	1 July 2013	5 September 2013
	20 June 2014	20 June 2014

Table 20. Treatments, crop species and seeding rates for summer cover crops from 2012-present. Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

Treatment	Crop Species	Seeding Rate
		---kg ha^{-1}---
Trt 1 (ShRCwGm)	Sunn Hemp, Radish, Cowpea, German Millet	33
Trt 2 (CnSsSuCw Sh)	Corn, Sorghum Sudan, Sunflower, Cowpea, Sunn Hemp	33
Trt 3 (MCwShLs)	Mungbean, Cowpea, Sunn Hemp, Laredo Soybean	33
Trt 4 (SfBGmR)	Safflower, Buckwheat, German Millet, Radish	33
Trt 5 (PmGmSs)	Pearl Millet, German Millet, Sorghum Sudan	33
Trt 6 (CwPmSsMLs)	Cowpea, Pearl Millet, Sorghum Sudan, Mungbean, Laredo Soybean	33
Control	Fallow Plot	

Table 21. Treatments, crop species composition, and estimated days to maturity for summer planted cover crops from 2011-present.

Crops Species	Trt 1	Trt 2	Trt 3	Trt 4	Trt 5	Trt 6	Days to Maturity
			% Species in each treatment				
Cowpea	40	36	35			21	60-90
Mungbean			35			21	90-120
Laredo Soybean			17			21	90-120
Sunn Hemp	20	16	13				60-90
S. Sudan		16			33	18	65-90
Corn		16					90-120
P. Millet					33	18	90-100
G. Millet	33			40	34		75-90
Sunflower		16					90-100
Radish	7			8			45-70
Buckwheat				12			70-90
Safflower				40			110-140

Table 22. Average winter wheat grain yield (kg ha^{-1}) following summer cover crop treatment or summer fallow for Lahoma, 2014. Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

Treatment	Grain Yield
	------kg ha^{-1}-----
Trt 1 (ShRCwGm)	2160
Trt 2 (CnSsSuCw Sh)	1900
Trt 3 (MCwShLs)	1984
Trt 4 (SfBGmR)	2142
Trt 5 (PmGmSs)	1919
Trt 6 (CwPmSsMLs)	1907
Fallow	2163

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level. Fallow plots labeled "N/A" were not planted, therefore no biomass yield was collected and water use efficiency was not calculated.

Table 23. Total soil water content (cm) to a depth of 110 cm in each treatment for four sample dates at Lahoma, Oklahoma. Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

	5 Sept 2013 Lahoma	28 Feb 2014 Lahoma	20 June 2014 Lahoma	3 Sept 2014 Lahoma
	----------------------------	cm	-------------------------	
Trt 1 (ShRCwGm)	21.2 b†B‡	25.4 a†A‡	25.4 a†A‡	15.7 a†B‡
Trt 2 (CnSsSuCw Sh)	20.7 bB	24.6 aA	25.7 aA	16.5 aB
Trt 3 (MCwShLs)	18.6 cB	22.7 bA	24.6 aA	15.9 aB
Trt 4 (SfBGmR)	21.7 bA	24.1 aA	23.7 aA	17.1 aB
Trt 5 (PmGmSs)	22.6 aA	25.4 aA	24.4 aA	16.2 aB
Trt 6 (CwPmSsMLs)	20.1 bA	23.2 bA	23.2 aA	16.4 aB
Fallow	25.3 aA	23.3 bA	21.2 bA	18.5 aA
Trt*Sample Date			***	

† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

‡Means within each row followed by the same uppercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level.

Table 24. Soil profile moisture content and biomass yields as measured on September 5, 2013 at Lahoma, OK and the differences in soil moisture between 6 mixtures and the fallow plots and the biomass produced per cm of soil moisture depletion (BMD), as calculated as the biomass divided by the difference in soil moisture. Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

Treatment	Profile Water Content	Soil Moisture Difference	Biomass Yield	BMD
	------------cm----------		---kg ha^{-1}---	---kg ha^{-1} cm^{-1}---
Trt 1 (ShRCwGm)	21.2 b†	4.1	3882	946 a†
Trt 2 (CnSsSuCw Sh)	20.7 b	4.6	3830	832 b
Trt 3 (MCwShLs)	18.6 c	6.7	3273	488 d
Trt 4 (SfBGmR)	21.7 b	3.7	2078	561 c
Trt 5 (PmGmSs)	22.6 a	2.7	3034	1123 a
Trt 6 (CwPmSsMLs)	20.1 b	5.2	3705	712 b
Fallow	25.3 a	N/A	N/A	N/A

