IMPACT OF COVER CROPS AND NITROGEN APPLICATION ON NITROUS OXIDE FLUXES AND GRAIN YIELD OF SORGHUM AND MAIZE

by

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B.S., University of Ghana, Ghana, 2007
M.S., Kansas State University, Manhattan, Kansas, USA, 2012

AN ABSTRACT OF A DISSERTATION

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Abstract

Leguminous cover crops systems have been envisaged as a critical component of sustainable agriculture due to their potential to increase soil productivity through cycling of carbon (C) and nitrogen (N) in agricultural systems. The objectives of this study were to evaluate the performance of leguminous summer cover crops; cowpea [*Vigna unguiculata* (L.) Walp.], pigeon pea [*Cajanus cajan* (L.) Millsp], sunn hemp (*Crotalaria juncea* L.) and double-cropped grain crops; grain sorghum [*Sorghum bicolor* (L.) Moench] and soybean [*Glycine max* (L.) Merr.] after winter wheat (*Triticum aestivum* L.) and to determine the effects of these crops and varying N rates in the cropping system on nitrous oxide (N_2O) emissions, growth and yield of succeeding grain sorghum and maize (*Zea mays* L.) crop, soil aggregation, aggregate-associated C, and N. Field and laboratory studies were conducted for two years. The cover crops and double-cropped grain crops were planted immediately after winter wheat harvest. The cover crops were terminated at the beginning of flowering. Nitrogen fertilizer (urea 46% N) rates of 0, 45, 90, 135, and 180 kg N ha^{-1} were applied to grain sorghum or maize in fallow plots. Pigeon pea and grain sorghum had more C accumulation than cowpea, sunn hemp and double-cropped soybean. Pigeon pea and cowpea had more N uptake than sunn hemp and the double-cropped grain crops. Fallow with N fertilizer application produced significantly greater N_2O emissions than all the cover crop systems. Nitrous oxide emissions were relatively similar in the various cover crop systems and fallow with 0 kg N ha^{-1}. Grain yield of sorghum and maize in all the cover crops and double cropped soybean systems was similar to that in the fallow with 45 kg N ha^{-1}. Both grain sorghum and maize in the double-cropped soybean system and fallow with 90 kg N ha^{-1} or 135 kg N ha^{-1} gave profitable economic net returns over the years. The double-cropped grain sorghum system increased aggregate-associated C and whole soil total C, and all the cover crop and the double-cropped soybean systems increased aggregate-associated N and soil N pools. Inclusion of leguminous cover crops without N fertilizer application reduced N_2O emissions and provided additional C accumulation and N uptake, contributing to increased grain yield of the following cereal grain crop.

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Dedication

To my Mum and Dad

CHAPTER 1 - LITERATURE REVIEW

General Introduction

World food production is largely dependent on the use of chemical fertilizers, mainly nitrogen (N), phosphorus (P) and potassium (K). With an increasing world population, especially in developing countries, future yield increases will even be more dependent on fertilizer nutrients because the increased production has to come from land currently in cultivation, given the limited potential for any significant expansion in cultivable land. The application of mineral fertilizers needed to obtain higher yields should complement nutrients available from other sources and match the needs of individual crop varieties. The doubling of agricultural food production worldwide is partly attributable to a sevenfold increase in the use of N fertilizers (Tilman et al., 2001). However, the increase use of synthetic N fertilizer has detrimental effects on the environment such as pollution of ground water and N_2O emissions from the soil. For instance, N_2O emissions that has inherent warming effects on the atmosphere will increase with subsequent effects on climate, especially an increase following severe climatic events such as drought and rising temperatures (Wuebbles, 2009).

Exploiting alternative cropping systems in N demand and efficiency has been proposed as a possible alternative for reducing the cost and reliance upon fertilizer N. Included in such proposals has been the use of leguminous cover crops that have the potential to fix atmospheric N. Leguminous cover crops can increase the input and cycling of carbon (C), N, and other nutrients in agricultural systems. Long-term accumulation of soil organic C and N improves the physical (soil structure through soil aggregation) and biological properties of soil, which can increase the productivity, water and nutrient use efficiencies of crops. The most sustainable agricultural systems will be achieved by maximizing long-term cover crop nutrient and C inputs and retention without creating short-term water and nutrient deficits.

Conservation Agriculture

Worldwide there are rising concerns about loss of soil productivity and the broader environmental implications of conventional agricultural. These concerns are coming mainly because of the aftermath of repeatedly tilling the soil, either by the use of plough, disc harrow or hoe. This has prompted some governments and farmers to search for alternative production methods that can maintain soil structure and productivity. “Conservation agriculture (CA) aims to conserve, improve and make more efficient use of natural resources through integrated management of available soil, water and biological resources combined with external inputs. It contributes to environmental conservation as well as to enhanced and sustained agricultural production. It can also be referred to as resource efficient or resource effective agriculture” (FAO, 2006). Conservation agriculture (CA) is becoming the obvious and increasingly popular alternatives due to the principles it is based upon (Fowler and Rockstrom, 2001). Conservation agriculture is more than just tilling the soil and then doing everything else the same. It is a holistic system with interactions among households, crops, and livestock because rotations and residues have many uses within households. The result is a sustainable agriculture system that meets the needs of farmers (Hobbs and Gupta, 2004). It is based on three principles; minimum soil disturbance, continuous soil cover and crop rotation.

Principle of Minimum Soil Disturbance

Agriculture impacts the environment in many ways, including impacts on global warming through the production of ‘greenhouse gases’ such as CO_2. In 2012, greenhouse gas emissions from agriculture accounted for approximately 9% of total U.S. greenhouse gas emissions (U.S.

EPA/OAP, 2014). However, agriculture also has a potential of acting as a CO_2 sink by sequestering it from the atmosphere in the form of soil carbon if proper practices are employed in production. A study conducted in the USA concluded that intensive tillage using moldboard plough results in major carbon loses immediately after tillage, and also found that the rate of carbon oxidation was reduced when the extent, frequency and magnitude of mechanical disturbance of the soil caused by tillage was minimized (Baker et al., 2007). Zero-tillage combined with permanent soil cover has been shown to result in a build-up of organic carbon in the surface layers (Lal, 2005). No-tillage minimizes SOM losses and is a promising strategy to maintain or even increase soil C and N stocks (Bayer et al., 2000).

Minimum soil disturbance also reduces soil erosion, because the soil is not loosened as is the case with conventional tillage. In conventional tillage the soil is continuously disturbed, making it easy to be carried by runoff leading to loss of nutrients. Reduced erosion brought by CA also benefits the environment in the sense that it enhances water conservation, because continuous vertical macro-pores are not destroyed and remain as drainage channels for rainwater into the soil.

A number of experiments in semi-arid and dry sub-humid locations in East and Southern Africa have demonstrated that minimum soil disturbance/minimum tillage practices reduce the risk of crop failure as they increase water conservation and crop yields. These positive results are attributed to water harvesting effects of minimum tillage practices (Hobbs et al., 2007).

Principle of Continuous Soil Cover

Crop residues result when a previous crop is left anchored or loose after harvest or when a cover crop (legume or non- legume) is grown and killed or cut to provide mulch. Externally applied mulch in the form of composts and manures also can be applied, although the economics of transport of this bulky material to the field may restrict its use to higher-value crops like vegetables (Hobbs et al., 2007). Kumar and Goh (2000) reported that crop residues of cultivated crops are a significant factor for crop production through their effects on soil physical, chemical and biological functions as well as water and soil quality.

The energy of raindrops falling on a bare soil result in destruction of soil aggregates, clogging of soil pores and rapid reduction of water infiltration with resulting runoff and soil erosion. Mulch intercepts this energy and protects the surface soil from soil aggregate destruction, which enhances the infiltration of water and reduces the loss of soil by erosion (Dormaar and Carefoot, 1996).

Moreover, surface mulch helps reduce water losses from the soil by evaporation and also helps moderate soil temperature. This promotes biological activity and enhances N mineralization, especially in the surface layers (Hatfield and Pruegar, 1996). In Brazil, Madari et al. (2005) found that no tillage (NT) with residue cover had greater aggregate stability, larger aggregate size values and more total organic carbon in soil aggregates than with tillage. Ground cover also promotes an increase in biological diversity not only below ground but also above ground. Kendall et al. (1995) reported that the number of beneficial insects was higher where there was ground cover and mulch and these help kept insect pests in check.

Cover crops and the resulting mulch or previous crop residues help reduce weed infestation through competition reducing available light required for germination. There is also evidence of allelopathic properties of cereal residues in respect to inhibiting surface weed seed germination (Jung et al., 2004). Cover crop residues contribute to the accumulation of organic matter in the surface soil horizon (Madari et al., 2005; Riley et al., 2005), and this effect is increased when combined with NT. Mulch also helps with recycling of nutrients, especially when legume cover crops are used, through the association with below-ground biological agents and by providing food for microbial populations.

Principle of Crop Rotation

Crop rotation provides an opportunity for nutrient cycling as roots at different depths are able to obtain nutrients from multiple soil layers. Nutrients that have been lost from the upper layers through leaching and are no longer available to short-rooted crops can be brought back to the surface by using deep-rooted crops in rotation. A diversity of crops in rotation enhances a diverse flora and fauna such as fungi and bacteria, which are also necessary for transformation of organic materials into available nutrients during decomposition. Other means of improving soil fertility and nutrient cycling are being encouraged. Intercropping cereals with legumes is encouraged because the legumes fix N (one of the macro-nutrients) from the atmosphere to further improve soil fertility.

Crop rotation also plays a phytosanitary role as it prevents the carryover of crop-specific pests and diseases from one season to another through residues. The diversity of crops achieved through crop rotation is also important as a climate change adaptation strategy because it reduces the susceptibility to unforeseen climatic events such as drought, floods and other biophysical occurrences such as pest outbreaks that might lead to crop failure (FAO, 2006).

Nitrogen Contribution of Summer Cover Crops to Soil Fertility

The future sustainability of crop production will depend greatly upon improvements in the soil resource base through its effective management in an environmentally benign manner (Singh et al., 2005). Use of summer cover crops in farming systems is one such management practice to improve soil health, reduce environmental pollution, and improve crop yields (Fageria et al., 2005). Cover crops can be leguminous and non-leguminous. The use of legume cover crops in improving agricultural sustainability is well recognized (Fageria et al., 2005).

Legume benefits to subsequent crops are attributed to the addition of N and non-N rotation factors such as disease and weed control, and to improved soil water holding capacity (Fageria et al., 2005). Legumes may also be used to reduce C and N losses from agricultural systems and increase soil C sequestration (Drinkwater et al., 1998). The main functions or use of cover crops in a cropping system are as N supplier or source, soil builder, erosion controller, subsoil loosened, weed controller and pest fighter (Clark, 2007). Appropriate cover crop species should be identified that provide satisfactory biomass production to cover the soil surface area and bring other benefits to improve yield of succeeding cash crops or plantation crops.

Pigeon pea

Pigeon pea is considered to have greater N fixation rates than other legume species (Chikowo et al., 2004). Nitrogen fixation rates in an African study were estimated to range from 40-97 kg ha^{-1} (Mafongoya et al., 2006). The plant can fix about 70 kg ha^{-1} atmospheric N per season by symbiosis until the mid-pod-fill stage. In Florida, N fixation from pigeon pea was estimated to be 250 kg N ha^{-1} (Reddy et al., 1986a). Other research from Africa and India shows N contributions from pigeon pea to the following crop in the rotation to be in the range of 40-60 Kg ha^{-1} of N (Odeny, 2007; Chauhan et al., 2004).

Estimates indicate that leaf-drop can contribute up to 40 kg $ha^{-1}$of N to the system (Mafongoya et al., 2006). Dry matter top growth production is about 6.3 tons ha^{-1}, contributing about 25 kg of N per ton of dry matter. Pigeon pea produces more N from plant biomass per unit area of land than many other legumes.

Pigeon pea offers the benefits of improving long-term soil quality and fertility when used as green manure (Onim et al., 1990), cover crop (Bodner et al., 2007), or alley crop (Mapa and Gunasena, 1995). Maize yields have been increased by 32.1% in West Africa by using pigeon pea as a cover crop (Sogbedji et al., 2006).

Rotation systems with pigeon pea not only increased the N status of the soils but that it also increased the amount of P available for the follow-up crops in the rotation (FFTC, 2000). In soils with a low P levels, pigeon pea was better able to take up P and maintained adequate growth while other crops such as maize and soybean were not able to survive under such low P conditions (Sinclair, 2004). Also, the roots of pigeon pea excrete organic acids such as citric, piscidic, and tartaric acid, which help to mobilize P in the soil. Previous research have found that varietal differences exist in terms of P soil recovery (Shibata and Yano, 2003; Sinclair, 2004). Overall, pigeon pea is an excellent source of organic N that can increase organic matter and improve soil structure and quality for crop productivity.

Sunn hemp

Sunn hemp under favorable growing conditions is capable of generating 7 ton ha^{-1} of air-dried aboveground biomass at 2 months of growth (Rotar and Joy, 1983). Others have shown that, sunn hemp has the potential to produce between 1 and 9 Mg ha^{-1} aboveground biomass in 45 to 90 days after planting, respectively (Schomberg et al., 2007; Mansoer et al., 1997). Although environmental conditions affect potential biomass production, substantial amounts of biomass can be achieved under typical late-summer and fall conditions to aid in erosion control, nematode and weed suppression, and N accumulation before frost occurs.

As a legume cover crop, sunn hemp can fix atmospheric N that is available over time to succeeding crops as it decomposes. With high fertilizer prices and sustainability concerns associated with synthetic soil amendments, sunn hemp has the potential to provide N to crops such as cotton, maize, and grain sorghum. Nitrogen production with sunn hemp varies depending on many factors, however reported N values in sunn hemp range between 110 and 160 kg ha^{-1} (Balkcom and Reeves, 2005; Mansoer et al., 1997). In most investigations, sunn hemp N content equals or exceeds N content of traditional winter legume cover crops (Reeves, 1994).

When incorporated into the soil, sunn hemp also enhances the abundance of free-living nematodes that play important roles in nutrient cycling (Wang et al., 2004) and result in higher soil nutrient content, organic matter, and cation exchange capacity, especially in soils low in organic matter (Marshall, 2002). Because most of the N and other macronutrients are found in leaves and flower heads (Marshall, 2002), use of sunn hemp as a mulch or green manure would be most beneficial at the early-to mid-flowering stages.

Cowpea

Cowpea has been identified as an ideal cover crop for many areas (Wang et al., 2005). Cowpea can produce abundant aboveground biomass (Creamer and Baldwin, 2000) and fixes substantial amounts of N which ranges from 50 to 115 kg N ha^{-1} (Bado et al., 2006). Typical biomass production ranges from 3.4 to 4.5 Mg ha^{-1} (Sarrantorio, 1994). In several years of screening trials at North Carolina, cowpea dry matter (4.3 Mg DM ha$^{- 1}$) out yielded soybean (4.0 Mg DM ha$^{- 1}$), but plots of sesbania (*Sesbania exaltata*) had top yields at about 5.7 Mg DM ha$^{- 1}$ (Creamer and Dabney, 2002). In two-year screening experiment in Nebraska, Power (1994) reported that cowpea produced about 5.8 Mg ha^{-1} DM.

Earlier studies in which cowpea was used in rotation with maize revealed that cowpea plays an important role in nutrient economies of cropping systems by reducing the need for N fertilizer through biological N fixation (BNF) (Carsky et al., 2001; Bagayoko et al., 2000;

Bationo and Ntare, 2000). The benefits of cowpea to N supply in the savanna zone of Africa through BNF have been estimated in the range of 60-80 kg ha^{-1} (Sanginga et al., 2000), whereas in California, Miller (1989) reported an average of 227 kg N ha^{-1}. Cowpea's heat-loving nature and its dense residues makes it an ideal mid-summer replenisher of soil organic matter and mineralizable N that can help to improve soil structure.

