COVER CROPS IN NO-TILLAGE CROP ROTATIONS IN EASTERN AND WESTERN KANSAS

by

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Abstract

Replacing fallow periods with cover crops can provide many benefits including soil quality improvements and reduced nitrogen fertilizer requirements. Field experiments were established near Garden City, KS with winter wheat and fallow phases as main plots, thirteen legume or non-legume cover crops, continuous winter wheat, and fallow as subplots, and cover crop termination method as sub-subplots. Treatments containing triticale had greatest water use efficiency (19.9 kg ha^{-1} mm^{-1}) and aboveground biomass (3550 kg ha^{-1}), but subsequent winter wheat yields were reduced due to a reduction in volumetric water content. Increased soil residue through greater cover crop biomass resulted in increased precipitation storage efficiency during the fallow period, but water requirements to produce biomass depleted soil moisture more than growing a low biomass crop or fallow. In years of above-average precipitation, low biomass cover crops might be grown with little to no negative effect on subsequent wheat yields. A second field experiment was established near Manhattan, KS with fallow, double crop soybean, and four cover crop treatments planted after wheat harvest in a winter wheat-grain sorghum-soybean no-till cropping system, with five nitrogen treatments applied to the sorghum crop to estimate nitrogen contribution of the cover crops. Greatest aboveground biomass production and nitrogen accumulation was observed with sorghum-sudangrass. At the 0 kg ha^{-1} N rate, grain sorghum yields were reduced 1200 kg ha^{-1} following sorghum-sudangrass, while all other cover crop treatments provided a 20-30 kg ha^{-1} N equivalent benefit. Sorghum yields might be reduced following large biomass producing cover crops when nitrogen is limiting, but a small nitrogen benefit might be realized following low C:N ratio cover crops. Cover crop productivity and their subsequent effects on grain sorghum performance were evaluated in field studies established near Manhattan and Hutchinson, KS in 2008 and 2009. Sixteen summer or fall cover crop species were planted in no-tillage winter wheat stubble and evaluated for biomass production, nitrogen concentration, and nitrogen accumulation. Summer annual grass species produced the greatest biomass, 3392 kg ha^{-1} and greater, and legume species accumulated the greatest amounts of nitrogen, averaging 43 kg ha^{-1}. Grain sorghum yields were 867 kg ha^{-1} greater following summer cover crops compared to fall cover crops. Cover crops had a significant effect on sorghum performance, with yields 1240 kg ha^{-1} greater following legume cover crops.

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CHAPTER 1 - Literature Review

Intensification of cropping systems can provide many benefits including greater water use efficiency, weed control, soil quality improvements, and fertility improvements (Leikam et al, 2007; McVay et al, 1989). Currently, herbicides and synthetic fertilizers are widely used to control weeds and supply nutrients for crop growth. Rising costs of these inputs have increased interest in incorporating cover crops into cropping systems as a possible replacement for fertilizers and herbicides (Sundermeier, 1999). Cover crops are classified as any plant introduced during or directly after the main cropping phase of a system and terminated before the planting of the next crop (Hartwig and Ammon, 2002). Cover crops might be grown in the summer or winter, be a legume or non-legume, and are typically left as standing residue. Many different cover crops are grown and managed for specific purposes in cropping systems. The use of cover crops to intensify a cropping system is not a new idea. This practice dates back to 300BC (Pain and Harrison, 1993; Pieters, 1927; Weston, 2005). Throughout the early 20th century, the use of cover crops to combat soil erosion and supply nitrogen (N) during times of fertilizer shortage was common (Aamodt, 1943; McKnee, 1931; Troeh et al, 2004).

Cover Crops and No-till

No-tillage cropping systems improve soil physical properties, such as increased soil organic matter and aggregate stability (Douglass and Goss, 1982; Heard et al., 1988; Six et al., 1999). Switching from conventional tillage to no-tillage might allow intensification of the cropping system due to an increase in stored available water (Nielsen et al., 2005; Norwood, 1999). A study by Wagger et al. (1992) found corn yields increased in no-tillage systems compared to conventional tillage systems in North Carolina. This increase was attributed to an increase in surface residue which reduced soil crusting, thereby reducing water runoff and improving soil water permeability. Heer and Krenzer (1989) reported an increase in the profile soil water during the spring in a no-tillage continuous winter wheat (*Tritcum aestivum*) system when compared to a conventional continuous winter wheat system. Stone and Schlegel (2006) reported an increase of 71 mm of saved stored soil water at the time of wheat planting in a wheat-summer crop-fallow no-till cropping system compared to a conventional tillage system.

The increase in available soil water with no-till, might allow farmers to grow cover crops during a fallow period with minimal reduction of available soil water to the following crop.

In conventional systems, tillage disrupts aggregates causing organic matter decomposition rates to increase. Reducing tillage might increase soil organic matter resulting in cooler soil temperatures in the fall and slow soil warming in the spring (Johnson and Lowery, 1985). Cooler soil temperatures in the fall and spring could cause negative outcomes on crop growth such as delayed emergence and seedling development (Kumudini et al., 2008; Rasmussen et al., 1997). No-tillage systems might also provide some environmental benefits. Shouse (1990) reported increased CO_2 sequestration from the atmosphere with no-tillage versus conventional tillage systems, possibly helping to slow global warming. Cover crops fit well with most no-till and conservation tillage cropping systems because they can be terminated chemically to provide surface mulch that helps conserve soil moisture and increase soil organic matter (Blevins et al., 1990).

One potential use of cover crops involves replacing the fallow period with a legume (Rice et al., 1993). Spring seeded cover crops such as alfalfa (*Medicago sativa* L.), field pea (*Pisum sativum* L.), lentil (*Lens culinaris*), and clover (*Trifolium repens*) were studied as possible replacements for the fallow period (Blackshaw et al., 2001). Troeh et al. (2004) found that tall, standing cover crops like wheat or triticale (*Triticosecale* spp.) helped reduce soil erosion by wind and water. Establishing plant roots and crop residue can decrease soil erosion and increase water infiltration rates (Bowman et al., 1999; Dabney, 1998; McVay et al., 1989; Stute and Posner, 1993). By the strictest definition, cover crops are not harvested. Fallow crops or flex crops might be grown as either a cover crop and not harvested, or harvested as a forage or grain crop. Growing a crop for grain requires more moisture than harvesting the crop as forage. Harvesting a fallow crop as forage results in an increase in soil water content for the following crop compared to fallow crops grown for grain (Nielsen et al., 2005). Preserving soil water is important for minimizing the variability in crop yield and maximizing the profitability of the cropping system. This is especially true in the semi-arid regions of the central Great Plains where water is often the limiting factor (Schlegel and Havlin, 1997). The central Great Plains environment consists of hot and windy growing periods during the summer months that increase soil surface water evaporation. The ability to minimize soil water evaporation is an important aspect of the cropping system. A long-term study by Lotter et al. (2003) found that in drought years, the yield of organic corn (*Zea mays* L.) and soybean (*Glycine max*) following a cover crop was greater than conventionally produced corn and soybean due to more stored soil moisture in the organic corn and soybean treatments. The central Great Plains winters are often cold and windy. The lack of vegetation and ground cover leave fields susceptible to wind and water erosion. Cover crops might reduce wind erosion by acting as a physical barrier that slows the moving force of the wind and raises the wind profile (Troeh et al., 2004). When used as cover crops, winter cereals can be highly effective at reducing wind and water erosion (Kessavalou and Walters, 1999).

Cover Crops, Nitrogen, and Weed Suppression

Cover crops can increase the efficient use of available nitrogen to subsequent crops, and legumes can potentially reduce the amount of N fertilizer required (Dekker et al., 1994; McVay et al., 1989; Shipley et al., 1992). Nitrogen must be mineralized from the cover crop residue prior to planting the following grain crop in order for the N to be utilized in that growing season. The availability of N from crop residue or fertilizer to subsequent crops is affected by several factors including precipitation, tillage, temperature, length of growing season, soil texture, and soil productivity (Dekker et al., 1994; Hesterman et al., 1992; Stute and Posner, 1995; Vyn et al., 2000). An increase in surface residue might result in decreased N availability due to lower N mineralization rates and greater N immobilization (Rice and Smith, 1984).

Including legume cover crops in crop rotations was shown to improve soil fertility and increase crop production (Blevins et al., 1990; Hargrove and Frye, 1987). Leikam et al. (2007) reported that N fixation in leguminous species can provide 14 kg ha^{-1} of N to the next crop. Blackshaw et al. (2001) measured a 16 to 52 kg ha^{-1} increase in N following a sweetclover cover crop compared to conventional tillage fallow treatments, and wheat yields were 47 to 75% greater following sweetclover than convention tilled fallow. The increased yield was partially attributed to an early termination date of the cover crop and greater time for N mineralization to occur (Blackshaw et al., 2001). Corn and sorghum yields were greater following a winter cover crop than fallow due to biologically fixed N (Blevins et al., 1990). Hargrove et al. (1986) found that sorghum (*Sorghum bicolor*) yields were generally greater in a no-till cropping system following a legume cover crop than following fallow. Due to the variable cost of N fertilizer

(NASS, 2008), the increased efficiency and fixation of N by cover crops is of particular interest to producers.

Although leguminous species are known for their N benefits, non-leguminous species such as sudangrass (*Sorghum bicolor*), millet (*Pennisetum americanum*), and canola (*Brassica napus* L.) reduce N leaching. Nitrogen is utilized by the plant and later released during mineralization of the plant's tissue, increasing the amount that becomes available to the following crop (Kuo et al., 1997; Sainju et al., 2000). Meisinger et al. (1990) found non-legume cover crops were better at reducing N leaching from the soil than legume or fallow. Cool season cover crops can be planted in the fall and provide vegetative cover during the winter. These winter cover crops use soil N, possibly preventing it from leaching over winter (Sainju and Singh, 2008). Since neither legume nor non-legume cover crops can provide all the advantages possible from the incorporation of a cover crop, a mixture of legume and non-legume species might be the most effective at providing multiple benefits (Sainju and Singh, 2008).

Cover crops can suppress weeds and might be used as a component of integrated pest management. Weed suppression is accomplished through competition, physical effects, and maintaining surface residues (Conklin et al., 2002; Creamer et al., 2000). In the central Great Plains, common rye (*Secale cereal*), large crabgrass (*Digitaria sanguinalis*), Kochia (*Kochia scoparia*), Downy Brome (*Bromus tectorum* L.), and other weeds are a common throughout the summer and winter growing periods. In the more arid regions where wheat-fallow is the predominant crop rotation, weed control becomes an issue during the fallow period. Typically, weeds are controlled by tillage or herbicides (Schlegel and Havlin, 1997). With the increasing adoption of no-till, few options remain for weed control, other than herbicides. Weed suppression through herbicides is effective, but limitations such as crop safety, re-plant interval restrictions, herbicide ineffectiveness, and weed resistance reduces weed control. With increasing reports of resistant weed species throughout the U.S., (Culpepper et al., 2008; Duke, 1998), cover crops might provide weed suppression during times that herbicides might be ineffective or unavailable.

Cover crops can provide valuable benefits such as N fixation, reduced N leaching, weed suppression, and wind and water soil erosion. However, for cover crops to be adopted the system must provide a monetary benefit. Many factors affect a producer's decision to include cover crops in their cropping system. When intensifying a cropping system, the potential problems that might occur must also be considered. Availability of cover crop seed, conflicts with planting and harvesting, equipment needs, and increased labor and time requirements are all factors that a producer must consider.

Cover Crops and Soil Available Water

Climate and precipitation patterns determine the feasibility of cover crops in many regions. With annual precipitation ranging from 380 mm in western Kansas to 915 mm in eastern Kansas (National Climatic Data Center, 2009), appropriate crop management becomes important for determining profitability and sustainability of a cropping system. In semiarid regions, the use of fallow to store water to stabilize crop yields is common. In the central Great Plains, the most common dryland cropping system has traditionally been winter wheat-fallow (Hinze and Smika, 1984; Schlegel and Havlin, 1997). Intensification of the wheat-fallow cropping system has emerged with the addition of a summer crop. Wheat-summer crop-fallow cropping systems are gaining popularity and are starting to replace the traditional wheat-fallow system (Schlegel and Havlin, 1997). Stubble mulching, which requires several tillage operations, was used during the fallow period to control weeds and prepare a seedbed (Allen and Fenster, 1986). As a combined result of tillage and erosion, soil organic matter content has declined 40 to 70% since cultivation began in the early 1900s (Haas et al., 1957).

A reduction in crop yield following cover crops was reported in the semi-arid regions of the central Great Plains due to a reduction in plant available water following a cover crop compared to fallow (Clark et al., 1995; Nielson et al., 2005). Water and N are the two most limiting factors to winter wheat grain production in the central Great Plains (Nielsen and Halvorson, 1991). Schlegel and Havlin (1997) reported that wheat yields were reduced 42 to 83% following hairy vetch (*Vicia sativa* L.) compared to fallow. Nielsen and Vigil (2005) found that leguminous cover crops grown during the fallow period of a winter wheat – fallow rotation reduced wheat yield 67% due to less soil water available for the wheat crop. Nielsen and Vigil (2005) observed less available soil water at wheat planting when termination date of the cover crop was delayed. The decrease in soil water at planting negatively affected subsequent wheat yields regardless of cover crop species. Nielsen and Vigil (2005) concluded that legumes grown in place of fallow in a wheat-fallow rotation reduced soil water for the following crop, and reduced wheat yield regardless of termination date. Clark et al. (1995) reported a similar observation when comparing termination dates of hairy vetch in corn production. Soil water and corn yields both decreased with a delay in cover crop termination date.

Success of cover crops depends on their ability to suppress weed growth, while not significantly decreasing the soil water needed for the following grain crop (Schelgel and Havlin, 1997; Unger and Vigil, 1998). Zentner et al. (2004) reported greater success of spring wheat yields following early legume planting and termination dates. The impact of growing a leguminous species on grain yields might be offset in part by the contribution of N to the system. Unfortunately, the fixation of N by the legume cover crop might not be great enough to offset the decreased profit in grain yield (Schelgel and Havlin, 1997).

Earlier termination of cover crops might help reduce the soil water depletion by the cover crop. Blackshaw et al. (2001) found that plant available water at spring wheat planting was not significantly different following sweetclover compared to fallow. Early termination allowed more time for soil water to re-charge before planting. It was noted that annual rainfall was greater than average for the duration of this study. During years of severe drought and minimal spring rainfall, the initial lower soil water content caused by cover crops will most likely negatively affect wheat yields. A study in south central Kansas by Janke et al. (2002) concluded that cover crops could substitute for all or part of the N required for the subsequent sorghum crop in years with adequate rainfall. In dry years, sorghum yields were less following a cover crop. The authors suggested that long-term soil improvements from repeated use of cover crops might help minimize yield reductions due to improved available soil water storage. Incorporating cover crops into the semi-arid regions of the central Great Plains might prove difficult due to limited precipitation and soil water availability.

Water Use and Retention in Soil

Maximizing soil water retention is important in environments with minimal annual precipitation. Fallow use efficiency refers to the percentage of water stored during the fallow period and is calculated as a ratio of stored soil water to the fallow precipitation (Baumhardt et al., 2008). An increase in surface residue increases soil surface shading, resulting in cooler soil temperatures and decreased wind speeds over the soil surface (Hatfield et al., 2001). Surface residue also protects the soil surface from crusting, which reduces water runoff and increases precipitation infiltration (Baumhardt and Lascano, 1996). Baumhardt and Lascano (1996) found that infiltration increased as the amount of wheat residue on the soil surface increased. Unger et al. (1994) showed similar results of decreased water runoff, and increased water infiltration and storage resulting from increased surface crop residue by a reduction in tillage. Cropping systems that increase surface residue, (such as reduced tillage and no-till) increase water use efficiency and fallow use efficiency (Nielsen et al., 2005). When combined with a more water efficient cropping system, the addition of cover crops that produce large amounts of biomass should increase soil organic matter and surface residues, possibly resulting in increased stored soil moisture. Selection of cover crops that produce large amounts of biomass must include those that have efficient water use. Nielsen et al. (2006) found that winter triticale had greater water use efficiency than either forage corn or foxtail millet (*Setaria italica*) in the semi-arid region of eastern Colorado. In a no-tillage cropping system, the water increase in stored soil moisture might enable a low water use forage crop to be grown during the fallow period without reducing subsequent grain crops yield.

Angus et al. (2001) define water use efficiency as the ratio of yield to water used during crop growth. The most common method of describing water use efficiency is

$$\mathrm{WUE} = \mathrm{Y}/\mathrm{ET}$$

where Y is the crop yield, and ET is the evapotranspiration of water during the growing season, including evaporation from the soil surface (E) and transpiration through the crop (T). Evaporation does not contribute to yield, but due to the difficulty of separating out evaporation from transpiration, water use efficiency is often estimated using total water use (ET) (Hatfield et al., 2001).

Research Question and Justification

Recently, the cost of fertilizer has increased (NASS, 2008). This has increased producer interest in modifying cropping systems to reduce input costs and maintain profits. Integrating cover crops into the crop rotation was promoted as a method to reduce N fertilizer requirements and increase cropping system profitability and sustainability (Blackshaw et al., 2001; Gan et al., 2003; Snapp et al., 2005). Cover crops were shown to increase soil organic matter and surface residue, thus increasing precipitation infiltration and soil water content, and reducing precipitation runoff (Nielsen et al., 2005).

Common no-till cropping systems in the central Great Plains include winter wheat and summer crops such as corn, grain sorghum, and soybean in wheat-summer crop-fallow, wheat-fallow, or wheat-summer crop rotations. Due to the high temperatures and variable precipitation that occurs during the critical periods of the growing season, the sustainability and profitability of incorporating cover crops into current no-till cropping systems is still under question. Additional research is needed to identify how crop rotations respond when including cover crops. The benefits of cover crops must be evaluated to determine if they are great enough to justify the further intensification of current cropping systems.

Therefore, the objectives of this research were to:

i.) Quantify the impact of cover crops in no-tillage crop rotations in eastern and western Kansas environments.
   a. Determine the impact of cover crops and N rates in typical Kansas no-till cropping systems. (Chapter 2)
   b. Determine cover crop water use efficiency and fallow precipitation storage efficiency of several different cover crops in a no-till wheat-fallow rotation in western Kansas. (Chapter 3)

ii.) Quantify biomass and N accumulation levels in various winter, spring, and summer cover crops. (Chapter 4)

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CHAPTER 2 - Effects of Cover Crops in No-tillage Crop Rotations

Abstract

Replacing fallow periods with cover crops can provide many benefits, including soil quality improvements, reduced nitrogen fertilizer requirements, reduced soil erosion, and increased water infiltration rates. Due to variable precipitation during the growing season in Kansas environments, cover crop impacts on cropping system sustainability and productivity are not consistent. The objective of this study was to evaluate the effects of several cover crops on a no-tillage cropping system. A no-tillage crop rotation of winter wheat (*Tritcum aestivum*)-grain sorghum (*Sorghum bicolor*)-soybean (*Glycine max)* was established in 2007, 2008, and 2009, with cover crops planted during the fallow period between wheat harvest and grain sorghum planting. Two summer-grown and two fall-grown species were evaluated for biomass production, nitrogen concentration, and nitrogen accumulation. Each growing period contained one legume and one non-legume cover crop species. Five nitrogen rate treatments of 0, 45, 90, 135, and 180 kg ha^{-1} were applied to the sorghum crop to estimate nitrogen contribution of the cover crops. The results of this study show that on average, summer-grown species produce greater biomass and subsequently accumulate more nitrogen in the aboveground biomass than the fall-grown species. On average, greatest aboveground biomass production (9031 kg ha^{-1}) and nitrogen accumulation (93 kg ha^{-1}) was observed with sorghum-sudangrass (*Sorghum vulgare* var. *Sudanese*), a summer-grown non-legume species. Grain sorghum yields following the sorghum-sudangrass cover crop were 1200 kg ha^{-1} less than sorghum following the other cover crops, double crop soybeans, or chemical fallow. All other cover crop treatments provided a 20-30 kg ha^{-1} N equivalent benefit at the 0 kg ha^{-1} N rate, with no nitrogen advantage observed at greater N rates. The results of this study indicate that large biomass-producing cover crops can reduce subsequent crop yields when nitrogen is limiting. Sorghum performance following the other cover crops was not different than sorghum performance following chemical fallow or double crop soybean. Although no cover crops were able to completely replace the benefit seen from applying nitrogen fertilizer, a small nitrogen benefit (20-30 kg ha^{-1}) might be realized with legume or low C:N ratio cover crops.

Introduction

Intensification of cropping systems can provide many benefits including greater water use efficiency, weed control, soil quality improvements and fertility improvements (Leikam et al., 2007; McVay et al., 1989). Currently, herbicides and fertilizers are widely used to control weeds and supply nutrients to the soil. Rising costs of inputs have increased interest in including cover crops in cropping systems as a possible replacement for fertilizers and herbicides (Sundermeier, 1999). Cover crops are classified as any plant introduced during or directly after the main cropping phase of a system and terminated before the planting of the next crop (Hartwig and Ammon, 2002). Although many classes of cover crops exist, cover crops are grown and managed to play a specific role in the cropping system.

Replacing fallow periods with cover crops provides many benefits to producers. Troeh et al. (2004) found that tall, standing cover crops like wheat or triticale help reduce soil erosion by wind and water. Establishing roots and residue can decrease soil erosion and increase water infiltration rates (Dabney, 1998; McVay et al., 1989). Preserving soil water is important for maximizing the sustainability and profitability of the cropping system. This is especially true in the arid regions of Kansas where water is often the limiting factor (Schlegel and Havlin, 1997). Lack of vegetation and ground cover can leave fields susceptible to wind and water erosion. Cover crops might reduce wind erosion by acting as a physical barrier that slows the moving force of the wind and raises the wind profile (Troeh et al., 2004). When used as cover crops, winter cereals can be highly effective at reducing wind and water erosion (Kessavalou and Walters, 1999).

Reduction or elimination of the nitrogen fertilizer requirement might be possible following legume cover crops (McVay et al., 1989). The availability of nitrogen from crop residue or fertilizer to subsequent crops can be affected by several factors including precipitation, temperature, length of growing season, soil type, and soil productivity (Dekker et al., 1994; Hesterman et al., 1992; Stute and Posner, 1995; Vyn et al., 2000). Leguminous cover crop species provide water and wind erosion protection as well as the added advantage of nitrogen fixation (Leikam et al., 2007; McKnee, 1931). Cool season cover crops can be planted in the fall and provide vegetative cover during the winter. These winter cover crops use soil nitrogen, possibly preventing it from leaching into the ground (Sainju and Singh, 2008). Accumulation of large amounts of biomass and increased soil organic N availability to the following crop occur following a cover crop. In some cases, green manure legume crops can supply the necessary N required for the following cereal crop and reduce fertilizer inputs (Baldock and Musgrave, 1980; Griffin et al., 2000). Although leguminous species are typically known for their nitrogen benefits, non-leguminous species such as sudangrass, millet and canola can provide nitrogen-trapping benefits. These species capture nitrogen from the soil profile that might otherwise leach from the rooting zone during a fallow period. This trapped nitrogen is released during the degradation of the plant's tissue and becomes available to the following crop (Kuo et al., 1997; Sainju et al., 2000). Non-legume cover crops are effective at increasing soil organic nitrogen through increased biomass production (Kuo et al., 1997). Meisinger et al. (1990) found non-legume cover crops to be better at reducing nitrogen leaching from the soil than legume or no cover crops. Because neither legume nor non-legume cover crops can provide all the advantages possible from utilizing a cover crop, a mixture of legume and non-legume species could be the most effective approach to maximize the available benefits (Sainju and Singh, 2008).

Inserting cover crops into the crop rotation has been promoted as a method to reduce nitrogen fertilizer requirements and increase cropping system sustainability (Blackshaw et al., 2001; Gan et al., 2003; Snapp et al., 2005). However, due to the high temperature and variable precipitation that occurs during the growing season in Kansas environments, cover crop impacts on cropping system sustainability and productivity is relatively unknown. The objective of this study was to quantify the effects of legume, non-legume, summer-grown, and fall-grown cover crops on a no-tillage sorghum-soybean-winter wheat rotation.

Materials and Methods

Field experiments were conducted in 2007, 2008, and 2009 at the Kansas State University Department of Agronomy Ashland Bottoms Research Farm approximately 8 km south of Manhattan, Kansas (39˚11'N 96˚35'W) on a Wymore silty clay loam soil (fine, smectitic, mesic Aquertic Argiudoll). Cover crops were evaluated in a 3-year, no-tillage crop rotation of winter wheat followed by cover crop-grain sorghum-soybean. Plots were arranged in a randomized complete block design with four replications. Each block was split by crop phase with each phase of the crop rotation present in each block every year. Rotational crop was randomized within each block. Each split-block was 36 m wide by 68 m long, and the cover crop treatment plot was 6 m wide by 68 m long. Six different cover crop treatments were established after wheat harvest. These cover crop species were chosen due to ease of obtaining seed, low seed cost, and a proven history of success in Kansas (Claassen, 1997; Heer, 1996). The chemical fallow was used as a check treatment, and the double crop soybean (*Glycine max*) was included as the most likely alternative to chemical fallow or cover crops following wheat harvest. Cover crops were established in two growing periods each containing one legume species and one non-legume species. In the summer growing period, the non-legume was sorghum-sudangrass (*Sorghum vulgare* var. *sudanese*) and the legume was late season soybean (*Glycine max*). During the fall, the non-legume was canola (*Brassica napus* L.) and legume was winter pea (*Pisum sativum*). Five nitrogen application rate sub-plots were established within each cover crop plot. Nitrogen rates of 0, 45, 90, 135, and 180 kg N ha^{-1} were applied prior to grain sorghum planting. The nitrogen source in 2008 was ammonium polyphosphate solution (10-32-00), and in 2009, urea was applied on the soil surface.

The soybean crop phase was planted with Asgrow 3803 soybean seed on 11 July 2007 and 5 June 2008 and with Asgrow 3403 on 22 May 2009 at a seeding rate of 432 000 seeds ha^{-1} on 0.76 m rows with a White 6700 planter (AGCO Corp., Duluth, GA). Seeding depth was 5 cm. In 2007, 2008, and 2009, ammonium polyphosphate solution (10-32-00) liquid fertilizer was applied at a rate of 93.5 L ha^{-1}. Stands were counted after full emergence in an area of 4.6 m^2. Weed control was obtained with two applications of glyphosate herbicide at 3.5 L ha^{-1}. The two applications of herbicide were sufficient to control weeds throughout the growing season. Plant heights were recorded at harvest. A length of 12.8 m was machine harvested from the center two rows of each plot with a Massey Ferguson 8XP plot combine (AGCO Corp., Duluth, GA) with a grain head. Grain moisture and test weight were estimated with a DICKEY-john GAC 2000 (DICKEY-john Corp., Springfield, IL). Grain protein content was estimated using a GrainSpec Whole Grain analyzer (Foss-NorthAmerica, Eden Prairie, MN).

The winter wheat crop phase was drilled on 30 October 2007, 3 November 2008, and 7 October 2009. In all years, the target-seeding rate was 115 kg ha^{-1}. In 2007 and 2008, seeding was performed with a Crustbuster (CrustBuster Inc., Dodge City, KS) drill. A John Deere 1590 no-tillage drill (Deere & Co., Moline, IL) was used in 2009. No fertilizer was applied at planting in 2007 and 2008. In 2009, 65 kg ha^{-1} of monoammonium phosphate (11-52-00) was applied with the wheat seed. Plant heights were measured at time of harvest. Wheat was harvested on

30 June in 2008 and 2009. An area of 19.5 m^2 was machine harvested from the center of the plot using a Hege plot combine (Wintersteiger Inc, Salt Lake City, UT). Grain moisture and test weights were estimated with a DICKEY-john GAC 2000 (DICKEY-john Corp., Springfield, IL). Wheat grain for protein concentration was estimated using a GrainSpec Whole Grain analyzer (Foss-NorthAmerica, Eden Prairie, MN).

Immediately after wheat harvest, the stubble was sprayed with 3.5 L ha^{-1} glyphosate herbicide to control volunteer weeds. The summer cover crops were planted into the standing winter wheat stubble with a Hege drill (Wintersteiger Inc, Salt Lake City, UT). Two applications of glyphosate herbicide were applied to the chemical fallow treatment throughout the summer to control weeds in all years. Sorghum-sudangrass was drilled at a seeding rate of 25 kg ha^{-1} in all years. The double crop soybean (variety Asgrow 3006) and late season soybean (variety Asgrow 5301) were drilled at a seeding rate of 395000 seeds ha^{-1} in all years. Throughout the summer months, the plots to be seeded to winter grown cover crops were maintained with recommended application rates of glyphosate herbicide for weed control. Winter cover crop treatments were drilled on 27 August 2007, 4 September 2008, and 10 August 2009. In all years, canola was seeded at 11 kg ha^{-1} and winter pea was seeded at 30 kg ha^{-1}. All cover crop species were drilled on a 25.4 cm row spacing.

Cover crop performance was measured throughout the growing season. Stand counts were measured on all cover crops 20 days after plant emergence within an area of 1.55 m^2. A rotary mower was used to terminate the sorghum-sudangrass on 1 September 2007 and late season soybean on 27 September 2007. Termination occurred on 22 September 2008 with a rotary mower and 18 September 2009 with a crop roller for both sorghum-sudangrass and late season soybean. On 27 August 2007, two 1.5 m^2 samples were hand harvested from the sorghum-sudangrass and late season soybean treatments. On 22 September 2008 and 18 September 2009, a 1.5 m^2 sample was hand harvested from every sub-plot within the sorghum-sudangrass and late season soybean treatments. Canola and winter pea were terminated with a rotary mower on 21 April 2008 and with herbicide (Glyphosate and 2,4-D) on 22 April 2009. In both years, two 1.5 m^2 samples were hand harvested from the canola and winter pea treatments prior to termination. In all years, sub-samples of each sample were dried in a forced-air dryer at 65° C until dry, and weighed to obtain dry mass. Dry samples were analyzed for nitrogen content (sulfuric acid/hydrogen peroxide digest) at the Kansas State University Soil Testing

Laboratory. Double crop soybean treatments were harvested 25 October 2007, 30 October 2008, and 5 October 2009. A 19.5 m^2 area was machine harvested from the center of each plot with a Hege plot combine (Wintersteiger Inc, Salt Lake City, UT). Grain moisture and test weight were estimated with a DICKEY-john GAC 2000 (DICKEY-john Corp., Springfield, IL) and protein concentrations were estimated with a GrainSpec Whole Grain analyzer (Foss-NorthAmerica, Eden Prairie, MN).