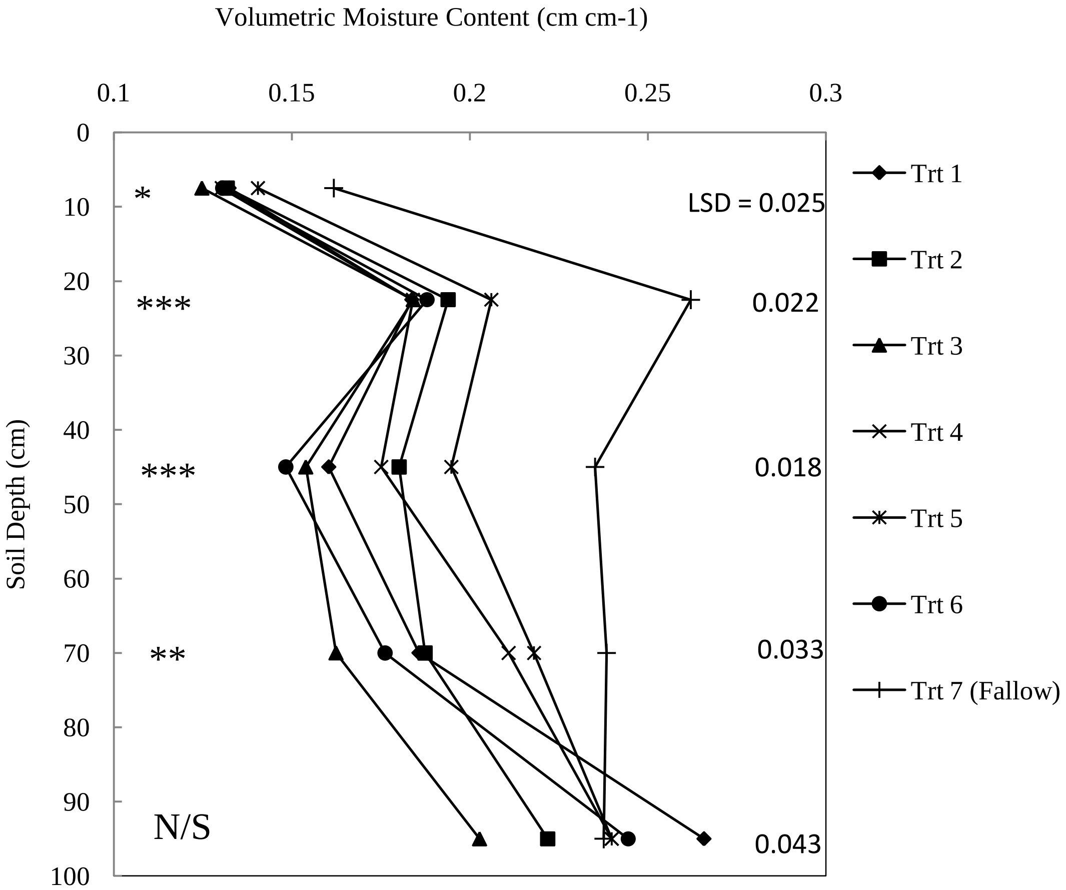
† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level. Fallow plots labeled "N/A" were not planted, therefore no biomass yield was collected and water use efficiency was not calculated.