Nitrous Oxide Emissions in No-Tillage Cropping System

Microbial processes regulate N transformations in the soil, controlling rates of N availability and producing metabolic products, such as N_2O (Smith et al., 2003). Bacteria and fungi mineralize organic N to ammonium (NH_4^+). Ammonium is either taken up by plants or further oxidized by microbes to nitrite (NO_2^-) and then nitrate (NO_3^-) via nitrification. Nitrous oxide is a byproduct of the aerobic oxidation, where a small proportion (0.1 to 10%) of the N "leaks out" as trace gases during nitrification (Firestone and Davidson, 1989).

When oxygen is depleted in the soil, nitrate is used as the alternative terminal electron acceptor by microbes and is reduced to N_2 via denitrification. Therefore, N_2O is an obligatory intermediate of this reduction series (Firestone and Davidson, 1989). Nitrification and denitrification are the dominant soil microbial processes producing N_2O and are most strongly influenced by (1) soil moisture content (del Prado et al., 2006; Linn and Doran, 1984); (2) temperature (Kallenbach et al., 2010); (3) NH_4^+ and NO_3^- concentrations in the soil (Ruser et al., 2001); (4) quantity of available soil organic C (Parton et al., 1996); and (5) soil pH (Wang and Rees, 1996).

Controls of Nitrous Oxide Emissions

Soil Moisture Content

Soil moisture content is a major driver of N_2O emissions as it regulates oxygen availability to soil microbes. Soil water content influences N_2O emissions for all soil types. Additions of water stimulate microbial activity, enhance net N mineralization, and initiate increases in soil mineral N levels (Chapin et al., 2002). Soil moisture can directly or indirectly influence denitrification by providing a suitable environment for microbial growth and activity, preventing the supply of oxygen to micro sites by filling soil pores. Furthermore, soil moisture releases available C and N substrates during wetting and drying cycles and through provision of a diffusion medium through which substrates and products are moved to and away from soil microorganisms (Aulakh et al., 1992).

It has been shown that, after rainfall and irrigation, denitrification rate increases due to decreased oxygen (O_2) diffusion into the soil (Ruser et al., 2001; Ryden and Lund, 1980). Therefore, the rate of N_2O emissions increases with increasing soil moisture content from air dry to field capacity (Dobbie and Smith, 2001; Sitaula and Bakken, 1993). Thus, the range of O_2 concentrations in the soil dictates whether nitrification or denitrification processes take place (Linn and Doran, 1984). Nitrifiers need oxygen for oxidation of NH_4^+, and aerobic activity declines when water-filled pore space (WFPS) exceeds 60% (Linn and Doran, 1984). In wetter soils, where WFPS exceeds 65%, denitrification dominates and can be limited by NO_3^- availability (Vale et al., 2007). Ruser et al. (2001) found strong correlation between N_2O emissions and soil NO_3^- content, but only when the WFPS was large enough (60−90%). Water filled pore space depends on the balance between the amount of water entering the soil from precipitation or irrigation and the combined effect of evapo-transpiration and drainage (Dobbie and Smith 2003, 2006).

Soil Temperature

Although soil moisture has a dominant effect on N_2O emissions, denitrification is extremely sensitive to rising temperatures. Temperature controls many biological processes in soils and in the case of N_2O production it may affect microbial processes by stimulating N_2O producing soil microorganisms. It has been found that nitrification and denitrification rates increase with increasing temperature (Luo et al., 2013; Koponen et al., 2006), both of which eventually lead to greater N_2O flux.

Previous studies indicating that denitrification proceeds at temperatures as low as -4°C and that temperatures above 5°C are required for the rates to be significant are cited by Granli and Bøckman (1994). Temperature exerts more control over soil N_2O production in soils that are not limited by soil moisture and substrate availability (Skiba et al., 1998; Smith et al., 1998). However, lack of relationship between N_2O emission and temperature has been observed in some studies (Schaufler et al., 2010; Sommer et al., 2000).

Nitrous oxide reaction to changes in temperature will not always be the same depending on the state (e.g. substrate availability) of the soil system, which may result in hysteresis curves as also observed for soil CO_2 respiration (Kirschbaum, 2006). Nitrous oxide released during rising temperatures can follow a different curve from falling temperatures owing to faster depletion of substrates (carbon compounds as well as nitrate). Temperatures around 0°C are of special interest as many soil microbes are still active and freeze/thaw processes lead to pulses of N_2O emissions with significant or dominant contributions to the annual N_2O budget (Wolf et al., 2010; Davidson et al., 2000). This may be driven by release of stored C during the thaw. These transition effects still hold many secrets in the understanding of environmental controls of N_2O release.

Soil Inorganic Nitrogen

The differences in N_2O emissions between fertilized and unfertilized soils are particularly evident in soils which have low available mineral N (Rees et al., 2006; Castaldi and Aragosa, 2002). Denitrification and nitrification rates increase in N fertilized systems (Sangeetha et al., 2009; Bremer, 2007; Ruser et al., 2006; Baggs et al., 2003; Weitz et al., 2001) because N provides a substrate for production of N_2O. The rate at which N_2O is produced and emitted from N fertilized soil depends on the amount and type of N fertilizer, application rates and method of application, soil types, and environmental conditions (Castaldi et al., 2006).

Readily soluble N fertilizers such as urea, anhydrous ammonia, urea ammonium nitrate, ammonium nitrate and ammonium sulfate are the most commonly used synthetic fertilizers in row-crop agriculture. In some soils, production of N_2O can be affected by the form of fertilizer applied. Venterea (2010) found that emissions of N_2O were 2 to 4 times greater from plots amended with anhydrous ammonia than from those amended with urea ammonium nitrate and broadcast urea. Tenuta and Beauchamp (2000) found that the relative magnitude of total N_2O emitted was greater from urea than from ammonium sulfate, which in turn was greater than from calcium ammonium nitrate.

Numerous field studies conducted on N input gradients in row-crop agriculture have found that emissions of N_2O correlate well with fertilizer N rate (Hoben et al., 2011; Millar et al., 2010; Dusenbury et al., 2008; Halvorson et al., 2008). In all of these studies, increasing the amount of N added to soil resulted in increased N_2O emissions, although the relationship was not always linear (Hoben et al., 2011; Halvorson et al., 2008). Fertilizer N applied in excess of crop needs results in high levels of soil mineral N that are quickly lost as N_2O via microbial processes, if soil moisture and C levels are not limiting (Ma et al., 2009). Therefore, management practices that improve N use efficiency can reduce soil mineral N availability, which may reduce N_2O losses (De Gryze et al., 2011; Scheer et al., 2008). Optimizing the balance between N input and N uptake lowers soil mineral N content (Hosono et al., 2006) and improves plant N recovery (Eickhout et al., 2006).

Soil Carbon Content

Denitrifying bacteria are heterotrophic; they require a C source for energy (Sylvia et al., 2005). The main sources of soil-available C are crop residues, manures, root exudates, and soil humus (Mulvaney et al., 1997). Increased C availability can increase denitrification directly by acting as an energy source and as an electron supply for the denitrification process (Azam et al., 2002; Fazzolari et al., 1998). Soil available C not only supports denitrification activity, but also stimulates the creation of microsite anaerobiosis due to increased consumption of O_2 as a result of aerobic respiration (Azam et al., 2002).

Soil pH

Soil pH another key regulators of the microbiological processes that affect N_2O and N_2 production and their ratios. Nitrification activity is generally higher with higher soil pH (> 6) (Bramley and White, 1989). The critical soil pH threshold for nitrification is 5; however, nitrification can occur even at a soil pH of 4.5 due to acid-adapted nitrifier strains (Bouwman, 1990). Denitrification has been reported to occur over a wide range of soil pH values (5 to 8) (Flessa et al., 1998; Ramos, 1996); however, laboratory experiments with artificially adjusted soil pH suggest, that under optimized conditions ($NO3^-$ and glucose amendments), denitrification can proceed even at pHs below 4 or above 10 (Šimek et al., 2002; Šimek and Hopkins, 1999).

Numerous laboratory and field studies have shown that soil pH affects N_2O and N_2 and the ratio of these gases (Stevens and Laughlin, 1998; Weier and Gilliam, 1986). Under controlled environment experiment, raising soil pH to 7 through lime application significantly increased N_2 emission from pasture and wetland soils treated with urine, urea and KNO_3 at 200 kg N ha^{-1} rate (Zaman et al., 2007).

Furthermore, types of chemical N fertilizers can also likely regulate N_2O:N_2 ratios, as $NH4^+$ based fertilizers (ammonium sulphate, ammonium nitrate, and mono-ammonium phosphate) are reported to lower soil pH after their application (Cai et al., 2002; Nobre, 2001). For instance, Mulvaney et al. (1997) reported that ammonium-based fertilizers with soil acidifying effects produce a higher N_2O:N_2 ratio compared to alkaline forming fertilizers (anhydrous ammonia, urea or di-ammonium phosphate).

Previous researches attribute high N_2O and low N_2 emissions in acidic conditions to the suppression of nitrous oxide-reductase at low soil pH (inhibition at soil pH 4.5) (Zaman et al., 2007; Stevens and Laughlin, 1998). It is also likely that all denitrifying enzymes are susceptible at low soil pH and produce N_2O from intermediate products (Nagele and Conrad, 1990). Šimek and Cooper (2002) reported that the lower rates of N_2 and high N_2O:N_2 ratio at low soil pH could be due to lower amounts of soil organic C and mineral N available to the denitrifying population under acid conditions rather than a direct effect of low pH on denitrification enzymes.

Mitigation Strategies of Nitrous Oxide Emissions

Mitigation strategies of reducing N_2O emissions from agricultural soils can be achieved by understanding the interrelationships among environmental drivers of nitrification and denitrification. Soil water content, N and C status, pH, and temperature are the principle environmental drivers of nitrification and denitrification. Weier et al. (1993) found that a single factor may not be enough to trigger the denitrification process in soils. Many of the environmental factors can be manipulated through management practices such as tillage, irrigation, N fertilizer source, timing and placement, or site- specific prescription of N fertilizer that accounts for differences in crop N demand (Adviento-Borbe et al., 2007).

Alternative practices to decrease N_2O emissions are important for mitigating climate change. Because N_2O emissions generally increase with N input, including, for example, N fertilization and residue decomposition, as proposed in the IPCC methodology for fertilized crops, crops that do not require N fertilization appear as a possible solution to limit N_2O emissions. Legumes have the capacity to fix atmospheric N_2 through BNF; allowing a reduction of N fertilizer use, both on the legume crop and on the following crop as soil mineral N availability is greater in the year following them (Jensen and Hauggaard-Nielsen, 2003).

Using legume crops as a source of N has thus been envisaged as a solution for decreasing N_2O emissions, but it is still under debate. In fact legume crops could themselves produce N_2O by different pathways: (1) during biological N_2 fixation itself, (2) after subsequent N input from the plant roots to the soil due to rhizodeposition, and (3) from the decomposition of crop residues and roots after the crop harvest and possible soil incorporation (Zhong et al., 2009). Although the latter two might be a N_2O source as legume tissues have a high N concentration, the BNF pathway seems less certain (Zhong et al., 2009). Whereas denitrification is known to occur in legume root nodules, the magnitude of this process and its contribution to soil emissions could be low compared to production by the soil microbial biomass. H´enault and Revellin (2011) showed that N_2O could even be consumed in legume nodules. Under field conditions large emissions were observed from several legume crops. Duxbury et al. (1982) reported relatively high cumulative fluxes of 2.3 and 4.2 kg N ha^{-1} yr^{-1} for an alfalfa field. In contrast, Velthof and

Mosquera (2011) estimated N emissions from a grass-clover canopy to vary between 0 and 1% of biologically fixed N_2, probably lower than from an equivalent amount of N fertilizer because the biologically fixed N is released slowly into the soil.

Knowledge of the trade-offs between emissions, N fertilizer management practice, cropping systems, and crop yield is therefore an essential requirement for informing management strategies that aim to reduce N_2O emissions without compromising productivity and economic returns.

Importance of Soil Aggregate Stability in No-Tillage System

Soil structure consists of an aggregate formed by the arrangement of soil particles, and depends on the interactions between primary particles and organic constituents to form stable aggregates (Caravaca et al., 2004). Soil aggregates, which have significant influence on soil physical and chemical properties, are the most basic units of soil structure and are an important component of the soil (Tisdall and Oades, 1982). Thus, the recognition of soil aggregate size distribution and soil aggregate stability is important to properly interpret soil structure. The stability of aggregates has substantial effects on soil fertility, quality and sustainability, and it is also a fundamental property that determines its productivity and resistance to erosion and degradation (Six et al., 2000; Raine and So, 1997). Aggregate stability is a highly complex parameter influencing a wide range of soil properties, including carbon stabilization, soil porosity, water infiltration, aeration, water retention, and resistance to erosion by water and overland flow, management practices and land use patterns (Wei et al., 2006). Arshad and Cohen (1992) described aggregate stability as one of the soil physical properties that can serve as an indicator of soil quality. Maintaining high stability of soil aggregates is essential for preserving soil productivity, minimizing soil erosion and degradation, and thus minimizing environmental pollution as well.

Basic Concepts of Soil Aggregation

Aggregates are secondary particles formed through the combination of mineral particles with organic and inorganic substances (Bronick and Lal, 2005). The complex dynamics of aggregation are the result of the interaction of many factors including the environment, soil management factors, plant influences and soil properties such as mineral composition, texture, soil organic carbon (SOC) concentration, pedogenic processes, microbial activities, exchangeable ions, nutrient reserves, and moisture availability (Kay, 1998).

Aggregates occur in a variety of manners and sizes. These are often grouped by size: macroaggregates (>0.25 mm) and microaggregates (< 0.25 mm) with these groups being further divided by size (Tisdall and Oades, 1982). Macroaggregates often form, not only around particles of undecomposed soil organic matter (SOM), but also from microaggregates because of binding agents such as polysaccharides and fungal hyphae (Beare et al., 1997; Tisdall and Oades, 1982). Macroaggregates are sensitive to land use changes and agricultural practices because they are less stable than microaggregates, due to stronger binding of the latter (Tisdall and Oades, 1982). Different size groups differ in properties such as binding agents, carbon, and N distribution.

Agents of Soil Aggregation

Soil Organic Carbon

Soil organic C creates regions of heterogeneity in the soil, leading to ‘‘hot spots’’ of aggregation. The chemical properties of SOC determine their charge and complexation capacities and influence decomposition rates, which have direct effects on aggregation (Schulten and

Leinweber, 2000). The aggregate binding effect of labile SOC is rapid but short (Kay, 1998) and slower decomposing SOC has subtler effects on aggregation, but the effects may be longer lived (Martens, 2000). Different sizes of soil aggregates have different storage capacities for organic carbon. Soil organic carbon might enhance soil aggregation, increase soil moisture retention and the activity of soil organisms, and at the same time, could improve soil fertility and productivity (Singh and Lal, 2005). The isolation of the readily decomposable labile C fraction within aggregates increases stability and durability by reducing its decomposition.

Soil Organic Matter

Soil organic matter influences soil structure and stability by binding soil mineral particles, reducing aggregate wet ability, and influencing the mechanical strength of soil aggregates, which is the measure for the coherence of inter-particle bonds (Onweremadu et al., 2007). Particulate organic matter (POM) is comprised of large particles of organic matter (0.25-2.00 mm) that exist as free POM light fraction or encrusted with soil particles, which in turn offers physical protection from decomposition (Plante and McGill, 2002). The light fraction in soil is generally associated with clay and polyvalent cations to form aggregates (Jastrow, 1996). Studies have found increased SOC and aggregation in no-till soils (Six et al., 1999) as a result of increases in light fraction-POM.