The grain sorghum crop phase was planted with sorghum hybrid DKS 54-00 on 9 June 2008 and 21 May 2009 at a seeding rate of 190 600 seeds ha^{-1} in 0.76 m rows with a White 6700 planter (AGCO Corp., Duluth, GA). Seeding depth was 5 cm. In 2007, corn hybrid DKC 67-74 was planted at a seeding rate of 12 150 seeds ha^{-1} instead of grain sorghum to initiate the cropping sequence after wheat harvest that year. No data was collected from the corn. Nitrogen was applied to the sub-plots within each cover crop treatment before grain sorghum planting in 2008 and 2009. Urea ammonium nitrate solution (32%) was injected below the residue in 2008 and dry Urea was surface broadcast applied in 2009. Post-plant, pre-emerge herbicide (Bicep Magnum) was applied to the sorghum immediately after sorghum planting in both years at a rate of 0.65 L ha^{-1}. Stands were counted after full emergence (30 days after planting) in an area of 4.6 m^2. Flag leaf samples were collected at half bloom and dried in a forced-air dryer at 65˚ C until dry. Dry samples were tested for nitrogen content (sulfuric acid/hydrogen peroxide digest) at the Kansas State University Soil Testing Laboratory. Sorghum plots were scanned with a GreenSeeker Model 505 hand held optical sensor (NTech Industries, Ukiah, CA) and CropCircle ACS-210 hand held optical sensor (Holland Scientific, Lincoln, NB) 60 days after sorghum planting to obtain a normalized difference vegetation index (NDVI) value. These crop sensors rely on crop reflectance to estimate nitrogen status in plants and were used to quantify observed differences in grain sorghum nitrogen status. Studies have shown strong relationships between spectral reflectance and nitrogen status in green vegetation (Bausch and Duke, 1996; Stone et al., 1996). Grain sorghum was harvested on 30 October 2008 and 13 November 2009. A length of 12.8 m was machine harvested from the center two rows with a Hege plot combine (Wintersteiger Inc, Salt Lake City, UT) in 2008, and a wintersteiger plot combine (Wintersteiger Inc, Salt Lake City, UT) 2009. Grain moisture and test weight were estimated with a DICKEY-john GAC 2000 (DICKEY-john Corp., Springfield, IL). Grain was analyzed for nitrogen concentration in the Kansas State University Soil Testing Laboratory (sulfuric acid/hydrogen peroxide digest). Plant height measurements were obtained at harvest. Plant head counts were recorded for an area of 4.6 m^2 prior to grain harvest.

Soil samples were taken each spring to establish baseline soil nutrient concentrations and to monitor changes over time. In April of 2008 and 2009, 18 soil core samples were taken in each crop phase in 0-5, 5-10, and 10-15 cm depth increments to determine soil pH, organic matter, phosphorus and potassium levels. A 60 cm profile N sample was taken from each cover crop treatment in the phase that was to be planted to grain sorghum in April of 2008 and 2009. These samples provided information on baseline soil nitrogen levels. Bulk density samples were collected from the grain sorghum phase in April of 2008. Three core samples were taken in 0-5, 5-10, 10-15, and 15-30 cm depth increments from each cover crop treatment within the block that had previously been harvested for grain sorghum.

Significance of main effect differences and their interactions was determined using the PROC MIXED procedure (SAS Institute, 2004) with year, crop phase, growing season, cover crop treatment, and nitrogen rate as fixed effects and replications as random effects. Regression analysis using SAS PROC REG was used to determine linear, quadratic, and cubic regression coefficients for variables showing significant nitrogen response. The regression curve with significant regression coefficients and smallest sum of squared residuals was chosen as the best fit for each data set.

Results and Discussion

There was not a significant interaction between year and cover crop treatment for winter wheat yield, grain nitrogen concentration, or plant height and no significant differences between wheat grown in the different cover crop plots for these measures of wheat performance (α = 0.05). No response was expected because the cover crop treatments and nitrogen rates had not been imposed in the plots before the winter wheat crop phase in 2008 and 2009. An average grain yield of 1710 kg ha^{-1} was observed over the two years with the grain nitrogen concentration averaging 23.22 g kg^{-1}. The winter wheat averaged 66.0 cm in height. The lack of significant differences in winter wheat yields, grain nitrogen concentration, and plant heights indicate that the experimental area was uniform before cover crop and nitrogen rate treatments were established.

Although analysis of the soybean crop phase yield, grain nitrogen concentration, stand count, and plant height indicated no significant ($\alpha = 0.05$) interaction between year and cover crop treatment, each year was analyzed separately due to the differences in previous management of the soybean plots. This was done to determine if the cover crop or nitrogen treatments had residual effects on the soybean crop phase in 2009. In 2008, the plots within the soybean crop phase had not previously received any cover crop or nitrogen treatments. The soybean crop phase harvested in 2009 was exposed to the cover crops in the summer and fall of 2007 and nitrogen treatments in the spring of 2008.

The analysis of the 2008 soybean yields, grain nitrogen concentrations, stand counts, and plant heights indicated no significant interaction between cover crop treatments and nitrogen rate, and no significant response to either cover crop or nitrogen rate ($\alpha = 0.05$). As with the winter wheat, this was expected because no cover crop treatments or nitrogen rates had been applied to these plots previously. In 2008, average soybean yield was 3744 kg ha^{-1} with a grain nitrogen concentration of 55.86 g kg^{-1}. Stand counts averaged 256 179 plants ha^{-1} with an average plant height of 96.15 cm.

The 2009 soybean analysis indicated no significant interaction between cover crop treatment and nitrogen rate ($\alpha = 0.05$), however, a significant ($\alpha = 0.05$) response to nitrogen rate was observed for soybean yields (Table 2.1). Soybean yields in 2009 following the 135 kg ha^{-1} nitrogen treatment applied before sorghum planting in 2008 was greater than soybean yield after all other nitrogen treatments. The reasons for this yield increase are not clear because a residual nitrogen effect would be expected for the 180 kg ha^{-1} rate as well. Additional years of soybean yield data should reveal if this was due to a carry-over nitrogen effect or simply an artifact of variability in soil nitrogen levels.

A significant ($\alpha = 0.05$) interaction was detected between all cover crop response variables and year (Table 2.2). Therefore, cover crop responses were analyzed by year. Cover crop treatments in 2007 differed in biomass yield, nitrogen concentration, and nitrogen yield (Table 2.3). Sorghum-sudangrass produced the greatest amount of aboveground biomass and contained the smallest nitrogen concentration (Table 2.3). The large amount of biomass resulted in sorghum-sudangrass accumulating the greatest amount of nitrogen in the aboveground biomass. Although canola produced the smallest amount of biomass, it contained the same concentration of nitrogen as the late-season soybean and winter pea. Canola stands were reduced during the winter of 2007-2008 with three blocks showing a 98% reduction in biomass compared to the fourth block. In years when canola survives the winter, greater biomass yields would be expected. On average, the summer-grown cover crops had greater biomass and nitrogen accumulation yields when compared to the fall-grown crops (Table 2.3). Legume cover crops produced on average 1298 kg ha^{-1} less biomass than the non-legume cover crops, but contained 9 g kg^{-1} greater nitrogen concentration.

The same cover crop treatments were established in 2008. No significant interaction between nitrogen rate and cover crop treatment was detected ($\alpha = 0.05$). As with the 2007 cover crops, no nitrogen treatments had been applied previously, so this result was expected. However, a significant response ($\alpha = 0.05$) to cover crop treatment was observed with cover crop biomass, nitrogen concentration, and stand counts (Table 2.4). On average, the summer-grown crops had greater biomass and nitrogen accumulation, with the fall-grown crops having a greater nitrogen concentration (Table 2.4). As in 2007, sorghum-sudangrass produced the greatest amount of biomass, but contained the smallest nitrogen concentration (Table 2.4). Late-season soybean produced the second greatest amount of biomass, but had a greater nitrogen concentration than sorghum-sudangrass. As a result, both sorghum-sudangrass and late-season soybean accumulated similar amounts of nitrogen in the aboveground biomass. Greatest concentrations of nitrogen were observed in the winter pea. Small biomass yields resulted in canola and winter pea accumulating little total nitrogen in the aboveground biomass. Relatively smaller winter pea stand counts in the fall may have contributed to the small winter pea biomass yields.

In 2009, only summer-grown cover crops are included because fall-grown treatments had not been terminated at the time of this manuscript preparation. Results for fall-grown cover crops will be reported at a later date. Sorghum-sudangrass produced a greater amount of aboveground biomass (Table 2.5). Late-season soybean produced less biomass, but contained a significantly greater concentration of nitrogen. This resulted in the late-season soybean accumulating greater amounts of nitrogen (Table 2.5). Across all three years, sorghum-sudangrass tended to have greatest biomass production, but contained lowest nitrogen concentrations. Late season soybean had the second greatest biomass, but greater nitrogen concentrations. Although biomass and nitrogen concentrations were consistent, nitrogen accumulation varied each year.

Double crop soybeans also were included as a common alternative to chemical fallow. Yields varied across years with 2009 producing the greatest yield (Table 2.6). In 2009, grain nitrogen concentration measurements were taken, showing that the soybean seed contained 57.9 g kg^{-1} of nitrogen. The double crop soybean yields observed were within the typical range for Kansas, with state yields averaging 1411 kg ha^{-1} during the 2007-2009 growing seasons (NASS, 2010).

An analysis of profile nitrogen after termination of spring cover crops and before sorghum planting showed no significant interaction ($\alpha = 0.05$) between year and cover crop treatment, but did indicate a response due to cover crop and a difference between years (Table 2.7). Canola, late-season soybean, and chemical fallow resulted in greater amounts of nitrogen in the soil profile when compared to other cover crop treatments (Table 2.7). Winter pea, double crop soybean, and sorghum-sudangrass had less profile nitrogen after the termination of the cover crops. When comparing the profile nitrogen across years, a reduction in profile N from 2008 to 2009 was observed in all treatments, suggesting nitrogen quantities within the soil profile decreased as available nitrogen was utilized by the growing crops. No significant differences were seen between summer and fall grown cover crops, or between legume and non-legume species.

Grain sorghum was primarily used to determine the effects of utilizing cover crops in a no-till cropping system because it was the crop that immediately followed the cover crop phase. An analysis of the grain sorghum crop phase indicated a significant interaction ($\alpha = 0.05$) between year and cover crop treatment for grain yield, flag leaf nitrogen concentration, stand count, heads per plant, and half-bloom date (Table 2.8). Therefore, the grain sorghum responses were analyzed separately by year.

An analysis of the 2008 grain sorghum data showed a cover crop response for grain yield, grain nitrogen content, and bloom date (Table 2.9). Flag leaf nitrogen and grain nitrogen content were the only two grain sorghum response variables to be influenced by nitrogen rate. In both cases, response to nitrogen interacted significantly ($\alpha = 0.05$) with cover crop treatment (Table 2.9).

Grain sorghum yield and bloom date showed significant responses to cover crop treatments, but no response to nitrogen rate in 2008 (Table 2.9). For both variables, the responses to cover crop treatment did not show an interaction with nitrogen rate. Grain sorghum yields did not differ following chemical fallow, sorghum-sudangrass, winter pea, and canola (Table 2.10). Yields following double crop soybean were significantly less than following all other post wheat harvest treatments (Table 2.10). Sorghum bloom dates followed a similar trend with sorghum following sorghum-sudangrass, winter pea, and canola blooming later than the other treatments (Table 2.10).

Small, linear responses in the flag leaf nitrogen concentration were observed with sorghum after double crop soybean, late season soybean, sorghum-sudangrass, and winter pea in 2008 (Figure 2.1). Sorghum following the canola and chemical fallow treatments showed no response to nitrogen. At the 0 and 45 kg ha^{-1} N rate, flag leaf nitrogen concentrations were significantly greater in sorghum after the chemical fallow treatment than after the other treatments ($\alpha = 0.05$). At nitrogen rates of 90 kg ha^{-1} and above, the flag leaf nitrogen concentrations were not significantly different between any of the treatments ($\alpha = 0.05$). Differences in flag leaf concentration at the low nitrogen rates might have been caused by the cover crops removing nitrogen from the soil whereas the chemical fallow left the nitrogen in place and available for the sorghum early in the growing season, assuming no N leaching occurred. As nitrogen rates increased, the nitrogen requirement was satisfied, minimizing differences in sorghum leaf nitrogen response to cover crops.

Grain nitrogen concentrations were less following the double crop soybean and sorghum-sudangrass cover crop treatments when compared to the other treatments at the 0 N rate in 2008 (Figure 2.2). One possible explanation for the results might be that nitrogen was immobilized in the biomass of sorghum-sudangrass and removed by grain harvest of the double crop soybeans and not available to the following sorghum crop. The measured profile N concentrations support this explanation with lowest profile N concentrations observed following the sorghum-sudangrass and double crop soybean treatments (Table 2.7). As the sorghum reached maturity, less nitrogen was available to the sorghum plant, resulting in the decrease in grain nitrogen concentration. Small linear responses in grain N concentration were observed with sorghum following canola, chemical fallow, double crop soybean, and late season soybean. Sorghum grain nitrogen concentration following sorghum-sudangrass and winter pea showed no response to nitrogen fertilizer rate. As with the flag leaf nitrogen concentrations, the decrease in nitrogen availability was not enough to affect sorghum yields.

Analysis of the 2009 grain sorghum showed a significant interaction ($\alpha = 0.05$) between cover crop and nitrogen rate for yield, flag leaf nitrogen concentration, plant height, bloom date, GreenSeeker NDVI, and CropCircle NDVI (Table 2.11). Yield increases were observed from the 0 kg ha^{-1} N rate up to the 90 kg ha^{-1} N rate where the yields leveled off (Figure 2.3). At the 0 kg ha^{-1} N rate, yields following sorghum-sudangrass were lower than after the other cover crops. As nitrogen rate increased to 45 kg ha^{-1}, the yields were not significantly different between cover crop treatments but still increased up to the 90 kg ha^{-1} rate. Grain sorghum yields were no different following a cover crop than following the chemical fallow treatment, with the exception of sorghum-sudangrass at the 0 kg ha^{-1} N rate. At the 0 kg ha^{-1} N rate, sorghum-sudangrass reduced yields by 2987 kg ha^{-1}. At nitrogen rates below 90 kg ha^{-1} a yield loss was observed following sorghum-sudangrass. At nitrogen rates above 90 kg ha^{-1}, there was no yield difference between any of the cover crop treatments with all cover crop treatments showing a similar response to nitrogen (Figure 2.3).

Grain sorghum flag leaf nitrogen concentration increased in response to increasing rates of nitrogen following all treatments except for sorghum-sudangrass in 2009 (Figure 2.4). All cover crop treatments containing a similar concentration of nitrogen in the flag leaves at the 0 kg ha^{-1} N rate. Sorghum flag leaf N concentration following sorghum-sudangrass did not change with increasing N rates, but sorghum flag leaf N concentration following all other cover crop treatments increased in N concentration by between 0.009 and 0.02 g kg^{-1} for each additional kg of N ha^{-1}.

The GreenSeeker NDVI analysis indicated a significant interaction between cover crop treatment and nitrogen rate in 2009 (Figure 2.5). Double crop soybean, late season soybean, and sorghum-sudangrass had increasing linear responses to nitrogen; and canola, chemical fallow, and winter pea had increasing quadratic responses to nitrogen. In all treatments, an increase in NDVI was observed from the 0 kg ha^{-1} N rate to the 135 kg ha^{-1} N rate. The NDVI continued to increase with increasing N rate for double crop soybean, late season soybean, and sorghum-sudangrass. The NDVI value reached saturation at the 135 kg ha^{-1} N rate for the canola, chemical fallow, and winter pea treatments. The CropCircle NDVI analysis was less sensitive and showed no cover crop response to nitrogen rate for sorghum after canola, late season soybean, and winter pea (Figure 2.6), but similar responses to those observed with GreenSeeker NDVI for sorghum-sudangrass, double crop soybean, and chemical fallow.

Grain sorghum plant height did not respond to nitrogen rate following the canola and double crop soybean treatments in 2009 (Figure 2.7). Sorghum following chemical fallow, late season soybean, sorghum-sudangrass, and winter pea all showed a similar response to nitrogen. Sorghum height was suppressed at N rates less than 90 kg ha^{-1} following winter pea and chemical fallow. Sorghum height increased linearly with increasing N rate following late-season soybean and sorghum-sudangrass, but the degree of response was greater after sorghum-sudangrass.

An analysis of grain sorghum bloom date showed that sorghum after chemical fallow and late season soybean had no response ($\alpha = 0.05$) to the nitrogen rates in 2009 (Figure 2.8). Sorghum following sorghum-sudangrass, canola, double crop soybean, and winter pea treatments reached half bloom later at N rates less than 45 kg ha^{-1}. Sorghum after all treatments bloomed within one day at N rates of greater than 90 kg ha^{-1}.

On average, grain sorghum showed favorable responses to the nitrogen treatments in 2009. An increase in grain yield, plant height, flag leaf nitrogen concentration, and NDVI were observed from the 0 kg ha^{-1} N rate up to the 90 kg ha^{-1} N rate. At rates greater than 90 kg ha^{-1}, values generally reached a peak and did not increase with the increase in nitrogen rates. Flag leaf nitrogen concentration was the exception, with an increase in nitrogen concentrations observed across all nitrogen treatments. In 2009, sorghum-sudangrass was the only cover crop treatment that had a negative effect on grain sorghum yields, and that reduction was observed only at the 0 kg ha^{-1} N rate. The other cover crop treatments and double crop soybean provided a 20 to 30 kg ha^{-1} N equivalent at the 0 kg ha^{-1} N rate, but the N advantage was not apparent with the application of nitrogen fertilizer. The nitrogen equivalent observed at the 0 N rate would satisfy 25-30% of the recommended nitrogen application rate for grain sorghum in this study.

These results suggest that nitrogen was not a limiting factor for sorghum in 2008. In 2009, nitrogen became limiting at the lower N rates but the sorghum crop's nitrogen requirement was met at N rates of 90 kg ha^{-1} and greater. Profile nitrogen measurements at the beginning of the sorghum crop phase and the lack of nitrogen response in the winter wheat and soybean indicate nitrogen was abundant in the soil profile in spring 2008. The reduction in soil profile N averages from 2008 to 2009 suggests that nitrogen reserves present in the soil prior to the establishment of this experiment were slowly being used by the crops during this experiment

(Table 2.7). It is hypothesized that responses to cover crop and nitrogen treatments will become more apparent as the nitrogen reserves in the soil continue to decline.

Conclusions

The results of this study show that on average, summer-grown species produce greater biomass and subsequently accumulate more nitrogen in the aboveground biomass than the fall-grown species. Sorghum-sudangrass had the greatest biomass and nitrogen accumulation across all years when compared to other cover crops. However, no benefit from the increase in nitrogen accumulation was observed in the following grain sorghum crop. A 1200 kg ha^{-1} grain sorghum yield reduction was observed with sorghum-sudangrass when compared to the other cover crop treatments and chemical fallow at the 0 kg ha^{-1} N rate in 2009. All other cover crop treatments and double crop soybean provided a 20-30 kg ha^{-1} N equivalent at the 0 kg ha^{-1} N rate, with no nitrogen advantage observed once nitrogen fertilizer was applied. Increased grain sorghum yields were observed with increasing nitrogen rates up to a rate of 90 kg ha^{-1} where yields reached maximum. On average, the lower yielding sorghum plots were shorter and contained less nitrogen in the flag leaf. The GreenSeeker hand held sensor was able to detect these differences and measured lower NDVI values for these plots. Cover crops that produce large amounts of biomass, such as sorghum-sudangrass, reduced subsequent crop yields when nitrogen is limiting in the soil. Although cover crops were not able to completely replace the N benefit seen from applying nitrogen fertilizer, a small nitrogen advantage might occur following legume or low C:N cover crops when nitrogen fertilizer is not applied. When fertilizer is applied, cover crops can be grown with no negative effect on subsequent sorghum yields, suggesting cover crops can be integrated into a typical no-till eastern Kansas cropping system.

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Figures and Tables

Table 2.1. Soybean response in 2009 to nitrogen rates applied to grain sorghum in 2008†.

Nitrogen Rate	Yield	Grain N Concentration	Stand Count	Height
kg ha^{-1}	kg ha^{-1}	g kg^{-1}	plants ha^{-1}	cm
0	4196 b	57.8 a	254 685 a	96.8 a
45	4151 b	57.7 a	255 355 a	96.9 a
90	4180 b	57.7 a	253 824 a	95.3 a
135	4275 a	57.6 a	249 505 a	96.0 a
180	4187 b	57.5 a	256 833 a	96.0 a

† Values in a column followed by the same letter are not significantly different, $\alpha = 0.05$.

Table 2.2. Analysis of variance for cover crops grown in 2007, 2008, and 2009.

Variable	Biomass	Nitrogen Concentration	Nitrogen Yield	Stand Count	Plant Height
			Pr > F		
Year	**	***	***	***	***
Cover Crop	***	***	***	***	***
Year*Cover Crop	**	***	***	***	***

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 2.3. 2007 Cover crop aboveground biomass, nitrogen concentration, and nitrogen accumulation†.

Cover Crop	Cover Crop Aboveground Biomass Biomass Yield	 Nitrogen Concentration	 Nitrogen Accumulation
	kg ha^{-1}	g kg^{-1}	kg ha^{-1}
Sorghum-sudangrass	8741 a	16.7 b	159 a
Late-season soybean	3876 b	29.3 a	115 b
Winter pea	2651 c	32.1 a	85 b
Canola	381 d	26.8 a	8 c
Contrast††			
Summer vs. Fall (SS, LSSB) (WP, C)	4793**	-6.5**	90**
Legume vs. Non-legume (LSSB, WP) (SS, C)	-1298**	9.0**	NS

† Values in a column followed by the same letter are not significantly different, α = 0.05.

†† Value represents difference in biomass yield, nitrogen concentration, and nitrogen accumulation between summer and fall seeded cover crops and legume and non-legume species.

** Significant at the 0.01 probability level.

Table 2.4. 2008 Cover crop aboveground biomass, nitrogen concentration, and nitrogen accumulation†.

	Cover Crop Aboveground Biomass			
Cover Crop	Biomass Yield	Nitrogen Concentration	Nitrogen Accumulation	Stand Count
	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	plants ha^{-1}
Sorghum-sudangrass	9272 a	8.83 d	84 a	1 174 806 a
Late-season soybean	4541 b	19.18 c	87 a	278 133 c
Winter pea	110 c	41.93 a	5 b	102 285 d
Canola	137 c	32.93 b	5 b	705 670 b
Contrast††				
Summer vs. Fall (SS, LSSB) (WP, C)	6783***	-23.43***	81***	322 492***
Legume vs. Non-legume (LSSB, WP) (SS, C)	-2379***	9.68**	NS	-750 029***

† Values in a column followed by the same letter are not significantly different, α = 0.05.

†† Value represents difference in biomass yield, nitrogen concentration, nitrogen accumulation, and stand count between summer and fall seeded cover crops and legume and non-legume species.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 2.5. 2009 Ashland summer-grown cover crops aboveground biomass, nitrogen concentration, nitrogen accumulation, stand count, and plant height comparison†.

	Cover Crop Aboveground Biomass			
Cover Crop	Biomass Yield	Nitrogen Concentration	Nitrogen Accumulation	Stand Count
	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	plants ha^{-1}
Sorghum-sudangrass	9080 a	4.05 b	37 b	1 389 723 a
Late-season soybean	5618 b	21.10 a	119 a	498 842 b

† Values in a column followed by the same letter are not significantly different, α = 0.05.

Table 2.6. Ashland cover crop double crop soybean yields and grain nitrogen concentration in 2007, 2008, and 2009†.

	Double Crop Soybean	
Year	Yield	Grain Nitrogen Concentration
	kg ha^{-1}	g kg^{-1}
2007	1446 b	--
2008	1434 b	--
2009	2835 a	57.9

† Values in a column followed by the same letter are not significantly different, $\alpha = 0.05$.

Table 2.7. Comparison of profile nitrogen before grain sorghum planting in 2008 and 2009†.

Cover Crop	Profile Nitrogen Concentration		
	2008	2009	Average
		kg ha^{-1}	
Chemical fallow	68.67	21.71	45.19 ab
Sorghum-sudangrass	41.65	20.99	31.32 bc
Late-season soybean	62.16	38.34	50.25 a
Double crop soybean	37.38	20.06	28.72 bc
Winter pea	31.27	18.41	24.84 c
Canola	79.63	31.98	55.80 a
Average	53.46 A	25.25 B	
Contrast††			
Summer vs. Fall (SS, LSSB, DBLSB) (WP, C)	NS	NS	NS
Legume vs. Non-legume (LSSB, DBLSB, WP) (SS, C)	NS	NS	NS

† Values in a column followed by the same lower-case letter and values in row followed by the same upper-case letter are not significantly different, α = 0.05. No significant interaction between year and cover crop treatment was observed for profile nitrogen (α = 0.05).

†† Value represents difference in profile nitrogen content between summer and fall seeded cover crops and legume and non-legume species.

Table 2.8. Analysis of variance for grain sorghum response variables in 2008 and 2009.

Source of Variation	Grain Yield	Grain N	Flag leaf N	Plant Height	Stand Count	Heads per plant	Bloom Date
	Pr > F						
Year	**	***	***	NS	***	***	***
Cover Crop	*	*	*	NS	***	NS	***
Nitrogen Rate	***	***	***	***	NS	NS	***
Cover Crop*Nitrogen Rate	*	NS	NS	NS	NS	NS	NS
Year*Cover Crop	***	NS	***	NS	***	**	***
Year*Nitrogen Rate	***	NS	NS	***	NS	NS	***
Year*Cover Crop*Nitrogen Rate	NS	NS	NS	NS	NS	NS	NS

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.

Table 2.9. Analysis of variance for grain sorghum responses in 2008.

Source of Variation	Grain Yield	Grain N	Flag Leaf N	Plant Height	Stand Count	Heads per plant	Bloom Date
	Pr > F						
Cover Crop	**	**	NS	NS	NS	NS	***
Nitrogen Rate	NS	***	***	NS	NS	NS	NS
Cover Crop*Nitrogen Rate	NS	**	**	NS	NS	NS	NS

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 2.10. Response of 2008 grain sorghum yields and bloom dates to cover crop treatments†.

Treatment	Yield	Half Bloom
	kg ha^{-1}	days after planting
Chemical fallow	8686 a	67 b
Sorghum-sudangrass	8267 ab	68 a
Late-season soybean	8099 b	63 c
Double crop soybean	6145 c	62 d
Winter pea	8759 a	68 a
Canola	8317 ab	68 a

† Values in a column followed by the same letter are not significantly different, $\alpha = 0.05$.

Table 2.11. Analysis of variance for grain sorghum response in 2009

Variable	Grain Yield	Grain N	Flag leaf N	Plant Height	Stand Count	Heads per plant	Bloom Date	GreenSeeker NDVI	CropCircle NDVI
					Pr > F				
Cover Crop	**	NS	**	NS	**	NS	***	**	***
Nitrogen Rate	***	**	***	***	*	NS	***	***	***
Cover Crop*Nitrogen Rate	**	NS	**	***	NS	NS	*	***	***

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.

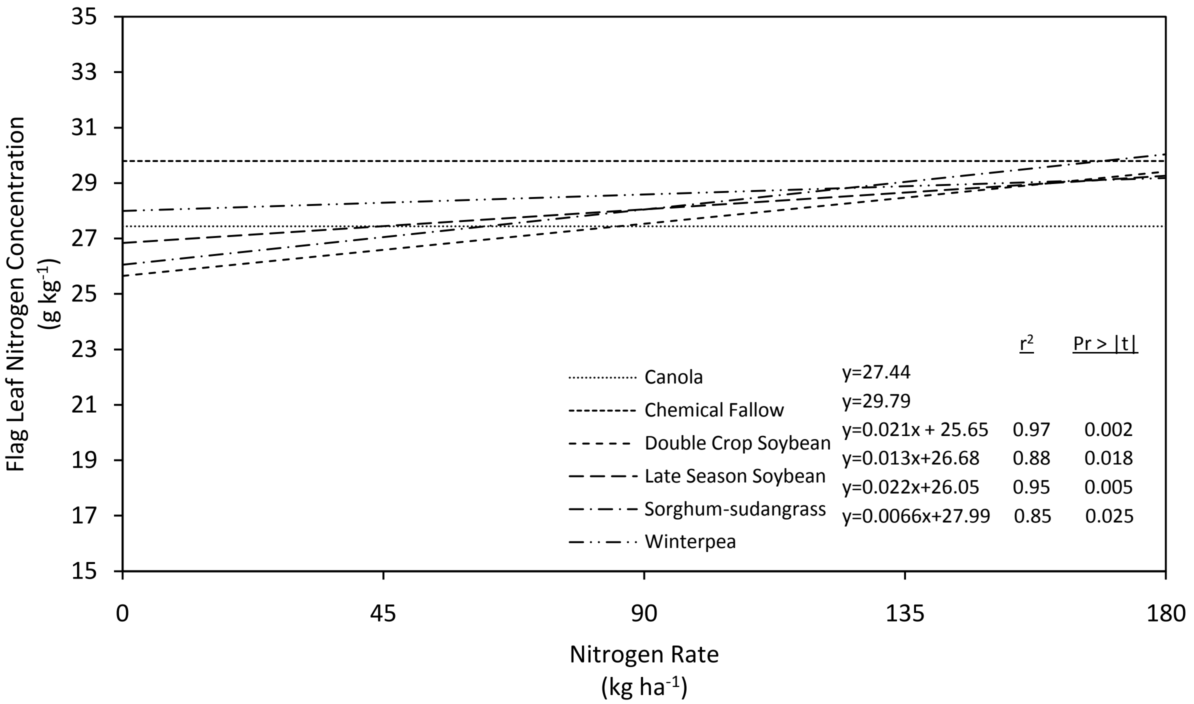

Figure 2.1. 2008 grain sorghum flag leaf nitrogen concentration interaction between cover crop treatment and nitrogen rate.

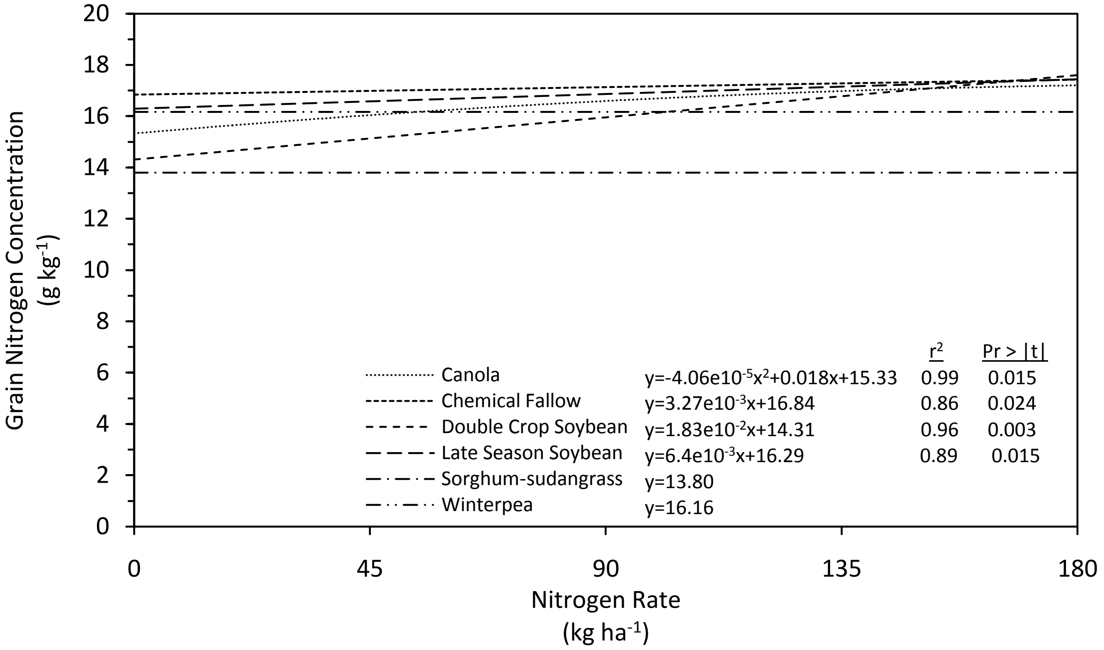

Figure 2.2. 2008 grain sorghum grain nitrogen concentration interaction between cover crop treatment and nitrogen rate.