Table 25. Soil profile moisture content and biomass yields as measured on September 3, 2014 at Lahoma, OK and the differences in soil moisture between 6 mixtures and the fallow plots and the biomass produced per cm of soil moisture depletion (BMD), as calculated as the biomass divided by the difference in soil moisture. Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

Treatment	Profile Water Content	Soil Moisture Difference	Biomass Yield	BMD
	------------cm----------		---kg ha^{-1}---	---kg ha^{-1}cm^{-1}---
Trt 1 (ShRCwGm)	15.7	2.7	2657	856 c†
Trt 2 (CnSsSuCw Sh)	16.5	2.0	2833	1265 a
Trt 3 (MCwShLs)	15.9	2.6	2312	978 b
Trt 4 (SfBGmR)	17.1	1.4	2028	1691 a
Trt 5 (PmGmSs)	16.2	2.3	2992	1371 a
Trt 6 (CwPmSsMLs)	16.4	2.0	2928	1422 a
Fallow	18.5	N/A	N/A	N/A

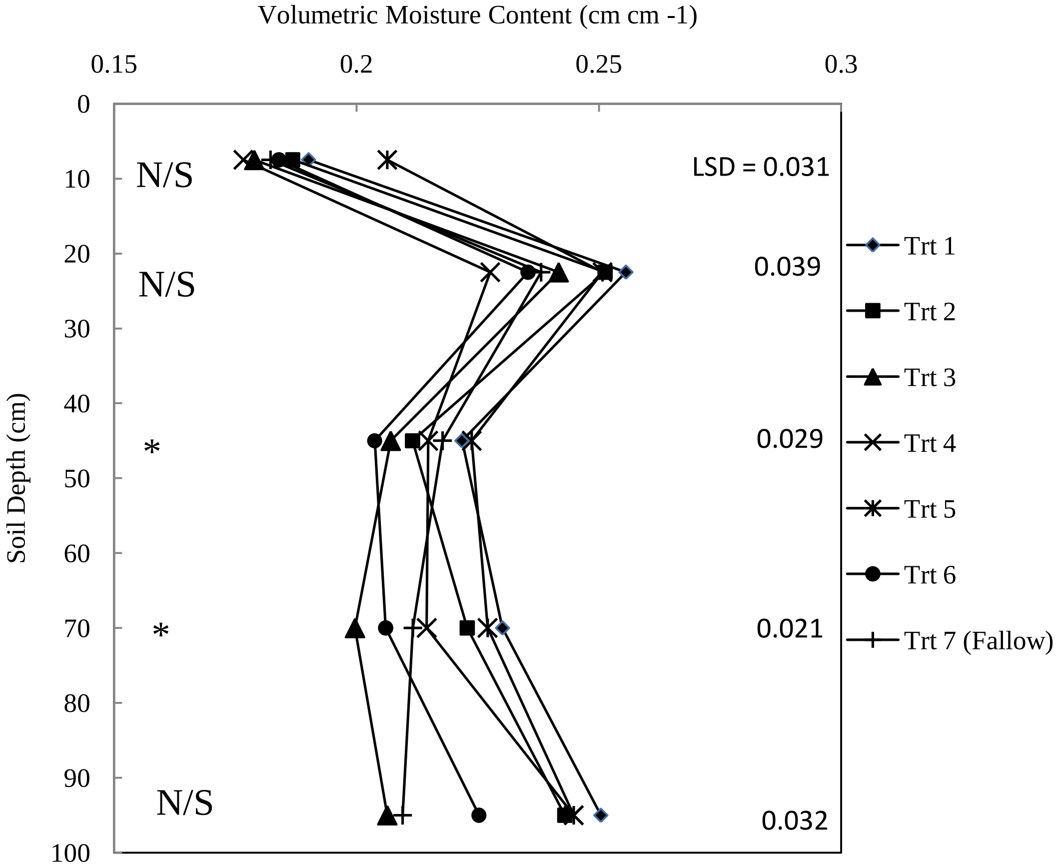
† Means within each column followed by the same lowercase letter are not significantly different at the 0.05 level of probability by Fisher's protected least significant difference test. Columns without letters following the mean indicate treatments were not significant by Fisher's F test, 5% level. Fallow plots labeled "N/A" were not planted, therefore no biomass yield was collected and water use efficiency was not calculated.

Figure 1. Volumetric moisture contents to a depth of 110 cm at Lahoma, Oklahoma as measured on September 5, 2013 after biomass harvest.