Macroaggregates have a large concentration of low density POM (Jastrow, 1996). Within macroaggregates, the decomposition of labile fraction in occluded organic matter (OOM) may lead to relative enrichment of recalcitrant C. Disruption of occluded organic matter within aggregates results in the exposure of labile fraction, making it available for microbial decomposition (Plante and McGill, 2002). The POM may be an important agent in binding microaggregates to form macroaggregates. As microorganisms decompose the POM, they produce extracellular polysaccharides that act as a binding agent (Jastrow, 1996) for aggregation.

Plant Species and Roots

The combined effects of the biochemical composition and amount of plant residues returned to soils and chemicals released from plants affect the rate and stability of aggregation, and the rate of aggregate turnover. Water-stable aggregates (WSA) are correlated with biochemical composition of plant residues: phenols, lignin, proteins, and phenols (Martens, 2000). Maize residues are high in phenols and increase aggregation compared with other crops, although continuous maize decreases microaggregates compared to maize grown in rotation (Martens, 2000; Raimbault and Vyn, 1991). Martens (2000) reported low aggregation of soil cultivated to soybean as a result of low concentration of phenols along with low residue return to the soil.

Plant roots and their rhizosphere have many effects on soil aggregation. Roots enmesh and realign soil particles and release exudates, resulting in physical, chemical and biological alterations that influence aggregation. Aggregation tends to increase with increasing root length density, microbial associations, glomalin, and percent cover significantly affect soil aggregate stabilization (Rillig et al., 2002). Chemically, roots enhance aggregation by releasing a variety of compounds that have a cementing effect on soil particles (Bronick and Lal, 2005). Roots increase the wet-dry cycling of adjacent soil that can increase aggregate stability in some cases and decrease in others, possibly related to clay type (Angers and Caron, 1998).

Different root systems affect aggregation differently, relating to different root properties, exudates and functions. Generally, extensive fibrous roots produce high levels of macroaggregation (Chan and Heenan, 1996). Leguminous plant roots are associated with higher microbial biomass, increased aggregation and water stable aggregates (WSA) than non-legumes. Aggregate stability in non-legumes is related to root mass (Haynes and Beare, 1997; Chan and Heenan, 1996). This helps in binding the microaggregates together.

Dissertation Hypotheses and Objectives

The hypotheses of this research were that (1) use of cover crops and efficient use and management of N fertilizer can decrease N_2O emissions compared with non-cover crop systems; (2) including leguminous cover crops in a cropping system would improve N availability and grain yield of the succeeding grain sorghum or maize crop; and (3) leguminous summer cover crops in no-tillage cropping system will provide additional biomass, increase SOC, and soil N and will subsequently improve aggregate-associated C and N compared with no cover crop system.

The objectives of this study were to (1) evaluate the performance of leguminous cover crops and double-cropped grain crops for aboveground biomass production, N uptake and carbon accumulation following winter wheat; (2) to quantify the effects of cover crops and N fertilizer on N_2O emissions in subsequent grain sorghum crop; and (3) to determine the effects of inclusion of summer cover crops and varying N rates in the cropping system on growth and yield of the succeeding grain sorghum or maize crop; (4) evaluate nitrogen fertilizer replacement values of (NFRVs) of summer cover crops; (5) to identify the cropping system that results in profitable economic net returns; and (6) to assess summer cover crops and double-cropped grain crops effects on aggregate stability, and aggregate- associated C and N pools.

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CHAPTER 2 - EFFECT OF COVER CROPS AND NITROGEN FERTILIZER ON NITROUS OXIDE EMISSIONS IN NO-TILLAGE MANAGED SYSTEM

ABSTRACT

Nitrous oxide (N_2O) is a greenhouse gas (GHG) with global warming potential 310 times that of carbon dioxide (CO_2) during a 100-year lifespan. Nitrous oxide emission from denitrification in agricultural soils often increases with nitrogen (N) fertilizer and soil nitrate (NO_3^-) concentrations. The objectives of this study were to (a) evaluate the performance of summer leguminous cover crops in terms of N uptake and carbon (C) accumulation following winter wheat (*Triticum aestivum* L.), and (b) to quantify the effects of summer leguminous cover crops and N fertilizer rates on N_2O emissions and grain yield of the subsequent grain sorghum [*Sorghum bicolor* L. Moench] crop. Field experiments were conducted on a well-drained Kennebec silt loam in Kansas. Fallow systems with 90 and 180 kg N ha^{-1} produced significantly greater N_2O emissions compared with all other cropping systems. Emissions of N_2O were relatively similar for various cover crops and fallow systems with 0 kg N ha^{-1}. Among cover crops, pigeon pea (*Cajanus cajan* (L.) Millsp) and cowpea [*Vigna unguiculata* (L.) Walp.] had greater C accumulation and N uptake than sunn hemp (*Crotalaria juncea* L.). Grain yield of sorghum following different cover crops was similar and significantly higher than fallow systems with 0 kg N ha^{-1}; however, the fallow systems with 90 and 180 kg N ha^{-1} produced maximum sorghum grain yields. We conclude that inclusion of leguminous cover crops reduced N_2O emissions compared with fallow system without inorganic N. This approach also provides additional C accumulation and N uptake, thus contributing to increased grain yield of the following cereal grain crop.

INTRODUCTION

Nitrogen moves in the environment and can be lost into the air as a gas or into water by moving through the soil or over the soil surface. These losses are primarily the result of timing asynchrony of the supply or availability of N and crop demand along with environmental factors. Of particular environmental concern are emissions of nitrous oxide (N_2O), a greenhouse gas from agricultural soils that can contribute to global warming and ozone destruction. Although emissions of N_2O are numerically smaller than those of other greenhouse gases (GHGs) such as carbon dioxide, they are a major contributor (about 15%) to global warming (Isermann, 1994), mostly because the global warming potential of N_2O is about 296 times higher than that of CO_2.

Agricultural soils are known to be the largest anthropogenic source of N_2O (Reay et al., 2012). Decreasing N_2O emissions from field-crop soils is necessary from not only an environmental quality perspective but also an agro-economic perspective, because it decreases the efficacy of expensive applied N fertilizers (Drury et al., 2014). The challenge for field-crop producers is that underuse of N fertilizer can result in lower crop yields, but overuse results in excess soil inorganic N, which may be lost as N_2O and/or leached as nitrate ($NO_3^−$) into surface and groundwater resources, simultaneously polluting the environment and wasting an expensive crop nutrient. Given that NO_3^- is a negatively charged anion that moves with water and is subject to many biological processes such as N uptake by crops, N immobilization by soil biota, movement below the root zone following large precipitation events, and conversion to nitric oxide, N_2O, and N_2 by soil denitrifies, maintaining the right amount of N in the root zone throughout the growing season is extremely difficult (Drury et al., 2014). Therefore, developing crop and soil management practices for efficient use of N and minimize N_2O emissions are important.

Legumes have the capacity to fix atmospheric N through biological N fixation (BNF), thus decreasing N fertilizer use on both the legume crop and the following cereal crop because soil mineral N availability is greater in the year following legumes (Jensen and Hauggaard-Nielsen, 2003). Nitrogen contents of legume crop residues vary based on residual soil N, adaptability to specific soil, and climatic conditions. Management factors also strongly influence the N content of legume cover crops and the contribution of N available to the following succeeding crop. Species selection and the time of growth termination of the cover crop also affects the N content of the residues, which subsequently affect the benefit derived from the succeeding crop (Blanco-Canqui et al., 2012).

Although the benefits of legume base rotation are largely attributable to improved N supply, improvement in soil physical and chemical properties such as bulk density, water-holding capacity, and improved cation exchange capacity are additional benefit (Cheruiyot et al., (2001). Use of leguminous cover crops that do not require N fertilization in a cropping system may help limit N_2O emissions, but the documented effects of cover crops on N_2O emissions have been mixed (Cavigelli et al., 2012); some studies have found cover crops to increase (Petersen et al., 2011) or have no consistent effect on (Smith et al., 2011) N_2O emissions.

Short-term peaks in N_2O emissions often have been observed after crop residues are returned to the soil (Millar et al., 2004). The magnitude of the emissions depends on the chemical composition and the quantity of plant residue added to the soil (Garcia-Ruiz and Baggs, 2007). The contents of N and C in plant residue are important variables in determining the N mineralization kinetics in the soil and thus also can affect soil N_2O emissions, which tend to be greater when the added crop residues have a low carbon-to-nitrogen ratio (Huang et al., 2004). In this context, the addition of legume cover crop residues, which are characterized by a high N concentration and a low carbon-to-nitrogen ratio to the soil, is expected to increase N_2O emission compared with emissions observed in grass-based cover crop residues. Garcia-Ruiz and Baggs (2007) reported N_2O emissions up to three times greater in a soil with a legume residue input than in a non-amended soil, but the magnitude of response to legume residue addition depends on environmental and soil conditions (Rochette et al., 2004). Inconsistent effects of cover crops on N_2O emissions and evidence for C limitation of agricultural N_2O emissions indicate that cover crop effects on the availability of C as well as NO_3-N can affect N_2O emissions. A clear understanding of the relationship between cover crops and N_2O emissions is particularly important because cover crops are increasingly promoted as a component of a GHG mitigation strategy (Eagle and Olander, 2012).

Greater N_2O emissions from agricultural soils are associated with higher N fertilization rates, elevated soil nitrate levels, and wetter soils (Drury et al., 2012) because of their impact on oxygen supply and substrate availability (labile organic C and mineral N); therefore, efficient use and management of N fertilizer along with selection of an appropriate cover crop that can provide N to the following cereal crop may help minimize N_2O emissions from the cropping system.

Understanding emissions from leguminous cover crops and N fertilizer amendments as a component of crop rotations in cropping systems is crucial. Our hypothesis is that use of cover crops and efficient use and management of N fertilizer can decrease N_2O emissions compared to non-cover crop systems. The objectives of this study were to (a) evaluate the performance of leguminous summer cover crops for N uptake and C accumulation following winter wheat, and (b) to quantify the effects of leguminous summer cover crops and nitrogen fertilizer on N_2O emissions and grain yield of the subsequent grain sorghum crop.

MATERIALS AND METHODS

Site Description and Experimental Design

Field experiments were conducted during the 2012-2013 and 2013-2014 growing seasons at Kansas State University Department of Agronomy research facilities (39°11’30”N, 96°35‘30”W). The responses of grain sorghum and N_2O emissions were quantified to different leguminous cover crops and varying N fertilizer levels on a well-drained Kennebec silt loam (fine-silty, mixed, superactive, mesic Cumulic Hapludolls).

The experiment consisted of no-tillage double-cropped leguminous cover crops following winter wheat rotated with grain sorghum. The cover crops were cowpea, pigeon pea, and sunn hemp. Plots were arranged in a randomized complete block design with four replications. Each plot was 9.1 m long and 4.5 m wide (6 rows). The inside two rows were used for data collection to eliminate border effects. Each replication was separated by two alleys to eliminate N fertilizer border effects. The field layout is presented as Wh-Fw-Sg+0N, wheat rotated with sorghum plus 0 kg N ha^{-1}; Wh-Fw-Sg+90N, wheat rotated with sorghum plus 90 kg N ha^{-1}; Wh-Fw-Sg+180N, wheat rotated with sorghum plus 180 kg N ha^{-1}; Wh-Cp-Sg+0N, double-cropped cowpea rotated with sorghum after wheat; Wh-Pg-Sg+0N, double-cropped pigeon pea rotated with sorghum after wheat; Wh-Su-Sg+0N, double-cropped sunn hemp rotated with sorghum after wheat.

Winter Wheat and Cover Crop Phase

Winter wheat was drilled in October 2011 and 2012. In both years, the target seeding rate was 115 kg ha^{-1}. Seeding was performed with a John Deere 1590 (Deere & Co., Moline, IL, USA). No fertilizer was applied at planting in either year. Wheat was harvested in June in 2012 and July in 2013 using a using a modified 2-row Gleaner (model EIII; AGCO Corporation, Duluth, GA). Immediately after wheat harvest, the stubble was sprayed with 3.5 L ha^{-1}

glyphosate 4 plus herbicide, (N-[(phosphonomethyl) glycine, to control weeds. The leguminous cover crops were planted into the standing winter wheat stubble with a John Deere 1590 fitted with a cone and equipped with residue managers. Cowpea, pigeon pea, and sunn hemp seeds were treated with a commercial soybean rhizobium inoculant and planted at a seeding rate of 56, 28, and 12.5 kg ha^{-1}, respectively, on June 19, 2012, and July 12, 2013, at a depth of 1.3 to 2.5 cm. Leguminous cover crops were evaluated throughout the growing season. Stand counts were conducted on all cover crops 20 days after plant emergence within an area of 4.5 m^2. Cover crop biomass production was estimated in 2012 by hand-harvesting two rows of 4.5-m^2 samples from all cover crop plots, and a portable rotary mower was used in 2013. After weighing, the fresh plant material was uniformly distributed on the harvested plots and left in the field to decompose, acting as green manure for the subsequent grain sorghum crop. Cowpea, pigeon pea, and sunn hemp cover crops were terminated 67, 88, and 84 days after planting, respectively, in 2012. Corresponding values in 2013 were 70, 90, and 88 days after planting, respectively, based on beginning of flowering. In both years, aboveground subsamples of each plot of the cover crops were dried in a forced-air dryer at 65°C until dry, and weighed to obtain dry matter content. The dried samples (leaves and stems) were ground in a Thomas Wiley laboratory mill (Model 4, Arthur H. Thomas Company, Philadelphia, PA, USA) and passed through a 2.0-mm screen. The dry samples were analyzed for N and carbon (C) by dry combustion (modified Dumas method) using a LECO CHN-2000 elemental analyzer (LECO Corp., St. Joseph, MI, USA) by the Kansas State University Soil Testing Laboratory. Nitrogen uptake and C accumulation of various cover crops were determined by multiplying mass of aboveground dry matter by percentage N concentration or percentage C concentration as follows:

Nitrogen uptake (kg ha^{-1}) = [(Aboveground dry matter, kg ha^{-1}) x (N concentration in dry matter / 100)]; and

Carbon uptake (kg ha^{-1}) = [(Aboveground dry matter, kg ha^{-1}) x (C concentration in dry matter / 100)]

Grain Sorghum Phase

The succeeding grain sorghum (DKS54−00) crop was planted in May (2013) and June (2014). Standard spacing for sorghum (75 cm between rows) was used during planting in both years with a target plant population of 125,000 plants ha^{-1}. Weeds were controlled with pre-emergence herbicide, atrazine (1-chloro-3-ethylamino-5-isopropylamino-2, 4, 6-triazine) and 2, 4-dichlorophenoxyacetic acid (2, 4-D) at the rate of 1.1 L ha^{-1}), with a tractor-mounted boom sprayer. Hand-weeding was also done as and when necessary throughout the growing season to keep fields weed-free.

Three N application rates in the form of urea (46% N) were established within fallow plots at rates of 0 kg N ha^{-1}, 90 kg N ha^{-1}, and 180 kg N ha^{-1}. Fertilizer was hand-broadcast 10 to 14 d after emergence of grain sorghum along the rows of each plot to ensure that N was evenly distributed. Fertilizer was applied on June 9 and June 6 in 2013 and 2014, respectively. Plots were mechanically harvested after physiological maturity using a 2-row Gleaner (modified EIII). Grain moisture and test weight were estimated with a DICKEY-John GAC 2000 (DICKEY-John Corp., Springfield, IL, USA). Grain yields in both years were corrected to 135 g kg^{-1} moisture content.