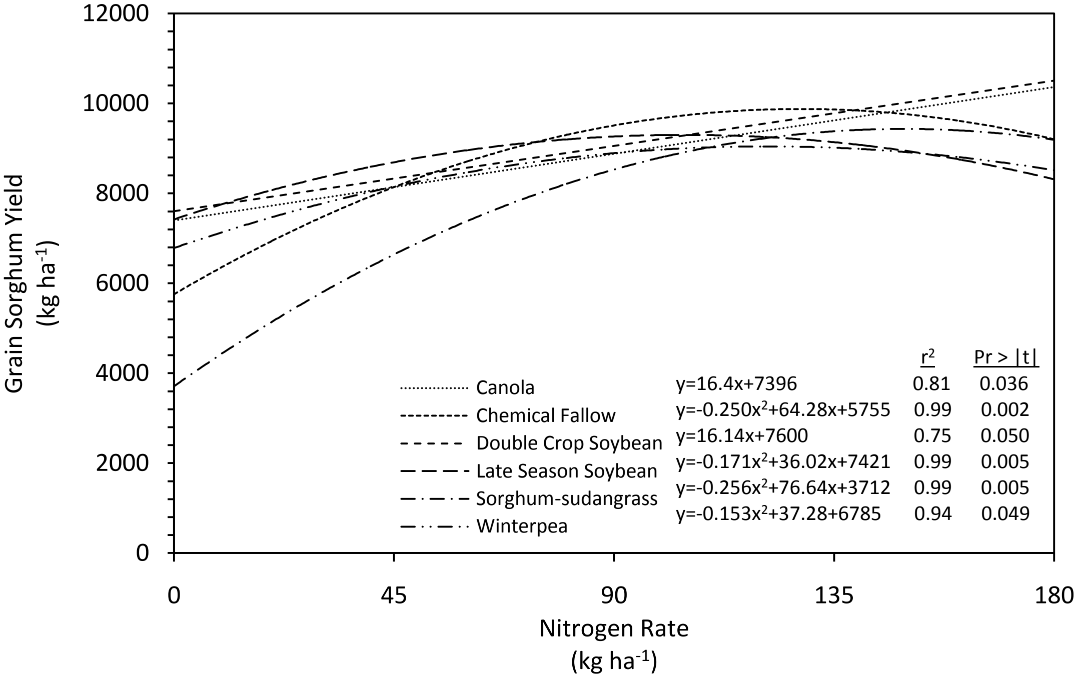

Figure 2.3. 2009 grain sorghum yield interaction between cover crop treatment and nitrogen rate.

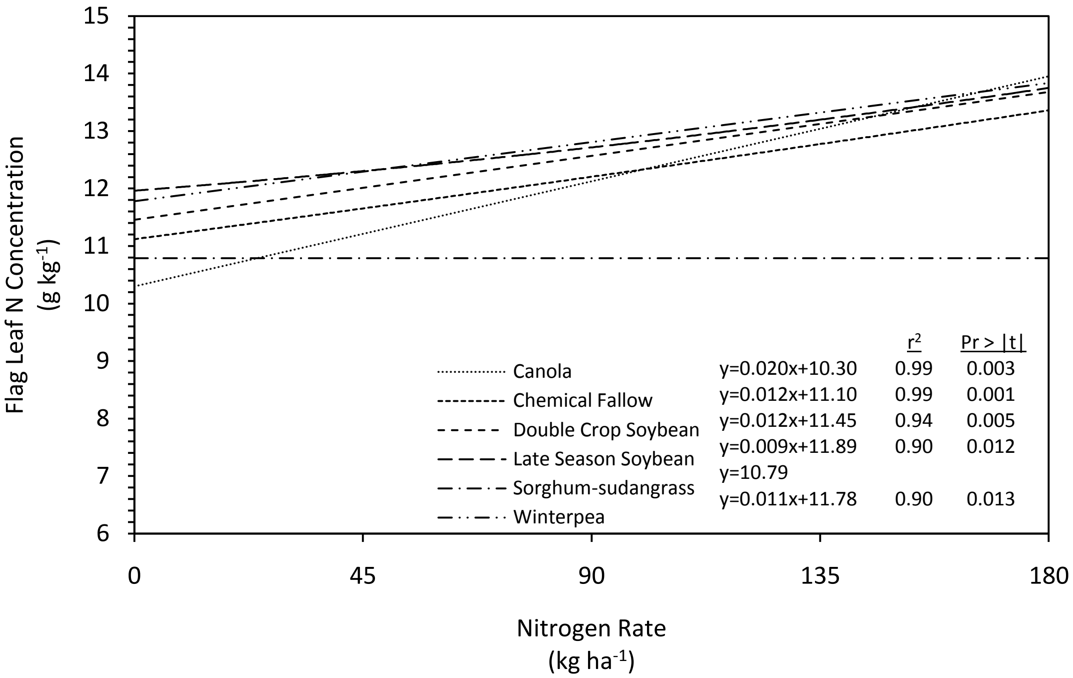

Figure 2.4. 2009 grain sorghum flag leaf nitrogen concentration interaction between cover crop treatment and nitrogen rate.

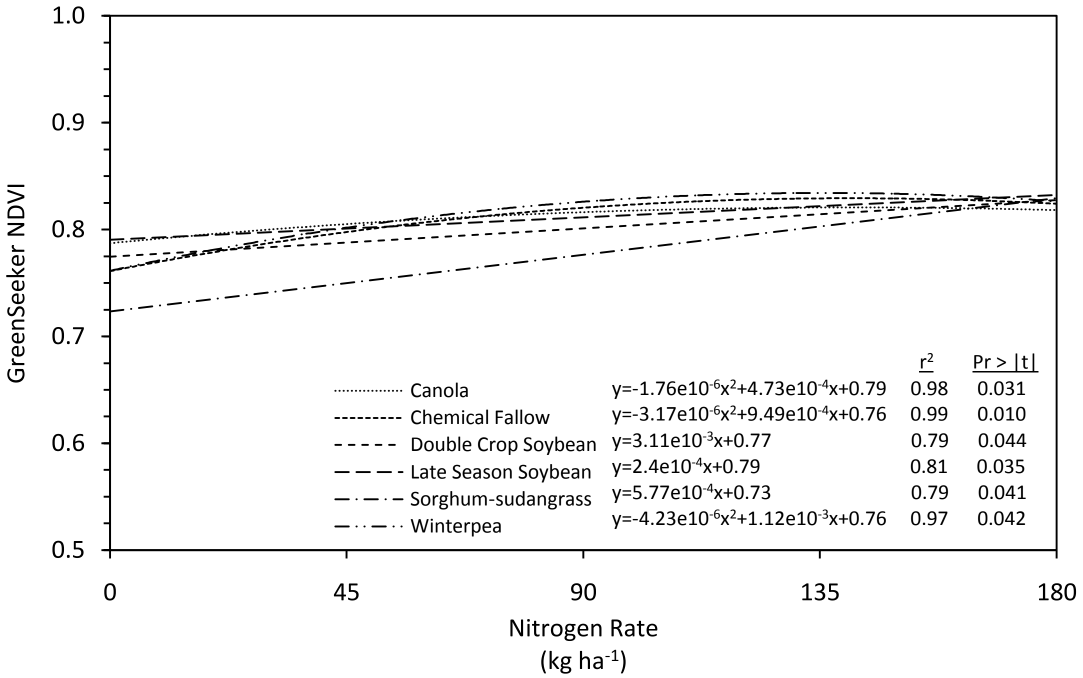

Figure 2.5. 2009 grain sorghum GreenSeeker NDVI interaction between cover crop treatment and nitrogen rate.

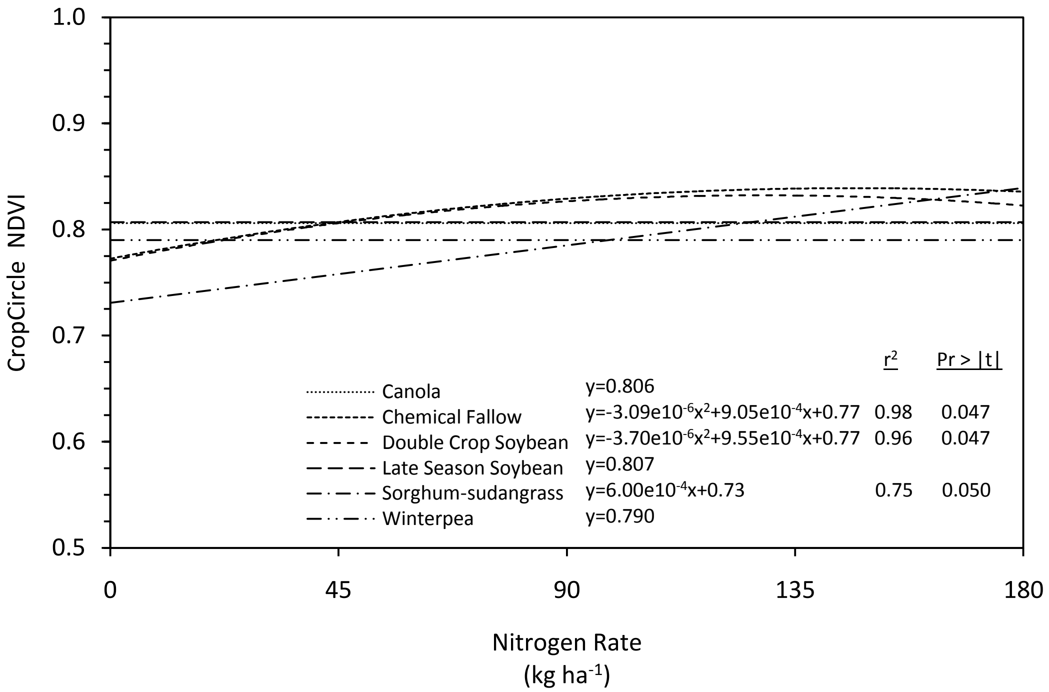

Figure 2.6. 2009 grain sorghum CropCircle NDVI interaction between cover crop treatment and nitrogen rate.

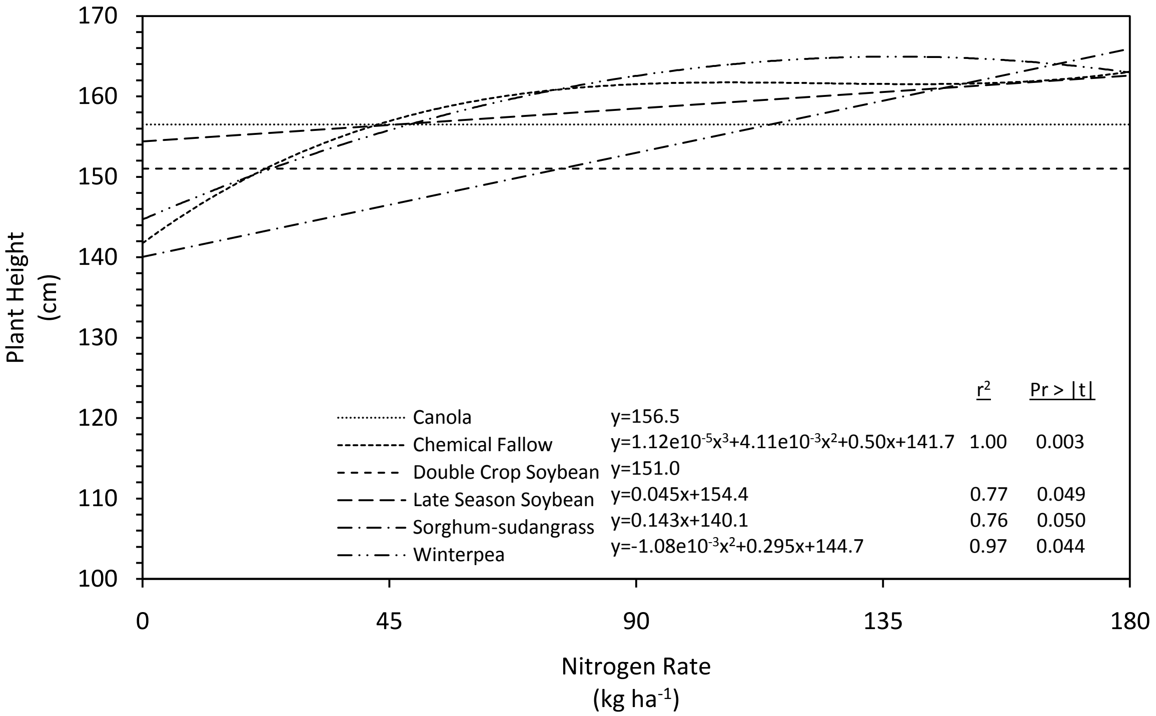

Figure 2.7. 2009 grain sorghum plant height interactions between cover crop treatment and nitrogen rate.

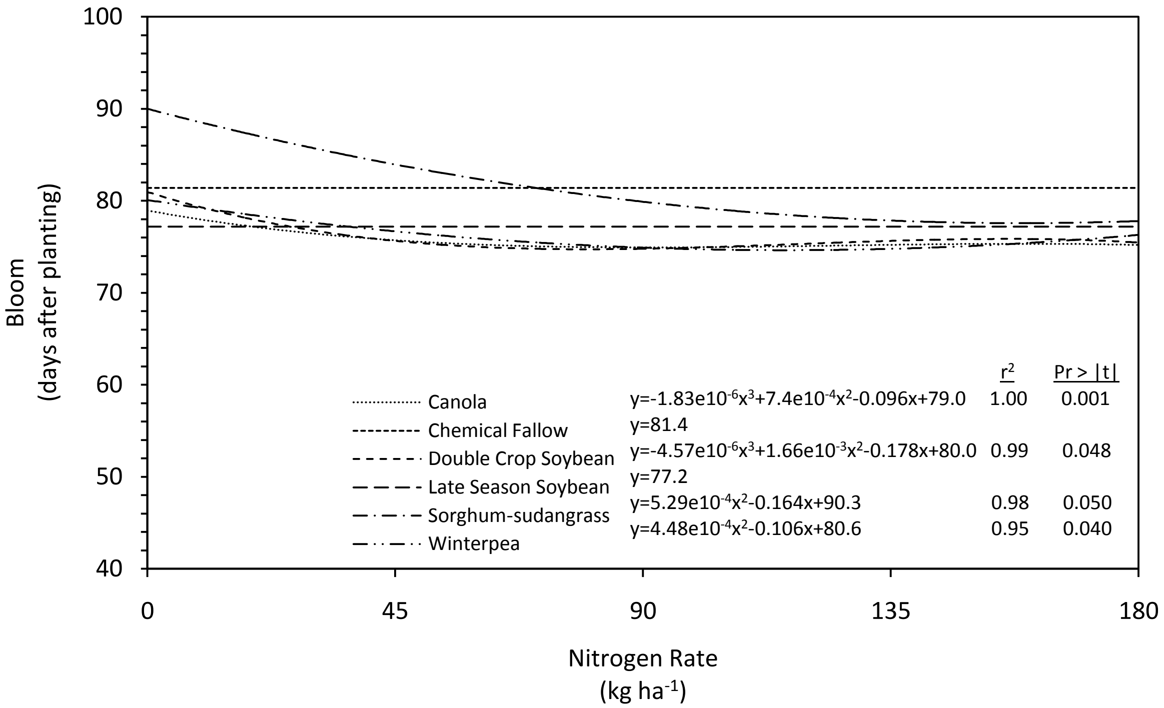

Figure 2.8. 2009 grain sorghum bloom date interaction between cover crop treatment and nitrogen rate.

CHAPTER 3 - Effects of Cover Crops on Soil Water in a No-tillage Wheat-Fallow Crop Rotation

Abstract

In the central Great Plains the most common dryland rotation is winter wheat-fallow where the fallow period is used to store water for the subsequent wheat crop. Field experiments were conducted during the 2007-2008 and 2008-2009 growing season at the Kansas State University Southwest Research-Extension Center in Garden City, KS. The objective was to evaluate the effects of replacing fallow with cover crops in a no-tillage winter wheat (*Triticum aestivum*)-fallow cropping system. The experiment was a randomized split-plot design with winter wheat and fallow phases as main plots, thirteen cover crops, continuous winter wheat, and fallow as subplots, and cover crop termination method as sub-subplots. A selection of winter and spring grown legume and non-legume species were planted during the fallow period between wheat crops and evaluated for water use efficiency, precipitation storage efficiency (PSE) during the fallow period, and effects on subsequent winter wheat yields. On average, treatments containing winter and spring triticale (*Triticale hexaploide* L.) had the greatest cover crop water use efficiency (19.9 kg ha^{-1} mm^{-1}) and aboveground biomass yield (3550 kg ha^{-1}). High biomass producing cover crops had lower PSE during the cover crop growing season due to greater water use. After cover crop termination, PSE was greatest among treatments with greater biomass production due to more soil residue during this part of the fallow period. Although cover crop residue increased PSE after cover crop termination, the water required to produce that residue depleted soil moisture more than growing a low biomass crop or fallow. As a result, low biomass cover crops left standing had greater PSE over the fall fallow period than high biomass crops. Wheat yield following high biomass producing treatments, such as those containing winter and spring triticale, subsequently were reduced 485 kg ha^{-1} compared to wheat yields following other cover crops and fallow. The results indicate that in years of average to above average annual precipitation, low biomass producing cover crops might be grown with little to no negative effect on subsequent wheat yields.

Introduction

Semiarid regions commonly use fallow to store water for stabilizing crop yields (Hinze and Smika, 1983). In the central Great Plains the most common dryland cropping system was traditionally winter wheat-fallow (Schlegel and Havlin, 1997). In more recent years, some producers have intensified the wheat-fallow rotation by including a summer crop in a wheat-summer crop-fallow rotation (Schlegel et al., 2002). Stubble mulching traditionally had been used during the fallow period to control weeds and prepare a seedbed, which required several tillage operations (Allen and Fenster, 1986). As a result of tillage, soil organic matter content decreased 40 to 70% during the first 60 years of crop production (Haas et al., 1957).

Cropping systems that utilize a long fallow period are prone to reduced soil organic matter and increased soil erosion (Larney et al., 1994). Replacing conventional tillage with no-till can reduce soil erosion (Bowman et al., 1999). However, reduced levels of soil organic matter remains a problem due to long periods of no crop growth which results in mineralization of organic matter by soil microbes (Blackshaw and Lindwall, 1995). Including a cover crop in the fallow period might reduce soil erosion and help improve soil quality (Stute and Posner, 1993). Another potential use of cover crops is growing a legume to fix nitrogen during the fallow period (Rice et al., 1993).

Cropping systems that increase surface residue, (such as reduced tillage and no-till) increase water use efficiency and fallow use efficiency (Nielsen et al., 2005; Nielsen and Vigil, 2010). When combined with a water efficient cropping system, the addition of cover crops that produce large amounts of biomass would likely increase soil organic matter over time, and possibly result in improved soil moisture storage. Selection of higher biomass cover crops must include those that have efficient water use.

Maximizing soil water retention is important in environments with minimal annual rainfall. Nielsen et al. (2005) showed that water storage increases as tillage intensity decreases during the summer fallow period. As a result, organic matter and crop residue increased on the soil surface with reduced tillage intensity. An increase in surface residue can increase soil surface shading, decrease soil temperatures, and reduce wind speed over the soil surface (Hatfield et al., 2001). Surface residue also protects the soil surface from crusting, which results in reduced water runoff and increased precipitation infiltration (Baumhardt and Lascano, 1996).

In the semi-arid regions of the central Great Plains, soil water content is often the most limiting factor for maximizing grain yields. Decreased grain yields following a cover crop were reported due to reduced stored soil water content following a cover crop compared to fallow (Clark et al., 1995; Nielson et al., 2005). Blackshaw et al. (2001) found that volumetric water content at spring wheat planting was not significantly less following sweetclover compared to non-sweetclover treatments. Early termination allowed more time for the soil water to re-charge before planting. Blackshaw et al. (2001) noted that annual rainfall was greater than average for the duration for this study. Mixed results were reported about the effects of intensifying traditional wheat-fallow no-till crop rotations with cover crops. The objective of this study was to evaluate the impacts of cover crops in a dryland no-tillage winter wheat-fallow cropping system by determining the cover crop water use efficiency and fallow precipitation storage efficiency of several different cover crops and termination methods, as well as determining the subsequent effect of volumetric water content on winter wheat yields.

Materials and Methods

A long-term field experiment was established in 2006 at the Kansas State University Southwest Research-Extension Center located in Garden City, Kansas (37˚59’N, 100˚48’W). The soil comples was a Ulysses-Colby silt loam (fine-silty, mixed mesic Aridic Haplustolls) with a pH of 7.7 and 1.5% organic matter. In 2007, 2008, and 2009, field experiments were conducted to determine the water use efficiency of cover crops, precipitation storage efficiency of the fallow period, and cover crop productivity in a winter wheat-fallow no-till cropping system. Cover crops were planted in place of fallow. Plots were established as a randomized split plot design with four replications. Each block was split by crop phase (wheat or fallow) with each crop phase of the crop rotation present each year. Each block measured 274 m by 41 m with the split-block measuring 137 m by 41 m. The main plots were randomly assigned to the winter wheat or fallow phase of the crop rotation. In the fallow phase, thirteen treatments were established in subplots measuring 9 m by 41m. Treatments included eight winter and five spring sown cover crops, continuous winter wheat, and fallow. Winter sown cover crops were winter triticale sown at 71 kg seed ha^{-1}, Austrian winter pea (*Lathyrus hirsutus*) harvested for forage sown at 109 kg seed ha^{-1}, Austrian winter pea harvested for grain sown at 109 kg seed ha^{-1}, Austrian winter pea/winter triticale mixture sown at 21/53 kg seed ha^{-1}, hairy vetch (*Vicia* *villosa*) sown at 28 kg seed ha^{-1}, hairy vetch/winter triticale mixture sown at 21/53 kg seed ha^{-1}, yellow sweetclover (*Melilotus officinalis*) sown at 19 kg seed ha^{-1}, and yellow sweetclover/winter triticale mixture sown at 22/53 kg seed ha^{-1}. Spring sown cover crops were spring triticale sown at 85 kg seed ha-$^{-1}$, spring lentil (*Lens culinaris*) sown at 28 kg seed ha^{-1}, spring lentil/spring triticale mixture sown at 21/64 kg seed ha^{-1}, spring pea (*Pisum sativum*) sown at 134 kg seed ha^{-1}, and spring pea/spring triticale mixture sown at 101/64 kg seed ha^{-1}. Winter cover crops were sown on 15 September 2007, 3 October 2008, and 1 October 2009 and spring cover crops were sown on 30 March 2008, and 5 March 2009. Cover crop species changed slightly each year as more suitable cover crop species were determined from other preliminary studies (Table 3.1).

Each subplot was split lengthwise by termination method, which were forage harvest or chemical termination. Cover crops were terminated when triticale headed or June 1st, whichever came first. Winter cover crops were terminated 15 May 2007, 13 May 2008, and 18 May 2009. Spring cover crops were terminated 1 June in 2007, 2008, and 2009. On the half that was harvested for forage, a 41 m by 1.5 m strip was mechanically harvested out of each cover crop plot with a Carter harvester (Carter Mfg. Co. Inc., Brookston, IN) 8 cm above the soil surface. Sub-samples were dried in a forced-air dryer at 65° C until dry, and weighed to obtain dry mass. The half that was not harvested was terminated chemically with recommended rates of glyphosate plus 2,4-D herbicide.

The winter wheat phase was planted 1 October 2007, 26 September 2008, and 24 September 2009 with a Fabro plot research drill (Swift Current, SK, Canada) and harvested 26 June 2008 and 1 July 2009. In all years, the target-seeding rate was 115 kg ha^{-1}. A Wintersteiger (Wintersteiger Inc., Salt Lake City, UT) plot combine was used to harvest a 2.4 m by 41 m strip from each cover crop plot. Grain moisture and test weights were estimated with a DICKEY-john GAC 2000 (DICKEY-john Corp., Springfield, IL).

A neutron probe (503 DR Hydroprobe, CPN Co., Martinez, CA) was used to determine volumetric water content. Samples were taken at depth increments of 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), and 122-152.5 cm (D5). Soil moisture differences were not detected at depths greater than 152.5 cm. Access tubes were installed in the cover crop treatments after winter wheat harvest on the side of the plot that was terminated chemically and left for cover. Readings were taken around the 1st of every month throughout the cover crop growing season as well as at the time of planting and termination of cover crops, and winter wheat planting. Soil core samples were taken from the side of the plot that was harvested for forage prior to winter wheat planting with a Giddings Model GSRPS soil probe (Giddings Machine Co., Windsor, CO) for gravimetric analysis. Samples were taken in 30.5 cm increments to a depth of 183 cm. These samples were dried in a forced-air dryer at 105˚ C for 48 hours, weighed to obtain dry mass, and gravimetric water content was calculated. Soil samples were also taken to determine bulk density. Soil samples were taken in 30.5 cm increments to a 152.5 cm depth. A 4.9 cm sample was pulled from the center of each 30.5 cm increment and dried in a forced-air dryer at 105˚ C for 48 hours to obtain a dry mass. Bulk density was used in combination with gravimetric water content to calculate volumetric water content. No differences were detected across the study blocks or treatments, so an average bulk density of 1.11 g/cm^3 was used for all calculations. In addition, a soil sample was obtained at the 0 - 7.4 cm depth from both the standing cover and hayed subplot at winter wheat planting to determine soil water content in the seed zone.

Cover crop water use efficiency (WUE) during the growing season was determined for all cover crop treatments. Cover crop WUE refers to the amount of aboveground biomass produced per unit of water used during the growing period, calculated as:

$$\mathrm{WUE}(\mathrm{kg\ ha}^{-1}\mathrm{mm}^{-1}) = \frac{[\text{cover crop biomass}]}{\left[\begin{pmatrix}\text{beginning soil water} - \\ \text{ending soil water}\end{pmatrix} + \begin{pmatrix}\text{precipitation between beginning} \\ \text{and ending soil water measurements}\end{pmatrix}\right]} \qquad \text{Equation 3.1}$$

The fallow period was divided into three time periods; fall cover crop planting to cover crop termination, cover crop termination to winter wheat planting, and the total fallow period from cover crop planting to winter wheat planting. Precipitation storage efficiency (PSE) was determined for each time period at 30.5 cm depth increments to a depth of 152.5 cm, as well as for the total profile (0-152.5 cm). PSE is the amount of precipitation that falls in a given time period that is stored in the soil profile (Nielsen and Vigil, 2010). It is calculated as:

$$\mathrm{PSE}(\%) = 100 \text{ x} \left[\frac{\begin{matrix}\text{ending soil water} - \\ \text{beginning soil water}\end{matrix}}{\begin{matrix}\text{precipication between beginning} \\ \text{and ending soil water measurements}\end{matrix}}\right] \qquad \text{Equation 3.2}$$

Significance of main effect differences and their interactions was determined at α = 0.05 using the PROC MIXED and PROC GLM procedures (SAS Institute, 2004) with year, crop phase, growing season and cover crop treatment as fixed effects and replication and all interactions with replication considered as random effects in the model.

Results and Discussion

Cover Crop Water Use Efficiency

Annual precipitation at Garden City varied during 2007, 2008, and 2009 (Table 3.2). Annual precipitation was 73.4 mm above average in 2009. Normal precipitation was received during 2007 and 2008. Although annual precipitation was normal, extreme high and low precipitation events were observed during important periods of growth. In 2008, below average precipitation of 66 mm was observed during the spring cover crop growing season. However, in 2009, precipitation during this period was 24.3 mm above average. In September of 2007, a large precipitation event occurred prior to taking soil moisture readings, which increased the volumetric water content at this sampling date. These random extremes in precipitation played an important role in influencing and explaining the results observed over the duration of this study.

Analysis of variance displayed a significant (α = 0.05) interaction between year and cover crop water use efficiency (WUE) and aboveground biomass (Table 3.3). Due to the variability between years, the results were analyzed separately for each year.

A significant (α = 0.05) response to cover crop treatment was seen in 2008 for cover crop WUE and biomass. Cover crops with the greatest WUE were spring lentil/spring triticale, spring pea/spring triticale, and spring triticale (Table 3.4). Clover treatments did not produce any harvestable biomass, thus WUE was not calculated for this treatment. Due to the lack of production with clover, clover was replaced in 2009 with winter lentil. Cover crops with the least WUE were vetch, winter pea (forage), and spring lentil. Spring lentil had low WUE due to low biomass production. On average, spring cover crops had greater WUE than winter cover crops, with 7.2 kg ha^{-1} more biomass produced per mm of precipitation received over the growing period (Table 3.4).

In 2008, aboveground biomass was not significantly different between winter and spring cover crops (Table 3.4). Clover/winter triticale, vetch/winter triticale, winter pea/winter triticale, and winter triticale produced the greatest amount of aboveground biomass with winter pea (forage) and spring lentil producing the least amount of biomass (Table 3.4). Due to the lack of difference between winter and spring cover crop biomass yields, and because spring crops have a shorter growing period, spring cover crop treatments had greater WUE than winter cover crops (Table 3.4). In part, the below average precipitation during the spring cover crop growing season in 2008 might have increased the crops WUE (Table 3.2).

Cover crops yielded differently in 2009. Water use efficiency and biomass differed by cover crop treatment and was affected differently by winter and spring cover crops (Table 3.5). On average, winter cover crops produced 1580 kg ha^{-1} greater biomass than spring crops (Table 3.5). Compared to 2008, water use efficiency was greater with winter cover crops rather than spring cover crops in 2009. The WUE of winter crops might have been greater than spring crops due to greater biomass production among winter crops than spring crops. On average, winter crops produced 10.2 kg ha^{-1} greater biomass per mm of precipitation than spring crops (Table 3.5). The cover crop treatments vetch/winter triticale, winter pea/winter triticale, and winter triticale produced the greatest amount of aboveground biomass. Lowest biomass yielding crops were winter lentil, winter pea (forage), vetch, and spring lentil. Vetch in monoculture did not produce any biomass due to marginal stand establishment in the winter and winter kill. Winter peas also had marginal stand establishment in the fall and some winter kill. However, vetch and winter peas grown in mixture with triticale had good winter survival. When comparing the biomass yields across years, cover crop treatments containing winter triticale tended to produce greater biomass, with vetch, winter pea (forage), and spring lentil consistently yielding the least biomass. WUE appeared to be variable based on environmental conditions such as extreme high or low temperature, freezes that impacted crop growth and precipitation pattern that affected precipitation capture and biomass production.

Precipitation Storage Efficiency during Fallow Period

Throughout the central Great Plains, a variety of PSE have been reported. Nielsen and Vigil (2010) reported average fallow PSE for a wheat/fallow system to range from 20% in a conventional tillage system, to 35% in a no-tillage system. A study by Greb et al. (1967)

reported a 3-year average fallow PSE from three locations (North Platte, NE; Sidney, MT; Akron, CO) of 29, 22, and 30%, respectively. A wide PSE within the fallow period was observed at the Garden City study. Many cover crop treatments and fallow displayed a negative PSE. These negative values are explained by above average precipitation between wheat harvest and cover crop seeding, which caused high soil water content when the beginning water measurements were taken. Rainfall during the fallow period also was above average. Cover crop growth used soil moisture, reducing PSE. Due to above average rainfall, much of the precipitation received during the cover crop growing period might have been lost to run-off or evaporation. Soil water measurements did not indicate an increase in soil water at deeper depths. All of these factors likely contributed to a negative PSE for many of the cover crop treatments and fallow.

PSE was calculated for three distinct time intervals: the cover crop growing season beginning in the fall, cover crop termination to winter wheat seeding, and the total fallow period from cover crop seeding to winter wheat seeding. Analysis of variance was performed on each fallow period during the 2008 and 2009 growing seasons. Significant ($\alpha = 0.05$) interactions between cover crop treatment and year were observed for all three fallow periods (Table 3.6). Due to the variability across years and within each soil depth increment, each year was analyzed separately.