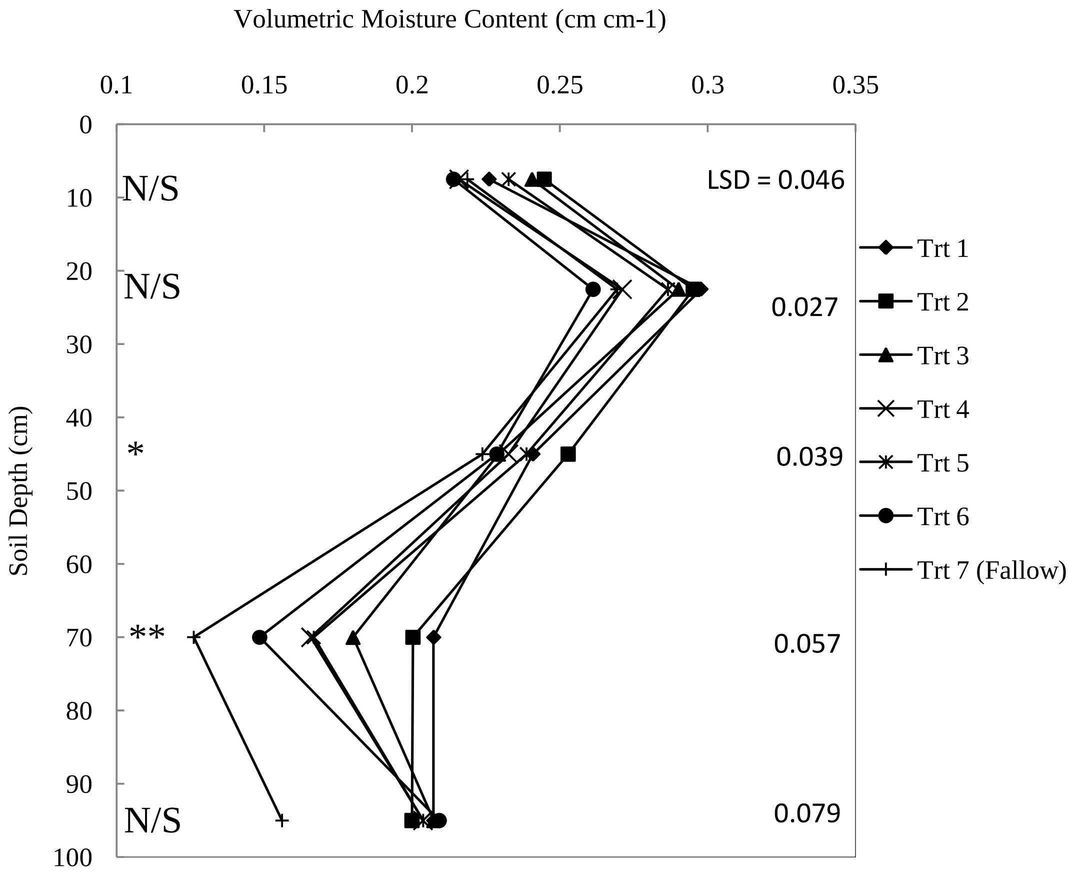
*Significant at P<0.05 level. **Significant at P<0.01. ***Significant at P<0.005. Values for Fisher's protected least significant difference test at α=0.05 level are listed on the right side of the Figure.

Figure 2. In-season volumetric moisture content to a depth of 110 cm at Lahoma, Oklahoma as measured on February 28, 2014.