The aboveground portions of 10 randomly selected plants from each plot were sampled at physiological maturity. Plant samples were separated into leaf, stem, and panicle components at sampling. All samples were dried at 60°C in a forced-air oven for 72 h and weighed. Based on the individual plot plant population, total aboveground biomass was calculated and expressed in kg ha^{-1}. The dried leaf and stem samples were ground in a Thomas Wiley laboratory mill and passed through a 2.0-mm screen. The panicles were threshed using a stationary thresher (Model LDB, ALAMACO, Nevada, US), and the grain was ground in a cyclone sample mill (Model 3010-030, Udy corporation, Fort Collins, CO, USA). Leaf, stem and grain N was determined by digesting the samples using a sulfuric acid-hydrogen peroxide digest. The extract containing ammonia was analyzed by a colorimetric procedure (nitroprusside-sodium hypochlorite) by the Kansas State University Soil Testing Laboratory. Nitrogen uptake and grain N uptake of grain sorghum were determined by multiplying aboveground dry matter mass by percentage N concentration or percentage grain concentration as follows:

Nitrogen uptake (kg ha^{-1}) = [(Aboveground dry matter, kg ha^{-1}) x (N concentration in dry matter / 100)]; and

Grain N uptake (kg ha^{-1}) = [(Grain yield, kg ha^{-1}) x (grain N concentration / 100)]

Soil Properties and Analyses

Composite soil samples were taken from each replication to a depth of 30 cm. Sampling was done using a hand probe, and samples consisted of 12 individual cores mixed to form individual composite samples. The soil was analyzed for pH, available P, exchangeable K, soil organic matter (SOM), S, and chloride. Soil physical properties such as sand, silt, and clay were determined for each replication. Analyses were conducted by the Kansas State University Soil Testing Laboratory.

The hydrometer method was used to determine soil texture. Soil samples were treated with sodium hexametaphosphate to complex Ca^{2+}, Al^{3+}, Fe^{3+}, and other cations that bind clay and silt particles into aggregates. Organic matter was suspended in the solution, and density of the soil suspension was determined with a hydrometer. Soil pH was estimated using a 1:1 slurry method with a 10-g scoop of soil and 10 mL of deionized water, and pH was measured by a dual-probe automated pH analyzer (Labfit Pty. Ltd., Burswood, WA, Australia). Mehlich-3 P was analyzed by the HCl-ammonium fluoride extraction method. Extractable (plant-available) K and Na were determined by the ammonium acetate (1 M, pH 7.0) extraction method. This analysis was performed by an inductively coupled plasma (ICP) spectrometer (Model 3110 Flame Atomic Absorption Spectrometer, PerkinElmer Corp., Norwalk, CT, USA). The Walkley-Black method was used to determine organic matter, and colorimetric analysis of the solution was performed with a PC910 Fiber Optic Spectrophotometer (Brinkmann Instruments, Inc., Westbury, NY, USA). Chloride was analyzed by the calcium nitrate extraction method and colorimetric analysis through the mercury thiocyanate method. Turbidimetric method was used to determine sulfate-S. The density of the suspension was then read in a colorimeter. For soil-extractable nitrate, 1 M KCl extraction (2 g in 20 mL for 15 min) and cadmium reduction/colorimetry was used. Ammonia was extracted from soil samples with 1 M KCl (2 g in 20 mL for 30 min) and measured by an indophenol colorimetric reaction. The results of soil analyses are presented in Table 2.1.

Soil Gas Sampling and Laboratory Analyses

Soil gas samples were collected using custom-built static polyvinyl chloride (PVC) chambers designed in accordance with the USDA-ARS GRACEnet Chamber-based Trace Gas Flux Measurement Protocol (Parkin and Venterea, 2010). The chambers consisted of two parts: a chamber anchor base and a vented sampling chamber head covered with reflective tape. The chamber base was made from white PVC pipe (30 cm inside diameter, 6 mm thick and 15 cm high). The chamber bases were driven 10 cm into the ground using a rectangular wooden block and a rubberized mallet, leaving a soil collar 5 cm above the ground in the center of the two middle rows.

Three tight-fitting butyl rubber septum were glued to the top of the flux chamber head (30 cm inside diameter, 6 mm thick and 10 cm high). A PVC vent tube 10 cm long and 4.8 mm inside diameter was inserted into the first butyl rubber cork on top of the flux chamber head to offset pressure differences between the inside and outside of the flux chamber during measurements. A thermometer was inserted into the second butyl rubber septum to measure temperature inside the flux chamber during measurements. The third butyl rubber septum was used as a sampling port into which a syringe needle was inserted during gas sampling. The chamber anchor bases were kept open at all times except during gas sampling.

During gas sampling, the chamber anchor bases were fitted with the tight-fitting vented chamber heads. At each gas sampling, the air inside the chamber was mixed by pumping air into the syringe and expelling the air three to five times. In 2013, gas sampling was started May 15 and ended Oct. 12, whereas in 2014, sampling began April 28 and ended Oct. 14. Gas samples were extracted at 0-, 15-, 30- and 45-min time intervals. Sampling was typically restricted to between 9:00 AM and 1:00 PM to avoid large temperature fluctuations during gas collection periods. Immediately after extraction, the 25-mL gas samples were transferred to 12-mL pre-evacuated vials sealed with butyl rubber septa (Exetainer vial, Labco Ltd., Lampeter, Ceredigion, UK), which over pressurized the system to ensure that in case of leakage, gas movement would be only out of the vials and not into the vials. We sampled every week and more intensively (twice/week) following fertilizer application and after rainfall events to cover most of the crop growth period. Sampling was reduced to once every 2 weeks when fluxes were observed to be at background levels. The 12-mL gas samples were transported to the laboratory for analyses. Gas concentrations were determined by gas chromatography (Model GC 14A; Shimadzu, Kyoto, Japan) equipped with a ^{63}Ni electron capture detector and a stainless steel column (0.318 cm diameter by 74.5 cm long) with Poropak Q (80-100 mesh, Shimadzu, Kyoto, Japan).

Surface Flux Calculation

Surface fluxes were calculated using the following equation by (Jantalia et al., 2008):

$$f = \frac{\Delta C}{\Delta t}\, x \frac{V}{A}\, x\, \frac{m}{V_m}$$

where:

f = the flux rate of soil gas (μgm^{-2} min^{-1})

$\Delta C/\Delta t$ = the rate of change of gas concentration inside the measuring chamber (μg min^{-1})

V = the head-space volume of the measuring chamber (0.0109 m^3)

A = the surface area of the measuring chamber (0.0706 m^2)

m = the molecular weight of N_2O (44 gmol^{-1})

Vm = the molar volume of gas (m^3 mol^{-1})

Cumulative Nitrous Oxide Calculation

The average N_2O flux for each treatment was the arithmetic means of four replications of each treatment. Total cumulative N_2O fluxes were calculated by plotting daily fluxes through time, interpolating linearly between them and integrating the area under the curve, which in effect assumes that fluxes changed linearly between sampling dates during the 25- and 26-d monitoring period in 2013 and 2014, respectively.

$$\text{Cumulative } N_2O \text{ (g N ha}^{-1}\text{)} = \text{Cumulative } N_2O \text{ (g N ha}^{-1}\text{)} = \sum_{i=1}^{n} \frac{(X_i + X_{i+1})}{2}\ (t_{i+1} - t_i)$$

where X_i was the initial N_2O-N flux (g ha^{-1}day^{-1}) reading, and X_{i+1} was the next reading at times ti and t_{i+1}, respectively, and n was the last N_2O-N flux estimated during the study period.

In addition, percentage emission factor (EF) was calculated according to the following equation, which assumes 10% applied N fertilizer lost from the soil through ammonia volatilization (IPCC, 1997):

$$EF = [(\text{cumulative flux}_{\text{(fertilizer treatment)}} - \text{cumulative flux}_{\text{(control)}}) / (\text{fertilizer applied})] \times 100$$

Ancillary Measurements

Soil samples were collected at six locations within each plot from 0- to 5-cm and 5- to 15-cm depth using a 19-mm ID soil core sampler (Oakfield Apparatus, Inc., Oakfield, WI) with a total of six cores per plot. Sampling locations were randomly selected from within the center 0.38 m of the inner -row region, avoiding areas affected by obvious wheel traffic compaction. Cores from each depth were pooled, homogenized, and refrigerated before analysis of each plot collected for the determination of mineral NO_3-N and NH_4-N. A 25-g fresh soil subsample from each sample was extracted with 100 mL 2M KCl, filtered (Whatman no. 42), shaken at 300 rpm for 60 min, then filtered. Soil mineral N concentrations (NH_4^+-N and NO_3-N) in the filtrate were determined colorimetrically with a TRAACS 800 Auto-Analyzer (Bran-Luebbe, Analyzing Technologies, Elmsford, NY, USA) by the K-State Soil Testing Laboratory. Surface water content (0 to 5 cm) and soil and air temperature were measured at the time of each gas flux sampling event using a dielectric constant-measurement Hydra Probe soil sensor (POGO, Stevens Systems Inc., Beaverton, OR, USA) and handheld digital thermometers (Fisher, Hampton, NH, USA), respectively. Soil water contents were determined on samples by weighing before and after samples were dried at 105°C.

Additional soil samples were collected for analysis of bulk density of a total of two sampling dates in both years. Because soil bulk density was observed not to vary with time or treatment during the period of measurement, soil volumetric water data were converted to water-filled pore space (WFPS) using the average bulk density (1.18 g cm^{-3}) for the site. Therefore, WFPS was calculated using the following equation:

WFPS = (soil gravimetric water content x bulk density) / [1-(bulk density / particle density)]

In addition, three different indices of yield-scaled N_2O emissions were calculated by dividing cumulative area-scaled emissions by (i) grain yield, (ii) grain N uptake, and (iii) total aboveground plant N uptake.

Daily precipitation and average air temperatures were obtained from the Kansas State University Digital Weather Library that collected data from weather station within 0.25 m of the experimental plots.

Data Analyses

Data were analyzed by PROC MIX in SAS (Version 9.1, SAS Institute, Cary, NC, USA). We subjected all data to normality tests using PROC UNIVARIATE. In the repeated-measures mixed models, block was included as a random effect and sampling date as the repeated factor, and treatments were considered fixed effects. The best model for covariance was tested by stepwise inclusion of different covariance structures available in SAS. Based on lower Akaike information criterion and convergence, we chose Ante-dependence 1, which permits the variance among observations to vary over time. Accumulated N_2O was estimated by linear interpolation between sampling dates. Treatment effects were assessed using analysis of variance (ANOVA) and differences assessed by the Fisher protected LSD method. Results were considered statistically significant at $P < 0.05$ unless noted otherwise.

RESULTS

Aboveground Biomass Accumulation, Carbon and Nitrogen Uptake by Cover Crops

Aboveground plant biomass, plant carbon accumulation, and plant N uptake were significantly ($P < 0.05$) affected by the interaction between site-year and cover crops (Fig. 2.1). Among the cover crops, pigeon pea had the greatest aboveground plant biomass, followed by cowpea and sunn hemp in 2012 when the rotation was established. Sunn hemp produced the greatest amount of aboveground plant biomass in 2013, but there was no difference between cowpea and pigeon pea (Fig. 2.1a).

Plant carbon accumulation was significantly ($P < 0.05$) greater for pigeon pea followed by sunn hemp and cowpea in 2012. Among the cover crops in 2013, sunn hemp had the greatest plant carbon accumulation, whereas pigeon pea and cowpea did not differ from each other (Fig. 2.1b).

Plant N uptake was greater for cowpea and pigeon pea relative to sunn hemp in 2012. On the other hand, no difference was found in 2013 between pigeon pea and sunn hemp for plant N uptake relative to cowpea (Fig. 2.1c). Carbon-to-nitrogen ratio was less than 20 for all cover crops in both years, and the ranking was similar in both years, with cowpea > pigeon pea > sunn hemp (Fig. 2.1d).

Temperature, Precipitation, and Water-Filled Pore Space

In 2012, maximum air temperature in June and July was 3.6 and 4.6°C, respectively, above the 30-year average. In 2013, maximum air temperature during the sampling period was below the 30-year average, except in September, when the maximum air temperature was above the 30-year average by 3.0°C. However, in 2014, maximum air temperature in May and August was above the 30-year average by 1.1°C (Fig. 2.2a). In both years the greatest maximum soil temperature was recorded in July and August (Fig. 2.2b).

Total precipitation during the growing seasons (April-October) 2012, 2013, and 2014 was 338 mm, 539 mm, and 576 mm, respectively, all below the 30-year average of 698 mm. At the start of gas sampling in 2013, two previous precipitation events resulted in a total of 20 mm, but this did not have a significant effect on WFPS (45%) (Fig. 2.2c). Water-filled pore space increased to 68% on day of year (DOY) 157 after several rainfall events totaling 46 mm. During the gas-sampling period, the lowest WFPS was recorded on DOY 251 as a result of less than 2 mm of rainfall from DOY 227 to DOY 251. In 2014, however, at WFPS at DOY 118 was 95% due to total precipitation amount of 69 mm on DOY 117. WFPS was generally greater than 50% in 2014, except on DOY 125 (46%), DOY 197 (20%), DOY 204 (18%), DOY 210 (10%), and DOY 271 (43%) due to precipitation amount less than 5 mm (Fig. 2.2d).

Growing Season Daily Nitrous Oxide Emissions

In 2013, N_2O emissions during late May and early June were about 30 g N_2O-N ha^{-1} d^{-1} and declined until urea fertilization (Fig. 2.3a). The daily emissions of N_2O-N differed significantly among the sampling dates, which were clearly related to precipitation events and WFPS. At DOY 175, emissions increased dramatically because a precipitation event of 27.18 mm resulted in WFPS of 89.5% (Figs. 2.2c and 2.3a). Among the cropping systems, Wh-Fw-Sg+180N usually had the greatest daily emission compared with Wh-Fw-Sg+90N and Wh-Cp-Sg+0N throughout the sampling period ($P < 0.05$), but Wh-Fw-Sg+0N, Wh-Pg-Sg+0N and Wh-Su-Sg+0N did not differ ($P > 0.05$) (Fig. 2.3a). The highest precipitation event during the sampling period was at DOY 258 with 70.36 mm and WFSP of 99.9%, but the precipitation event did not influence the emission because fluxes were near background levels. Due to the fact that, much of the soil nitrate was used by the growing plants.

Emissions in 2014 were generally lower than in 2013 (often < 30 g N ha^{-1} d^{-1}) (Fig. 2.3b). Within the season, N_2O emissions were low from late April through early June, then increased considerably on DOY 167, with total precipitation of 21 mm and WFPS of 88% (Figs. 2.2d and 2.3b), especially for Wh-Fw-Sg+90N, Wh-Fw-Sg+180N, and Wh-Cp-Sg+0N (Fig. 2.3b). Emissions of N_2O were affected by N application, amount of rainfall, and soil N available from the cover crop residues. In 2014, precipitation was low from early July through early August, which resulted in low N_2O emissions as a result of decreased WFPS. The most notable emissions were from Wh-Fw-Sg+90N and Wh-Fw-Sg+180N, which peaked in mid-August following closely spaced rainfall events (Fig. 2.2d and Fig. 2.3b).

Soil Inorganic Nitrogen

Soil inorganic N was affected by day of sampling and cropping systems ($P < 0.05$). Soil inorganic N (NO_3-N and NH_4-N) at both 0- to 5-cm and 5- to 15-cm depths in 2013 and 2014 was less than 10 µg N g^{-1} soil at the beginning of each growing season and start of gas sampling (Fig. 2.4). Generally, more soil inorganic N was found in the Wh-Fw-Sg+90N and Wh-Fw-Sg+180N in both years. Maximum soil inorganic N concentrations were observed 11 to 15 d after N application in 2013 and 2014.