Precipitation Storage Efficiency - Cover Crop growing season

During the cover crop growing season, beginning in the fall for winter and spring crops, the termination methods were not applied to the cover crop treatments, so only the effects from year and treatment were analyzed. An analysis of variance for the 2008 cover crop growing season indicated a significant ($\alpha = 0.05$) response to cover crop treatment at all five soil depth increments and in the total soil profile (Table 3.7). On average, winter wheat fallow had greater PSE than cover crops, at soil depths D4 and D5 (Tables 3.7). At soil depths D1 to D3, clover and vetch had similar PSE as fallow, and other treatments had lower PSE. This similarity of clover to fallow was likely because clover produced little biomass. At the deeper depths (D4 and D5), the PSE was greatest among clover, vetch, and all of the spring cover crops; spring lentil, spring lentil/spring triticale, spring pea, spring pea/spring triticale, and spring triticale (Table 3.7). Within the total soil profile spring pea and fallow had the greatest PSE, with clover/winter triticale, winter pea (grain), winter pea/winter triticale, winter triticale, and winter wheat having the lowest PSE (Table 3.7). On average, continuous winter wheat had a lower PSE than any of the cover crop treatments.

The 2009 cover crop growing season analysis showed a different trend. Analysis of variance indicated a significant ($\alpha = 0.05$) response to cover crop treatment with winter planted cover crops having greater PSE than spring cover crops (Table 3.8). As with 2008, fallow had greater PSE than the average of all cover crop treatments. At all soil depths PSE was greatest among winter lentil, vetch, winter pea (forage) and winter pea (grain), and fallow (Table 3.8). Lowest PSE was observed with spring pea/spring triticale, vetch/winter triticale, winter lentil/winter triticale, winter pea/winter triticale, winter triticale, and continuous winter wheat. In both years, continuous winter wheat averaged less PSE than cover crops (Table 3.8).

Precipitation Storage Efficiency - Cover Crop Termination to Winter Wheat Seeding

The second fallow period from cover crop termination to winter wheat seeding was used to determine the effects of cover crop and termination method on PSE during the summer months before winter wheat was planted in the fall. In 2008, analysis of variance indicated significant ($\alpha = 0.05$) response to cover crop treatment and termination method at all soil depths and in the total soil profile, but no interaction between cover crop treatment and termination method (Table 3.9). On average, standing cover showed a 36% increase in PSE in the total soil profile compared to hay (Table 3.9). Cover crop treatments that produced greater biomass, such as those containing triticale, tended to have greater PSE (Table 3.9). This response was mainly seen at the D1 and D2 depths. At the D3 to D5 depths, all cover crop treatments had similar low PSE, and clover, clover/winter triticale, winter pea/winter triticale, and winter triticale had the greatest PSE. Precipitation storage efficiency in the total soil profile was greatest with clover/winter triticale, winter pea/winter triticale, winter triticale, spring lentil, spring lentil/spring triticale, and spring pea/spring triticale (Table 3.9).

In 2009, analysis of variance indicated a significant ($\alpha = 0.05$) response to cover crop treatment and termination method at all depths and in the total soil profile, but no interaction between cover crop treatment and termination method (Table 3.10). The total soil profile PSE was greatest in the vetch/winter triticale, winter pea/winter triticale, winter triticale, and spring pea/spring triticale (Table 3.10). Individual depth increments tended to follow the same pattern with treatments containing triticale having greater PSE compared to treatments that did not contain triticale. This increase in PSE would most likely be attributed to greater residue covering the ground during this part of the fallow period. A significant (α = 0.05) response to termination method was seen with a 21% greater PSE in standing cover than hay (Table 3.10). This response would suggest increased biomass production led to greater PSE during this part of the fallow period.

Precipitation Storage Efficiency - Total Fallow Period

The period from cover crop seeding in the fall to winter wheat seeding was analyzed to determine the effect of cover crop and termination method treatments on PSE for this fallow period. In 2008, analysis of variance showed a significant (α = 0.05) response to cover crop and termination method at all depths and the total soil profile but no interaction between cover crop treatment and termination method (Table 3.11). A 17% increase in PSE was seen in the standing cover compared to hay. Clover, vetch, spring pea, and fallow had greater total soil profile PSE than all other cover crops (Table 3.11). Limited biomass production in the clover and vetch might have caused these treatments to respond similarly to fallow. At depths D1 and D2, fallow and most cover crops had greater PSE than continuous winter wheat. At depth increments D3 through D5 clover and spring pea consistently had the greatest PSE. On average, continuous winter wheat had lower PSE and fallow had greater PSE than cover crops (Table 3.11).

Analysis of variance in 2009 showed a significant (α = 0.05) response to cover crop treatment and termination method but no interaction between cover crop treatment and termination method (Table 3.12). The same trend as 2008 was observed, with standing cover averaging 12% greater PSE than hay (Table 3.12). Differences between cover crops were more apparent at the deeper soil depths. Among cover crop treatments, winter lentil, vetch, winter pea (forage), and spring triticale had the greatest PSE, while the lowest PSE was observed for winter lentil/winter triticale, vetch/winter triticale, winter pea/winter triticale, spring lentil, spring lentil/spring triticale, spring pea, and spring pea/spring triticale (Table 3.12). As in 2008, continuous winter wheat had the lowest and fallow had greatest PSE (Tables 3.12). This was likely due to treatments with triticale having less soil moisture at the D4 and D5 soil depths at the time of cover crop termination. These results indicate that, although increasing soil residue through more cover crop biomass production can increase PSE after termination of the cover crop, creating that biomass depletes soil moisture more than growing a low biomass crop. In this study a low biomass crop left standing resulted in greater PSE for the entire fallow period than a high biomass crop.

Volumetric Water Content at Winter Wheat Seeding

Analysis of variance for all three years indicated that volumetric water content at the time of winter wheat seeding displayed a significant interaction between year and cover crop treatment for all five depth increments and total profile water concentration, so the results were analyzed separately for each year (Table 3.13). Significant interactions were observed at various depths between year and termination method and year by termination method by treatment (Table 3.13)

In 2007, a significant ($\alpha = 0.05$) response to termination method was observed at depths D2-D5 and in the total profile (Table 3.14). Response to cover crop treatments were observed in depths D3-D5 and in the total profile. Within cover crop treatments, clover/winter triticale had the greatest volumetric water content at winter wheat planting at depths D3-D5 and in the total profile (Table 3.14). Continuous winter wheat had the least volumetric water content at the same soil profile depths. At depths D4 and D5, other cover crops such as clover, pea/winter triticale, winter pea (forage) and fallow had volumetric water content levels comparable to clover/winter triticale. The greater volumetric water content following clover/winter triticale might be attributed in part to little clover growth during the cover crop growing season and the lower seeding rate of triticale planted in mixture than in monoculture. This would have resulted in the clover/winter triticale and clover monoculture treatments having similar amount cover crop growth and water use as fallow. Most cover crop treatments had similar total volumetric water content levels as fallow. On average, treatments that were terminated and left for cover rather than hayed had 18 mm more water in the total soil profile at winter wheat seeding (Table 3.14).

In 2008, a significant ($\alpha = 0.05$) response to cover crop treatment and termination method was observed for volumetric water content at winter wheat seeding for all five depth increments and total profile water content (Table 3.15). Water content within the 0-7.6 cm seed zone showed a response to cover crop treatment only. A comparison of the two termination methods indicated greater volumetric water content in the cover crop treatments left standing for cover when compared to the treatments harvested for hay at all depths except in the seed zone (Table

3.16). On average, treatments left for cover had 70 mm more water in the soil profile than treatments harvested for hay. When comparing individual cover crop treatments, clover, spring pea and fallow had greater volumetric water content at all depth increments, in the total profile, and in the seed zone compared to other cover crop treatments (Table 3.16). Other treatments such as vetch, vetch/winter triticale, and winter pea/winter triticale all had the highest volumetric water content in the first two depth increments. At depth 3, depth 4, and depth 5, clover, spring pea, and fallow had the greatest volumetric water content. In general, the greater differences in volumetric water content were observed at the deeper depth increments and the total profile. On average, fallow had greater volumetric water content at all depth increments and in the total profile than cover crop treatments, except clover and spring pea (Table 3.16). For reasons explained earlier, clover likely had similar soil water content as fallow. In 2008, soil moisture levels were high following spring pea at the time of winter wheat seeding. Continuous winter wheat had the least amount of volumetric water content all soil depth increments, total profile, and seed zone (Table 3.16). Of the cover crops, clover/winter triticale, winter pea harvested for grain, winter triticale, and spring triticale had the least volumetric water content. On average, treatments containing triticale had 17 mm less volumetric water content in the total soil profile than treatments that did not have triticale.

In 2009, analysis of variance indicated a significant ($\alpha = 0.05$) interaction between termination method and cover crop treatment, and significant responses to termination method and cover crop treatment (Table 3.17). The significant interaction between termination method and cover crop treatment at the D3, D4 and D5 depth increments was due to winter lentil, vetch, winter triticale, and spring lentil/spring triticale treatments having no difference in volumetric water content between termination methods (Table 3.17). All other cover crop treatments had greater volumetric water content in standing cover than hayed (Table 3.18). On average, standing cover had 59 mm more water in the total soil profile than hay. Continuous winter wheat, fallow, and winter pea (grain) were the exception to this, because those plots were not subject to different termination methods. None of the hayed cover crop treatments and winter lentil/winter triticale, vetch, vetch/winter triticale, winter pea (forage), winter pea/winter triticale, spring lentil, spring pea, spring pea/spring triticale, and spring triticale left standing all had comparable soil moisture as fallow. Continuous winter wheat was lower in volumetric water content when compared to cover crops terminated as standing cover, but was comparable to all of the cover crops terminated as a hay crop except vetch and winter pea (forage) (Table 3.18). Above-average rainfall during April, June, July, and September of 2009 might have helped reduce the differences seen between cover crop treatments when the cover crop was left standing, but not when hayed (Table 3.2).

Winter Wheat Yields

Due to the variability in previous cover crop treatments, each year was analyzed separately. An analysis of variance indicated no significant ($\alpha = 0.05$) response to cover crop treatment or termination method in 2008 (Table 3.19). Winter wheat yields in 2008 averaged 1474 kg ha^{-1}. In 2009, analysis of variance indicated a significant ($\alpha = 0.05$) response to cover crop treatment, but no response to termination method and no interaction between cover crop treatment and termination method (Table 3.20). Grain yields were lowest for continuous winter wheat (Table 3.20). Greatest yields were observed for the clover, vetch, winter pea (forage), spring lentil, and spring pea treatments. Although significant yield increases were seen following the clover treatment, this increase cannot be attributed to the clover cover crop. During the cover crop growing season clover produced low biomass and the treatment should have responded similarly to the fallow treatment. On average, yields were 263 kg ha^{-1} greater following a spring cover crop than a winter cover crop (Table 3.20). Correlation analysis of volumetric water content at winter wheat seeding and winter wheat grain yield showed a positive relationship between soil water content at the D4, D5, and the total profile depths and grain yield (Table 3.21). As soil water content increased at these depths or in the total soil profile, grain yield increased as well (Figures 3.1 and 3.2).

Based on the winter wheat yield results and volumetric water content at wheat seeding, we concluded that the amount of volumetric water at the time of winter wheat seeding had an effect on winter wheat grain production. In 2008, a general trend was seen for the cover crop treatments that contained triticale having less volumetric water content than treatments that did not contain triticale (Table 3.16). In 2009, wheat yields following triticale treatments were reduced 485 kg ha^{-1} compared to wheat yields following other cover crop treatments (Table 3.20). The correlation between cover crop biomass and water content at wheat seeding shows a negative relationship at the D4 ($r^2 = 0.39$, $p = 0.011$) and D5 ($r^2 = 0.44$, $p = 0.002$) depths, with volumetric water content decreasing as cover crop biomass increased. The results suggest that high biomass-producing treatments, such as triticale, might use greater amounts of soil water from deeper depths within the soil profile (Table 3.16). The soil water content at the deeper depths becomes important during the winter wheat growing season in times of limited precipitation where the plant must utilize water stored deeper in the soil profile. Previous research conducted in dry regions of the Great Plains suggested that the use of cover crops during the fallow period will reduce the following crop yields due to a reduction in volumetric water content (Schlegel and Havlin, 1997). In years of low annual precipitation the use of cover crops in place of the fallow period is likely to cause yield reduction in the following wheat crop. During years of drought, yield reductions resulting from reduced volumetric water content at the deeper soil profile depths would most likely be greater than those observed within this study. Above average precipitation during 2008 and 2009 might have minimized the effects that cover crops had on subsequent wheat yields. However, the results from this study suggests that in years of above average annual rainfall, low biomass producing cover crops such as clover, vetch, spring lentil, spring pea, and winter pea might be grown with little to no reduction in soil profile water and no negative effect on the subsequent winter wheat yields (Table 3.20).

Conclusions

Treatments containing winter and spring triticale had the greatest cover crop water use efficiency (19.9 kg ha^{-1} mm^{-1}) and aboveground biomass yield (3550 kg ha^{-1}). During the cover crop growing season, high biomass producing cover crops had lower PSE due to greater water use. After cover crops were terminated, PSE was greatest in treatments that had produced greater amounts of biomass and were left standing rather than hayed. After cover crop termination, PSE was greater following cover crops either left standing or hayed compared to fallow. The increase in PSE was attributed to greater amounts of crop residue covering the soil during that part of the fallow period. Although high biomass producing cover crops stored more soil water after they were terminated, the increased PSE after termination was not enough to overcome the water reduction that occurred earlier in the fallow period. Overall, greatest PSE and volumetric water content at winter wheat seeding was observed following fallow, which resulted in greater wheat yields. Wheat yields following treatments containing winter and spring triticale were reduced 485 kg ha^{-1} compared to wheat yields following the other cover crop treatments, which were often similar to wheat yields following fallow. The results indicated that in years of average to above average annual precipitation, low biomass producing cover crops left as standing cover or hayed might be grown with little to no negative effect on subsequent wheat yields.

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Figures and Tables

Table 3.1. Cover crop treatments planted in 2007 to 2009 at Garden City, KS.

Season	Cover Crop	Year Produced† 2007	2008	2009	2010
Winter	Yellow sweetclover	X	X		
Winter	Yellow sweetclover/Winter triticale		X		
Winter	Hairy vetch	X	X	X	X
Winter	Hairy vetch/Winter triticale		X	X	X
Winter	Winter lentil			X	X
Winter	Winter lentil/Winter triticale			X	X
Winter	Winter pea (forage)	X	X	X	X
Winter	Winter pea (grain)		X	X	X
Winter	Winter pea/Winter triticale		X	X	X
Winter	Winter triticale	X	X	X	X
Spring	Spring lentil	X	X	X	X
Spring	Spring lentil/Spring triticale		X	X	X
Spring	Spring pea	X	X	X	X
Spring	Spring pea/Spring triticale		X	X	X
Spring	Spring triticale		X	X	X

† Represents the year the cover crops were terminated.

Table 3.2. Monthly and total precipitation at Garden City, KS in 2007, 2008, and 2009.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
								mm					
2007	14.7	15.7	44.5	73.4	30.2	63.5	41.9	67.1	53.3	5.8	2.5	33.8	446.7
2008	7.6	14.0	7.1	41.7	49.0	78.7	31.5	63.8	17.8	119.1	8.6	0.8	439.6
2009	1.5	1.8	29.2	110.7	47.5	94.0	80.3	56.1	40.1	74.9	9.9	5.3	550.7
Average†	10.9	12.2	35.1	41.9	86.1	73.2	65.8	65.0	31.8	23.0	21.8	10.4	477.3

† 1971-2000 Average precipitation, Kansas State University Weather Library (2010).

Table 3.3. 2008 and 2009 cover crop water use efficiency and aboveground biomass significance of main effects and interactions.

Variable	Water Use Efficiency	Biomass
	kg ha^{-1} mm^{-1}	kg ha^{-1}
Year	*	*
Cover Crop	***	***
Year*Cover Crop	***	***

* Significant at the 0.05 probability level.

*** Significant at the 0.001 probability level.

Table 3.4. 2008 cover crop water use efficiency and aboveground biomass†.

Cover Crop		Water Use Efficiency	Biomass
		kg ha^{-1} mm^{-1}	kg ha^{-1}
Clover		0.0	0
Clover/Winter triticale		16.9 bc	4027 ab
Vetch		4.8 d	1052 e
Vetch/Winter triticale		19.0 bc	4380 a
Winter pea (forage)		4.7 d	983 ef
Winter pea/Winter triticale		17.6 bc	4144 a
Winter triticale		15.5 c	3638 ab
Spring lentil		6.7 d	874 ef
Spring lentil/Spring triticale		21.2 ab	2602 cd
Spring pea		15.0 c	1805 de
Spring pea/Spring triticale		24.7 a	3057 bc
Spring triticale		24.4 a	3023 bc
	LSD‡	4.4	1021
Contrast†††			
Winter vs. Spring		-7.2***	NS
Treatments containing Triticale vs. Non-Triticale Treatments†† (CLWT, VWT, WPWT, WT, SLST, SPST, ST) (CL, V, WPF, WPG, SL, SP)		13.6***	2611***

† Values in a column followed by the same letter are not significantly different, α = 0.01.

†† CLWT, clover/winter triticale; VWT, vetch/winter triticale; WPWT, winter pea/winter triticale; WT, winter triticale; SLST, spring lentil/spring triticale; SPST, spring pea/spring triticale; ST, spring triticale; CL, clover; V, vetch; WPF, winter pea (forage); WPG, winter pea (grain); SL, spring lentil; SP, spring pea.

††† Value represents difference in response between winter and spring seeded cover crops, and treatments containing triticale and treatments not containing triticale.

‡ LSD – Least significant difference, α = 0.05.

*** Significant at the 0.001 probability level.

Table 3.5. 2009 cover crop water use efficiency and aboveground biomass†.

Cover Crop	Water Use Efficiency	Biomass
	kg ha^{-1} mm^{-1}	kg ha^{-1}
Winter lentil	1.7 e	300 e
Winter lentil/Winter triticale	24.5 b	4148 b
Vetch	0.0 e	0 e
Vetch/Winter triticale	29.8 a	5043 a
Winter pea (forage)	3.5 de	597 de
Winter pea/Winter triticale	34.5 a	5846 a
Winter triticale	31.2 a	5293 a
Spring lentil	2.1 e	410 e
Spring lentil/Spring triticale	7.5 cd	1418 cd
Spring pea	8.9 c	1692 c
Spring pea/Spring triticale	11.0 c	2080 c
Spring triticale	8.7 c	1659 c
LSD‡	5.1	884
Contrast††		
Winter vs. Spring	10.2***	1580***

† Values in a column followed by the same letter are not significantly different, α = 0.01.
†† Value represents difference in response between winter and spring seeded cover crops.
‡ LSD – Least significant difference, α = 0.05.
*** Significant at the 0.001 probability level.

Table 3.6. 2008 and 2009 precipitation storage efficiency within each fallow period†.

	Depth‡					
Variable	D1	D2	D3	D4	D5	Total Profile
Cover Crop Growing Season (Oct – Cover Crop Termination)						
Year	***	***	***	***	***	***
Cover Crop	***	***	***	***	***	***
Year*Cover Crop	**	**	*	**	***	**
Cover Crop Termination to Winter Wheat Seeding						
Year	NS	***	*	**	NS	NS
Cover Crop	***	***	***	**	NS	***
Termination Method	***	***	***	***	***	***
Cover Crop*Termination	NS	**	**	NS	*	**
Year*Cover Crop	***	***	**	*	NS	**
Year*Termination Method	***	***	***	**	NS	***
Year*Cover Crop*Termination Method	NS	NS	**	*	NS	*
Total Fallow Period (Oct – Winter Wheat Seeding)						
Year	***	***	***	***	***	***
Cover Crop	NS	**	***	***	**	***
Termination Method	***	***	***	***	***	***
Cover Crop*Termination	NS	NS	NS	NS	NS	NS
Year*Cover Crop	NS	**	**	**	**	**
Year*Termination Method	**	**	*	NS	NS	*
Year*Cover Crop*Termination Method	NS	NS	NS	NS	NS	NS

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† Cover crop growing season runs from cover crop seeding (about 1 October for winter and 1 March for spring) to cover crop termination (about 1 June); Cover crop termination to winter wheat seeding runs from cover crop termination (about 1 June) to about 1 October; Total fallow period runs about 15 September to about 1 October.

‡ Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), 0-152.5 cm (total profile), and 0-7.6 cm (seed zone).

Table 3.7. 2008 cover crop precipitation storage efficiency‡.

Cover Crop	Precipitation Storage Efficiency D1	D2	D3	D4	D5	Total Profile
	%					
Clover	-5.6	-8.4	-11.3	-10.5	-11.7	-47.5
Clover/Winter triticale	-18.2	-16.3	-18.4	-18.7	-18.4	-89.9
Vetch	-8.1	-8.3	-9.9	-8.7	-9.9	-44.9
Vetch/Winter triticale	-15.1	-12.9	-13.7	-14.9	-14.3	-70.8
Winter pea (forage)	-6.4	-11.2	-14.3	-15.6	-17.4	-64.9
Winter pea (grain)	-18.9	-17.1	-16.8	-15.5	-17.4	-85.7
Winter pea/Winter triticale	-16.4	-18.9	-19.3	-17.7	-18.0	-90.4
Winter triticale	-17.3	-19.4	-19.7	-19.0	-18.4	-93.9
Spring lentil	-30.9	-24.0	17.3	-4.3	2.8	-73.8
Spring lentil/Spring triticale	-24.4	-24.9	-14.8	-0.2	6.9	-57.3
Spring pea	-21.9	-17.0	-9.0	0.5	7.3	-40.1
Spring pea/Spring triticale	-25.2	-23.9	-19.3	-3.9	4.1	-68.3
Spring triticale	-25.6	-18.2	-13.9	0.4	3.6	-53.7
Continuous Winter wheat	-22.2	-23.2	-22.9	-19.9	-17.3	-105.6
Fallow	0.5	-4.1	-4.9	-4.1	-5.5	-18.2
LSD†	6.5	6.1	6.1	6.3	4.6	23.3
Contrast						
Winter seeded vs. Spring seeded	***	***	NS	***	***	*
All Cover Crops vs. Fallow	***	***	**	NS	NS	***
All Cover Crops vs. Continuous Winter Wheat	NS	**	**	**	**	**

† LSD – Least significant difference, α = 0.05.

‡ Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), and 0-152.5 cm (total profile).

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 3.8. 2009 cover crop precipitation storage efficiency‡.

Cover Crop	Precipitation Storage Efficiency					
	D1	D2	D3	D4	D5	Total Profile
	%					
Winter lentil	-0.3	4.2	14.3	16.7	9.8	44.7
Winter lentil/Winter triticale	-11.5	-3.3	-1.4	3.3	13.6	0.6
Vetch	3.6	4.3	10.0	18.1	15.1	51.0
Vetch/Winter triticale	-10.0	-6.6	-2.0	8.2	7.0	-3.4
Winter pea (forage)	2.8	2.5	12.4	16.1	13.6	47.5
Winter pea (grain)	2.6	3.9	11.6	12.5	10.5	41.1
Winter pea/Winter triticale	-14.6	-7.7	-0.5	4.0	5.1	-13.6
Winter triticale	-10.1	-4.7	-2.9	5.6	9.1	-2.9
Spring lentil	-17.4	-1.0	6.7	10.3	9.6	8.2
Spring lentil/Spring triticale	-7.3	-2.5	1.2	7.0	10.6	9.0
Spring pea	-4.4	-4.6	4.9	8.5	9.6	14.2
Spring pea/Spring triticale	-8.1	-6.0	-0.2	5.7	9.5	1.0
Spring triticale	-6.7	-4.4	-1.8	6.8	11.4	5.3
Continuous Winter wheat	-10.2	-6.7	-4.9	-0.6	8.8	-13.6
Fallow	0.4	3.7	10.9	16.8	17.2	48.9
LSD†	5.8	2.2	5.1	6.0	NS	14.6
Contrast						
Winter seeded vs. Spring seeded	*	***	*	NS	NS	**
All Cover Crops vs. Fallow	*	***	**	*	*	***
All Cover Crops vs. Continuous Winter Wheat	NS	***	**	**	NS	**

† LSD – Least significant difference, α = 0.05.

‡ Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), and 0-152.5 cm (total profile).

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 3.9. 2008 precipitation storage efficiency from cover crop termination to winter wheat seeding‡.

Cover Crop		Precipitation Storage Efficiency					
		D1	D2	D3	D4	D5	Total Profile
		%					
Clover		-5.4	-3.9	-1.9	-1.4	5.2	-7.4
Clover/Winter triticale		5.0	2.6	0.7	-0.6	-0.5	7.2
Vetch		-0.5	-4.0	-7.1	-6.5	-3.5	-21.5
Vetch/Winter triticale		5.7	1.3	-2.8	-2.1	-2.0	0.1
Winter pea (forage)		-3.6	-3.7	-4.0	-1.9	-0.1	-13.4
Winter pea (grain)		-6.5	-1.2	-6.4	-6.0	-2.6	-9.6
Winter pea/Winter triticale		4.8	5.2	2.3	-0.9	-1.2	10.2
Winter triticale		6.2	4.9	1.4	0.6	-1.2	11.9
Spring lentil		7.2	4.0	-0.9	-3.3	-2.9	5.0
Spring lentil/Spring triticale		7.0	5.9	-1.2	-4.5	-1.8	5.3
Spring pea		5.4	0.4	-1.9	-5.6	-4.7	-6.4
Spring pea/Spring triticale		7.9	4.1	-0.3	-2.2	-1.4	8.1
Spring triticale		4.4	3.3	-9.0	-4.0	-1.9	-0.1
Continuous Winter wheat		4.0	-3.9	-1.2	-2.4	-3.8	-0.6
Fallow		-1.8	-5.9	-5.5	-5.8	-0.8	-22.6
	LSD†	4.5	3.0	2.4	2.4	4.1	8.2
Termination Method							
Cover		7.9	5.6	1.7	-0.1	0.5	15.5
Hay		-1.8	-3.4	-5.5	-5.8	-3.5	-20.0
	LSD†	1.3	0.7	0.9	0.9	1.7	3.4
Contrast							
Winter seeded vs. Spring seeded		***	***	NS	*	NS	*
All Cover Crops vs. Fallow		***	***	NS	NS	NS	***
All Cover Crops vs. Continuous Winter Wheat		NS	NS	NS	NS	NS	NS

† LSD – Least significant difference, α = 0.05.

‡ Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), and 0-152.5 cm (total profile).

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 3.10. 2009 precipitation storage efficiency from cover crop termination to winter wheat seeding‡.

Cover Crop		Precipitation Storage Efficiency					
		D1	D2	D3	D4	D5	Total Profile
		%					
Winter lentil		-2.8	-4.6	-3.6	-2.3	-1.3	-14.8
Winter lentil/Winter triticale		6.0	-0.6	-2.6	-1.5	-1.8	-0.4
Vetch		-3.1	-4.2	-2.3	-1.9	-1.5	-13.6
Vetch/Winter triticale		7.0	1.1	0.3	-1.3	-2.3	4.7
Winter pea (forage)		-3.2	-2.8	-3.1	-1.7	-0.3	-11.0
Winter pea (grain)		-1.2	-4.9	-4.4	-2.7	-2.0	-15.3
Winter pea/Winter triticale		7.4	1.7	1.0	-1.7	-0.1	8.4
Winter triticale		6.6	0.7	0.8	1.3	1.2	10.5
Spring lentil		10.2	-4.0	-5.6	-5.1	-4.4	-9.0
Spring lentil/Spring triticale		3.0	-0.1	0.9	-0.3	-1.8	1.7
Spring pea		3.0	-0.4	-3.0	-4.0	-4.2	-8.7
Spring pea/Spring triticale		5.9	2.2	0.1	-2.1	-2.6	3.6
Spring triticale		5.6	1.2	-0.1	-2.0	-3.0	1.7
Continuous Winter wheat		5.9	2.4	-0.8	-3.6	-4.6	-0.8
Fallow		0.7	-1.3	-1.3	-1.3	-0.6	-3.9
	LSD†	3.2	1.7	1.9	1.9	1.7	7.4
Termination Method							
Cover		5.6	1.5	0.4	-0.2	-0.1	7.3
Hay		1.2	-3.3	-3.6	-3.9	-3.9	-13.5
	LSD†	1.4	1.1	1.0	0.7	0.6	4.0
Contrast							
Winter seeded vs. Spring seeded		**	**	NS	*	***	NS
All Cover Crops vs. Fallow		NS	NS	NS	NS	NS	NS
All Cover Crops vs. Continuous Winter Wheat		NS	***	NS	NS	**	NS

† LSD – Least significant difference, α = 0.05.

‡ Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), and 0-152.5 cm (total profile).

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 3.11. 2008 precipitation storage efficiency for total fallow‡.

	Precipitation Storage Efficiency					
Cover Crop	D1	D2	D3	D4	D5	Total Profile
	%					
Clover	-5.5	-6.1	-6.5	-5.9	-3.2	-27.3
Clover/Winter triticale	-6.5	-6.7	-8.7	-9.6	-9.3	-40.8
Vetch	-4.2	-5.1	-8.5	-7.6	-6.7	-33.1
Vetch/Winter triticale	-4.6	-5.7	-8.2	-8.4	-8.1	-35.0
Winter pea (forage)	-5.0	-7.4	-9.1	-8.6	-8.7	-38.8
Winter pea (grain)	-6.1	-9.0	-11.6	-10.7	-9.9	-47.3
Winter pea/Winter triticale	-5.7	-6.7	-8.4	-9.2	-9.5	-39.5
Winter triticale	-5.2	-7.1	-9.1	-9.2	-9.7	-40.4
Spring lentil	-5.9	-7.7	-8.5	-7.6	-7.4	-37.2
Spring lentil/Spring triticale	-6.4	-7.6	-9.3	-8.7	-7.1	-39.4
Spring pea	-5.0	-5.2	-5.2	-4.3	-3.9	-23.6
Spring pea/Spring triticale	-6.1	-7.1	-8.8	-7.5	-6.7	-36.2
Spring triticale	-5.7	-7.9	-9.7	-8.6	-8.2	-40.2
Continuous Winter wheat	-9.0	-10.3	-11.9	-11.0	-10.3	-52.5
Fallow	-4.4	-5.0	-4.5	-3.4	-3.1	-20.5
LSD†	3.3	3.0	2.9	3.6	2.5	13.4
Termination Method						
Cover	-3.3	-4.9	-6.8	-6.6	-6.5	-28.2
Hay	-8.1	-9.2	-10.3	-9.4	-8.4	-45.4
LSD†	3.0	2.8	2.6	6.2	1.6	12.5
Contrast						
Winter seeded vs. Spring seeded	NS	NS	**	**	*	NS
All Cover Crops vs. Fallow	NS	**	***	***	***	***
All Cover Crops vs. Continuous Winter Wheat	***	***	***	***	*	***

† LSD – Least significant difference, α = 0.05.

‡ Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), and 0-152.5 cm (total profile).

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 3.12. 2009 precipitation storage efficiency for total fallow‡.

Cover Crop		Precipitation Storage Efficiency					
		D1	D2	D3	D4	D5	Total Profile
				%			
Winter lentil		-1.9	-1.7	2.9	4.6	2.7	6.9
Winter lentil/Winter triticale		-0.4	-1.6	-2.1	0.2	3.8	0.1
Vetch		-0.6	-1.1	1.8	5.3	4.5	9.9
Vetch/Winter triticale		0.8	-1.7	-0.5	2.1	1.1	1.8
Winter pea (forage)		-1.0	-0.9	2.6	4.8	4.8	10.3
Winter pea (grain)		0.1	-1.7	1.4	2.8	2.6	5.3
Winter pea/Winter triticale		-0.6	-1.7	0.5	0.4	1.9	0.4
Winter triticale		0.5	-1.3	-0.6	2.9	4.1	5.6
Spring lentil		-0.5	-2.5	-0.9	1.9	3.1	1.2
Spring lentil/Spring triticale		-1.2	-2.0	-0.4	2.5	3.2	2.1
Spring pea		-0.3	-2.8	-0.1	2.0	2.6	1.3
Spring pea/Spring triticale		-1.5	2.1	0.2	2.8	3.6	3.0
Spring triticale		0.2	-0.4	0.4	3.0	4.4	7.6
Continuous Winter wheat		0.1	-0.9	-2.3	-2.5	0.3	-5.4
Fallow		0.6	0.5	3.1	5.2	5.9	15.3
	LSD†	1.3	0.8	1.7	1.7	1.5	4.4
Termination Method							
Cover		1.0	0.1	1.6	3.7	4.4	10.6
Hay		-1.7	-2.9	-0.8	1.4	2.1	-1.9
	LSD†	0.7	0.4	1.1	0.7	0.7	1.6
Contrast							
Winter seeded vs. Spring seeded		NS	*	*	NS	NS	NS
All Cover Crops vs. Fallow		NS	***	**	**	**	***
All Cover Crops vs. Continuous Winter Wheat		NS	NS	**	***	***	***

† LSD – Least significant difference, α = 0.05.