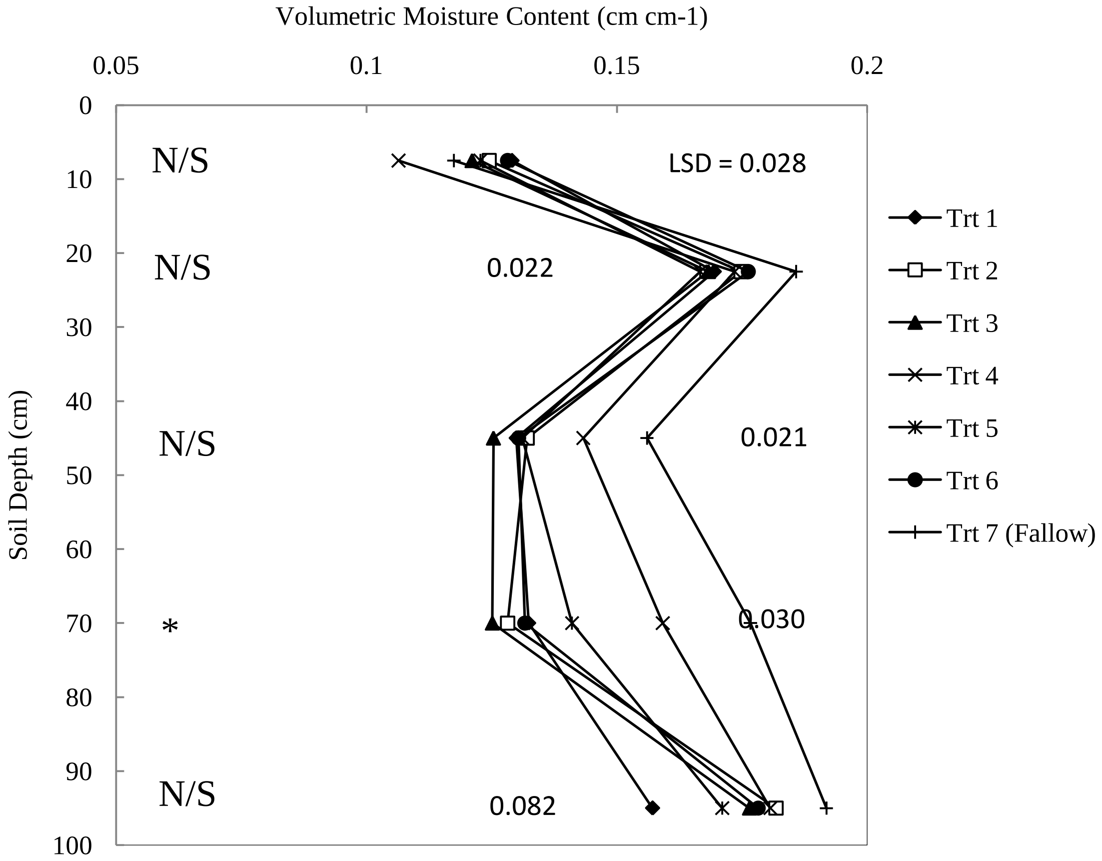
*Significant at P<0.05 level. **Significant at P<0.01. ***Significant at P<0.005. Values for Fisher’s protected least significant difference test at α=0.05 level are listed on the right side of the Figure.

Figure 3. Volumetric moisture contents to a depth of 110 cm at Lahoma, Oklahoma as measured on June 20, 2014 after wheat harvest.



*Significant at P<0.05 level. **Significant at P<0.01. ***Significant at P<0.005. Values for Fisher's protected least significant difference test at α=0.05 level are listed on the right side of the Figure.

Figure 4. Volumetric moisture contents to a depth of 110 cm at Lahoma, Oklahoma as measured on September 3, 2014 after biomass harvest.



*Significant at P<0.05 level. **Significant at P<0.01. ***Significant at P<0.005. Values for Fisher's protected least significant difference test at α=0.05 level are listed on the right side of the Figure.

APPENDICES

Figure 5. Monthly rainfall distribution (cm) for 2011 in Geary, Oklahoma.

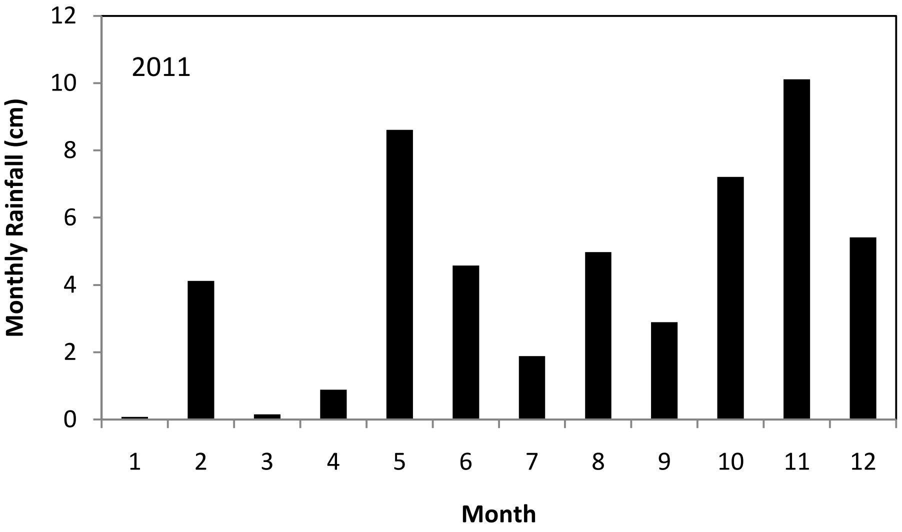


Figure 6. Monthly rainfall distribution (cm) for 2012 in Geary, Oklahoma.