Maximum soil inorganic N at the 0- to 5-cm soil depth for NO_3-N and NH_4-N was observed at DOY 168 in 2013 and DOY 154 in 2014 (Figs. 2.4a, b, c and d). Among the cropping systems, Wh-Fw-Sg+180N had the greatest soil NO_3-N and NH_4-N concentrations, followed by Wh-Fw-Sg+90N (Figs. 4a, b, c and d). No difference was found between Wh-Cp-Sg+0N and Wh-Pg+Sg+0N. Similarly, Wh-Fw-Sg+0N and Wh-Su-Sg+0N were not statistically different for soil NO_3-N concentration. A similar trend was found for NH_4-N at the 5- to 15-cm depth (Figs. 2.4e, f, g and h). In general, soil inorganic N concentration decreased continually from early July through the end of October. Overall, the pattern of soil inorganic N concentration throughout each growing season was Wh-Fw-Sg+180N > Wh-Fw-Sg+90N > Wh-Pg-Sg+0N ≥ Wh-Cp-Sg+0N ≥ Wh-Su-Sg+0N > Wh-Fw-Sg+0N.

Growing Season Cumulative Nitrous Oxide Emissions

A significant ($P < 0.05$) treatment effect was observed on cumulative N_2O emissions at the end of the sampling period. The values for cumulative emissions for each treatment closely reflected daily emissions. In 2013, Wh-Fw-Sg+180N had the greatest cumulative (annual) emissions, followed by Wh-Fw-Sg+90N and Wh-Cp-Sg+0N (Fig. 2.5a). No difference was detected between Wh-Fw-Sg+0N, Wh-Pg-Sg+0N and Wh-Su-Sg+0N (Fig. 2.5a). Similarly in 2014, Wh-Fw-Sg+180N had the greatest annual emission compared with Wh-Fw-Sg+90N and Wh-Cp-Sg+0N, whereas Wh-Pg-Sg+0N had 0.813 kg N_2O-N ha^{-1} yr^{-1} (Fig. 2.5b). No statistical difference was detected between Wh-Fw-Sg+0N and Wh-Su-Sg+0N (Fig. 2.5b).

Sorghum Grain Yield Following Cover Crops and Specific Nitrous Oxide Emissions

Sorghum grain yield differed significantly ($P < 0.05$) among the treatments in both years (Tables 2.2 and 2.3). In 2013, Wh-Fw-Sg+180N produced the greatest grain yield, followed by Wh-Fw-Sg+90N, and Wh-Fw-Sg+0N produced the least grain (Table 2.3). Sorghum grain yield was similar following pigeon pea and cowpea but was usually greater than fallow at 0 N kg ha^{-1} and sunn hemp (Table 2.2). Similar trends were observed in 2014 (Table 2.3).

Aboveground biomass, N uptake, grain N uptake, and total N uptake were significantly greater for Wh-Fw-Sg+90N and Wh-Fw-Sg+180N than for all other treatments in both years

(Tables 2.2 and 2.3), but sorghum following cover crops had significantly greater aboveground biomass, plant N uptake, grain N uptake and total N uptake than fallow at 0 kg N ha^{-1}.

In both years, emissions of N_2O estimated as per-unit grain yield, per-unit grain N uptake, and per-unit total plant N uptake were significantly greater for Wh-Fw-Sg+180N and Wh-Fw-Sg+90N compared with any other cropping systems without N application (Tables 2.2 and 2.3). Nitrous oxide emissions per unit of grain yield, per unit of grain N uptake, and per unit of total plant N uptake for sorghum following cover crops were comparable to those from the 0-kg N ha^{-1} treatment. Emission factor was greater in Wh-Fw-Sg+180N than in Wh-Fw-Sg+90N in both years (Tables 2.2 and 2.3).

DISCUSSION

Agriculture contributes 75-85% of the total annual N_2O emissions to the atmosphere (UNEP, 2013; Reay et al., 2012; IPCC, 2007). Thus, development of management practices that decrease N_2O emissions would have a significant impact on atmospheric GHG levels and their subsequent effects on climate change (Calderia et al., 2004). The interrelationships among fertilizer N application, soil water content, crop growth, soil N dynamics, and N losses through N_2O emissions during the season are complex. Nitrogen fertilizer is a major contributor to N_2O emissions from cultivated soils (Stehfest and Bouwman, 2006). Kim et al. (2012) found increased N_2O emissions with increased N rates, but some studies have not found consistent increases in N_2O emissions with increasing N fertilizer rate (van Groenigen et al., 2004; Adviento-Borbe et al., 2007).

In-season N_2O emissions were related to timing of N fertilizer application, rainfall events, and cover crops (Figs. 2.2 through 2.4). The first N_2O emission was observed 11 to 15 d after fertilization and depended on the wetness of the soil during fertilizer application. In 2013, the first flux was recorded 15 d after urea application, which was 29.3% of the season emissions, and in 2014 it was 11 d after urea application, which was also 33.2% of total season emissions (Figs. 2.3a and b). In a long-term tillage and crop rotation study on silty loam soil in Indiana, Omonode et al. (2011) found that 50% of the N_2O emissions occurred shortly after N fertilizer was applied. In our study, cumulative N_2O emissions were greater in fertilized cropping systems (180 kg N ha^{-1} and 90 kg N ha^{-1}) compared with cover crops or fallow systems without N fertilizer (Fig. 2.5). Nitrous oxide emissions in the fertilized plots peaked under wet conditions (WFPS >60%) favorable to denitrification. The 114 mm of precipitation in June through July 2013 was significantly less than the average rainfall (241 mm) but contributed to the wet soil conditions, which favored these high N_2O losses during the latter part of the growing season. Almaraz et al. (2009) observed that denitrification and N_2O emissions increase with higher WFPS, reaching maximum N_2O emission at WFPS values from 60 to 75% and with maximum denitrification occurring at saturation.

Nitrous oxide emissions were greater in 2013, with losses from 1.1 to 4.5 kg N ha^{-1} $year^{-1}$ compared with 2014 losses of 0.46 to 4.4 kg N ha^{-1} $year^{-1}$. In addition to the influence of fertilizer application and rainfall events, the pool of NO_3-N and NH_4-N also can influence timing of N_2O emissions (Hellebrand et al., 2008). The soil was low in mineral N content (2-5 µg N g^{-1}) at the beginning of emission measurements in each growing season when N fertilizers were not applied (Fig. 2.4). Soil mineral N concentrations always increased after N-fertilizer application to 15 to 100 µg N g^{-1}soil but were never high for longer than three weeks and were always back to less than 10 µg N g^{-1}soil at the end of the growing season. The high N_2O emissions measured from mid-June through early July 2013 also corresponded to large decreases in soil inorganic N at both the 0- to 5-cm and 5- to 15-cm depths. Hence, the variability in precipitation following N application in both years contributed to elevated N_2O emissions, especially in Wh-Fw-Sg+90N and Wh-Fw-Sg+180N. Overall, soil inorganic N in 2014 was greater than 2013 after N application, which could help explain the contrasting results regarding N_2O emissions.

The use of cover crops can decrease N_2O emissions from cropping systems because of their ability to decrease mineral N availability for N_2O-producing processes (McSwiney et al., 2010; Eagle and Olander, 2012). Pigeon pea and sunn hemp had significantly lower N_2O emissions than cowpea (Fig. 2.5). The lower emissions from pigeon pea and sunn hemp treatments in both years could be due to less water-soluble C, greater accumulation of C and N, or readily decomposable organic C in these plant tissues. The growth, biomass accumulation, and N uptake by cover crops can vary based on adaptability to specific soil and climatic conditions. Among the cover crops, pigeon pea had the greatest C accumulation and aboveground biomass in the relatively drier year of 2012 (338 mm rainfall during cover crop season), but sunn hemp performed better in the wetter year of 2013 (539 mm rainfall). Overall performance of all cover crops was better in 2012 than in 2013 because rainfall was better distributed throughout the cropping season in 2012. These differences in rainfall events explain the difference in total aboveground biomass that eventually influenced N uptake and C accumulation among the various cover crops in 2012 and 2013.

The performance of the grain sorghum crop that followed various cropping systems was significantly influenced by N application and cover crops. Sorghum grain yield was significantly greater with 90 kg N ha^{-1} and 180 kg N ha^{-1} than in cropping systems with no fertilizer applied; however, sorghum grain yield following cowpea, pigeon, and sunn hemp over the fallow system with 0 kg N ha^{-1} was 42, 37, and 14% higher, respectively, in 2013 and 47, 49, and 44%, respectively, in 2014 (Tables 2.2 and 2.3). This result suggests the contribution of N and C from the cover crops was beneficial to the following cereal grain crop. Cheruiyot et al. (2001) showed that incorporation of the legume cover crop in a cereal production system can help improve N availability, resulting in improved biomass accumulation and grain yield of maize, because leguminous cover crop biomass is a source of organic matter that stimulates soil biological activity and results in better nutrient and moisture management.

van Groenigen et al. (2010) suggested that it was better to assess N_2O emissions as a function of crop yield. In our study, the ratios of N_2O cumulative fluxes to grain yields of sorghum in 2013 and 2014 ranged from 178 to 598 and 105 to 571 g N_2O-N Mg yield^{-1}, respectively (Tables 2.2 and 2.3). Overall, in both years, N_2O emissions per unit of grain yield or per unit grain N uptake or total N uptake was greatest in 180, followed by 90 kg N ha^{-1} (Tables 2.2 and 2.3). This result also was reflected in emission factors, which provided the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. The emission factors in both years was greater in the Wh-Fw-Sg+180N than in Wh-Fw-Sg+90N (Tables 2.2 and 2.3), which clearly shows that higher emission factors are usually associated with higher N rates.

CONCLUSIONS

Cropping systems significantly influenced N_2O emissions, plant N uptake, C accumulation by cover crops, and grain yields of sorghum that followed various systems. Fallow systems with 90 and 180 kg N ha^{-1} produced significantly greater N_2O emissions than all other cropping systems. Nitrous oxide emissions were relatively similar for various cover crop systems and fallow system with 0 kg N ha^{-1} of fertilizer application. Among various cropping systems with cover crops, pigeon pea and cowpea had greater C accumulation and N uptake than sunn hemp. Grain yield of sorghum following different cover crops was similar and usually significantly greater than fallow systems with 0 kg N ha^{-1}; however, the fallow systems with 90 and 180 kg N ha^{-1} produced the maximum grain yield. We conclude that inclusion of leguminous cover crops without inorganic N addition reduced N_2O emissions compared with fallow system without inorganic N. This approach also provides additional C accumulation and N uptake, thus contributing to increased grain yield of the following cereal grain crop.

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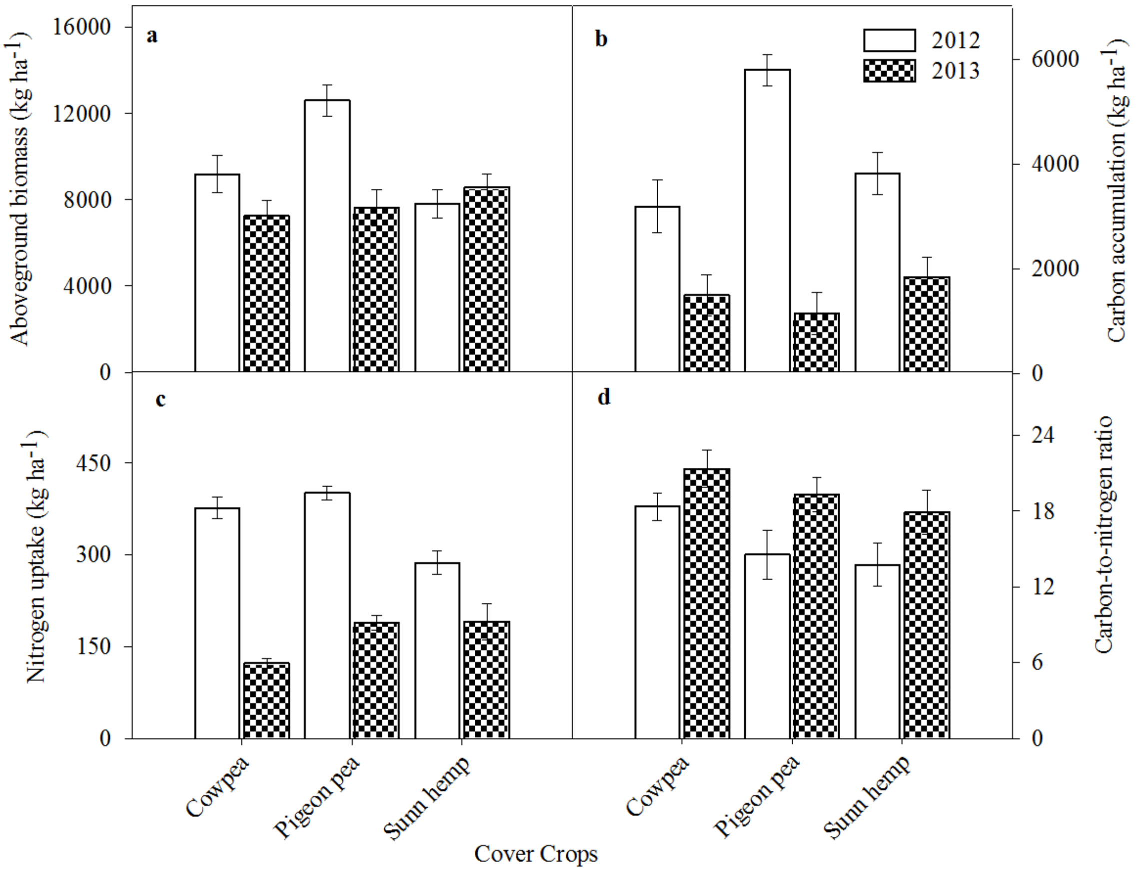

Figure 2.1. Effects of year by cover crops on (a) aboveground plant biomass, (b) C accumulation, (c) N uptake, and (d) carbon-to-nitrogen ratio.