‡ Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), and 0-152.5 cm (total profile).

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 3.13. 2007, 2008, and 2009 volumetric water content at winter wheat seeding significance of main effects and interactions.

	Depth†						
Variable	D1	D2	D3	D4	D5	Total Profile	Seed Zone
Year	***	***	***	***	***	***	***
Termination Method	***	***	***	***	***	***	**
Cover Crop	NS	**	***	***	***	***	**
Termination Method*Cover Crop	NS	NS	**	NS	NS	NS	NS
Year *Termination Method	***	*	NS	NS	NS	NS	**
Year*Cover Crop	***	***	**	***	**	**	NS
Year*Termination*Cover Crop	**	NS	NS	*	NS	NS	NS

† Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), 0-152.5 cm (total profile), and 0-7.6 cm (seed zone).

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 3.14. 2007 volumetric water content at winter wheat seeding.

Cover Crop	Depth‡ D1	D2	D3	D4	D5	Total Profile
	mm					
Clover	54	70	73	75	70	342
Clover/Winter triticale	61	74	98	74	73	388
Pea/Winter triticale	60	74	77	76	73	361
Vetch	55	64	66	68	67	321
Vetch/Winter triticale	60	70	72	72	68	341
Winter pea (forage)	60	72	74	76	73	355
Winter pea (grain)	60	69	73	72	68	343
Continuous Winter wheat	57	69	62	49	45	283
Fallow	58	76	77	78	75	364
LSD†	NS	NS	9	6	4	21
Termination Method						
Cover	58	73	79	75	68	352
Hay	58	68	70	69	64	334
LSD†	NS	2	4	5	3	11
Contrast						
Winter seeded vs. Spring seeded	NS	NS	NS	NS	NS	NS
All Cover Crops vs. Fallow	NS	*	NS	NS	*	NS
All Cover Crops vs. Continuous Winter Wheat	NS	NS	**	***	***	***

† LSD – Least significant difference, α = 0.05.

‡ Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), and 0-152.5 cm (total profile).

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 3.15. 2008 volumetric water content at winter wheat seeding significance of main effects and interactions.

	Depth†						
Variable	D1	D2	D3	D4	D5	Total Profile	Seed Zone
Termination Method	***	***	***	***	**	***	NS
Cover Crop	**	***	***	***	***	***	**
Termination Method*Cover Crop	NS	NS	NS	NS	NS	NS	NS
Contrast							
Winter planted vs. Spring planted	NS	NS	NS	NS	NS	NS	NS
All Cover Crops vs. Fallow	NS	**	***	***	**	***	NS
All Cover Crops vs. Continuous Winter Wheat	***	***	**	**	**	***	***
Treatments containing Triticale vs. Non-Triticale Treatments†† (CLWT, VWT, WPWT, WT, SLST, SPST, ST) (CL, V, WPF, WPG, SL, SP,)	NS	NS	NS	**	**	*	NS

† Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), 0-152.5 cm (total profile), and 0-7.6 cm (seed zone).

†† CLWT, clover/winter triticale; VWT, vetch/winter triticale; WPWT, winter pea/winter triticale; WT, winter triticale; SLST, spring lentil/spring triticale; SPST, spring pea/spring triticale; ST, spring triticale; CL, clover; V, vetch; WPF, winter pea (forage); WPG, winter pea (grain); SL, spring lentil; SP, spring pea.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 3.16. 2008 volumetric water content at winter wheat seeding.

Cover Crop	D1	D2	D3	D4	D5	Total Profile	Seed Zone
				mm			
Clover	69	76	67	60	71	343	9.8
Clover/Winter triticale	65	74	58	46	46	288	10.6
Vetch	74	76	59	54	56	319	9.9
Vetch/Winter triticale	72	78	60	50	51	312	9.9
Winter pea (forage)	71	71	57	49	48	296	8.9
Winter pea (grain)	64	64	47	41	43	262	10.5
Winter pea/Winter triticale	68	74	60	47	45	293	10.5
Winter triticale	69	72	57	47	44	289	10.4
Spring lentil	67	70	59	53	53	303	9.5
Spring lentil/Spring triticale	65	70	56	49	53	294	9.7
Spring pea	71	80	72	67	68	358	10.6
Spring pea/Spring triticale	66	72	58	54	56	307	9.7
Spring triticale	68	69	54	49	50	291	9.1
Continuous Winter wheat	55	59	45	39	42	240	7.1
Fallow	73	80	75	71	71	371	10.0
LSD†	6	7	9	7	9	30	1.5
Termination Method							
Cover	77	81	66	57	57	339	9.8
Hay	58	64	58	46	49	269	9.7
LSD†	4	5	5	3	3	18	NS

Depth‡ (spanning header over D1–Seed Zone)

† LSD – Least significant difference, α = 0.05.

‡ Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), 0-152.5 cm (total profile), and 0-7.6 cm (seed zone).

Table 3.17. 2009 volumetric water content at winter wheat seeding significance of main effects and interactions.

	Depth†						
Variable	D1	D2	D3	D4	D5	Total Profile	Seed Zone
Termination Method	***	***	***	***	***	***	***
Cover Crop	NS	NS	*	***	***	**	**
Termination Method*Cover Crop	***	***	***	***	***	***	NS
Contrast							
Winter seeded vs. Spring seeded	NS	NS	NS	NS	NS	NS	NS
All Cover Crops vs. Fallow	*	**	**	**	**	***	***
All Cover Crops vs. Continuous Winter Wheat	NS	NS	NS	**	***	**	***
Treatments containing Triticale vs. Non-Triticale Treatments†† (WLWT, VWT, WPWT, WT, SLST, SPST, ST) (WL, V, WPF, WPG, SL, SP,)	NS	NS	NS	NS	NS	NS	NS

† Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), 0-152.5 cm (total profile), and 0-7.6 cm (seed zone).

†† WLWT, winter lentil/winter triticale; VWT, vetch/winter triticale; WPWT, winter pea/winter triticale; WT, winter triticale; SLST, spring lentil/spring triticale; SPST, spring pea/spring triticale; ST, spring triticale; WL, winter lentil; V, vetch; WPF, winter pea (forage); WPG, winter pea (grain); SL, spring lentil; SP, spring pea.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 3.18. 2009 volumetric water content at winter wheat seeding treatment effects.

	Depth‡												
Cover Crop	D1		D2		D3		D4		D5		Total Profile		Seed Zone
	Cover	Hay	Cover	Hay	Cover	Hay	Cover	Hay	Cover	Hay	Cover	Hay	
	mm												
Winter lentil	80	64	85	73	82	74	76	70	71	62	394	344	29.6
Winter lentil/Winter triticale	87	71	91	76	85	64	81	63	77	60	421	334	37.8
Vetch	80	70	93	78	89	81	86	80	84	74	431	384	32.4
Vetch/Winter triticale	87	74	91	76	86	71	86	59	77	52	430	332	39.6
Winter pea (forage)	89	67	90	75	88	77	83	77	78	71	428	367	35.7
Winter pea (grain)	85	85	80	80	81	81	77	77	74	74	396	396	21.2
Winter pea/Winter triticale	93	76	95	73	89	66	80	57	70	59	428	331	38.3
Winter triticale	82	68	89	73	85	69	75	67	69	57	400	334	36.8
Spring lentil	89	67	89	67	85	60	80	62	74	63	417	320	36.8
Spring lentil/Spring triticale	81	68	85	75	74	76	74	74	72	67	386	360	34.7
Spring pea	89	69	88	64	84	69	80	63	76	56	418	321	37.8
Spring pea/Spring triticale	79	68	56	73	84	72	82	69	78	63	410	345	35.3
Spring triticale	79	75	98	78	88	69	85	67	84	65	444	353	37.0
Continuous Winter wheat	81	81	84	84	72	71	58	58	51	51	347	347	20.1
Fallow	86	86	97	97	91	91	86	86	83	83	444	444	21.4
LSD†	7	7	9	9	9	9	9	9	8	8	35	35	4.8
Termination Method													
Cover	85		90		84		79		75		413		38
Hay	73		76		73		69		64		354		34
LSD†	2		4		6		6		4		22		3

† LSD – Least significant difference, α = 0.05.

‡ Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), 0-152.5 cm (total profile), and 0-7.6 cm (seed zone).

Table 3.19. 2008 winter wheat yields at Garden City, KS.

Variable	Yield
	kg ha^{-1}
Cover Crop	NS
Contrast	
Winter seeded vs. Spring seeded	NS
All Cover Crops vs. Fallow	NS
All Cover Crops vs. Continuous Winter Wheat	NS

Table 3.20. 2009 winter wheat yields at Garden City, KS.

Cover Crop		Yield
		kg ha^{-1}
Clover		6039
Clover/Winter triticale		4971
Vetch		5786
Vetch/Winter triticale		5432
Winter pea (forage)		5826
Winter pea (grain)		5078
Winter pea/Winter triticale		5239
Winter triticale		5206
Spring lentil		5948
Spring lentil/Spring triticale		5290
Spring pea		6049
Spring pea/Spring triticale		5584
Spring triticale		5678
Continuous Winter wheat		3850
Fallow		5571
	LSD†	329
Contrast††		
Winter seeded vs. Spring seeded		-263***
All Cover Crops vs. Fallow		NS
All Cover Crops vs. Continuous Winter Wheat		1700***
Treatments containing Triticale vs. Non-Triticale Treatments††† (CLWT, VWT, WPWT, WT, SLST, SPST, ST) (CL, V, WPF, WPG, SL, SP)		-485***

† LSD – Least significant difference, α = 0.05.

†† Yield value represents difference in yield between winter and spring seeded cover crops, cover crops and continuous winter wheat, and treatments containing triticale and treatments not containing triticale.

††† CLWT, clover/winter triticale; VWT, vetch/winter triticale; WPWT, winter pea/winter triticale; WT, winter triticale; SLST, spring lentil/spring triticale; SPST, spring pea/spring triticale; ST, spring triticale; CL, clover; V, vetch; WPF, winter pea (forage); WPG, winter pea (grain); SL, spring lentil; SP, spring pea.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 3.21. Correlation of 2009 winter wheat yield and soil available water.

	Depth†					
Winter Wheat Yield	D1	D2	D3	D4	D5	Total Profile
Pearson Correlation Coefficient	NS	NS	NS	0.66	0.69	0.62
P value	NS	NS	NS	**	***	**

** Significant at the 0.01 probability level.

*** Significant at the 0.0001 probability level.

† Depth increments are measured as 0-30.5 cm (D1), 30.5-61 cm (D2), 61-91.5 cm (D3), 91.5-122 cm (D4), 122-152.5 cm (D5), and 0-152.5 cm (total profile).

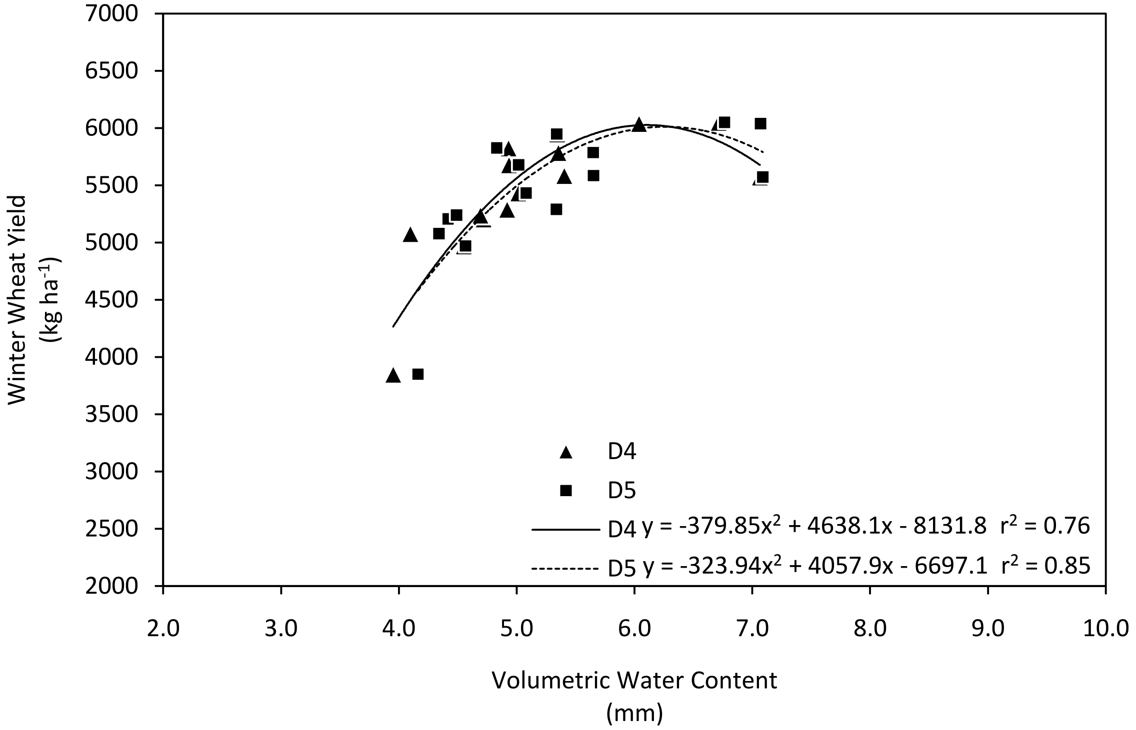

Figure 3.1. **Relationship of 2009 winter wheat yield with soil water content at the D4 (91.5-122 cm) and D5 (122-152.5 cm) depths at Garden City, KS.**

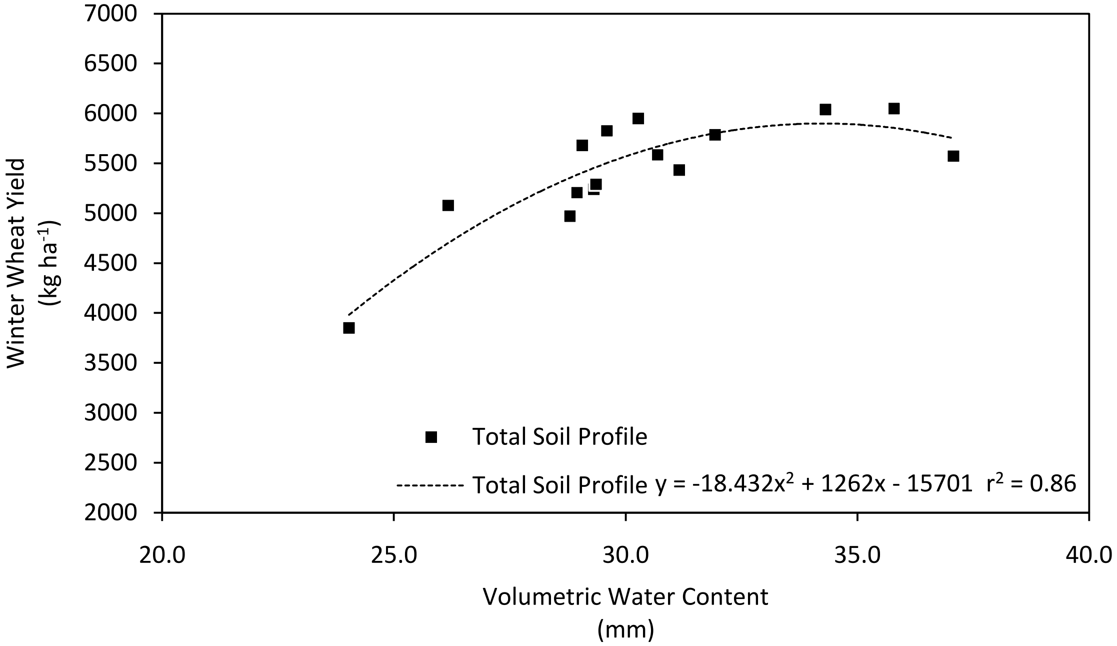

Figure 3.2. **Relationship of 2009 winter wheat yield with total soil profile (0-152.5 cm) water content at Garden City, KS.**

CHAPTER 4 - Comparison of Cover Crops in Kansas and their effect on Subsequent Grain Sorghum Performance

Abstract

With the increased cost of fertilizer and herbicide, interest has grown regarding management options that reduce input costs while maintaining cropping system productivity. Intensifying cropping systems with the addition of cover crops has been promoted as a method of reducing weed populations while reducing nitrogen fertilizer requirements and maintaining overall system productivity. Due to variable precipitation patterns and year-to-year variability in amount of precipitation across the state of Kansas, cover crop productivity and their effect on a following grain crop can vary. A study evaluating cover crops in different Kansas environments was conducted to compare the productivity of several different cover crops and their subsequent effects on grain sorghum (*Sorghum bicolor*) performance. A selection of legume and non-legume species was evaluated for biomass production, nitrogen concentration, and nitrogen accumulation. Eight summer-grown and eight fall-grown cover crops were planted into no-till winter wheat stubble at Manhattan, KS in 2008 and 2009 and Hutchinson, KS in 2009. In all locations, summer-grown crop treatments produced the greatest aboveground biomass and nitrogen accumulation. Within the summer-grown treatments, annual grass species produced the greatest amounts of biomass ($\geq$3392 kg ha^{-1}) and legume species accumulated the greatest amounts of nitrogen, averaging 43 kg ha^{-1}. On average, grain sorghum yields were 867 kg ha^{-1} greater following a summer-grown cover crop compared to sorghum planted after a fall-grown cover crop. Cover crop treatments that resulted in greater grain sorghum yield also resulted in sorghum that displayed greater normalized difference vegetation index (NDVI) values, greater flag leaf nitrogen concentration, and reached half bloom sooner than sorghum after treatments resulting in low grain sorghum yields. Strong correlations were observed between grain sorghum yield, NDVI value, flag leaf nitrogen concentration, and days after planting until half bloom. These results indicated that cover crops had a significant effect on grain sorghum performance, with greatest performance seen following warm-season legume cover crops.

Introduction

Traditionally, Kansas grain producers have relied on fallow to increase stored soil moisture for the following crop. This is particularly important in semi-arid regions that receive limited annual precipitation and utilize long fallow periods. Research has shown that when switching to no-till, the cropping system can be intensified because of increased stored available water (Nielsen et al., 2005; Norwood, 1999). Intensification of cropping systems can provide additional benefits, including weed control, soil quality improvements, and fertility improvements (Leikam et al., 2007; McVay et al., 1989).

Adding cover crops between grain crops intensifies cropping systems and can provide many potential benefits. Troeh et al. (2004) found that standing cover crops help reduce soil erosion by wind and water. Reductions in wind erosion were attributed to the cover crop residue acting as a physical barrier that slowed the moving force of wind and raised the wind profile. Cover crop roots and surface residue can increase water infiltration rates, reducing erosive runoff (Dabney, 1998; McVay et al., 1989). The ability of cover crops to suppress weeds has been promoted as a form of integrated pest management. Significant reductions in weed populations have been demonstrated with the introduction of cover crops (Currie and Klocke, 2005). Weed suppression is accomplished through plant competition, allelopathy, and maintaining surface residues (Conklin et al., 2002; Creamer and Baldwin, 2000). Typically, weed control in no-till cropping systems is achieved with chemical herbicides. Although weed control with chemical herbicides is effective, limitations such as product label restrictions, re-plant interval restrictions, and herbicide-tolerant weed populations leaves room for improvement.

Including legume cover crops in rotations has been shown to improve soil fertility and increase crop production (Blevins et al., 1990; Hargrove and Frye, 1987). An increase in soil nitrogen can occur with the introduction of a leguminous cover crop (Rice et al., 1993). Blackshaw et al. (2001) measured a 16 to 52 kg ha^{-1} increase in nitrogen present in the soil following a leguminous cover crop when compared to fallow treatments. In some cases, green manure legume crops can supply the nitrogen required for the following cereal crop and reduce fertilizer inputs (Baldock and Musgrave, 1980; Griffin et al., 2000). Non-leguminous cover crops provide nitrogen benefits as well. Cover crops that have high biomass yields, such as sorghum-sudangrass or pearl millet, can trap nitrogen, reducing leaching or denitrification losses. Rate and amount of mineralization of nitrogen from the cover crop residue depends on the nitrogen content of the residue, the carbon:nitrogen (C:N) ratio of the residue, as well as soil temperature, moisture, and aeration (Frankenberger and Abdelmagid, 1985; Kue et al., 1996). As C:N ratios of crop residues increase, the net nitrogen mineralization of applied residue nitrogen will decrease (Wagger et al., 1985). The addition of organic matter to the soil with a high (>25:1) C:N ratio has been shown to immobilize mineral nitrogen for the following crop (Allison and Klein, 1962). Organic matter with a lower (15:1-20:1) C:N ratio will degrade more quickly. Aulakh et al. (1991) observed net mineralization of nitrogen following the incorporation of a vetch cover crop with a low (12:1) C:N ratio and immobilization of nitrogen after the incorporation of corn (60:1) and wheat (40:1) residue with high C:N ratios.

Mixtures of cover crops can optimize benefits from a number of different species at the same time (Clark, 2007). Deep-rooted cover crops can be combined with shallow-rooted cover crops to utilize water and nutrients throughout more of the soil profile. Combining species with high C:N ratios (mature cereals) with species that have low C:N ratios (legumes) can influence mineralization of cover crop residues. Allelopathic suppression of weeds has been shown to be species specific (Conklin et al., 2002); therefore, a larger spectrum of weed control might be possible with a mixture of cover crops.

In the central Great Plains Region, water is often the limiting factor for crop growth. In regions of relatively low rainfall, cropping systems that reduce soil water content can have negative impacts on grain yields of the following crop (Ebelhar et al., 1984). Similar observations have been made in studies conducted across the state of Kansas. Schlegel and Havlin (1997) found that in areas of low annual precipitation (430 mm), grain sorghum yields were reduced following a vetch cover crop. A study by Janke et al. (2002) demonstrated that a winter annual legume cover crop could substitute for all or part of the nitrogen requirement for the following grain sorghum crop, with adequate rainfall. In dry years, grain sorghum yields were reduced following a legume cover crop. Janke et al. (2002) suggested that soil improvements resulting from long-term use of cover crops might eventually eliminate the yield reduction.

Climate varies greatly across Kansas with average annual precipitation ranging from 44 cm in Tribune, KS to 105 cm in Parsons, KS (National Climatic Data Center, 2009). Due to variable precipitation patterns and year-to-year variability in precipitation amount and distribution across the state, cover crop sustainability, productivity, and effects on a following crop can vary greatly. The objective of this study was to evaluate the performance of cover crop species and mixtures in several Kansas environments by quantifying the aboveground biomass and nitrogen accumulation of various summer-grown and fall-grown cover crops and their effects on a subsequent grain sorghum crop.

Materials and Methods

Field studies were conducted at three non-irrigated locations in Kansas in 2008 and 2009 to determine growth potential and nitrogen accumulation in the aboveground biomass of several cover crop species and mixtures. Studies were conducted on an Ivan and Kennebec silt loam soil (fine-silty, mixed, mesic Cumulic Hapludolls) at the Agronomy Research Farm near Manhattan (39˚11’N 96˚35’W, Manhattan-08), a Wymore silty clay loam soil (fine, smectitic, mesic Aquertic Argiudolls) at the Ashland Bottoms Research Farm near Manhattan (39˚11’N 96˚35’W, Manhattan-09), and an Ost loam soil (fine-loamy, mixed, superactive, mesic Udic Argiustolls) at the South Central Experiment Field near Hutchinson (38˚03’N 95˚55’W).

A selection of legume and non-legume species was included in each of two growing periods (summer or fall). Summer non-legume cover crop species included sorghum-sudangrass (*Sorghum vulgare* var. *sudanese*), pearl millet (*Pennisetum glaucum*), and buckwheat (*Fagopyrum esculentum*). Summer legume species included forage soybean (*Glycine max*), lablab bean (*Lablab purpureus*), sunnhemp (*Crotalaria juncea* L.), and cow pea (*Vigna unguiculata* L.). Two mixtures also were established during the summer growing period. Mixture 1 contained sorghum-sudangrass, pearl millet, sunnhemp, and cow pea, and mixture 2 contained cowpea and pearl millet. The mixtures in this study were chosen based on plant physiological characteristics and desirable traits of individual cover crop species. Double crop soybean (*Glycine max*) was included in the summer cover crop treatments as the most likely alternative to cover crops following wheat harvest. The fall-grown non-legume species included canola (*Brassica napus* L.), barley (*Hordeum vulgare*), annual ryegrass (*Lolium multiflorum*), oat (*Avena sativa* L.), and winter triticale (*Triticale hexaploide*). Legume species grown in the fall included Austrian winter pea (*Pisum sativum*), and yellow sweetclover (*Melilotus officinalis* L.). Two mixtures were established in the fall. Mixture 1 contained winter pea and winter triticale and mixture 2 contained yellow sweetclover and winter triticale.

Cover crop growth and production were evaluated using a randomized split-block design with three or four replications depending on location and year. Cover crops were randomized within growing period (summer or fall) and growing period was randomized within each block. In 2008, summer and fall cover crops were grown at the Manhattan-08 location. In 2009, only summer cover crops were grown at the Manhattan-09 and Hutchinson location due to time constraints for collecting data. Summer-grown species were planted on 14 July 2008 at the Agronomy Research Farm (Manhattan-08), 2 July 2009 at the Ashland Bottoms Research Farm (Manhattan-09), and 23 July 2009 at the South Central Experiment Field (Hutchinson). At the Manhattan-09 location, the number of replications was limited to three due to space limitations. Fall-grown species were planted on 4 September 2008 at the Manhattan-08 location. Cover crops were no-till planted into standing winter wheat stubble at all locations both years. Prior to cover crop planting, the wheat stubble was sprayed with 3.5 L ha^{-1} Roundup herbicide to eliminate actively growing weeds. A second glyphosate application was required two weeks before planting fall cover crops. No fertilizer was applied before planting cover crops at any of the three locations.

Cover crops were established at recommended seeding rates for each crop (Table 4.1) and evaluated through the growing season. Cover crop stands were estimated 20 days after plant emergence by counting plants in a 1.55 m^2 area. Termination of summer-grown cover crops occurred on 19 September 2008 at the Manhattan-08 location, 17 September 2009 at the Manhattan-09 location, and 23 September 2009 at the Hutchinson location. Fall-grown cover crops were terminated 22 April 2009 at the Manhattan-08 location. A BCS model 712 sickle-bar mower was used to terminate all cover crops. At time of cover crop termination, a 1.55 m^2 sample was hand harvested at ground level for estimation of biomass yield. Samples were separated by cover crop species and weighed. Subsamples were taken from each plot sample, dried in a forced-air dryer at 65˚ C until dry and weighed to obtain dry weight. Dry subsamples were analyzed for nitrogen content (sulfuric acid/hydrogen peroxide digest). A 12.5 m^2 area was machine harvested from each double-crop soybean plot to estimate grain yields using a Massey Ferguson 8XP plot harvester with a grain head. Grain moisture and test weight were estimated with a DICKEY-john GAC 2000 (DICKEY-john Corp., Springfield, IL) and grain protein concentrations were estimated with a GrainSpec Whole Grain analyzer (Foss-NorthAmerica, Eden Prairie, MN).

In 2009 at the Agronomy Research Farm (Manhattan-08), grain sorghum was planted into the existing cover crop plots. The grain sorghum hybrid, DKS 54-00 was planted on 5 May 2009 at a seeding rate of 190 600 seeds ha^{-1} in 0.76 m rows with a John Deere MaxEmerge^{TM} (Deere & Co., Moline, IL) planter equipped with residue managers. Seeding depth was 5 cm. Bicep Magnum (Syngenta Crop Protection, Greensboro, NC) post-plant, pre-emerge herbicide was applied at a rate of 0.65 L ha^{-1}. Grain sorghum stands were evaluated 30 days after plant emergence by counting plants in a 1.55 m^2 area. Flag leaf samples were obtained from each plot at half-bloom and dried in a forced-air dryer at 65˚C until dry. Flag leaf samples were analyzed for nitrogen concentration (sulfuric acid/hydrogen peroxide digest). Sorghum plots were scanned with a GreenSeeker Model 505 hand held optical sensor (NTech Industries, Ukiah, CA) and CropCircle ACS-210 hand held optical sensor (Holland Scientific, Lincoln, NB) 60 days after sorghum planting to obtain a normalized difference vegetation index (NDVI) value. These crop sensors rely on crop reflectance to estimate nitrogen status in plants and were used to quantify observed differences in grain sorghum nitrogen status. Studies have shown strong relationships between spectral reflectance and nitrogen status in green vegetation (Bausch and Duke, 1996; Stone et al., 1996). A length of 7.3 m was machine harvested from the center two rows of each plot with a Massey Ferguson 8XP plot harvester with a grain head. Grain moisture and test weight were estimated with a DICKEY-john GAC 2000 (DICKEY-john Corp., Springfield, IL). Grain was analyzed for nitrogen concentration in the Kansas State University soil testing lab by sulfuric acid/hydrogen peroxide digest. Plant height measurements were obtained at harvest. Plant head counts were recorded for an area of 11.1 m^2. Seed weight was determined by weighing 300 seeds from a subsample of grain obtained from each plot at harvest.

Significance of treatment differences was determined using the PROC MIXED and PROC GLM procedures (SAS Institute, 2004) with location, year, growing season, and cover crop species designated as fixed effects and replications as random effects. Relationships between response variables were quantified via calculation of Pearson correlation coefficients using the PROC CORR procedure in SAS.

Results and Discussion

Cover Crop Performance

Analysis of variance indicated that summer cover crop treatments that were present at all locations displayed a significant (α = 0.05) interaction between location and cover crop treatment for cover crop biomass, aboveground nitrogen accumulation and concentration, and cover crop plant population so the results were analyzed separately for each location (Table 4.2). When comparing the fall-grown species to the summer-grown species, on average, the summer-grown species produced more biomass but contain lower nitrogen concentrations than the fall-grown species (Table 4.3). In the Manhattan-08 study, both groups of cover crop species accumulated similar amounts of nitrogen in above-ground biomass. Summer cover crop stands were significantly different at the different locations (Tables 4.2, 4.4). Cover crop plant stands tended to be lowest at the Hutchinson location. Below-normal precipitation in July caused dry soil conditions and unfavorable planting conditions, contributing to the decreased plant populations at that location (Table 4.5).

Aboveground biomass production varied by cover crop species and location. The sorghum-sudangrass/pearl millet/sunnhemp/cowpea mixture had the greatest aboveground biomass production at the Manhattan-08 location (Table 4.6). The least amount of aboveground biomass at the Manhattan-08 location was produced by buckwheat, lablab bean, cowpea, sunnhemp, and forage soybean. At the Manhattan-09 location, the greatest aboveground biomass was produced by sorghum-sudangrass and the sorghum-sudangrass/pearl millet/sunnhemp/cowpea mixture. The least biomass was observed with buckwheat and lablab bean. Buckwheat stand counts and biomass were both less than for the other cover crops. Sorghum-sudangrass produced the greatest amount of aboveground biomass at the Hutchinson location, with buckwheat and sunnhemp producing the least (Table 4.6). The sorghum-sudangrass/pearl millet/sunnhemp/cowpea mixture (Mix 2) produced the greatest amount of biomass at both Manhattan locations and the second greatest amount of biomass at the Hutchinson location (Table 4.6). Buckwheat and lablab bean were consistently among the lowest biomass producing cover crops. The annual grass cover crops and mixtures tended to have greater plant populations and biomass yields at all locations. On average, legumes produced significantly less biomass than non-legumes at all locations (Table 4.6). Cover crop mixtures produced as much or more than the average of the components, with the more complex mixture producing significantly more biomass than its components at two of three locations. The biomass yields of the mixtures were consistent between years and locations whereas single species tended to vary.