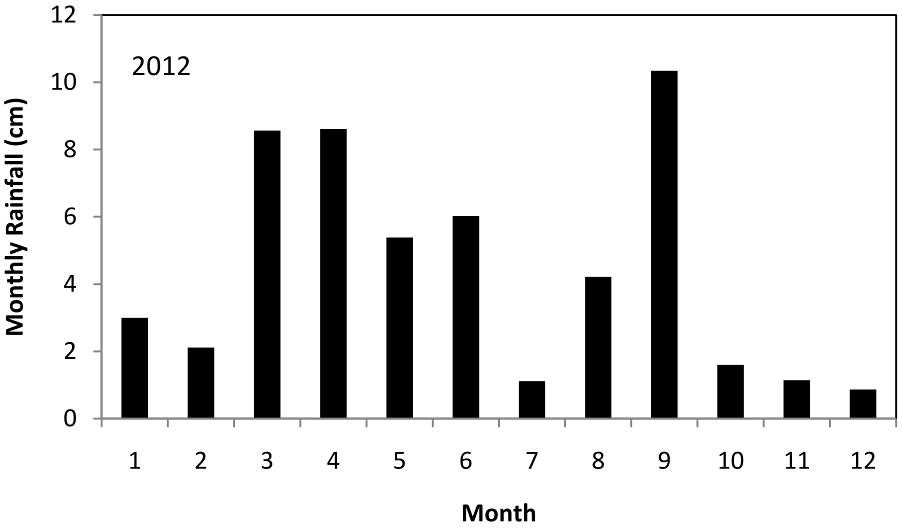


Figure 7. Monthly rainfall distribution (cm) for 2013 in Geary, Oklahoma.

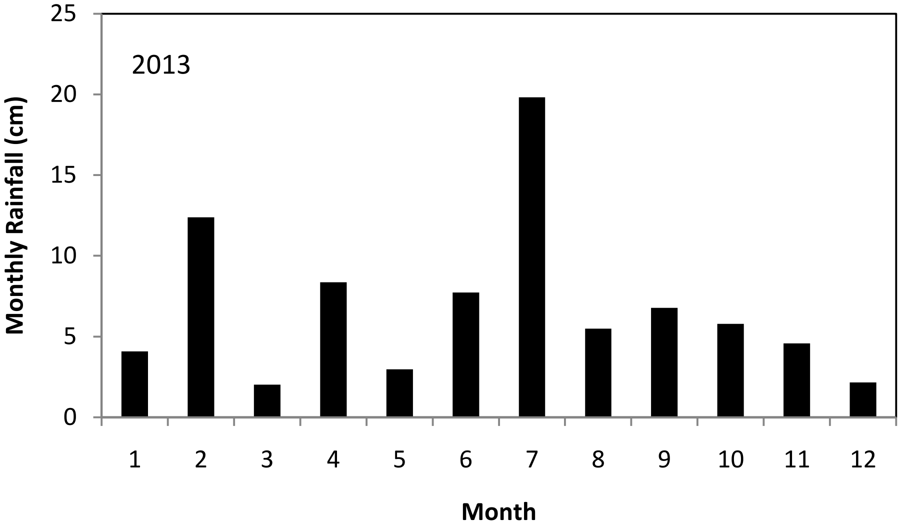


Figure 8. Monthly rainfall distribution (cm) for 2014 in Geary, Oklahoma.