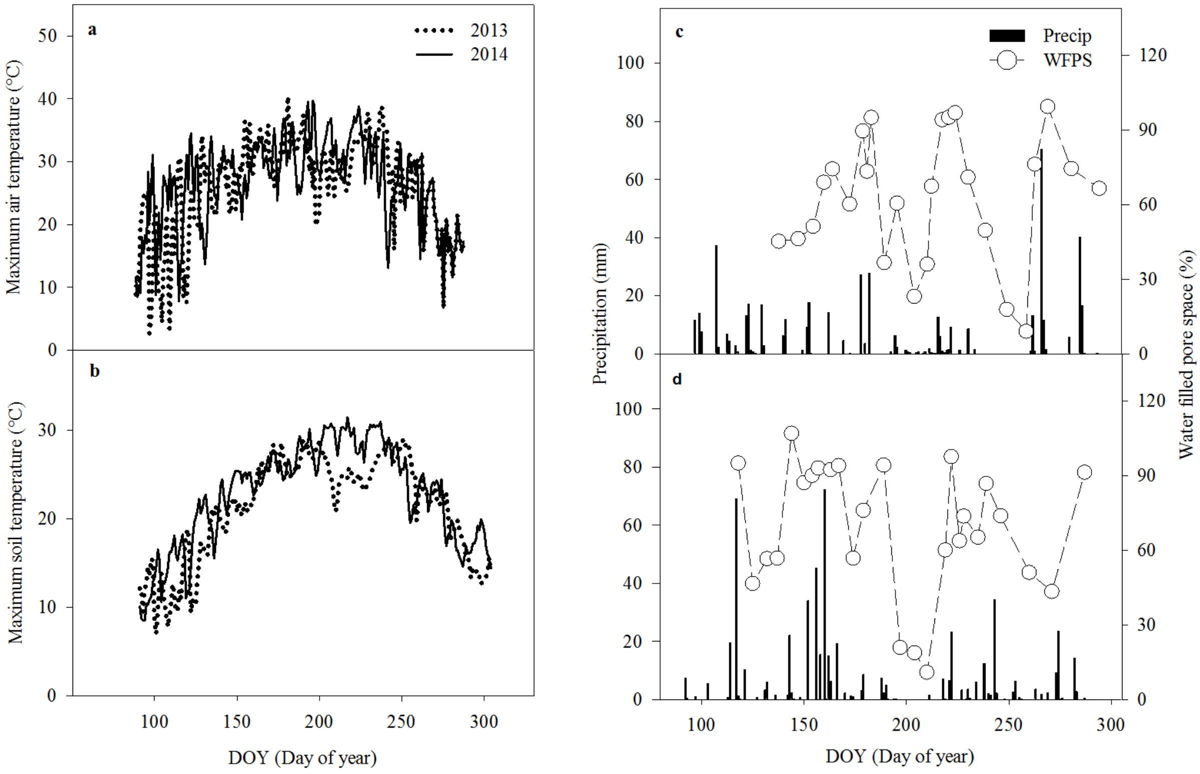

Figure 2.2. Daily (a) daily (a) maximum air temperature in 2013 and 2014, (b) maximum soil temperature in 2013 and 2014, (c) precipitation (precip.) and water-filled pores space (WFPS) in 2013, and (d) precipitation and WFPS in 2014.

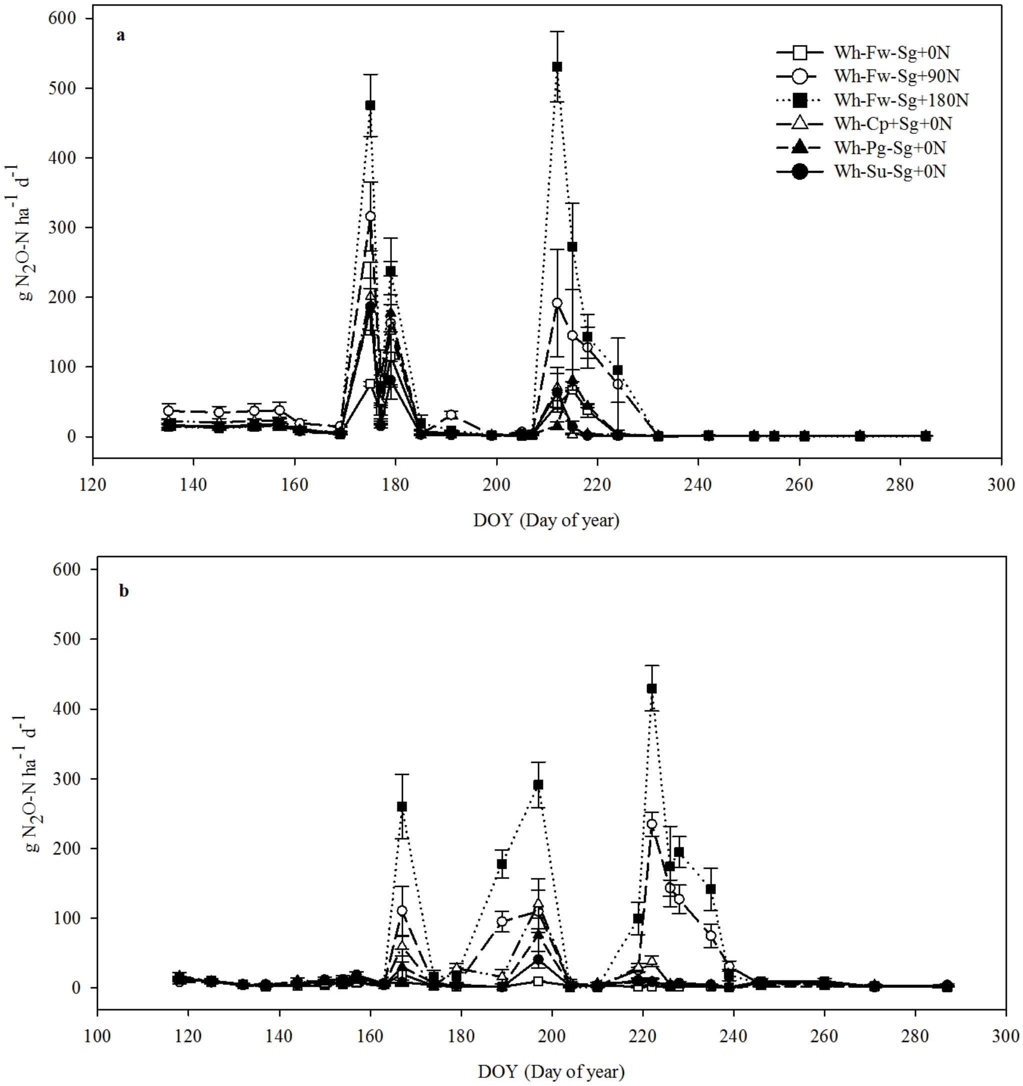

Figure 2.3. Effects of different sampling days and various cropping systems on daily N_2O-N emissions in (a) 2013 and, (b) 2014 growing seasons.

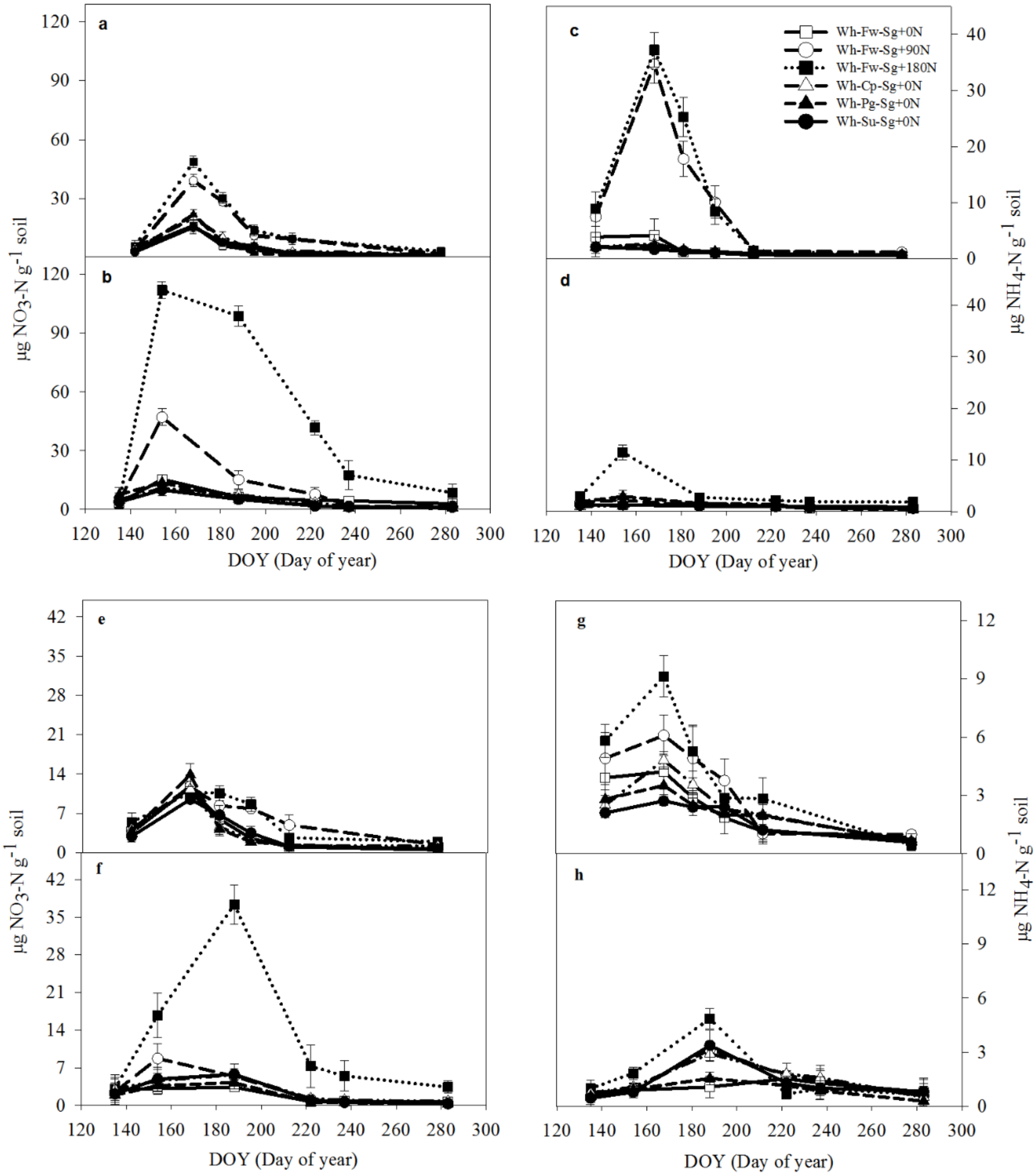

Figure 2.4. Effects of cropping systems and sampling dates on (a) NO_3-N at 0- to 5-cm depth in 2013 (b) NO_3-N at 0- to 5-cm depth in 2014 (c) NH_4-N at 0- to 5-cm depth in 2013, (d) NH_4-N at 0- to 5-cm depth in 2014, (e) NO_3-N at 5- to 15-cm depth in 2013 (f) NO_3-N at 5- to 15-cm depth in 2014, (g) NH_4-N at 5- to 15-cm depth in 2013, and (h) NH_4-N at 0- to 15-cm depth in 2014.

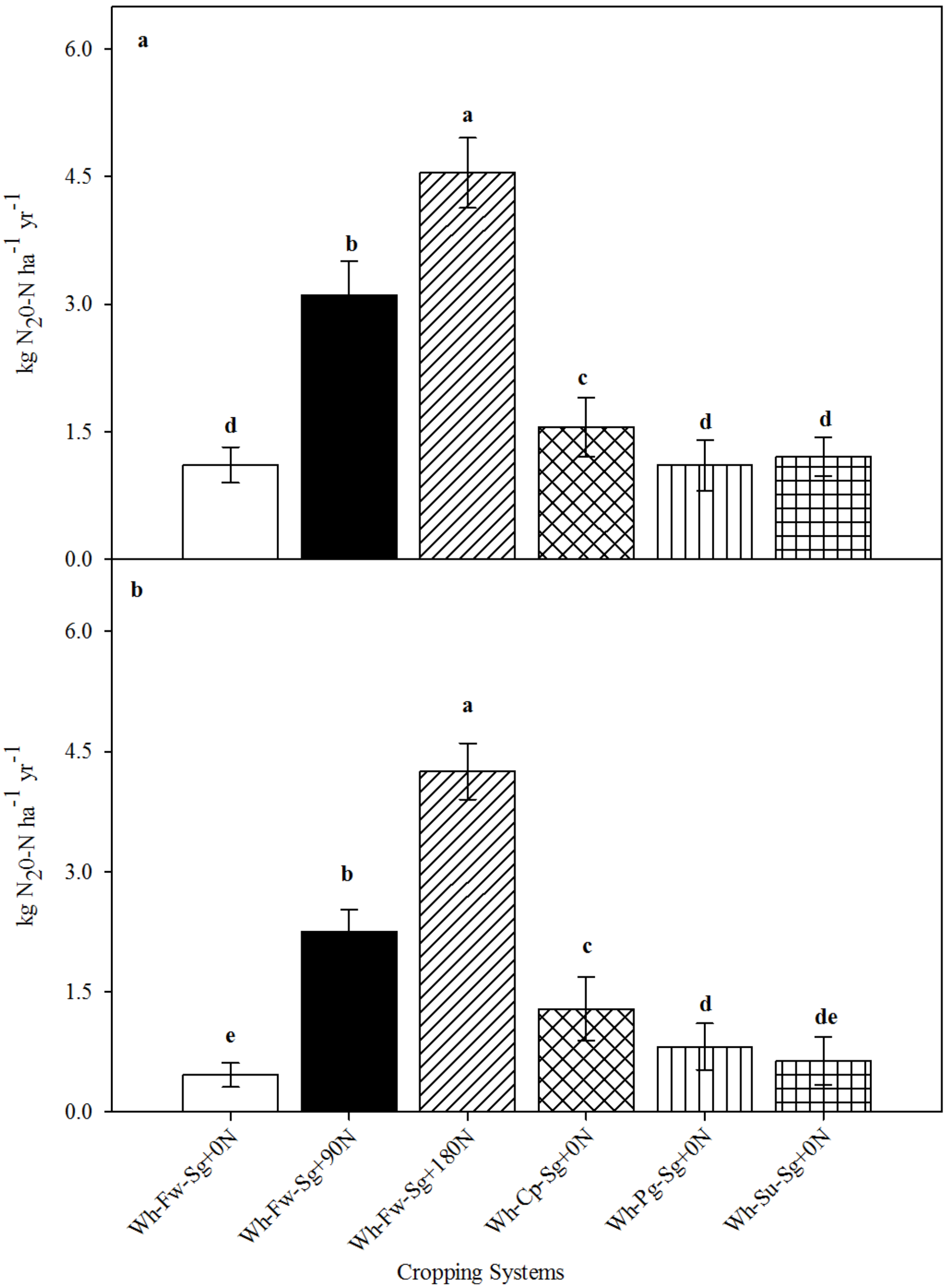

Figure 2.5. Cumulative N_2O-N emissions of different cropping systems in (a) 2013 and, (b) 2014 growing seasons.

Table 2.1. Physical and chemical characteristics of soil from the two fields.

Parameters	Units	First field	Second field
Sand	%	14.0	18.0
Silt	%	55.0	49.0
Clay	%	31.0	33.0
pH		8.00	6.30
Mehlich-3 P	mg kg^{-1}	10.2	12.5
K	mg kg^{-1}	221	208
Na	mg kg^{-1}	16.9	17.5
Cl^-	mg kg^{-1}	8.30	7.20
SO_4-S	mg kg^{-1}	1.90	2.60
Organic Matter	%	3.00	2.90

Table 2.2. Effects of N rate and cropping systems on cumulative N_2O-N emissions, grain yield, N uptake, and N_2O emission per unit of grain N and total N uptake of grain sorghum in 2013 growing season.

Cropping system	Grain yield	Aboveground N uptake	Grain N uptake	Total N uptake	N_2O- N emission: Per unit of grain yield	N_2O- N emission: Per unit grain N uptake	N_2O- N emission: Per unit total N uptake	Emission factor
	……………………… kg ha^{-1}		………………………		g N Mg^{-1}	……..g N kg^{-1}	……..	%
Wh-Fw-Sg+0N	4540	36.3	34.6	70.9	246.3	32.2	15.6	-
Wh-Fw-Sg+90N	7134	56.1	55.8	111.9	438.0	50.1	25.2	1.91
Wh-Fw-Sg+180N	7581	61.1	62.0	123.2	598.0	81.4	40.6	2.22
Wh-Cp-Sg+0N	6439	44.3	46.0	90.3	243.0	30.2	16.8	-
Wh-Pg-Sg+0N	6228	43.9	55.9	99.8	178.1	19.8	11.1	-
Wh-Su-Sg+0N	5181	38.6	42.2	80.9	231.7	28.6	14.9	-
LSD (0.05)	1327	22.7	16.9	35.9	80.6	9.6	8.4	

Table 2.3. Effects of N rate and cropping systems on cumulative N_2O-N emissions, grain yield, N uptake, and N_2O emission per unit of grain N and total N uptake of grain sorghum in 2014 growing season.