Nitrogen concentrations in the aboveground biomass varied across locations and cover crop treatments (Table 4.7). Nitrogen concentrations were greatest in the forage soybean and cowpea treatments at the Manhattan-08 location, with the smallest nitrogen concentrations present in the sorghum-sudangrass, cowpea/pearl millet mixture, and sorghum-sudangrass/pearl millet/sunnhemp/cowpea mixture (Table 4.7). Results were similar at the Manhattan-09 location where forage soybean had the greatest nitrogen concentration and sorghum-sudangrass had the smallest nitrogen concentration in the aboveground biomass. At the Hutchinson location the smallest nitrogen concentrations were observed in the sorghum-sudangrass, pearl millet, and sorghum-sudangrass/pearl millet/sunnhemp/cowpea mixture. Across all study locations, forage soybean consistently contained the greatest and sorghum-sudangrass contained the smallest concentration of nitrogen (Table 4.7). On average, annual legume species contained more nitrogen than the non-legume species. Mixtures tended to have nitrogen concentrations that were similar to or less than the average of their component species (Table 4.7).

Aboveground biomass and nitrogen concentrations were used to calculate the nitrogen accumulation in the aboveground biomass of the cover crop species (Table 4.8). Forage soybean, pearl millet treatments, and both mixtures accumulated the greatest amounts of aboveground biomass nitrogen at the Manhattan-08 location (Table 4.8). All other cover crop treatments produced less nitrogen in the aboveground biomass. Due to the variability in estimates of nitrogen accumulation in the aboveground biomass at this location, the cowpea/pearl millet mixture was not different than the treatments that produced the greatest or least aboveground nitrogen. At the Manhattan-09 location, forage soybean, sunnhemp, and the sorghum-sudangrass/pearl millet/sunnhemp/cowpea mixture produced the greatest nitrogen yield in the aboveground biomass. Lablab bean, buckwheat, pearl millet and sorghum-sudangrass yielded the least nitrogen in the aboveground biomass (Table 4.8). Similar results were seen at the Hutchinson location where forage soybean, cowpea, and cowpea/pearl millet mixture produced the most nitrogen, and buckwheat the least amount of aboveground biomass nitrogen.

On average, the cover crop treatments that produced the most biomass accumulated the greatest amounts of nitrogen. Nitrogen concentration and nitrogen accumulation were not correlated, but biomass yield and nitrogen accumulation showed a strong positive correlation ($r = 0.67$, significant at $\alpha = 0.05$). The cover crop mixtures were among the greatest biomass producers and also accumulated the greatest amount of nitrogen. The sorghum-sudangrass/pearl millet/sunnhemp/cowpea mixture accumulated more nitrogen than any of the independent species at both Manhattan locations. At the Hutchinson location, cowpea accumulated the greatest amount of nitrogen. The Hutchinson location tended to produce less biomass and accumulate less nitrogen than either of the Manhattan studies, perhaps due to the lower monthly precipitation during July and August (Table 4.5).

Double crop soybean yields, plant populations, and grain nitrogen concentrations were compared in all experiments (Table 4.9). Plant populations and yields were greatest at the Manhattan-08 and Manhattan-09 locations. Grain nitrogen concentrations did not differ between locations (Table 4.9). Long-term double crop soybean yields in Kansas typically average between 1250 and 1875 kg ha^{-1} (NASS, 2010). The double crop soybean yields observed in 2009 at the Manhattan location are similar to those found around the state. The low soybean yields at the Hutchinson location may be attributed to the poor stand establishment (Kilgore et al., 1997). Planting conditions at the Hutchinson location were not ideal due to limited rainfall and dry soils during the time of cover crop planting (Table 4.5). The regression of grain yield on plant populations ($r^2 = 0.83$) showed that grain yield increased as plant populations increased (Figure 4.1).

Fall-grown cover crops were planted at the Manhattan-08 location in 2008. Plant stands were adequate for all cover crop treatments (Table 4.10). Aboveground biomass yields were greatest for the winter triticale and winter pea/winter triticale mixture. Non-legume species tended to produce greater amounts of biomass when compared to legume species (Table 4.10). Smallest biomass yields were observed with the winter pea, annual ryegrass, annual fescue, and yellow sweetclover treatments. Cover crop treatments that put on growth primarily in the spring produced the least biomass. Cool spring temperatures and early termination dates could account for the limited growth in some of these species.

As with the summer-grown crops, legume species averaged significantly greater plant nitrogen concentration (Table 4.10), but some non-legumes had similar nitrogen concentrations.

Greatest nitrogen concentrations in the aboveground cover crop biomass were observed in the canola, winter pea, and yellow sweetclover. Barley, oat, winter triticale, winter pea/winter triticale mixture, and the yellow sweetclover/winter triticale mixture contained the smallest concentrations of nitrogen. The nitrogen concentration in the mixtures was not as great as the average nitrogen concentration in the individual species and was no different than the grass component (Table 4.10).

Cover crop aboveground biomass and nitrogen concentration were used to calculate nitrogen accumulation in the aboveground biomass. Nitrogen accumulation was greatest in the canola, barley, winter triticale, winter pea/winter triticale mixture, and yellow sweetclover/winter triticale mixture (Table 4.10). Winterpea, annual ryegrass, and annual fescue yielded the least nitrogen. Winter triticale produced greater biomass when left as a monocrop than when included in the two mixtures (Table 4.10). The split block analysis of variance of both summer and fall-planted crops revealed that the winter pea/winter triticale mixture, the yellow sweetclover/winter triticale mixture, winter triticale, and canola biomass, nitrogen concentration, and nitrogen accumulation similar ($\alpha = 0.05$) to the sorghum-sudangrass, pearl millet, cowpea, forage soybean, and both summer mixtures (Tables 4.6, 4.7, 4.8, and 4.10).

Grain Sorghum Response Following Cover Crops

Grain sorghum responses to cover crop treatments were analyzed by cover crop growing season as well as across growing seasons. On average, sorghum yields were 867 kg ha^{-1} greater following summer cover crops compared to fall cover crops (Table 4.11). Within the summer cover crops, grain sorghum yields following double crop soybeans were greater than after all other cover crops. Yields after sorghum-sudangrass were smallest within summer grown cover crops. Sorghum yields following canola were greatest among winter cover crops. When all cover crop treatments were compared, sorghum yields following canola, winter pea, and yellow sweetclover were not different than the yields following pearl millet, lablab bean, cowpea, sunnhemp, forage soybean, double crop soybean, cowpea/pearl millet mixture, and sorghum-sudangrass/pearl millet/sunnhemp/cowpea mixture.

Flag leaf nitrogen concentration was used as an indicator of mid-season plant nitrogen status (Evans, 1983). Greatest flag leaf nitrogen concentrations were seen following canola, with smallest flag leaf concentrations following oat and the yellow sweetclover/winter triticale mixture. These results follow the same trend as grain sorghum yields. Following summer-grown cover crops, concentrations were greatest following double crop soybean and smallest following pearl millet, similar to the yield response. Comparisons across all cover crop treatments indicate that yields following canola and yellow sweetclover were similar to yields following summer cover crop treatments. The regression of grain sorghum yield on flag leaf nitrogen concentration ($r^2 = 0.73$) shows that grain sorghum yield increased by 8.73 kg ha^{-1} for every increase of 1 g kg^{-1} in flag leaf nitrogen (Figure 4.2).

On average, the nitrogen concentrations within the sorghum grain following fall-grown cover crops were not different than the nitrogen concentration following summer-grown species (Table 4.11). Differences between the individual summer and winter grown crops were minimal, with many winter crop treatments producing grain nitrogen concentrations similar to those found following fall cover crop treatments.

Grain sorghum plant heights followed a similar trend, with no difference between the average plant height for sorghum grown after summer and fall cover crops (Table 4.11). Sorghum was tallest following double crop soybean and shortest following sorghum-sudangrass within the summer treatments. Grain sorghum height did not differ within the fall cover crops.

On average, grain sorghum bloomed 3 days later following fall cover crop treatments when compared with summer cover crop treatments (Table 4.11). Grain sorghum following double crop soybean and canola bloomed earliest. Sorghum following sorghum-sudangrass, winter pea/winter triticale mixture, and yellow sweetclover/winter triticale mixture were last to reach the half bloom stage. Typically, these treatments had the smallest sorghum grain yields as well. On average, the treatments that resulted in later sorghum bloom date also had less sorghum grain yield. The regression of grain sorghum yield on days after planting to bloom ($r^2 = 0.83$) shows that sorghum yields decreased with increasing days till half bloom (Figure 4.3).

Grain sorghum NDVI values were, on average, greater following summer cover crop treatments (Table 4.11). Both the GreenSeeker and the CropCircle hand held sensor NDVI values were greatest for sorghum following double crop soybean, forage soybean, sunnhemp, cowpea, cowpea/pearl millet mixture, canola, winter pea, oat, annual fescue, and yellow sweetclover. Sorghum following the sorghum-sudangrass, winter triticale, and winter pea/winter triticale mixture treatments had the smallest NDVI values, as well as poor yields. The regressions of grain sorghum yield on GreenSeeker NDVI ($r^2 = 0.92$) and CropCircle NDVI ($r^2 =$

0.92) both show a strong positive relationship between grain sorghum yields and NDVI values (Figure 4.4 and Figure 4.5). Higher reflectance measurements can give good indications of leaf greenness and total biomass. This observation is consistent with those found by other studies that showed relationships between spectral reflectance, chlorophyll content and nitrogen status (Bausch and Duke, 1996; Stone et al., 1996).

Grain sorghum seed weight, plant heads per ha^{-1}, and plant populations were all found to be not significantly different for sorghum grown after the different cover crops (Table 4.11). Treatments with greater yielding grain sorghum tended to have a greater number of seeds per head (Table 4.11), suggesting that the increase or decrease in sorghum yields was a result of variability in the size of the grain sorghum head.

Conclusions

Results of this study show that annual grasses produce the greatest amounts of aboveground biomass and legume species have greater nitrogen concentration in the plant tissue. Summer-grown species produced greater biomass and subsequently accumulated more nitrogen than the fall-grown species. Sorghum yields varied depending on previous cover crop. Grain sorghum following the cover crops that resulted in high yielding grain sorghum all displayed high NDVI values, high flag leaf nitrogen content, and reached half bloom sooner than cover crops resulting in low yielding grain sorghum. Due to the strong correlations observed between grain sorghum yield, NDVI values, flag leaf nitrogen content, and days after planting to half bloom, we can conclude that cover crops can have a significant effect on the subsequent grain sorghum crop. The increase in grain sorghum yields might have been a result of greater quantities of nitrogen available to the sorghum plant throughout the growing season supplied by nitrogen fixation in legume species or greater availability of nitrogen from plant tissue in low C:N cover crop species. The results indicate grain sorghum, on average, performs better following a summer-grown cover crop when compared with fall-grown cover crops. Within summer-grown crops, warm-season legume species were more favorable than warm-season grass species for subsequent grain sorghum production.

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Figures and Tables

Table 4.1. Cover crop seeding rates at Manhattan, KS in 2008 and 2009 and Hutchinson, KS in 2009.

Summer-grown Species	Seeding Rate	Fall-grown Species	Seeding Rate
	kg ha^{-1}		kg ha^{-1}
Sorghum-sudangrass	27	Canola	11
Pearl Millet	28	Winter pea	34
Buckwheat	50	Barley	67
Lablab Bean	34	Annual Ryegrass	11
Cowpea	34	Oat	101
Sunnhemp	11	Winter Triticale	67
Forage Soybean	67	Annual Fescue	11
Double Crop Soybean	67	Yellow Sweetclover	17
Mixture 1: Cowpea	27	Mixture 1: Winter pea	27
Pearl Millet	22	Winter Triticale	54
Mixture 2: Sorghum-sudangrass	22	Mixture 2: Yellow Sweetclover	14
Pearl Millet	22	Winter Triticale	54
Sunnhemp	9		
Cowpea	27		

Table 4.2. Analysis of variance for experiments at Manhattan, KS in 2008 and 2009 and Hutchinson, KS in 2009.

Source of Variation	Biomass	N Concentration	N Yield	Plant Population
	Pr > F			
Location	**	**	**	**
Cover Crop	**	**	**	**
Location*Cover Crop	**	*	*	**

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

Table 4.3. Comparison of summer-grown and fall-grown cover crop aboveground biomass, aboveground nitrogen accumulation and concentration, and plant population at the Manhattan in 2008†.

Cover Crop	Cover Crop Aboveground Biomass		
	Biomass Yield	Nitrogen Concentration	Nitrogen Accumulation
	kg ha^{-1}	g kg^{-1}	kg ha^{-1}
Summer-grown	3044 a	13.42 b	33.2 a
Fall-grown	1815 b	22.16 a	34.6 a

† Values in a column followed by the same letter are not significantly different, $\alpha = 0.05$.

Table 4.4. Summer cover crop plant populations at Manhattan, KS 2008 and 2009 and Hutchinson, KS in 2009†.

	Location		
Cover Crop Species	Manhattan-08	Manhattan-09	Hutchinson
		plants ha^{-1}	
Sorghum-sudangrass	463 905 b	238 708 cd	123 492 bcd
Pearl Millet	606 997 a	547 112 b	158 123 bc
Buckwheat	390 072 bc	343 252 c	90 169 cd
Lablab Bean	46 397 e	54 885 e	67 954 cd
Cowpea	49 004 e	81 022 e	92 129 cd
Sunnhemp	84 287 e	91 476 e	31 363 d
Forage Soybean	119 570 e	147 232 de	41 164 d
Cowpea/Pearl Millet (Mix 1)	338 454 cd	568 021 b	201 247 b
Sorghum-sudangrass/Pearl Millet/Sunnhemp/Cowpea (Mix 2)	274 423 d	870 327 a	353 489 a
Contrasts††			
Legume vs. Non-Legume (LLB, CP, SH, FSB) (SS, PM, BW)	-412 178***	-282 704***	-65 775*
Mix 1 vs. Components (CP, PM)	NS	253 954**	NS
Mix 2 vs. Components (SS, PM, SH, CP)	NS	630 747***	252 212***

† Values in a column followed by the same letter are not significantly different, $\alpha = 0.05$.

†† Value represents difference in plant population between legume and non-legume species, mix 1 and components found in mix 1, and mix 2 and components found in mix 2.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 4.5. Monthly rainfall distribution at Manhattan, KS in 2008 and 2009 and Hutchinson, KS in 2009.

Location	May	Jun	Jul	Aug	Sep	Total
Manhattan			mm			
2008	121	304	129	117	178	849
2009	12	207	128	135	46	528
Normal†	126	131	110	87	87	541
Hutchinson						
2009	78	104	48	90	162	482
Normal	109	104	92	73	73	451

† 1971-2000 Normals, Kansas State University Weather Library (2010).

Table 4.6. Summer cover crop aboveground biomass (dry matter) at Manhattan, KS in 2008 and 2009 and Hutchinson, KS in 2009†.

	Location		
Cover Crop Species	Manhattan-08	Manhattan-09	Hutchinson
		kg ha^{-1}	
Sorghum-sudangrass	4675 b	6442 a	10 190 a
Pearl Millet	4464 b	4521 b	3 392 cd
Buckwheat	1243 c	1610 d	116 e
Lablab Bean	855 c	1688 d	2 109 cd
Cowpea	1302 c	2947 c	4 973 bc
Sunnhemp	1979 c	4574 b	1 817 de
Forage Soybean	1994 c	4188 b	2 431 d
Cowpea/Pearl Millet (Mix 1)	4199 b	4649 b	4 656 bc
Sorghum-sudangrass/Pearl Millet/Sunnhemp/Cowpea (Mix 2)	6748 a	6105 a	6 177 b
Contrasts††			
Legume vs. Non-Legume (LLB, CP, SH, FSB) (SS, PM, BW)	-1943***	-842*	-1 484**
Mix 1 vs. Components (CP, PM)	1315*	NS	NS
Mix 2 vs. Components (SS, PM, SH, CP)	3658***	1484**	NS

† Values in a column followed by the same letter are not significantly different, α = 0.05.

†† Value represents difference in aboveground biomass between legume and non-legume species, mix 1 and components found in mix 1, and mix 2 and components found in mix 2.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 4.7. Summer cover crop aboveground biomass nitrogen concentration at Manhattan, KS in 2008 and 2009 and Hutchinson, KS in 2009†.

	Location		
Cover Crop Species	Manhattan-08	Manhattan-09	Hutchinson
		g kg^{-1}	
Sorghum-sudangrass	6.03 d	4.77 f	3.40 e
Pearl Millet	10.00 c	8.27 e	7.00 e
Buckwheat	11.03 c	12.77 d	11.28 bc
Lablab Bean	14.95 b	11.47 de	9.50 bcd
Cowpea	22.83 a	18.10 b	12.35 bc
Sunnhemp	15.80 b	16.27 bc	13.50 b
Forage Soybean	23.98 a	22.53 a	17.55 a
Cowpea/Pearl Millet (Mix 1)	8.25 cd	12.73 d	8.43 cd
Sorghum-sudangrass/Pearl Millet/Sunnhemp/Cowpea (Mix 2)	7.93 cd	13.43 cd	5.60 e
Contrasts††			
Legume vs. Non-Legume (LLB, CP, SH, FSB) (SS, PM, BW)	10.37**	8.57**	6.00**
Mix 1 vs. Components (CP, PM)	-8.16**	NS	NS
Mix 2 vs. Components (SS, PM, SH, CP)	-5.73**	NS	-3.46*

† Values in a column followed by the same letter are not significantly different, α = 0.05.

†† Value represents difference in aboveground biomass nitrogen concentration between legume and non-legume species, mix 1 and components found in mix 1, and mix 2 and components found in mix 2.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

Table 4.8. Summer cover crop aboveground nitrogen accumulation at Manhattan, KS in 2008 and 2009 and Hutchinson, KS in 2009†.

	Location		
Cover Crop Species	Manhattan-08	Manhattan-09	Hutchinson
		kg ha^{-1}	
Sorghum-sudangrass	27.7 bc	31.0 de	34.1 b
Pearl Millet	48.6 ab	37.9 cde	23.7 b
Buckwheat	13.8 c	20.9 e	1.5 c
Lablab Bean	13.3 c	19.6 e	30.7 b
Cowpea	29.7 bc	53.3 bcd	56.6 a
Sunnhemp	30.2 bc	75.7 ab	22.9 b
Forage Soybean	47.9 ab	94.6 a	42.8 ab
Cowpea/Pearl Millet (Mix 1)	33.4 abc	59.1 bc	38.1 ab
Sorghum-sudangrass/Pearl Millet/Sunnhemp/Cowpea (Mix 2)	54.6 a	82.0 a	34.3 b
Contrasts††			
Legume vs. Non-Legume (LLB, CP, SH, FSB) (SS, PM, BW)	NS	30.9***	18.5**
Mix 1 vs. Components (CP, PM)	NS	NS	NS
Mix 2 vs. Components (SS, PM, SH, CP)	20.6*	32.5**	NS

† Values in a column followed by the same letter are not significantly different, α = 0.05.

†† Value represents difference in nitrogen accumulation between legume and non-legume species, mix 1 and components found in mix 1, and mix 2 and components found in mix 2.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 4.9. Double crop soybean yields at Manhattan, KS in 2008 and 2009 and Hutchinson, KS in 2009†.

	Double Crop Soybean		
Location	Grain Yield	Nitrogen Concentration	Plant Population
	kg ha^{-1}	g kg^{-1}	plants ha^{-1}
Manhattan-08	925 a	58.26 a	308 140 a
Manhattan-09	1261 a	59.09 a	354 933 a
Hutchinson	255 b	54.84 a	93 572 b

† Values in a column followed by the same letter are not significantly different, $\alpha = 0.05$.

Table 4.10. Fall cover crop aboveground biomass, aboveground nitrogen accumulation and concentration, and plant populations at the Manhattan-08 location†.

	Cover Crop Aboveground Biomass			
Cover Crop Species	Biomass Yield	Nitrogen Concentration	Nitrogen Accumulation	Plant Population
	kg ha^{-1}	g kg^{-1}	kg ha^{-1}	plants ha^{-1}
Canola	1594 cd	28.25 ab	41.2 ab	1 639 114 abc
Winter pea	615 e	31.68 a	17.7 cd	146 810 f
Barley	2513 b	15.65 de	35.2 ab	1 310 000 bcd
Annual Ryegrass	1080 de	20.48 cd	19.9 cd	1 156 736 de
Oat	2267 bc	14.73 e	29.9 bc	1 702 035 ab
Winter Triticale	3487 a	15.83 de	48.8 a	1 169 644 cde
Annual Fescue	557 e	25.63 bc	12.5 d	1 271 281 bcd
Yellow Sweetclover	600 e	33.60 a	18.1 ab	2 052 119 a
Winter pea/Winter Triticale (Mix 1)	2974 ab	17.85 de	47.1 a	793 746 e
Yellow Sweetclover/ Winter Triticale (Mix 2)	2461 b	17.95 de	38.9 ab	1 471 331 bcd
Contrasts††				
Legume vs. Non-Legume (WP, YSC) (C, B, AR, O, WT, AF)	-1309***	12.50***	-13.4**	-275 337*
Mix 1 vs. Components (WP, WT)	923**	-5.91*	13.85*	NS
Mix 2 vs. Components (YSC, WT)	NS	-6.77**	NS	NS

† Values in a column followed by the same letter are not significantly different, α = 0.05.

†† Value represents difference in biomass, nitrogen concentration, nitrogen accumulation, and plant population between legume and non-legume species, mix 1 and components found in mix 1, and mix 2 and components found in mix 2.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

Table 4.11. Grain sorghum performance following cover crops at the Manhattan-08 location†.

Cover Crop Species	Grain Yield	Grain N Content	Flag Leaf N Content	Seed Weight	Plant Heads	Seeds per Head	Plant Height	Plant Population	Plant Half Bloom	GreenSeeker NDVI	CropCircle NDVI
	kg ha^{-1}	g kg^{-1}	g kg^{-1}	g seed^{-1}	heads ha^{-1}	Seeds head^{-1}	cm	plants ha^{-1}	days after planting		
Sorghum-sudangrass	2667	11.37	15.78	0.0297	86 582	1037	129	333 960	92	0.66	0.62
Pearl Millet	3905	10.40	14.86	0.0310	91 242	1380	133	369 453	89	0.72	0.71
Buckwheat	3373	10.87	16.16	0.0307	86 224	1274	133	351 707	88	0.70	0.70
Lablab Bean	4688	10.18	19.22	0.0298	93 753	1678	134	374 293	82	0.74	0.73
Cowpea	5169	10.35	20.00	0.0387	97 876	1365	139	383 973	82	0.76	0.76
Sunnhemp	4932	9.95	19.57	0.0290	93 932	1811	137	363 000	82	0.75	0.75
Forage Soybean	4629	10.55	19.17	0.0300	95 904	1609	139	366 227	83	0.75	0.75
Double Crop Soybean	6075	11.34	20.28	0.0305	91 604	2174	147	342 027	81	0.77	0.77
Cowpea/Pearl Millet (Mix 1)	4486	10.93	18.42	0.0306	91 243	1606	135	366 227	86	0.76	0.74
Sorghum-sudangrass/ Pearl Millet/Sunnhemp/Cowpea (Mix 2)	4566	10.98	18.10	0.0307	69 015	2155	133	330 733	86	0.72	0.71
Summer Cover Crop Average	4449	10.69	18.15	0.0311	89 738	1609	136	358 160	85	0.73	0.73
Summer Cover Crop LSD†	579	0.60	1.65	NS	NS	221	7	NS	3	0.02	0.02
Canola	5278	9.88	19.55	0.0295	99 310	1802	142	354 933	81	0.76	0.76
Winter pea	4310	10.23	15.99	0.0297	86 403	0680	136	340 413	83	0.73	0.72
Barley	3207	11.29	16.12	0.0310	90 167	1147	131	358 160	91	0.69	0.68
Annual Ryegrass	3321	10.84	16.38	0.0327	86 224	1178	132	293 627	91	0.68	0.67
Oat	3647	9.63	15.58	0.0293	85 686	1453	133	343 640	84	0.72	0.71
Winter Triticale	2583	12.14	16.30	0.0322	83 356	962	130	348 480	91	0.66	0.85
Annual Fescue	3830	10.69	17.23	0.0308	88 016	1413	136	312 987	87	0.72	0.71
Yellow Sweetclover	4392	9.74	18.47	0.0302	90 526	1607	135	346 867	83	0.74	0.73
Winter pea/Winter Triticale (Mix 3)	2806	11.44	15.99	0.0310	87 299	1367	132	345 153	92	0.66	0.65
Yellow Sweetclover/ Winter Triticale (Mix 4)	2447	11.06	15.74	0.0313	92 498	845	130	353 350	92	0.68	0.67
Fall Cover Crop Average	3582	10.69	16.74	0.308	88 949	1313	134	339 761	88	0.70	0.72
Fall Cover Crop LSD†	787	0.60	1.45	NS	NS	205	4	NS	3	0.03	0.03
Summer vs. Fall LSD†	691	0.60	1.56	NS	NS	213	6	NS	3	0.03	0.03

† LSD – Least significant difference, α=0.05.

Table 4.12. Contrasts for grain sorghum performance following cover crops at the Manhattan-08 location.

Cover Crop Species	Grain Yield	Grain N Content	Flag Leaf N Content	Seeds per Head	Plant Height	Plant Half Bloom	GreenSeeker NDVI	CropCircle NDVI
	kg ha^{-1}	g kg^{-1}	g kg^{-1}	Seeds head^{-1}	cm	days after planting		
Contrast†								
Legume vs. Non-Legume (LLB, CP, SH, FSB, DCSB, WP, YSC) (SS, PM, BW, C, B, AR, O, WT, AF)	1350**	NS	2.51*	267**	5*	-6*	NS	NS
Mix 1 vs. Components (CP, PM)	NS	NS	NS	NS	NS	NS	NS	NS
Mix 2 vs. Components (SS, PM, SH, CP)	NS	NS	NS	757**	NS	NS	NS	NS
Mix 3 vs. Components (WP, WT)	NS	NS	NS	546**	NS	5*	NS	NS
Mix 4 vs. Components (YSC, WT)	-1041*	NS	NS	-440**	NS	5*	NS	NS

† Value represents difference in response variables between legume and non-legume species, mix 1 and components found in mix 1, mix 2 and components found in mix 2, mix 3 and components found in mix 3, and mix 4 and components found in mix 4.

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

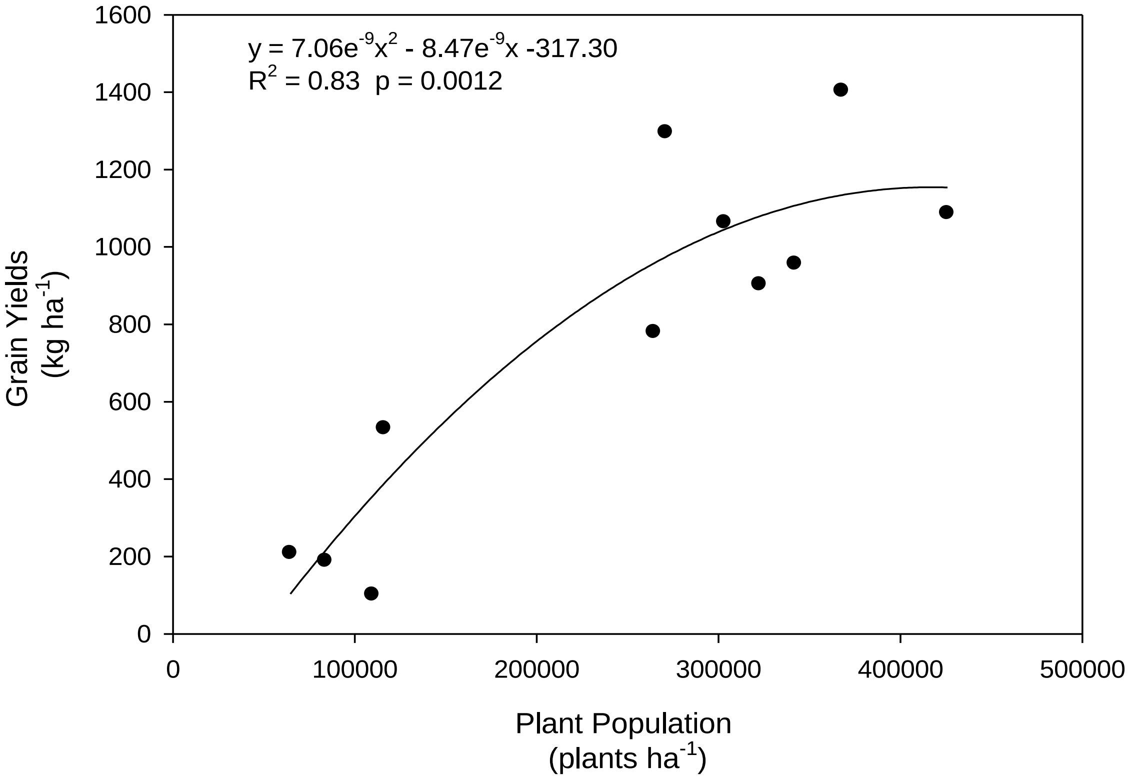

Figure 4.1. Relationship between soybean plant populations and grain yield at Manhattan, KS 2008 and 2009 and Hutchinson, KS in 2009.

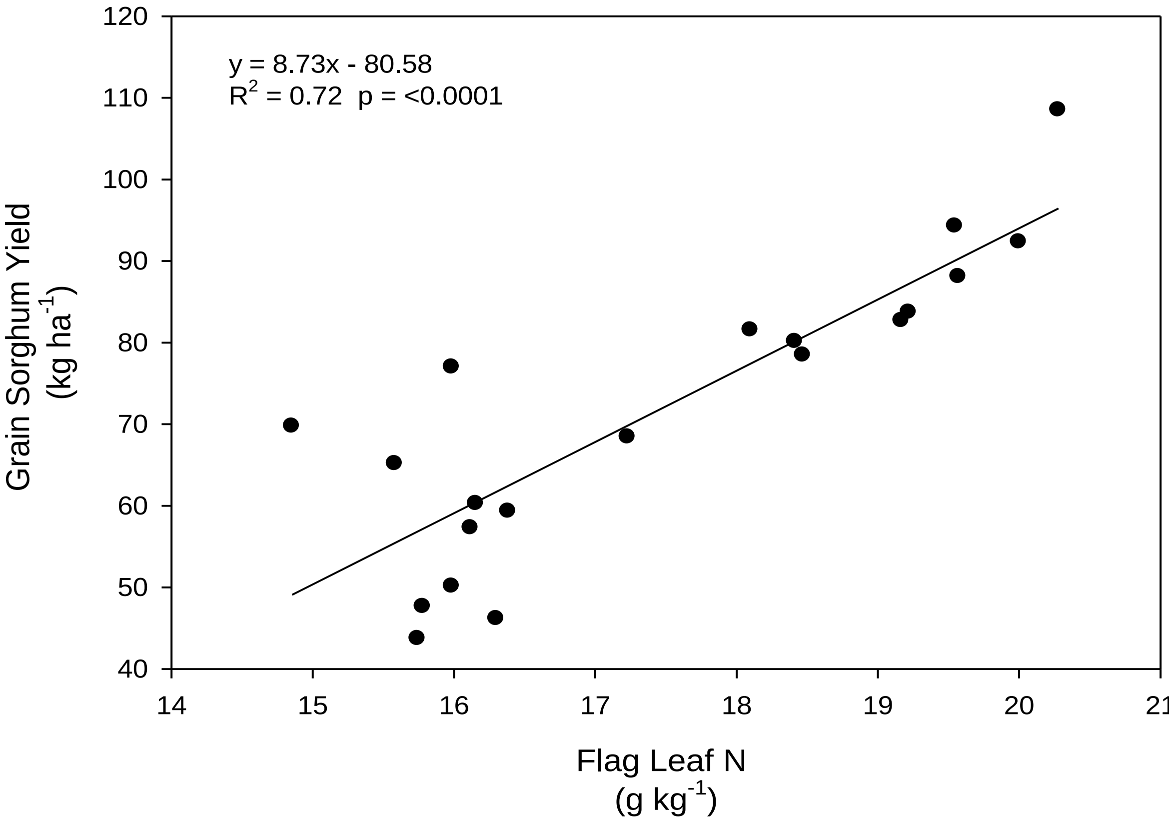

Figure 4.2. Relationship between grain sorghum yield and flag leaf nitrogen concentration at Manhattan in 2008.