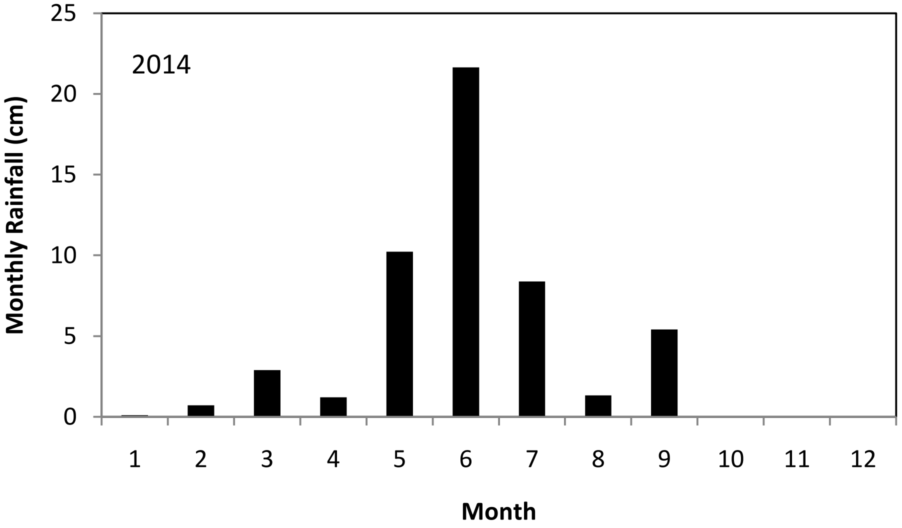


Figure 9. Monthly rainfall distribution (cm) for 2012 in Lahoma, Oklahoma.

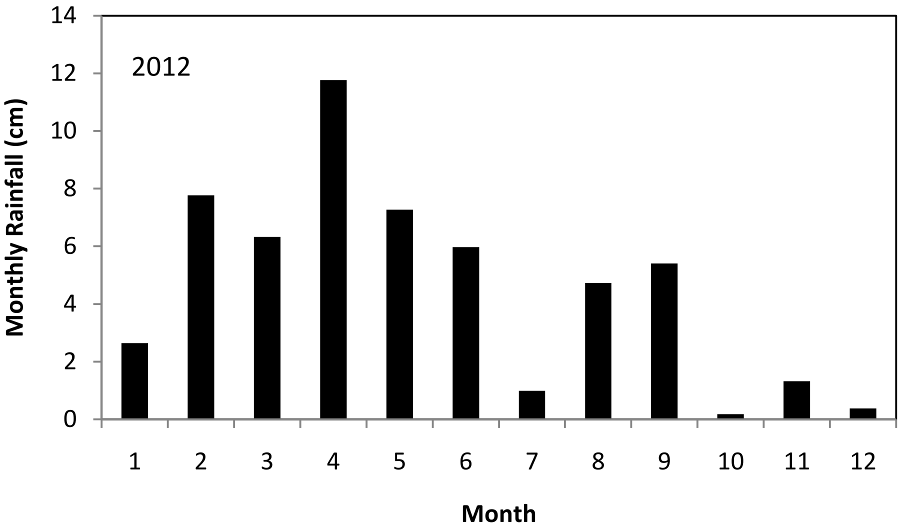


Figure 10. Monthly rainfall distribution (cm) for 2013 in Lahoma, Oklahoma.

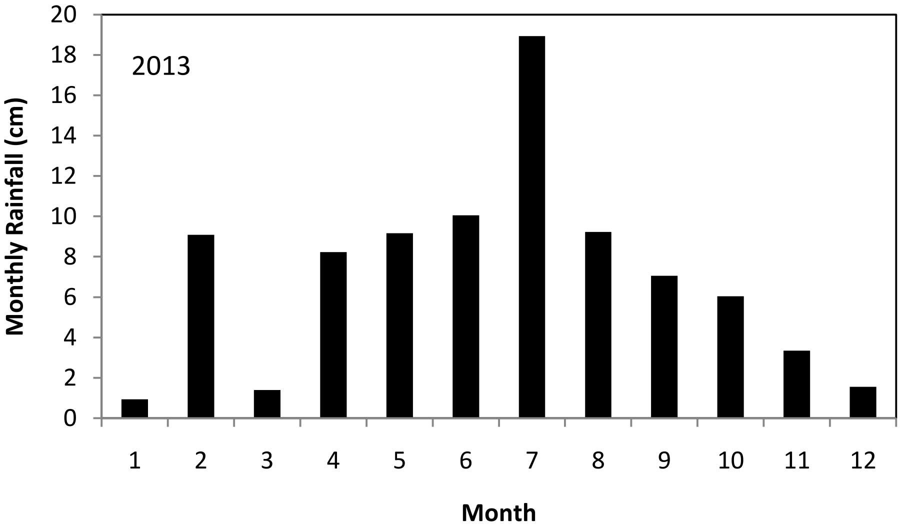


Figure 11. Monthly rainfall distribution (cm) for 2014 in Lahoma, Oklahoma.