Cropping system	Grain yield	Aboveground N uptake	Grain N uptake	Total N uptake	N_2O- N emission: Per unit of grain yield	N_2O- N emission: Per unit grain N uptake	N_2O- N emission: Per unit total N uptake	Emission factor
	……………………… kg ha^{-1}			………………………	g N Mg^{-1}	………g N kg^{-1}…….		%
Wh-Fw-Sg+0N	4197	21.8	31.5	53.3	109.3	20.1	11.9	-
Wh-Fw-Sg+90N	6853	46.6	64.4	110.9	325.8	69.2	40.2	1.98
Wh-Fw-Sg+180N	7754	38.6	84.1	122.7	571.3	54.2	37.1	2.11
Wh-Cp-Sg+0N	6176	24.5	50.7	75.2	207.3	44.3	29.9	-
Wh-Pg-Sg+0N	6238	29.1	41.9	71.0	131.1	30.7	18.1	-
Wh-Su-Sg+0N	6049	30.1	47.1	77.9	105.5	17.0	10.4	-
LSD (0.05)	1763	9.6	20.2	20.3	97.5	37.9	6.2	

CHAPTER 3 - IMPACT OF COVER CROPS AND VARYING NITROGEN RATES ON GROWTH AND YIELD OF GRAIN SORGHUM

ABSTRACT

Leguminous cover crop systems have been envisaged as a critical component of sustainable agriculture because of their potential to increase soil productivity through cycling of carbon and nitrogen in agricultural systems. We hypothesized that including leguminous cover crops in a cropping system would improve N availability and grain yield of the succeeding grain sorghum [*Sorghum bicolor* (L.) Moench] crop. Our objective was to determine the effects of inclusion of summer cover crops and varying N rates in the cropping system on growth and yield of the succeeding grain sorghum crop grown in no-tillage system. Field experiments were conducted in 2012-2013 and 2013-2014 growing seasons in Kansas. Leguminous summer cover crops and double-cropped soybean residues improved soil N availability, and N was subsequently used by the succeeding crop. Across years and cropping systems, mean increases in grain yield as a result of including cowpea [*Vigna unguiculata* (L.) Walp.], pigeon pea [*Cajanus cajan* (L.) Millsp], sunn hemp (*Crotalaria juncea* L.), double-cropped soybean [*Glycine max* (L.) Merr.], and double-cropped grain sorghum in the rotation compared with a fallow system with 0 kg N ha^{-1} were 56, 62, 43, 32, and 3%, respectively, and N fertilizer replacement values across years were 53.3, 64, 36.1, 27, and -2.5 kg N ha^{-1}, respectively. Through the years, grain sorghum in the double-cropped soybean cropping system and the fallow system with 90 kg N ha^{-1} gave sustained economic net returns.

INTRODUCTION

Grain sorghum is one of the most drought- and stress-tolerant crops grown in the world, especially in semiarid regions. For this reason, much of the world’s grain sorghum is grown in high-risk environments where other crops are more likely to fail or be unprofitable. Although grain sorghum uses N efficiently, either on par with or better than C_3 cereals, N deficiency suppresses plant growth and dry matter accumulation (Zhao et al., 2005). Leguminous cover crops have been envisaged as a critical component of sustainable cropping systems because of their potential to increase soil productivity through cycling of C, N, and other nutrients (especially P) in agricultural systems (Chikowo et al., 2004) and have been used to improve environmental quality by reducing soil erosion and nutrient losses through surface runoff. Winter cover crops have been emphasized (Clark et al., 1995). Blackshaw et al. (2001) measured a 16- to 52-kg ha^{-1} increase in soil N following a sweet clover [*Melilotus officinalis* (L.) Pall.] cover crop compared with fallow treatments, and wheat (*Triticum aestivum* L.) yields were 47 to 75% greater following sweet clover than fallow treatments, suggesting enhanced N availability from the legume residue.

Little information is available on the contribution of summer cover crops to succeeding cereal crop production under a no-tillage (NT) system. Agricultural management systems that involve soil management practices such as NT have the potential to generate both economic and environmental benefits, including mitigating soil erosion, reducing energy use and C emissions, enhancing timeliness of planting, and saving labor and time (West and Marland, 2002). No-tillage is also environmentally friendly because it sequesters C in the soil (West and Marland, 2002). The improvements generated by the adoption of NT techniques often have positive effects on crop growth and yield. Studies have shown that the effects of NT on crop productivity can vary with other crop management practices, and that NT generally produces a better result when combined with a well-planned crop rotation (Amato et al., 2013).

Previous research has demonstrated that leguminous cover crops can decrease inorganic N fertilizer requirements and production costs through symbiotic N_2 fixation (Cherr et al., 2006). In addition, N accumulation in plant biomass can provide large amounts of mineralized N if the entire growth is uniformly distributed onto the soil surface in an NT system. Summer cover crops such as cowpea, pigeon pea, and sun hemp are considered to have greater N fixation capacity than other legume crop species (Chikowo et al., 2004). Temperature has a great influence on the distribution, growth, yield, and quality of most grain legume crops. These summer cover crops have better heat tolerance than some typical legumes that have been grown in the U.S. (soybean, clovers (*Trifolium* sp, etc); for instance, pigeon pea can tolerate long-term stress during its growth cycle, especially the long-duration varieties (Subbarao et al., 2000). Optimal growing temperature is 18 to 30°C. In contrast, (Liu et al., 2008) reported that soybean is very sensitive to temperature changes, and that suitable temperature for growth and development ranged from 15 to 25°C.

Nitrogen fixation capacity on a yearly basis in an African study were estimated to range from 30 to 125 kg N ha^{-1} (Ennin Kwabiah and Osei Bonsu, 1993) and 40 to 97 kg ha^{-1} (Mafongoya et al., 2006) for cowpea and pigeon pea, respectively. In addition, N_2 fixation from soybean ranged from 36 to 82%, and total N_2 fixed in aboveground biomass ranged from 40 to 224 kg N ha^{-1} (Schipanski et al., 2010). Unkovich and Pate (2000) found that soybean fixed an average of 175 kg N ha^{-1} yr^{-1} in irrigated production, and 100 kg N ha^{-1} yr^{-1} in dryland production. Balkcom and Reeves (2005) found that the amount of N in sunn hemp residues averaged 144 kg ha^{-1}, similar to crimson clover (*Trifolium incarnatum* L.) and hairy vetch *(Vicia* *villosa* Roth), which are common winter legume crops in the southern U.S. Nitrogen availability to a subsequent crop from legume cover crops can vary with management options, such as tillage; soil and environmental conditions, such as temperature and soil moisture; and tissue quality characteristics, such as content of C, N, cellulose, lignin, and polyphenols (Varco et al., 1993; Fox et al., 1990).

Nitrogen nutrition is a critical component of any cereal production system. Nutrient inputs from chemical fertilizers are needed to replace nutrients that are exported and lost during cropping to maintain a positive nutrient balance; however, inorganic fertilizer should be used judiciously because of its high cost. Recent volatility in supplies and prices of natural gas and synthetic N fertilizer (Huang et al., 2009) suggests a need to develop and refine alternative strategies for supplying N for grain sorghum production. Previous research has shown that application of N increased aboveground biomass and grain yield of grain sorghum (Mahama et al., 2014; Kaizzi et al., 2012). Increases in grain sorghum grain yield were mainly associated with improving panicle number, grain number per panicle, and grain weight (Buah et al., 2012). Mahama et al. (2014) observed that application of N up to 90 kg ha^{-1} increased grain number, grain yield, and harvest index in grain sorghum. Greater yields and components of yields with increases in N application were also observed in maize and wheat (Ma et al., 2006; Demotes-Mainard and Jeuffroy, 2004). Increases in leaf photosynthesis rates were observed under higher N levels in grain sorghum (Cechin, 1998).

Little research has been done on the responses of grain sorghum to summer leguminous cover crops with no N fertilizer application on various physiological and yield traits. Enhanced understanding of grain sorghum responses to N and its performance under summer leguminous cover crops and associations among various traits are needed to develop improved and sustainable cropping systems. We hypothesized that including leguminous cover crops in a cropping system would improve N availability and grain yield of the succeeding grain sorghum crop. Our objective was to determine the effects of inclusion of summer cover crops and varying N rates in the cropping system on growth and yield of the succeeding grain sorghum crop grown in no-tillage system.

MATERIALS AND METHODS

Site Description and Experimental Design

Field experiments were conducted at two sites in the 2012-2013 and 2013-2014 growing seasons on separate fields to evaluate the response of grain sorghum to summer cover crops and varying N fertilizer rates. Both sites for the study were located on Kansas State University (KSU) Department of Agronomy research facilities near Manhattan, KS. One experimental site was situated on a Reading silt loam soil (fine-silty, mixed, mesic Typic Argiudolls; 39°08’35.3”N, 96°37’39.2”W), and the other was on a well-drained Kennebec silt loam (fine-silty, mixed, superactive, mesic Cumulic Hapludolls; 39°11’30”N, 96°35‘30”W). The experiments were implemented on sites that had not been tilled for at least the previous six years. The field layout is summarized as follows: Wh-Fw-Sg+0N, wheat rotated with grain sorghum plus 0 kg N ha^{-1}; Wh-Fw-Sg+45N, wheat rotated with grain sorghum plus 45 kg N ha^{-1}; Wh-Fw-Sg+90N, wheat rotated with grain sorghum plus 90 kg N ha^{-1}; Wh-Fw-Sg+135N, wheat rotated with grain sorghum plus 135 kg N ha^{-1}; Wh-Fw-Sg+180N, wheat rotated with grain sorghum plus 180 kg N ha^{-1}; Wh-Cp-Sg+0N, cowpea rotated with grain sorghum after wheat; Wh-Pg-Sg+0N, pigeon pea rotated with grain sorghum after wheat; Wh-Su-Sg+0N, sunn hemp rotated with grain sorghum after wheat; Wh-Sb-Sg+0N, double-cropped soybean rotated with grain sorghum after wheat; Wh-Sg-Sg+0N, double-cropped grain sorghum rotated with grain sorghum after wheat.

Soil Sampling and Analyses

In both years, composite soil samples were taken from each replication to a depth of 60 cm. Sampling was done using a hand probe (3.2 cm diameter), and samples consisted of 12 to 15 individual cores mixed to form individual composite samples. The soil was analyzed for pH, available P, exchangeable K, soil organic matter (SOM), S, and Cl^- Soil physical properties such as sand, silt, and clay were also determined for each replication to a depth of 30 cm at both sites. Another set of soil samples for the 30- to 60-cm depth were analyzed for soil nitrate and ammonium. Analyses were conducted by the KSU Soil Testing Laboratory.

The hydrometer method was used to determine soil texture. Soil pH was estimated using a 1:1 slurry method with a 10-g scoop of soil and 10 mL of deionized water. Mehlich-3 P was analyzed by the HCl-ammonium fluoride extraction method. Extractable (plant-available) K and Na were determined by the ammonium acetate (1 M, pH 7.0) extraction method. The Walkley-Black method was used to determine organic matter. Chloride was analyzed by calcium nitrate extraction. The turbidimetric method was used to determine sulfate-S. Ammonia was extracted from soil samples with 1 M KCl (2 g in 20 mL, 30 min) and measured by an indophenol colorimetric reaction.

The results of soil analyses presented in Table 3.1 document the substantial differences in soil textural and chemical properties between the two experimental sites. Soil texture probably exerts more influence on soil productivity and management requirements than any other physical characteristics of soil (Kay and Angers, 1999). The soil texture at Ashland Bottoms consisted of more than 50% of sand and <1 soil organic matter (SOM). The SOM content of most agricultural soils in Kansas ranges from 1 to 5%, with an average of 2.2%. Soil organic matter is roughly 5% N. At Agronomy North Farm (ANF), the soil texture consisted of <20% sand and >2.5 SOM. Soil ammonium and nitrate were greater at ANF in both years. The differences between the two sites in texture and SOM can influence grain sorghum response to N fertilizer application, previous cover crops, and double-cropped grain crops (soybean and grain sorghum).

Winter Wheat and Cover Crop Phase

Cover crops were evaluated in the 2011-2012 and 2012-2013 growing seasons after winter wheat. Plots were arranged in a randomized complete block design with four replications. Each plot dimension was 9.1 m long and 4.5 m wide (6 rows). Winter wheat was drilled in October 2011 and September 2012 with a target seeding rate of 115 kg ha^{-1} and 19-cm row spacing with no fertilizer applied at planting. The wheat was harvested in July in both site-years, and the stubbles were sprayed immediately after harvest with 3.5 L ha^{-1} glyphosate 4 plus herbicide [N-(phosphonomethyl) glycine] to control weeds and volunteer wheat.

Three different cover crops, cowpea, pigeon pea, and sunn hemp, were established in the standing wheat stubble with a John Deere 1590 (Deere & Co., Moline, IL, USA) equipped with residues managers in July in both years and at both sites. Chemical fallow was used as a check treatment, and double-cropped soybean and grain sorghum were included as the most likely cash crop alternatives following winter wheat harvest. Cowpea, pigeon pea, and sunn hemp seeds were treated with a commercial rhizobium inoculant and planted at a seeding rate of 57, 28, and 13 kg ha^{-1}, respectively, on 19 June 2012 and 12 July 2013 at a depth of 1.3 to 2.5 cm. The double-cropped soybean (KS3406RR) and grain sorghum (DKS28-05) were planted at seeding rates of 350,000 and 125,000 seeds ha^{-1}, respectively.

At physiological maturity, aboveground portion of 10 plants from each plot planted to grain sorghum were randomly sampled. Two 2.5-m rows were sampled at R7 stage for soybean. Samples were dried at 60°C in a forced-air oven for 72 h and weighed. Based on the individual plot plant population, total aboveground biomass was determined and expressed per unit area.

The dry samples were ground with a Wiley mill (Model 4, Arthur H. Thomas Company, Philadelphia, PA) and analyzed for total N and carbon (C) by dry combustion (modified Dumas method) using a LECO CHN-2000 elemental analyzer (LECO Corp., St. Joseph, MI).

Leguminous cover crop performance was measured throughout the growing season. Stand counts were made for all cover crops 20 days after plant emergence within an area of 4.5 m^2. In 2012, two rows of 4.5-m^2 samples were hand-harvested from all cover crop plots, but a portable rotary mower was used for harvesting in 2013. The fresh plant material cut from the summer leguminous cover crop plots were then uniformly distributed on the harvested plots and left in the field to decompose. Cowpea, pigeon pea, and sunn hemp cover crops were terminated based on beginning flowering at 67, 88, and 84 d after emergence, respectively, in 2012. Corresponding values in 2013 were 70, 90, and 88 d, respectively. In both years, aboveground subsamples from each plot of the cover crops were dried in a forced-air dryer at 60°C until dry, then weighed to obtain dry matter content. The dried samples were ground with a Wiley Mill and analyzed for N and C by dry combustion (modified Dumas method) using a LECO CHN-2000 elemental analyzer (LECO Corp., St. Joseph, MI) at the KSU Soil Testing Laboratory. Nitrogen uptake and C accumulation of the various cover crops were determined by multiplying aboveground dry matter weight by percentage N concentration or percentage C concentration.

Double-cropped soybean and grain sorghum were harvested in October in both years with a two-row combine harvester using a modified two-row Gleaner (model EIII; AGCO Corporation, Duluth, GA) equipped with a weighing balance. Grain moisture and test weight were estimated with a DICKEY-John GAC 2000 (DICKEY-John Corp., Springfield, IL).