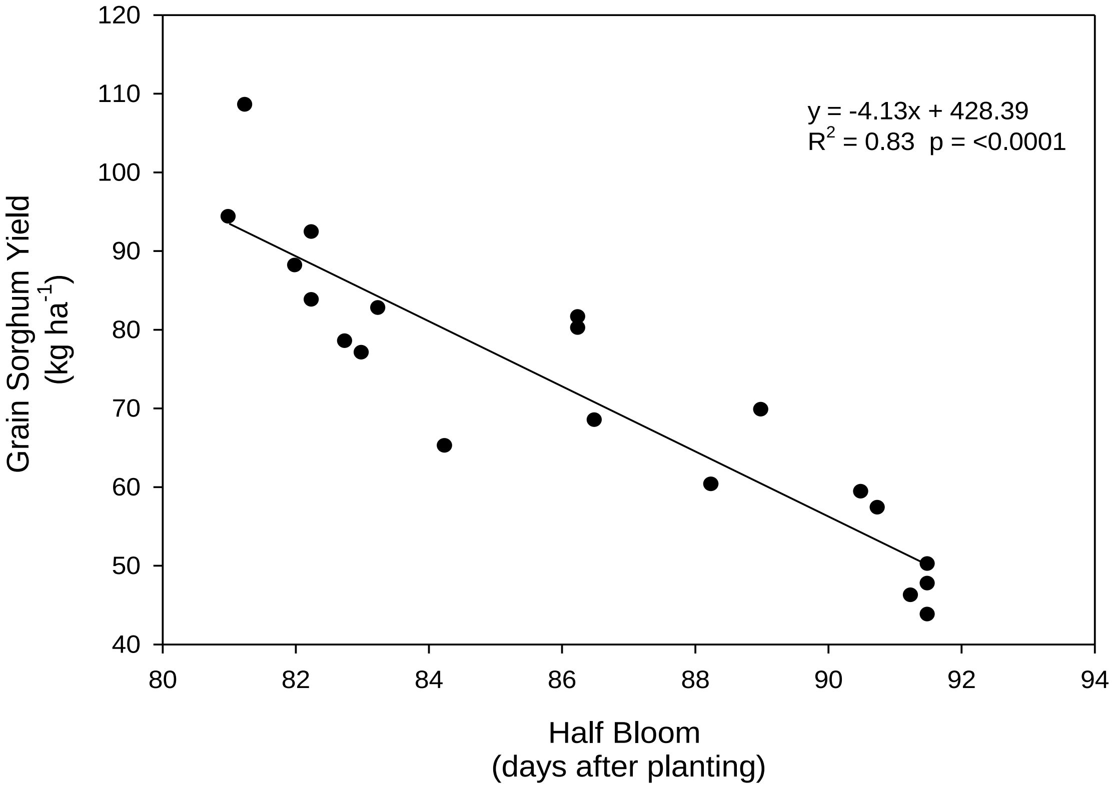

Figure 4.3. Relationship between grain sorghum yield and grain sorghum half bloom at Manhattan in 2008.

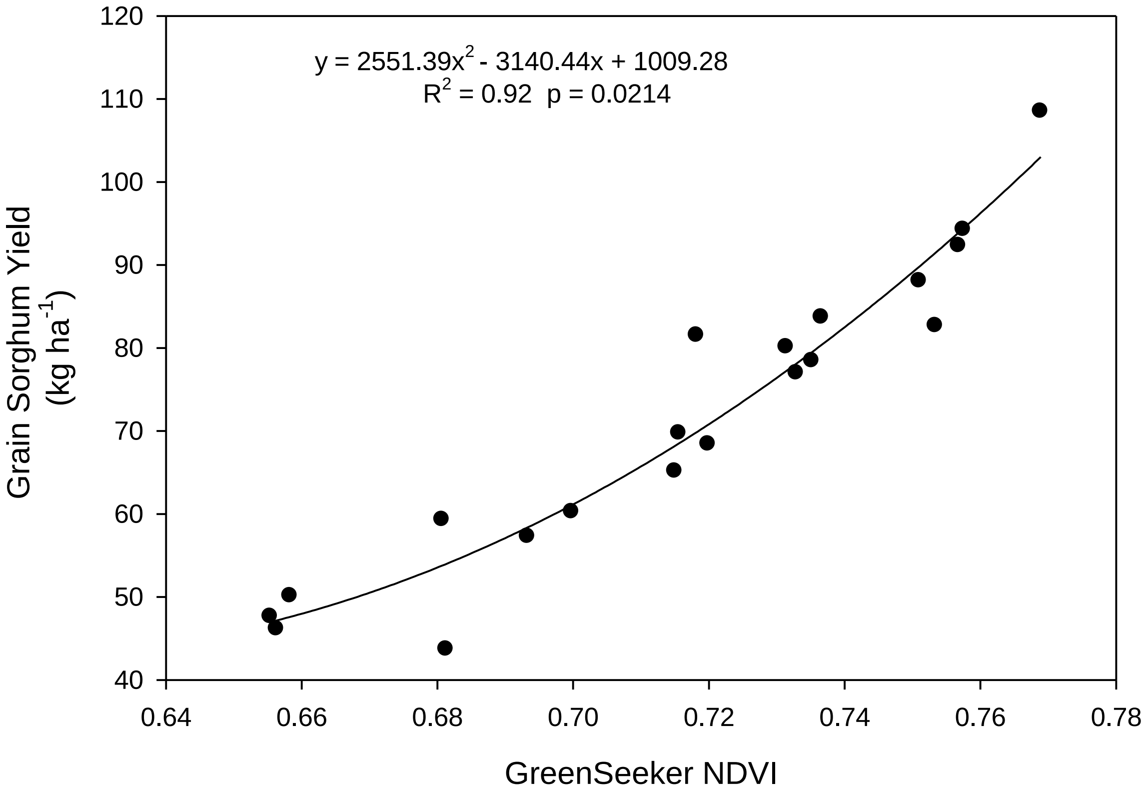

Figure 4.4. Comparison of grain sorghum yield and GreenSeeker NDVI value at the Manhattan-08 location.

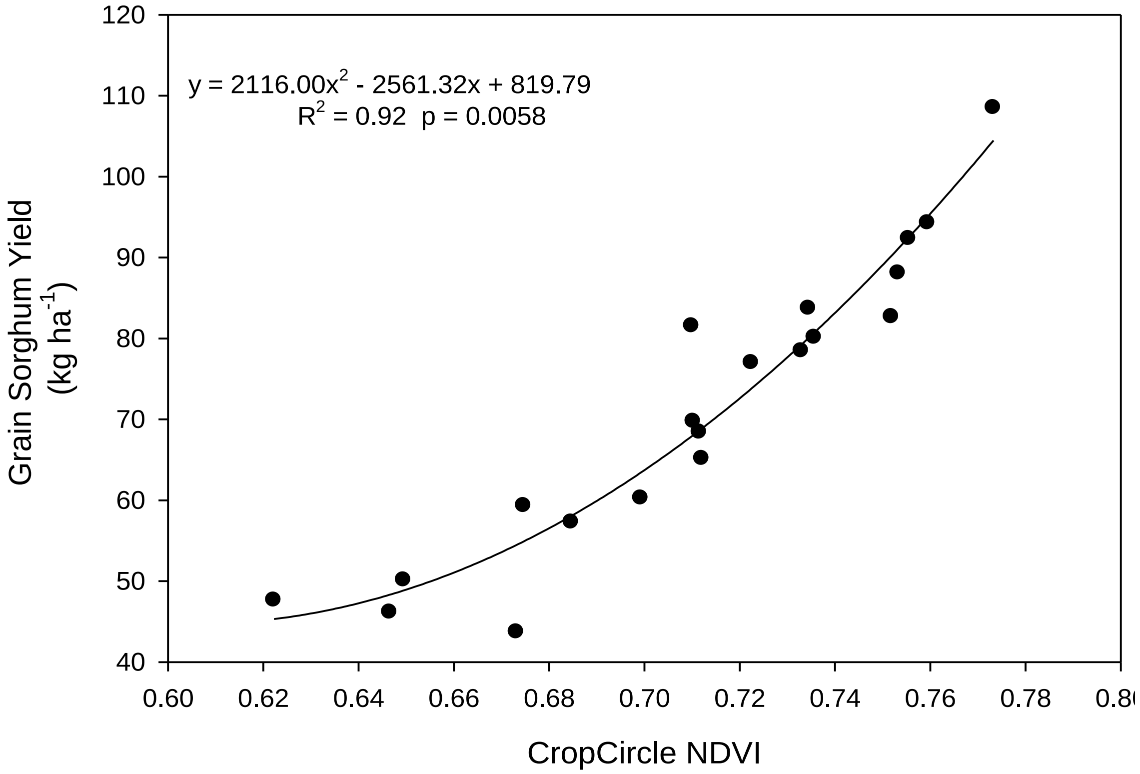

Figure 4.5. Comparison of grain sorghum yield and CropCircle NDVI value at the Manhattan-08 location.

CHAPTER 5 - Research Conclusions and Impacts

Historically, Kansas producers have used tillage as a means to control weeds, incorporate residue, and prepare a seedbed for the subsequent grain crop (Allen and Fenster, 1986). Rising costs of fertilizer and other crop production inputs have increased the risk and complexity of managing current cropping systems. No-till has gained popularity as farmers pursue more efficient ways to manage cropping systems. Many challenges must be overcome when designing cropping systems that minimize economic risk, while maintaining system profitability. Integrating cover crops has been promoted as a means to reduce nitrogen fertilizer requirements and increase cropping system profitability and sustainability, while reducing weed population densities (Blackshaw et al. 2001; Zentner et al., 2003).

In many areas of Kansas, water availability is the deciding factor for cropping system management practices. Research has shown that when switching to no-till, the cropping system can be intensified because of increased stored available water (Nielsen et al., 2005; Norwood, 1999). In other areas of Kansas, annual precipitation amounts are greater, but year-to-year variability in precipitation amount and distribution causes a high degree of uncertainty in cropping system production.

Previous studies in Kansas have suggested that cover crops might use too much soil water, reducing crop yields to an unacceptable level (Schlegel and Havlin, 1997). The negative effects of cover crops on the following crop yields were minimized with early cover crop termination dates. The purpose of this research was to identify potential cover crops that can be integrated into current cropping systems that will reduce soil erosion, nitrogen fertilizer requirements, and weed populations, and increase overall cropping system profitability and sustainability.

The results of this study indicate that cover crops show potential when integrated into wheat-fallow and wheat-grain sorghum-soybean crop rotations. In western Kansas, wheat yields were not reduced following cover crops that produced relatively less biomass. This suggests that a cover crop might be used to increase soil physical characteristics, prevent soil erosion, and suppress weeds during the fallow period with little negative impact on the following grain crop. Other benefits of cover crops, such as growing forage for grazing or hay production might be obtainable if the producer is willing to accept a small reduction in crop yields. More research is needed to determine system sustainability during years of average, or reduced annual precipitation. In eastern Kansas, the research the results indicate that cover crops fit well into common no-till cropping systems. When fertilizer is used, little negative effect is seen on subsequent grain yields following cover crops. The decision of which cover crop works best will be based on the needs of the individual producer. Crops that produce large biomass yields might be grown for forage or weed suppression, and legume or low carbon: nitrogen (C:N) cover crops might be grown for erosion protection, weed suppression, or a potential nitrogen benefit.

System profitability and sustainability will ultimately be decided by the needs of the individual producer. Some yield reductions may be acceptable if the producer is gaining something else from the cropping system. During the fallow period, a producer will typically apply 2-3 herbicide applications to control weed populations. The cost of integrating a cover crop would include cost of seeding and termination. Cover crop seed prices vary depending on species, but many are relatively inexpensive. Termination costs would range from chemical termination with herbicide, to mechanically harvesting for forage. In a situation where the producer owns a livestock herd, the benefit seen from the forage produced or winter grazing potential may be greater than the costs to establish and terminate a cover crop. Many summer-grown cover crops, such as sorghum-sudangrass, might not require chemical termination because the plant will die during the natural occurring freeze in the fall. This might allow a producer to remove the top growth as forage earlier in the growing season, and still allow for some re-growth to occur before the cove crop is terminated by the fall freeze. The standing re-growth would increase soil organic matter, prevent wind and water erosion, and suppress weeds during the winter months. These decisions will need to be evaluated by the individual producer to see if intensifying their crop rotation with cover crops provides a net benefit to the entire farm enterprise. The large selection of cover crops available allows a producer to choose the species that best fits their crop rotation and individual needs. Current research indicates great potential for the use of cover crops to maximize efficiency of current no-till cropping systems, but the future is still unknown. More research is needed to determine long term effects of including cover crops in Kansas no-till cropping systems.

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Appendix A - Chapter 2

Raw Data

This section of the appendix contains data from the second chapter, *Effects of Cover Crops in No-tillage Crop Rotations*, that was not included in the chapter text.

Table A.1. Ashland soil pH, buffer pH, phosphorus, potassium, zinc, and organic matter arranged by study year, block, and depth.

Year	Block	Depth	pH	Buffer pH	Mehlich-3 P	K	Zn	O.M.
				SMP	ppm	ppm	ppm	%
2008	101-130	0-2in	5.9	6.4	84	524	2.7	12.1
2008	101-130	2-4in	6.1	6.7	23	358	2.3	2.7
2008	101-130	4-6in	5.9	6.6	15	258	2.1	3.4
2008	131-160	0-2in	5.8	6.7	46	494	2.9	13.4
2008	131-160	2-4in	6.3	6.8	12	329	2.5	1.3
2008	131-160	4-6in	6.0	6.7	9	246	2.3	1
2008	161-190	0-2in	6.3	6.7	34	521	3.0	9.6
2008	161-190	2-4in	6.5		12	357	2.8	1.8
2008	161-190	4-6in	6.1	6.7	13	242	2.5	0.9
2008	201-230	0-2in	6.5		32	513	3.0	8.3
2008	201-230	2-4in	6.6		9	329	2.8	0.9
2008	201-230	4-6in	6.1	6.6	6	249	2.5	1
2008	231-260	0-2in	6.0	6.8	36	525	2.9	11.8
2008	231-260	2-4in	6.4	6.9	12	351	2.7	1
2008	231-260	4-6in	5.9	6.7	9	233	2.4	0.7
2008	261-290	0-2in	5.8	6.8	53	522	3.1	15
2008	261-290	2-4in	6.3	6.9	13	358	2.7	2.5
2008	261-290	4-6in	6.0	6.7	14	242	2.5	0.3
2008	301-330	0-2in	6.1	6.8	30	498	2.8	11.6
2008	301-330	2-4in	6.4	6.9	12	321	2.5	0.9
2008	301-330	4-6in	6.0	6.7	14	217	2.4	0.6
2008	331-360	0-2in	5.9	6.8	50	516	2.9	13.5
2008	331-360	2-4in	6.3	6.8	17	343	2.7	3.9
2008	331-360	4-6in	6.0	6.6	11	214	2.4	2.2
2008	361-390	0-2in	6.4	6.9	36	419	2.9	7.1
2008	361-390	2-4in	6.6		11	244	2.4	0.8
2008	361-390	4-6in	6.3	6.7	7	152	2.1	0.3
2008	401-430	0-2in	6.6		28	419	3.0	9.7
2008	401-430	2-4in	6.7		13	228	2.5	0.8
2008	401-430	4-6in	6.4	6.7	6	149	2.4	0.6
2008	431-460	0-2in	6.2	6.8	40	421	2.7	8.4
2008	431-460	2-4in	6.5		10	245	2.4	0.6
2008	431-460	4-6in	6.2	6.7	10	180	2.1	0.4
2008	461-490	0-2in	5.7	6.7	95	496	2.8	16.6
2008	461-490	2-4in	6.2	6.9	12	306	2.5	2.5
2008	461-490	4-6in	6.2	6.8	10	200	2.2	1.7
2009	101-130	0-2in	5.9	6.8	31	430	18.0	2.3
2009	101-130	2-4in	6.2	6.8	11	315	1.3	2.0
2009	101-130	4-6in	6.2	6.9	9	254	1.6	2.0
2009	131-160	0-2in	6.1	6.7	28	456	18.3	2.8
2009	131-160	2-4in	6.1	6.8	11	359	1.2	2.7

2009	131-160	4-6in	5.8	6.5	16	268	1.5	2.3
2009	161-190	0-2in	6.0	6.8	27	455	13.8	2.9
2009	161-190	2-4in	6.1	6.7	17	357	1.3	2.5
2009	161-190	4-6in	5.7	6.6	12	274	1.3	2.2
2009	201-230	0-2in	6.1	6.7	31	430	8.2	2.4
2009	201-230	2-4in	6.0	6.7	18	318	1.2	2.2
2009	201-230	4-6in	5.8	6.6	11	258	1.4	2.2
2009	231-260	0-2in	5.8	6.6	37	418	13.5	2.2
2009	231-260	2-4in	5.9	6.7	10	328	1.4	2.4
2009	231-260	4-6in	5.9	6.6	9	254	1.0	2.2
2009	261-290	0-2in	6.1	6.8	31	442	18.5	2.9
2009	261-290	2-4in	6.2	6.7	12	358	1.7	2.5
2009	261-290	4-6in	5.8	6.7	11	279	1.3	2.1
2009	301-330	0-2in	6.0	6.8	34	403	8.2	2.5
2009	301-330	2-4in	6.1	6.8	27	296	0.9	2.1
2009	301-330	4-6in	5.9	6.6	14	288	1.0	2.2
2009	331-360	0-2in	6.2	6.8	26	405	11.7	2.3
2009	331-360	2-4in	6.3	6.9	15	304	1.2	2.2
2009	331-360	4-6in	6.2	6.7	12	227	1.3	2.3
2009	361-390	0-2in	6.3	6.9	23	406	10.7	2.8
2009	361-390	2-4in	6.4	6.9	12	267	1.3	3.8
2009	361-390	4-6in	6.0	6.9	11	207	1.4	2.3
2009	401-430	0-2in	6.3	6.8	27	368	8.4	2.4
2009	401-430	2-4in	6.0	6.8	23	250	1.0	2.4
2009	401-430	4-6in	6.1	6.7	9	204	0.9	2.2
2009	431-460	0-2in	5.9	6.8	37	355	7.7	2.6
2009	431-460	2-4in	6.2	6.8	15	260	1.2	2.3
2009	431-460	4-6in	5.7	6.7	14	221	1.0	2.2
2009	461-490	0-2in	6.0	6.8	43	387	19.0	2.7
2009	461-490	2-4in	6.25	6.8	11	287	1.2	2.2
2009	461-490	4-6in	6.04	6.7	48	236	0.9	2.1

Table A.2. Bulk Density Samples for the Ashland study location

Plot	Depth	Gravimetric Water Content	Volumetric Water Content	Bulk Density
		(g/g)	(g/cm^{-3})	(g/cm^{-3})
162	0-2"	0.24	0.33	1.37
	2-4"	0.22	0.34	1.51
	4-6"	0.24	0.41	1.73
	6-8"	0.26	0.40	1.51
163	0-2"	0.19	0.28	1.51
	2-4"	0.21	0.30	1.41
	4-6"	0.22	0.35	1.58
	6-8"	0.24	0.36	1.52
164	0-2"	0.20	0.20	1.05
	2-4"	0.22	0.34	1.55
	4-6"	0.23	0.40	1.78
	6-8"	0.27	0.44	1.66
166	0-2"	0.18	0.21	1.16
	2-4"	0.18	0.22	1.23
	4-6"	0.20	0.28	1.40
	6-8"	0.21	0.35	1.68
167	0-2"	0.20	0.22	1.08
	2-4"	0.22	0.30	1.39
	4-6"	0.23	0.34	1.47
	6-8"	0.25	0.36	1.45
170	0-2"	0.21	0.26	1.27
	2-4"	0.21	0.30	1.43
	4-6"	0.22	0.32	1.44
	6-8"	0.24	0.41	1.69
173	0-2"	0.16	0.18	1.09
	2-4"	0.19	0.28	1.50
	4-6"	0.20	0.23	1.17
	6-8"	0.22	0.26	1.19
174	0-2"	0.24	0.29	1.21
	2-4"	0.22	0.29	1.33
	4-6"	0.22	0.30	1.36
	6-8"	0.25	0.29	1.16
175	0-2"	0.21	0.23	1.09
	2-4"	0.22	0.26	1.18
	4-6"	0.24	0.37	1.57
	6-8"	0.24	0.36	1.52
176	0-2"	0.22	0.24	1.09
	2-4"	0.21	0.34	1.64
	4-6"	0.21	0.27	1.24
	6-8"	0.23	0.28	1.24
177	0-2"	0.19	0.18	0.92
	2-4"	0.20	0.31	1.53
	4-6"	0.21	0.32	1.57
	6-8"	0.23	0.33	1.42
178	0-2"	0.15	0.16	1.08
	2-4"	0.17	0.20	1.17
	4-6"	0.19	0.25	1.28
	6-8"	0.22	0.31	1.44
181	0-2"	0.21	0.29	1.40
	2-4"	0.22	0.25	1.16
	4-6"	0.24	0.35	1.47
	6-8"	0.24	0.35	1.46
183	0-2"	0.24	0.28	1.16
	2-4"	0.22	0.30	1.34
	4-6"	0.22	0.36	1.65
	6-8"	0.24	0.41	1.70
184	0-2"	0.19	0.22	1.16
	2-4"	0.22	0.25	1.13
	4-6"	0.23	0.35	1.53
	6-8"	0.24	0.35	1.47
186	0-2"	0.24	0.33	1.38
	2-4"	0.22	0.30	1.40
	4-6"	0.22	0.33	1.53
	6-8"	0.25	0.40	1.58
187	0-2"	0.21	0.22	1.05
	2-4"	0.21	0.26	1.22
	4-6"	0.21	0.28	1.33
	6-8"	0.23	0.35	1.54
188	0-2"	0.19	0.18	0.97
	2-4"	0.20	0.34	1.73
	4-6"	0.21	0.24	1.12
	6-8"	0.22	0.35	1.61
202	0-2"	0.24	0.27	1.13
	2-4"	0.23	0.19	0.83
	4-6"	0.23	0.39	1.67
	6-8"	0.24	0.36	1.52
203	0-2"	0.18	0.21	1.15
	2-4"	0.20	0.24	1.21
	4-6"	0.21	0.31	1.45
	6-8"	0.26	0.39	1.54
204	0-2"	0.16	0.22	1.33
	2-4"	0.20	0.22	1.14
	4-6"	0.22	0.26	1.17
	6-8"	0.25	0.39	1.58
206	0-2"	0.24	0.28	1.20
	2-4"	0.23	0.26	1.14
	4-6"	0.22	0.34	1.56
	6-8"	0.23	0.44	1.93
207	0-2"	0.14	0.16	1.21
	2-4"	0.16	0.24	1.47
	4-6"	0.16	0.23	1.43
	6-8"	0.18	0.23	1.28
208	0-2"	0.16	0.16	1.03
	2-4"	0.18	0.25	1.42
	4-6"	0.19	0.25	1.32
	6-8"	0.29	0.46	1.59
213	0-2"	0.16	0.19	1.17
	2-4"	0.18	0.24	1.28
	4-6"	0.21	0.30	1.44
	6-8"	0.23	0.27	1.20

214	0-2"	0.17	0.20	1.16
	2-4"	0.19	0.23	1.18
	4-6"	0.21	0.33	1.59
	6-8"	0.26	0.36	1.41
215	0-2"	0.16	0.20	1.23
	2-4"	0.17	0.22	1.33
	4-6"	0.19	0.24	1.28
	6-8"	0.28	0.43	1.55
216	0-2"	0.20	0.27	1.35
	2-4"	0.20	0.26	1.31
	4-6"	0.21	0.26	1.26
	6-8"	0.23	0.42	1.84
219	0-2"	0.17	0.22	1.34
	2-4"	0.18	0.25	1.35
	4-6"	0.19	0.22	1.18
	6-8"	0.22	0.40	1.78
220	0-2"	0.16	0.22	1.32
	2-4"	0.20	0.24	1.22
	4-6"	0.21	0.29	1.40
	6-8"	0.30	0.48	1.62
221	0-2"	0.23	0.32	1.41
	2-4"	0.22	0.30	1.41
	4-6"	0.22	0.34	1.53
	6-8"	0.22	0.40	1.80
223	0-2"	0.17	0.24	1.39
	2-4"	0.21	0.31	1.49
	4-6"	0.22	0.28	1.29
	6-8"	0.23	0.38	1.68
224	0-2"	0.16	0.21	1.29
	2-4"	0.18	0.23	1.27
	4-6"	0.20	0.24	1.23
	6-8"	0.25	0.41	1.66
	0-2"	0.22	0.28	1.26
	2-4"	0.23	0.31	1.36
	4-6"	0.23	0.37	1.61
	6-8"	0.26	0.48	1.81
229	0-2"	0.21	0.29	1.39
	2-4"	0.22	0.33	1.54
	4-6"	0.22	0.29	1.27
	6-8"	0.28	0.40	1.43
363	0-2"	0.21	0.29	1.36
	2-4"	0.20	0.27	1.37
	4-6"	0.20	0.22	1.12
	6-8"	0.21	0.27	1.28
364	0-2"	0.29	0.41	1.43
	2-4"	0.23	0.34	1.47
	4-6"	0.23	0.30	1.32
	6-8"	0.26	0.30	1.18
365	0-2"	0.21	0.26	1.23
	2-4"	0.16	0.23	1.40
	4-6"	0.17	0.25	1.47
	6-8"	0.21	0.31	1.53
366	0-2"	0.26	0.36	1.36
	2-4"	0.24	0.39	1.65
	4-6"	0.22	0.29	1.35
	6-8"	0.23	0.35	1.53
369	0-2"	0.24	0.38	1.61
	2-4"	0.21	0.35	1.63
	4-6"	0.22	0.34	1.57
	6-8"	0.26	0.43	1.61
370	0-2"	0.26	0.31	1.19
	2-4"	0.23	0.29	1.27
	4-6"	0.23	0.30	1.30
	6-8"	0.28	0.45	1.65
371	0-2"	0.24	0.35	1.46
	2-4"	0.22	0.36	1.65
	4-6"	0.21	0.36	1.68
	6-8"	0.22	0.31	1.38
373	0-2"	0.21	0.28	1.29
	2-4"	0.19	0.24	1.21
	4-6"	0.22	0.36	1.62
	6-8"	0.27	0.35	1.28
375	0-2"	0.19	0.25	1.32
	2-4"	0.16	0.22	1.40
	4-6"	0.16	0.22	1.36
	6-8"	0.20	0.29	1.43
376	0-2"	0.25	0.39	1.58
	2-4"	0.23	0.32	1.36
	4-6"	0.22	0.26	1.17
	6-8"	0.24	0.35	1.49
378	0-2"	0.25	0.36	1.43
	2-4"	0.21	0.30	1.46
	4-6"	0.22	0.35	1.60
	6-8"	0.30	0.50	1.68
379	0-2"	0.28	0.33	1.19
	2-4"	0.24	0.38	1.60
	4-6"	0.23	0.35	1.57
	6-8"	0.28	0.44	1.56
381	0-2"	0.25	0.35	1.41
	2-4"	0.23	0.32	1.39
	4-6"	0.22	0.28	1.25
	6-8"	0.21	0.30	1.44
382	0-2"	0.22	0.32	1.44
	2-4"	0.18	0.24	1.32
	4-6"	0.19	0.27	1.43
	6-8"	0.23	0.36	1.55
384	0-2"	0.26	0.42	1.63
	2-4"	0.23	0.28	1.17
	4-6"	0.24	0.38	1.59
	6-8"	0.28	0.38	1.38
387	0-2"	0.25	0.39	1.59
	2-4"	0.22	0.30	1.34
	4-6"	0.21	0.29	1.35
	6-8"	0.22	0.36	1.60
388	0-2"	0.24	0.28	1.17
	2-4"	0.21	0.24	1.13

	4-6"	0.22	0.28	1.29
	6-8"	0.23	0.41	1.78
389	0-2"	0.22	0.31	1.38
	2-4"	0.20	0.31	1.53
	4-6"	0.20	0.27	1.32
	6-8"	0.28	0.44	1.58
401	0-2"	0.19	0.27	1.38
	2-4"	0.19	0.22	1.16
	4-6"	0.20	0.31	1.57
	6-8"	0.21	0.35	1.69
403	0-2"	0.21	0.31	1.44
	2-4"	0.20	0.28	1.41
	4-6"	0.20	0.28	1.40
	6-8"	0.30	0.41	1.40
405	0-2"	0.22	0.29	1.36
	2-4"	0.17	0.22	1.25
	4-6"	0.20	0.28	1.44
	6-8"	0.29	0.38	1.32
407	0-2"	0.27	0.38	1.42
	2-4"	0.23	0.32	1.37
	4-6"	0.23	0.33	1.43
	6-8"	0.24	0.35	1.44
408	0-2"	0.26	0.38	1.46
	2-4"	0.22	0.33	1.48
	4-6"	0.23	0.33	1.41
	6-8"	0.27	0.40	1.47
409	0-2"	0.25	0.31	1.26
	2-4"	0.23	0.36	1.56
	4-6"	0.24	0.35	1.44
	6-8"	0.30	0.35	1.16
412	0-2"	0.18	0.26	1.44
	2-4"	0.16	0.25	1.52
	4-6"	0.17	0.26	1.53
	6-8"	0.23	0.36	1.57
414	0-2"	0.20	0.30	1.50
	2-4"	0.19	0.26	1.37
	4-6"	0.20	0.30	1.47
	6-8"	0.29	0.37	1.26
415	0-2"	0.21	0.26	1.26
	2-4"	0.17	0.24	1.46
	4-6"	0.19	0.26	1.39
	6-8"	0.26	0.43	1.61
416	0-2"	0.27	0.33	1.22
	2-4"	0.25	0.36	1.42
	4-6"	0.23	0.33	1.40
	6-8"	0.21	0.38	1.76
419	0-2"	0.26	0.38	1.42
	2-4"	0.24	0.29	1.25
	4-6"	0.24	0.30	1.29
	6-8"	0.27	0.43	1.59
420	0-2"	0.18	0.22	1.21
	2-4"	0.19	0.24	1.29
	4-6"	0.20	0.31	1.52
	6-8"	0.25	0.36	1.47
421	0-2"	0.18	0.22	1.24
	2-4"	0.17	0.21	1.21
	4-6"	0.17	0.25	1.45
	6-8"	0.22	0.34	1.55
423	0-2"	0.20	0.28	1.34
	2-4"	0.23	0.32	1.42
	4-6"	0.22	0.36	1.59
	6-8"	0.29	0.41	1.40
424	0-2"	0.28	0.42	1.51
	2-4"	0.24	0.37	1.57
	4-6"	0.23	0.35	1.55
	6-8"	0.27	0.40	1.48
427	0-2"	0.25	0.32	1.27
	2-4"	0.25	0.37	1.50
	4-6"	0.24	0.38	1.56
	6-8"	0.26	0.41	1.59
429	0-2"	0.25	0.40	1.61
	2-4"	0.23	0.37	1.63
	4-6"	0.23	0.34	1.48
	6-8"	0.28	0.42	1.49
430	0-2"	0.25	0.32	1.30
	2-4"	0.22	0.25	1.13
	4-6"	0.22	0.32	1.43
	6-8"	0.23	0.35	1.54

Table A.3. Seeding rates, planting dates, and harvesting dates for cover crops and rotational crops at Ashland, KS.