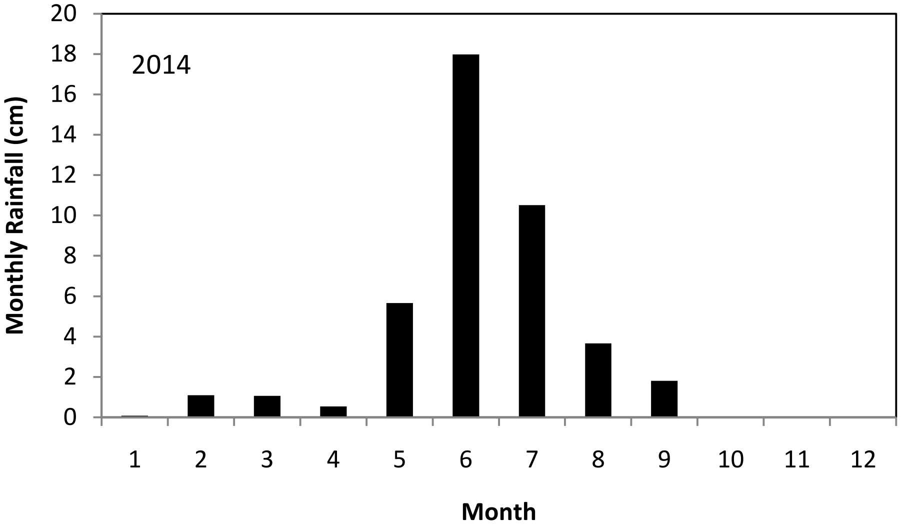


Table 26. Average stand count of summer cover crop treatments for Lahoma, 2014. Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

Treatment	Stand Count
	--total plants m^{-2}--
Trt 1 (ShRCwGm)	84
Trt 2 (CnSsSuCw Sh)	38
Trt 3 (MCwShLs)	41
Trt 4 (SfBGmR)	58
Trt 5 (PmGmSs)	87
Trt 6 (CwPmSsMLs)	56

Table 27. Average stand count of summer cover crop treatments for Lahoma, 2014. Crop type for each treatment is abbreviated: Buckwheat (B), Corn (Cn), Cowpea (Cw), German Millet (Gm), Laredo Soybean (Ls), Mungbean(M), Pearl Millet (Pm), Radish (R), Sorghum Sudan (Ss), Safflower (Sf), Sunflower (Su), Sunn Hemp (Sh).

	Sh	Cw	Cn	Ss	Pm	Gm	R	Ls	B	Sf	Su	M
						-----Stand Count m^{-2}-----						
Trt 1 (ShRCwGm)	21	11	-	-	-	49	3	0	-	-	-	-
Trt 2 (CnSsSuCw Sh)	6	12	11	7	-	-	-	-	-	-	2	-
Trt 3 (MCwShLs)	11	13	-	-	-	-	-	12	-	-	-	5
Trt 4 (SfBGmR)	-	-	-	-	-	22	10	-	14	12	-	-
Trt 5 (PmGmSs)	-	-	-	23	24	40	-	-	-	-	-	-
Trt 6 (CwPmSsMLs)	-	8	-	23	10	-	-	13	-	-	-	2

VITA

Kevin Brian Meeks

Candidate for the Degree of

Doctor of Philosophy

Thesis: TYPE FULL TITLE HERE IN ALL CAPS

Major Field: Crop Science

Biographical:

Education:

Completed the requirements for the Doctor of Philosophy in Crop Science at Oklahoma State University, Stillwater, Oklahoma in December, 2014.

Completed the requirements for the Master of Science in your Crop Science at Texas Tech University, Lubbock, Texas in 2011.

Completed the requirements for the Bachelor of Science in Animal Science at Texas Tech University, Lubbock, Texas in 2007.

Professional Memberships: American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America.