	2007			2008			2009		
Operation	Date	Rate (Seeds/acre)	Rate (lbs/a)	Date	Rate (Seeds/acre)	Rate (lbs/a)	Date	Rate (Seeds/acre)	Rate (lbs/a)
Planted Soybean	11-Jul	170000		5-Jun	173000		22-May	173000	
Planted Grain Sorghum	11-Jul	30000		9-Jun	77200		21-May	77200	
Planted Winter Wheat	6-Jul		100	3-Nov		90	7-Oct		90
Harvested Soybean	25-Oct			28-Oct			5-Oct		
Harvested Grain Sorghum				30-Oct			8-Nov		
Harvested Winter Wheat				30-Jun			30-Jun		
Planted Summer Cover Crops									
Sorghum-sudangrass	10-Jul		25	11-Jul		25	2-Jul		25
Double-crop Soybean	10-Jul		60	11-Jul		60	2-Jul		60
Late-season Soybean	10-Jul		60	11-Jul		60	2-Jul		60
Terminated Summer Cover Crops									
Sorghum-sudangrass	27-Aug			22-Sep			18-Sep		
Double-crop Soybean	25-Oct			30-Oct			5-Oct		
Late-season Soybean	27-Aug			22-Sep			18-Sep		
Planted Fall Cover Crops									
Canola	27-Aug		10	4-Sep		10	10-Aug		10
Winter pea	27-Aug		27	4-Sep		27	10-Aug		27
Terminated Fall Cover Crops									
Canola				23-Apr			22-Apr		
Winter pea				23-Apr			22-Apr		

Appendix B - Chapter 3

SAS Code

This section of the appendix contains SAS Code from the third chapter, *Effects of Cover Crops on Water Efficiency in No-tillage Crop Rotations*, that might be needed for further research. Data are arranged as they appeared in the chapter and are referenced to figures and tables in which they appear.

Table B.1. SAS Proc MIXED code used to analyze volumetric water content. Analysis used to generate tables 3.2, 3.3, 3.4, 3.5, 3.6, 3.7, and 3.8.

```
data WWVWC;
input year plot block termination $ treatment $ season $ D1 D2 D3 D4 D5 total
seedzone;
cards;
proc print data=WWVWC;
run;
%macro mixloc(y);
proc mixed data=WWVWC;
class year block termination treatment;
model &y = termination treatment termination*treatment/ddfm=satterth;
random block block*treatment;
lsmeans treatment nrate treatment*nrate/pdiff;
%mend mixloc;
%mixloc(D1);
%mixloc(D2);
%mixloc(D3);
%mixloc(D4);
%mixloc(D5);
%mixloc(total);
%mixloc(seedzone);
      run;
```

Table B.2. SAS Proc MIXED code used to analyze winter wheat yields. Analysis used to generate tables 3.10, 3.11, and 3.12.

```
data WW;
input year plot block termination $ season $ treatment $ yield;
cards;
Proc sort;
by treatment;
proc print data=WW;
run;
%macro mixloc(y);
proc mixed data=WW;
class year block termination treatment;
model &y = treatment/ddfm=satterth;
random block;
      contrast 'fall vs spring' treatment 1 1 0 -6 1 1 1 1 0;
      contrast 'all other vs wwf' treatment 1 1 0 1 1 1 1 1 -7;
      contrast 'all other vs ccw' treatment 1 1 -7 1 1 1 1 1 0;
lsmeans treatment/pdiff;
%mend mixloc;
%mixloc(yield);
run;
```

Table B.3. SAS Proc CORR code used to analyze the correlation between winter wheat yields and plant available water. Analysis used to generate table 3.13.

```
data corr;
input year plot block termination $ treatment $ season $ D1 D2 D3 D4 D5 total
seedzone wwyield;
cards;
Proc Print data=corr; title 'raw data';
run;
Proc corr data=corr nosimple;
var d1 d2 d3 d4 d5 total seedzone wwyield;
run;
```

Table B.4. SAS Proc GLM code used to analyze cover crop water use efficiency and biomass. Analysis used to generate tables 3.14, 3.15, 3.16, 3.17, and 3.18.

```
data WUE;
input year plot block treatment $ season $ WUE biomass;
cards;
proc print data=wue;
run;
proc glm data=wue;
class plot treatment season;
model wue biomass = treatment;
contrast 'fall vs spring' treatment -5 -5 7 7 7 7 7 -5 -5 -5 -5 -5;
contrast ' trit vs nontrit' treatment -7 5 -7 5 -7 5 5 -7 5 -7 5 5;
means season/LSD lines;
lsmeans treatment termination/stderr;
run;
```

Table B.5. SAS Proc MIXED code used to analyze precipitation use efficiency during the fallow period. Analysis used to generate tables 3.19, 3.20, 3.21, 3.22, 3.23, 3.24, 3.25, 3.26, 3.27, 3.28, 3.29, 3.30, and 3.31.

```
data PSE;
input year plot block termination $ treatment $ season $ D1 D2 D3 D4 D5
total;
cards;
proc sort;
by treatment;
proc print data=PSE;
run;
%macro mixloc(y);
proc mixed data=PSE;
class year block treatment termination;
model &y = treatment termination treatment*termination/ddfm=satterth;
random block;
contrast 'fall vs spring' treatment 5 5 0 -8 -8 -8 -8 -8 5 5 5 5 5 5 0;
contrast ' all vs wwf' treatment 1 1 0 1 1 1 1 1 1 1 1 1 1 1 -13;
contrast 'all vs cww' treatment 1 1 -13 1 1 1 1 1 1 1 1 1 1 1 0;
lsmeans termination treatment/pdiff;
%mend mixloc;
%mixloc(D1);
%mixloc(D2);
%mixloc(D3);
%mixloc(D4);
%mixloc(D5);
%mixloc(total);
run;
```

Appendix C - Chapter 4

Raw Data

This section of the appendix contains all of the raw data from the fourth chapter, *Comparison of Cove Crops in Kansas and their effect on Subsequent Grain Sorghum Performance*, which might be needed for further research. Data are arranged as they appeared in the chapter and are referenced to figures and tables in which they appear.

Table C.1. Cover crop biomass, nitrogen concentration, nitrogen accumulation and plant population arranged by study location, plot, block, growing season, and cover crop treatment. Data used to generate tables 4.4, 4.6, 4.7, 4.8, 4.9, and 4.11.

Location	Plot	Block	Growing Season	Cover Crop	Biomass	Nitrogen Concentration	Nitrogen Accumulation	Plant Population
					kg ha^{-1}	g kg^{-1}	kg ha^{-1}	plants ha^{-1}
HUTCH	101	1	SUMMER	SH	1171	172.19	20.17	127473
HUTCH	102	1	SUMMER	BW	201	130.48	2.62	525826
HUTCH	103	1	SUMMER	CP	4341	159.90	69.41	270880
HUTCH	104	1	SUMMER	SSPMSHCP	7477	59.00	44.79	2182975
HUTCH	105	1	SUMMER	FSB	1930	159.91	30.87	207144
HUTCH	106	1	SUMMER	SS	12161	24.57	29.88	764838
HUTCH	108	1	SUMMER	LLB	3998	89.34	35.71	111539
HUTCH	109	1	SUMMER	PM	5041	54.84	27.64	987916
HUTCH	110	1	SUMMER	CPPM	5727	71.30	40.74	1593412
HUTCH	201	2	SUMMER	FSB	1643	173.20	28.45	223078
HUTCH	202	2	SUMMER	BW	201	144.08	2.90	350551
HUTCH	203	2	SUMMER	SS	10220	41.97	42.89	812640
HUTCH	205	2	SUMMER	SSPMSHCP	5789	64.50	37.32	2437921
HUTCH	206	2	SUMMER	SH	5282	116.46	61.52	302748
HUTCH	207	2	SUMMER	CP	7983	64.20	51.21	1513742
HUTCH	208	2	SUMMER	LLB	1639	91.41	14.98	111539
HUTCH	209	2	SUMMER	PM	1110	64.75	7.19	239012
HUTCH	210	2	SUMMER	CPPM	4417	136.08	60.11	191209
HUTCH	301	3	SUMMER	BW	67	118.50	0.79	478024
HUTCH	302	3	SUMMER	FSB	4074	155.53	63.36	254946
HUTCH	303	3	SUMMER	PM	3577	84.69	30.29	1242862
HUTCH	304	3	SUMMER	SSPMSHCP	6853	51.60	35.33	2374185
HUTCH	306	3	SUMMER	SS	11987	34.51	41.37	621431
HUTCH	307	3	SUMMER	LLB	1773	92.01	16.31	207144
HUTCH	308	3	SUMMER	SH	1350	120.48	16.26	254946
HUTCH	309	3	SUMMER	CP	5448	120.08	65.42	191209
HUTCH	310	3	SUMMER	CPPM	5246	59.10	30.92	1386269
HUTCH	401	4	SUMMER	SS	11282	34.13	38.51	812640
HUTCH	402	4	SUMMER	FSB	3245	213.00	69.11	318682
HUTCH	403	4	SUMMER	CP	4507	149.69	67.46	270880
HUTCH	404	4	SUMMER	CPPM	5469	71.33	39.03	1736820
HUTCH	405	4	SUMMER	SH	338	131.95	4.46	79671
HUTCH	406	4	SUMMER	BW	53	58.85	0.31	844509
HUTCH	407	4	SUMMER	PM	5471	74.91	40.98	1386269
HUTCH	409	4	SUMMER	SSPMSHCP	7553	47.80	36.11	1625281
HUTCH	410	4	SUMMER	LLB	6519	108.00	70.40	1226928

MANHATTAN-08	101	1	WINTER	YSCWT	3344	169.88	56.80	2151068
MANHATTAN-08	102	1	WINTER	O	2378	172.00	40.90	4381808
MANHATTAN-08	103	1	WINTER	WPWT	4048	172.82	69.96	1959866
MANHATTAN-08	104	1	WINTER	YSC	805	281.00	22.63	4302137
MANHATTAN-08	105	1	WINTER	AF	738	217.00	16.01	2724688
MANHATTAN-08	106	1	WINTER	B	2671	154.00	41.13	2406011
MANHATTAN-08	107	1	WINTER	WT	3635	158.00	57.44	3250504
MANHATTAN-08	108	1	WINTER	AR	1200	236.00	28.32	2836220
MANHATTAN-08	109	1	WINTER	C	2710	336.00	91.07	3011498
MANHATTAN-08	110	1	WINTER	WP	687	277.00	19.04	366481
MANHATTAN-08	111	1	SUMMER	SH	1954	168.85	32.99	462081
MANHATTAN-08	112	1	SUMMER	BW	1325	117.40	15.56	2310406
MANHATTAN-08	113	1	SUMMER	CP	1827	187.46	34.25	207140
MANHATTAN-08	114	1	SUMMER	SSPMSHCP	5503	69.27	38.12	1736788
MANHATTAN-08	115	1	SUMMER	FSB	2693	246.26	66.31	701089
MANHATTAN-08	116	1	SUMMER	SS	4212	75.20	31.67	3330172
MANHATTAN-08	118	1	SUMMER	LLB	2177	160.16	34.86	207140
MANHATTAN-08	119	1	SUMMER	PM	4621	104.65	48.35	4843887
MANHATTAN-08	120	1	SUMMER	CPPM	6872	92.28	63.42	2039531
MANHATTAN-08	201	2	SUMMER	FSB	2114	203.01	42.92	924163
MANHATTAN-08	202	2	SUMMER	BW	1138	91.87	10.46	2374142
MANHATTAN-08	203	2	SUMMER	SS	6269	58.67	36.78	3123032
MANHATTAN-08	205	2	SUMMER	SSPMSHCP	8764	95.54	83.73	1609318
MANHATTAN-08	206	2	SUMMER	SH	2720	163.16	44.39	509883
MANHATTAN-08	207	2	SUMMER	CPPM	3336	108.74	36.28	2007664
MANHATTAN-08	208	2	SUMMER	LLB	742	163.65	12.14	286809
MANHATTAN-08	209	2	SUMMER	PM	5306	69.17	36.70	2708752
MANHATTAN-08	210	2	SUMMER	CP	2117	253.22	53.62	239008
MANHATTAN-08	211	2	WINTER	C	1330	289.00	38.43	3696650
MANHATTAN-08	212	2	WINTER	WP	684	274.00	18.75	398348
MANHATTAN-08	213	2	WINTER	B	2534	168.00	42.57	2533480
MANHATTAN-08	214	2	WINTER	WT	5050	143.00	72.22	2342277
MANHATTAN-08	215	2	WINTER	AR	1662	211.00	35.06	2485676
MANHATTAN-08	216	2	WINTER	YSCWT	2942	168.05	49.44	3154903
MANHATTAN-08	217	2	WINTER	AF	519	284.00	14.74	2198872
MANHATTAN-08	218	2	WINTER	O	2920	165.00	48.18	4302137
MANHATTAN-08	219	2	WINTER	WPWT	3887	176.63	68.66	1816461
MANHATTAN-08	220	2	WINTER	YSC	509	278.00	14.15	5736180
MANHATTAN-08	301	3	SUMMER	BW	1390	119.36	16.59	2358208
MANHATTAN-08	302	3	SUMMER	FSB	2060	255.19	52.58	653287
MANHATTAN-08	303	3	SUMMER	PM	2588	75.42	19.52	3616981
MANHATTAN-08	304	3	SUMMER	SSPMSHCP	7355	61.72	45.39	1704921
MANHATTAN-08	306	3	SUMMER	SS	5473	39.35	21.54	2565348
MANHATTAN-08	307	3	SUMMER	LLB	531	129.84	6.90	334611
MANHATTAN-08	308	3	SUMMER	SH	1510	162.45	24.53	525817
MANHATTAN-08	309	3	SUMMER	CP	805	216.60	17.43	382412
MANHATTAN-08	310	3	SUMMER	CPPM	2837	84.83	24.07	2071398
MANHATTAN-08	311	3	WINTER	WPWT	1927	183.88	35.43	1848322
MANHATTAN-08	312	3	WINTER	O	2371	143.00	33.90	3601049
MANHATTAN-08	313	3	WINTER	C	1380	281.00	38.79	3537314
MANHATTAN-08	314	3	WINTER	AF	539	279.00	15.04	2963695
MANHATTAN-08	315	3	WINTER	AR	925	196.00	18.13	4270270
MANHATTAN-08	316	3	WINTER	YSCWT	1612	197.23	31.79	4126865
MANHATTAN-08	317	3	WINTER	YSC	656	407.00	26.68	4875757
MANHATTAN-08	318	3	WINTER	WP	555	309.00	17.15	382411
MANHATTAN-08	319	3	WINTER	B	1729	149.00	25.76	3170834
MANHATTAN-08	320	3	WINTER	WT	3881	167.00	64.81	3601049
MANHATTAN-08	401	4	WINTER	YSC	717	378.00	27.10	5353769

MANHATTAN-08	402	4	WINTER	C	1720	224.00	38.53	5943320
MANHATTAN-08	403	4	WINTER	YSCWT	3129	183.41	57.38	5098832
MANHATTAN-08	404	4	WINTER	AF	699	245.00	17.12	4668611
MANHATTAN-08	405	4	WINTER	WP	827	407.00	33.65	302740
MANHATTAN-08	406	4	WINTER	O	2486	109.00	27.10	4525213
MANHATTAN-08	407	4	WINTER	AR	1049	176.00	18.47	1832391
MANHATTAN-08	408	4	WINTER	WT	3057	165.00	50.45	2358208
MANHATTAN-08	409	4	WINTER	WPWT	3460	179.83	62.23	2214803
MANHATTAN-08	410	4	WINTER	B	4326	155.00	67.06	4827953
MANHATTAN-08	411	4	SUMMER	SS	4992	68.14	34.01	2294473
MANHATTAN-08	412	4	SUMMER	FSB	2067	254.58	52.62	637354
MANHATTAN-08	413	4	SUMMER	CP	1084	255.55	27.70	366478
MANHATTAN-08	414	4	SUMMER	CPPM	5766	44.49	25.65	2135132
MANHATTAN-08	415	4	SUMMER	SH	2415	137.70	33.25	557684
MANHATTAN-08	416	4	SUMMER	BW	1716	113.11	19.41	2469745
MANHATTAN-08	417	4	SUMMER	PM	7485	150.96	113.00	3632915
MANHATTAN-08	419	4	SUMMER	SSPMSHCP	8610	89.91	77.41	1641183
MANHATTAN-08	420	4	SUMMER	LLB	384	144.36	5.54	302743
MANHATTAN-09	101	1	SUMMER	SH	5299	150.19	79.58	701101
MANHATTAN-09	102	1	SUMMER	BW	2434	142.79	34.75	2103304
MANHATTAN-09	103	1	SUMMER	CP	3500	174.42	61.05	366485
MANHATTAN-09	104	1	SUMMER	SSPMSHCP	7337	99.93	73.32	3999465
MANHATTAN-09	105	1	SUMMER	FSB	4957	226.37	112.22	812640
MANHATTAN-09	106	1	SUMMER	SS	7151	52.56	37.58	1067586
MANHATTAN-09	108	1	SUMMER	LLB	1607	106.04	17.04	350551
MANHATTAN-09	109	1	SUMMER	PM	5885	101.30	59.62	3728585
MANHATTAN-09	110	1	SUMMER	CPPM	4681	110.05	51.52	4142872
MANHATTAN-09	201	2	SUMMER	FSB	4853	232.44	112.80	971982
MANHATTAN-09	202	2	SUMMER	BW	1335	132.98	17.75	1896161
MANHATTAN-09	203	2	SUMMER	SS	8755	48.84	42.76	1497808
MANHATTAN-09	205	2	SUMMER	SSPMSHCP	7556	162.47	122.77	6054967
MANHATTAN-09	206	2	SUMMER	SH	4256	172.55	73.44	621431
MANHATTAN-09	207	2	SUMMER	CPPM	5835	113.24	66.07	3011550
MANHATTAN-09	208	2	SUMMER	LLB	1931	103.45	19.98	430221
MANHATTAN-09	209	2	SUMMER	PM	5111	65.19	33.32	3139023
MANHATTAN-09	210	2	SUMMER	CP	3294	172.37	56.78	557694
MANHATTAN-09	301	3	SUMMER	BW	1645	107.29	17.65	2278580
MANHATTAN-09	302	3	SUMMER	FSB	4260	217.98	92.85	908245
MANHATTAN-09	303	3	SUMMER	PM	4195	81.81	34.32	3139023
MANHATTAN-09	304	3	SUMMER	SSPMSHCP	5620	141.15	79.33	5863758
MANHATTAN-09	306	3	SUMMER	SS	5741	41.22	23.66	1800556
MANHATTAN-09	307	3	SUMMER	LLB	2135	134.75	28.77	223078
MANHATTAN-09	308	3	SUMMER	SH	5815	174.14	101.27	350551
MANHATTAN-09	309	3	SUMMER	CP	3108	197.46	61.38	557694
MANHATTAN-09	310	3	SUMMER	CPPM	5106	158.74	81.04	3234627

Table C.2. Double crop soybean yield, grain nitrogen concentration, and plant population arranged by study location, plot, and block. Data used to generate table 4.10.

Location	Plot	Block	Yield	Grain Nitrogen Concentration	Plant Population
			kg ha^{-1}	g kg^{-1}	plant ha^{-1}
Hutchinson	107	1	531	54.72	116160
Hutchinson	204	2	208	54.88	64533
Hutchinson	305	3	188	54.88	83894
Hutchinson	408	4	101	54.88	109706
Manhattan 08	117	1	780	57.36	264580
Manhattan 08	204	2	1063	58.69	303301
Manhattan 08	305	3	956	58.40	342020
Manhattan 08	418	4	902	58.60	322659
Manhattan 09	107	1	1296	58.40	271040
Manhattan 09	204	2	1403	59.68	367840
Manhattan 09	305	3	1087	59.20	425921

Table C.3. Manhattan 2008 grain sorghum yield, flag leaf N concentration, grain N concentration, seed weight, head count, plant height, stand count, bloom dates, GreenSeeker NDVI, and CropCircle NDVI arranged by plot, block, growing season and cover crop treatment. Data used to generate table 4.12 and figures 4.1, 4.2, 4.3, 4.4, and 4.5.

Location	Plot	Block	Season	Cover Crop Treatment	Grain Yield	Flag Leaf Nitrogen Concentration	Grain Nitrogen Concentration	Seed Weight	Head Count	Plant Height	Stand Count	Bloom	GreenSeeker NDVI	CropCircle NDVI
					kg ha^{-1}	g kg^{-1}	g kg^{-1}	g seed^{-1}	head ha^{-1}	cm	plant ha^{-1}	days after planting		
Manhattan 08	101	1	WINTER	YSCWT	2666	15.82	11.45	0.032	96083	128	387200	92	0.71	0.68
Manhattan 08	102	1	WINTER	O	4317	19.22	9.72	0.030	106121	140	400107	72	0.76	0.76
Manhattan 08	103	1	WINTER	WPWT	2623	15.81	12.71	0.033	104687	131	406560	92	0.66	0.65
Manhattan 08	104	1	WINTER	YSC	5201	18.65	10.24	0.032	105404	134	413013	83	0.76	0.75
Manhattan 08	105	1	WINTER	AF	3145	15.88	11.19	0.032	89630	134	322667	90	0.73	0.70
Manhattan 08	106	1	WINTER	B	2703	14.40	11.48	0.029	99668	128	374293	92	0.72	0.68
Manhattan 08	107	1	WINTER	WT	1862	14.78	13.20	0.033	81025	125	367840	91	0.65	0.61
Manhattan 08	108	1	WINTER	AR	4213	17.38	10.60	0.032	93215	134	329120	90	0.73	0.71
Manhattan 08	109	1	WINTER	C	6540	19.60	10.15	0.032	107556	140	380747	81	0.78	0.77
Manhattan 08	110	1	WINTER	WP	4447	16.81	11.17	0.030	91064	131	367840	84	0.73	0.71
Manhattan 08	111	1	SUMMER	SH	5444	21.82	10.26	0.031	102536	140	361387	81	0.74	0.74
Manhattan 08	112	1	SUMMER	BW	4070	15.18	10.00	0.031	91781	134	329120	91	0.73	0.73
Manhattan 08	113	1	SUMMER	CP	4822	19.49	10.07	0.031	98951	131	380747	83	0.74	0.74
Manhattan 08	114	1	SUMMER	SSPMSHCP	3694	16.77	11.20	0.033	88196	128	342027	90	0.67	0.66
Manhattan 08	115	1	SUMMER	FSB	4464	18.55	10.48	0.028	98234	131	348480	90	0.75	0.73
Manhattan 08	116	1	SUMMER	SS	3463	15.79	11.32	0.030	81025	131	329120	91	0.69	0.67
Manhattan 08	117	1	SUMMER	DBLSB	5910	17.97	11.06	0.030	89630	146	309760	82	0.78	0.77
Manhattan 08	118	1	SUMMER	LLB	4668	21.02	10.43	0.030	102536	128	406560	81	0.74	0.73
Manhattan 08	119	1	SUMMER	PM	4069	16.23	10.58	0.032	91064	131	342027	85	0.74	0.72
Manhattan 08	120	1	SUMMER	CPPM	4527	16.71	11.04	0.031	90347	128	367840	90	0.72	0.73
Manhattan 08	201	2	SUMMER	FSB	5247	19.84	11.05	0.031	98951	143	400107	81	0.78	0.78
Manhattan 08	202	2	SUMMER	BW	4069	18.84	12.50	0.030	88913	134	367840	81	0.71	0.70
Manhattan 08	203	2	SUMMER	SS	3262	15.88	11.82	0.030	90347	128	354933	92	0.65	0.62
Manhattan 08	204	2	SUMMER	DBLSB	6235	21.99	11.36	0.031	96083	140	374293	81	0.77	0.77
Manhattan 08	205	2	SUMMER	SSPMSHCP	4454	19.25	10.75	0.031	91781	131	367840	84	0.72	0.71
Manhattan 08	206	2	SUMMER	SH	4674	19.89	10.01	0.028	89630	134	329120	81	0.74	0.74
Manhattan 08	207	2	SUMMER	CPPM	3895	15.73	10.78	0.032	92498	131	419467	91	0.71	0.71
Manhattan 08	208	2	SUMMER	LLB	4377	18.03	10.18	0.031	92498	131	354933	83	0.73	0.73
Manhattan 08	209	2	SUMMER	PM	4262	13.05	10.79	0.034	93932	134	374293	90	0.71	0.71
Manhattan 08	210	2	SUMMER	CP	5486	20.59	10.19	0.032	96083	137	400107	81	0.76	0.75
Manhattan 08	211	2	WINTER	C	5095	17.49	9.45	0.029	104687	140	387200	81	0.75	0.76
Manhattan 08	212	2	WINTER	WP	4223	19.15	10.05	0.031	89630	137	342027	84	0.73	0.72

Manhattan 08	213	2	WINTER	B	3618	14.82	10.81	0.032	96800	131	361387	91	0.69	0.69
Manhattan 08	214	2	WINTER	WT	2317	17.00	12.27	0.033	89630	128	342027	92	0.64	0.62
Manhattan 08	215	2	WINTER	AR	3133	16.50	11.26	0.034	85327	128	322667	90	0.67	0.67
Manhattan 08	216	2	WINTER	YSCWT	1895	14.79	11.13	0.031	86044	128	380747	92	0.67	0.67
Manhattan 08	217	2	WINTER	AF	4747	18.52	10.54	0.029	88196	137	354933	83	0.73	0.73
Manhattan 08	218	2	WINTER	O	4267	17.59	9.94	0.029	81025	128	354933	84	0.75	0.75
Manhattan 08	219	2	WINTER	WPWT	2538	16.18	11.77	0.028	82459	128	361387	90	0.65	0.64
Manhattan 08	220	2	WINTER	YSC	4764	18.52	9.96	0.029	78157	131	290400	83	0.75	0.75
Manhattan 08	301	3	SUMMER	BW	2996	14.61	9.33	0.030	85327	131	354933	90	0.70	0.68
Manhattan 08	302	3	SUMMER	FSB	4583	21.41	9.61	0.029	95366	140	387200	81	0.74	0.74
Manhattan 08	303	3	SUMMER	PM	4050	14.97	10.31	0.029	95366	131	380747	91	0.71	0.71
Manhattan 08	304	3	SUMMER	SSPMSHCP	4301	16.68	10.69	0.031	9321	128	342027	90	0.71	0.71
Manhattan 08	305	3	SUMMER	DBLSB	6182	20.58	11.14	0.032	86761	146	342027	81	0.75	0.76
Manhattan 08	306	3	SUMMER	SS	2018	15.79	10.64	0.030	80308	125	329120	91	0.64	0.61
Manhattan 08	307	3	SUMMER	LLB	4426	19.12	9.87	0.028	82459	131	374293	84	0.72	0.71
Manhattan 08	308	3	SUMMER	SH	4572	19.46	9.91	0.029	87479	134	354933	84	0.76	0.75
Manhattan 08	309	3	SUMMER	CP	5080	20.26	10.31	0.029	96800	134	374293	84	0.77	0.77
Manhattan 08	310	3	SUMMER	CPPM	4241	19.58	10.50	0.029	90347	134	296853	83	0.74	0.74
Manhattan 08	311	3	WINTER	WPWT	1751	16.17	10.82	0.030	74572	128	290400	92	0.62	0.60
Manhattan 08	312	3	WINTER	O	3890	14.66	9.21	0.029	85327	134	316213	90	0.71	0.71
Manhattan 08	313	3	WINTER	C	5351	22.47	9.83	0.028	96800	146	322667	81	0.76	0.76
Manhattan 08	314	3	WINTER	AF	4236	16.41	10.14	0.033	86044	134	309760	90	0.71	0.71
Manhattan 08	315	3	WINTER	AR	3362	16.84	10.58	0.031	90347	131	271040	90	0.68	0.68
Manhattan 08	316	3	WINTER	YSCWT	2144	15.40	10.51	0.031	102536	131	354933	91	0.66	0.66
Manhattan 08	317	3	WINTER	YSC	4142	19.96	9.63	0.030	78874	140	309760	81	0.72	0.73
Manhattan 08	318	3	WINTER	WP	4205	18.85	9.47	0.028	74572	137	342027	83	0.72	0.71
Manhattan 08	319	3	WINTER	B	3137	18.36	10.95	0.034	75289	131	322667	90	0.67	0.66
Manhattan 08	320	3	WINTER	WT	2216	16.84	12.12	0.034	88196	128	393653	92	0.65	0.65
Manhattan 08	401	4	WINTER	YSC	3463	16.75	9.13	0.030	99668	134	374293	84	0.71	0.70
Manhattan 08	402	4	WINTER	C	4128	18.64	10.11	0.030	88196	140	329120	81	0.74	0.74
Manhattan 08	403	4	WINTER	YSCWT	3082	16.96	11.16	0.031	85327	134	290400	91	0.69	0.69
Manhattan 08	404	4	WINTER	AF	3194	18.11	10.91	0.029	88196	137	264587	83	0.70	0.71
Manhattan 08	405	4	WINTER	WP	4365	19.81	10.23	0.029	90347	137	309760	81	0.75	0.75
Manhattan 08	406	4	WINTER	O	2115	14.86	9.64	0.029	70270	131	303307	91	0.64	0.64
Manhattan 08	407	4	WINTER	AR	2576	14.82	10.93	0.034	76006	134	251680	92	0.64	0.64
Manhattan 08	408	4	WINTER	WT	3938	16.58	10.95	0.029	74572	140	290400	90	0.69	0.70
Manhattan 08	409	4	WINTER	WPWT	4312	15.79	10.44	0.032	87479	140	322667	92	0.71	0.71
Manhattan 08	410	4	WINTER	B	3371	16.90	11.93	0.029	88913	134	374293	90	0.70	0.71
Manhattan 08	411	4	SUMMER	SS	1923	15.66	11.71	0.029	94649	134	322667	92	0.60	0.59
Manhattan 08	412	4	SUMMER	FSB	4222	16.87	11.09	0.032	91064	143	329120	81	0.75	0.75
Manhattan 08	413	4	SUMMER	CP	5288	19.67	10.82	0.032	99668	155	380747	81	0.76	0.77
Manhattan 08	414	4	SUMMER	CPPM	5279	21.65	11.40	0.030	91781	149	380747	81	0.76	0.77

Manhattan 08	415	4	SUMMER	SH	5037	17.12	9.75	0.028	96083	143	406560	82	0.77	0.78
Manhattan 08	416	4	SUMMER	BW	2358	15.99	11.64	0.031	78874	134	354933	91	0.66	0.69
Manhattan 08	417	4	SUMMER	PM	3239	15.17	9.91	0.030	86761	137	380747	90	0.70	0.71
Manhattan 08	418	4	SUMMER	DBLSB	5972	20.57	11.82	0.028	93932	155	342027	81	0.78	0.79
Manhattan 08	419	4	SUMMER	SSPMSHCP	5814	19.71	11.28	0.029	86761	146	271040	81	0.77	0.76
Manhattan 08	420	4	SUMMER	LLB	5279	18.70	10.23	0.029	97517	146	361387	81	0.75	0.77