Grain Sorghum Phase

Prior to planting grain sorghum, all plots were sprayed with glyphosate 4 plus herbicide [N-(phosphonomethyl) glycine] at 3.5 L ha^{-1} and 2,4-dichlorophenoxyacetic acid at 2.4 L ha^{-1}. Grain sorghum was then planted at a target seeding rate of 125,000 plant ha^{-1}. Standard spacing for grain sorghum, 75 cm between rows, was used during planting at both sites and years. Nitrogen fertilizer (urea 46% N) rates of 0, 45, 90, 135, and 180 kg N ha^{-1} were applied to grain sorghum in fallow system plots. The fertilizer was hand-broadcast 10 to 14 d after emergence along the rows of each plot to ensure that N was evenly distributed. Herbicides used for pre-emergence weed control for both sites and years were: Calisto (active ingredients (a.i): Mesotrione 40% [0.48 kg a.i L^{-1}], other ingredients 60%) at a rate of 0.37 L ha^{-1} and Bicep II Magnum (active ingredients: Atrazine 33.0%, Atrazine-related compounds 0.7% [0.37 kg a.i L^{-1}], S-metolachlor 26.1% [0.29 kg a.i L^{-1}], other ingredients 40.2%) (Syngenta Crop Protection Inc., Greensboro, NC) at a rate of 2.75 L ha^{-1} using a tractor-mounted boom sprayer. Hand weeding was also done as and when necessary throughout the growing season to keep fields weed-free. The inside two rows were used for data collection to eliminate border effects.

The aboveground portion of 10 plants from each grain sorghum plot were randomly sampled at physiological maturity and separated into leaves, stems, and panicles. Samples were dried at 60°C in a forced-air oven for 72 h and weighed. Based on the individual plot plant population, total aboveground biomass was calculated and expressed per unit area. The dried leaf and stem samples were ground in a Thomas-Wiley laboratory mill to pass through a 2.0-mm screen. The panicles were threshed in a stationary thresher (Model LDB, ALMACO, Nevada, IA) and the grain ground in a cyclone sample mill (Model 3010-030, Udy Corporation, Fort Collins, CO). Nitrogen concentration was analyzed by wet-digesting samples with H_2SO_4 and

H_2O_2, and the total N in the digest was analyzed by a colorimetric procedure (nitroprusside-sodium hypochlorite) using an RFA autoanalyzer (Alpkem Co., Clackamas, OR).

In both years and sites, 10 plants were tagged in the two middle rows for phenological measurement (days to 50% flowering), growth traits (plant height), and physiological traits. Physiological measurement such as leaf chlorophyll index was measured with the aid of a soil plant analysis development (SPAD) chlorophyll meter (Model 502, Minolta Corp., Tokyo, Japan). Readings were taken at 5 growth stages. At growth stage 3, readings were taken from the uppermost fully expanded leaves from 10 different plants in each plot and averaged to one value per plot. At growth stages six through nine, the fully expanded leaf below the flag leaf was used to measure leaf chlorophyll index. Two representative plants were tagged at growth stages 5 through 7 in each plot within each replication from which photosynthesis, transpiration, stomatal conductance, and intercellular CO_2 concentration using a handheld photosynthesis system (CI-340, CID Bio-Science, Camas, WA) were measured. All measurements were taken between 11:00 AM and 3:00 PM on a clear-sky day.

Plots were mechanically harvested after physiological maturity using a modified two-row Gleaner equipped with a weighing balance. Grain moisture and test weight were estimated with a DICKEY-john GAC 2000. Yields at both sites and years were then corrected to 135 g kg^{-1} moisture content. Kernels plant^{-1} were counted with the aid of seedburo counting machine (Model 77, Inpack Systems, Madison, WI).

Components of N Use Calculations

Nitrogen use was calculated as follows.

Nitrogen uptake (kg ha^{-1}) = [(Aboveground dry matter) x (N concentration in dry matter 100)]

Carbon uptake (kg ha^{-1}) = [(Aboveground dry matter) x (C concentration in dry matter / 100)]

Grain N uptake (kg ha^{-1}) = [(Grain yield) x (grain N concentration / 100)]

Nitrogen utilization efficiency (kg kg^{-1}) = Grain yield / total N uptake

Nitrogen harvest index = [(Grain N uptake / total N uptake)] x 100

Economic Analyses

Economic analyses were performed based on statistically significant treatments of the experiment to determine fallow systems with N rates, summer cover crop systems, double-cropped soybean, and double-cropped grain sorghum cropping systems that gave acceptable net returns at low cost to producers (CIMMYT, 1988). Economic analyses were done using the prevailing US market price (USDA-NASS, 2013) for inputs at planting and for output at the time of harvest. All costs and benefits were calculated on hectare basis in US dollars. Concepts used in the economic analyses are defined as follows: Mean grain yield of grain sorghum is the average yield (kg ha^{-1}) of each treatment in each year. The gross benefit per hectare is the product of field prices of grain sorghum and the mean yield for each treatment. The total variable cost (TVC) is the sum of field cost of fertilizer and application, herbicides and application, seeds, harvesting, and hauling cost. The net benefit per hectare (NB) for each treatment is the difference between the gross benefit and the total variable cost. For each of the treatments, a percentage marginal rate of return (MRR) was calculated. The percentage MRR between any pair of treatments denotes the return per unit of investment in fertilizer expressed as a percentage of that investment. To obtain an estimate of these returns, the following formula was used.

MRR (between treatments 1 and 2) = [(Change in net benefit (NB_1-NB_2) / (change in TVC (TVC_2-TVC_1))] x 100.

Thus, an MRR of 100% implies a return of one dollar on every dollar of expenditure for the given variable input.

Data Analyses

Statistical analyses were performed using PROC MIXED, PROC CORR, and PROC REG in SAS 9.1 (SAS Institute, 2003). The normality of distribution of the studied traits were tested using the Shapiro-Wilk normality test. A three-way analysis of variance was carried out to determine the effects of years (Y), cropping systems (CS), and site (S) and combination of all the interactions. Cropping system, site, and year were treated as fixed effects, and replication was treated as a random effect. Mean separation for significant effects was performed using Tukey's honestly significant difference test at 0.05%. Tests for homogeneity of variances (Hartley, 1950) across sites showed that variances were homogenous. Data from all sites and years were therefore pooled.

RESULTS

Weather Conditions

Precipitation and temperature during the cropping season varied among site years of the study. Maximum temperature in July was 4.6°C above the 30-year average in 2012. Total precipitation (April-October) in 2012, 2013, and 2014 was 338 mm, 539 mm, and 576 mm, respectively. These were below the 30-year average of 698 mm.

Aboveground Biomass Accumulation, Carbon, and Nitrogen Uptake by Cover Crops

No three-way interactions were observed between site, year, and cropping system for any of the parameters measured or computed in this study. Therefore, discussion of the results will focus on two-way interactions and main effects as appropriate. Although the summer cover crops and double-cropped grain crops performance depended on year, it was similar at both sites. The response of cropping system differed with year ($P < 0.05$) for aboveground biomass, plant N uptake, total plant C and C/N ratio of the summer cover crops and the grain crops (double-cropped soybean and double-cropped grain sorghum) (Fig. 3.1). Among the summer cover crops, pigeon pea had the most aboveground plant biomass, followed by sunn hemp and cowpea in 2012. In 2013, sunn hemp produced the most aboveground biomass, but no significant difference was detected between cowpea and pigeon pea (Fig. 3.1a). Double-cropped grain sorghum and double-cropped soybean in both years had similar aboveground biomass, but aboveground biomass of cowpea and pigeon pea did not differ in 2014.

Total N uptake of cowpea and pigeon pea was relatively greater than that of sunn hemp and double-cropped soybean in 2012. In 2013, no significant difference was found among cowpea, sunn hemp, and soybean for plant N uptake and all were lower than pigeon pea (Fig. 3.1b). Double-cropped grain sorghum had the least total N uptake in both years (Fig. 3.1b).

Plant carbon accumulation was similar for pigeon pea and sunn hemp but was significantly greater than that of cowpea, double-cropped soybean, and double-cropped grain sorghum in 2012 (Fig. 3.1c). In 2013, sunn hemp had the greatest plant C accumulation, followed by double-cropped grain sorghum. Plant C accumulation was similar for pigeon pea and double-cropped soybean, whereas cowpea had the least plant C accumulation. Carbon/nitrogen ratios were similar for all the cover crops and double-cropped soybean and were less than 25:1 in both years. Double-cropped grain sorghum had the greatest C/N ratio and was greater than 30:1 in both years (Fig. 3.1d).

Physiology Traits of Grain Sorghum

Response of sorghum to cropping systems differed with year ($P < 0.05$) for leaf chlorophyll index and photosynthetic rate (Fig. 3.2). Leaf chlorophyll index for cover crop systems and the double-cropped soybean cropping system did not differ significantly in 2013 (Fig. 3.2a), and a similar trend was observed in 2014. Grain sorghum in the fallow system with 0 kg N ha^{-1} or in the double-cropped grain sorghum cropping system had the smallest leaf chlorophyll index in both years. Leaf chlorophyll index in all of the summer cover crop systems and the double-cropped soybean system in both years was equivalent to leaf chlorophyll index in the fallow system with N fertilizer application of 45 kg ha^{-1}. Leaf chlorophyll index response to N fertilizer application in both years was quadratic (2013: $r^2 = 0.94$; $P = 0.0260$; 2014: $r^2 = 0.99$; $P = 0.0042$). Overall, leaf chlorophyll index was greater in 2013 than in 2014 (Fig. 3.2a).

In both years, photosynthetic rate was greater in systems with pigeon pea, sunn hemp, and double-cropped soybean than in the cowpea cropping system. The double-cropped grain sorghum system had the smallest photosynthetic rate (Fig. 3.2b). Photosynthetic rate was similar for the fallow system with 90 kg N ha^{-1}, all cover crop systems, and the double-cropped soybean system in 2013 (Fig. 3.2b). Photosynthetic rate in 2014 was similar for all of the cover crop systems, the double-cropped soybean system, and the fallow system with N fertilizer application of 45 kg ha^{-1}. Photosynthetic rate increased with an increasing rate of N fertilizer application in the absence of cover or double-crops in both years (2013: $r^2 = 0.93$; $P = 0.0044$; 2014: $r^2 = 0.94$; $P = 0.0041$).

Cropping systems affected ($P < 0.05$) stomatal conductance, transpiration rate, and intercellular CO_2 concentration (C_i) of the subsequent sorghum crop (Table 3.2). Stomatal conductance followed no particular trend in its response to N fertilizer application except that it was greater with the application of 180 kg N ha^{-1}. Stomatal conductance was similar for sorghum in all of the cover crop systems, the double-cropped soybean cropping system, and fallow systems with N fertilizer application less than 180 kg N ha^{-1}. Grain sorghum in the double-cropped grain sorghum cropping system had the lowest stomatal conductance.

Fallow system with 0 kg N ha^{-1} had the lowest transpiration rate, but transpiration rate did not differ in pigeon pea and double-cropped grain sorghum cropping systems and fallow systems with N fertilizer application. Furthermore, cowpea, sunn hemp, and double-cropped soybean cropping systems had similar transpiration rates over the years. Intercellular CO_2 concentration was similar in the fallow system with 180 kg N ha^{-1}, the sunn hemp, and the double-cropped soybean cropping systems. The cowpea cropping system had C_i similar to that of fallow systems with 0 kg N ha^{-1} to 135 kg N ha^{-1}. Pigeon pea and double-cropped grain sorghum cropping systems had the lowest C_i (Table 3.2).

Phenology and Growth Traits of Grain Sorghum

Cropping systems had a significant ($P < 0.05$) effect on days to flowering (DTF) (Table 3.2). Fallow systems with N fertilizer application of 90 kg ha^{-1} or more flowered 1 to 3 d earlier than those with 45 kg N ha^{-1} and 7 to 9 d earlier than systems with 0 kg N ha^{-1}. Flowering was similar for grain sorghum after all legumes (summer cover crops or double-cropped soybean) and did not differ from when 45 kg N ha^{-1} was applied in the fallow system. In the double-cropped grain sorghum cropping system, DTF was similar to that for grain sorghum in the fallow system without N fertilizer application (Table 3.2).

Cropping systems significantly ($P < 0.05$) affected aboveground biomass at physiological maturity (Table 3.2). Aboveground biomass at physiological maturity in cropping systems with any of the summer cover crops or the double-cropped soybean cropping system was similar to aboveground biomass in the fallow system with 45 kg N ha^{-1}. The double-cropped grain sorghum cropping system and the fallow system with 0 kg N ha^{-1} had the least aboveground biomass at physiological maturity (Table 3.2). Response of grain sorghum aboveground biomass at physiological maturity to N fertilizer application fit a quadratic curve ($r^2 = 0.97$; $P = 0.0041$).

At maturity, cropping systems had a significant ($P < 0.05$) effect on sorghum plant height. Plant height was not significantly different in fallow systems with N fertilizer application or in cover crop systems, but plant height was significantly shorter in the fallow system with 0 kg N ha^{-1} and in the double-cropped grain sorghum cropping system (Table 3.2).

Components of Yield and Grain Yield

Response of sorghum to cropping systems differed with year ($P < 0.05$) for kernels $plant^{-1}$ and grain yield. Kernels $plant^{-1}$ was greater in 2013 than in 2014 (Fig. 3.2c). In 2013, grain sorghum kernels $plant^{-1}$ in either cowpea or pigeon pea cropping systems was relatively similar to kernel $plant^{-1}$ in the fallow system with 45 kg N ha^{-1}. Furthermore, grain sorghum in the sunn hemp cropping system had fewer kernels $plant^{-1}$ compared with that of grain sorghum in the double-cropped soybean cropping system. But the fallow system with 0 kg N ha^{-1} and the double-cropped grain sorghum system had the fewest kernels $plant^{-1}$ (Fig. 3.2c). Grain sorghum kernels $plant^{-1}$ in 2014 in cowpea, pigeon pea, and double-cropped soybean cropping systems were similar and comparable to kernel $plant^{-1}$ in the fallow system with 45 kg N h^{-1} (Fig. 3.2c). In addition, the sunn hemp cropping system had kernels $plant^{-1}$ greater than that of double-cropped grain sorghum system. In both years, kernels $plant^{-1}$ increased with increasing N fertilizer application (2013: $r^2 = 0.99$, $P =0.0041$; 2014: $r^2 = 0.96$; $P = 0.0018$).

Grain sorghum in the pigeon pea cropping system had the greatest grain yield and was equivalent to grain yield in the fallow system with 90 kg N ha^{-1}. Grain yield in the cowpea cropping system was equivalent to that of the fallow system with 45 kg N ha^{-1} in 2013 (Fig.

3.2d). Grain sorghum in the sun hemp and double-cropped soybean cropping system had similar grain yield. In 2014, grain yield was significantly greater in all the cover crops systems compared with double-cropped soybean system (Fig. 3.2d). Overall, grain yield in any of the cover crop systems was equivalent to grain yield in the fallow system with 45 kg N ha^{-1} in 2014. Grain yield was significantly greater in 2013 than in 2014, and the response to N fertilizer application was a quadratic curve (2013: $r^2 = 0.99$; $P = 0.0031$; 2014: $r^2 = 0.95$; $P = 0.0219$).

There was a significant ($P < 0.05$) effect of cropping system on 100-kernel weight (HKW) (Table 3.2). Grain sorghum in the various cover crop systems and the double-cropped soybean system had HKW similar to grain sorghum in the fallow system with 45 to 90 kg ha^{-1}. The fallow system with 0 kg N ha^{-1} and grain sorghum in the double-cropped grain sorghum cropping system had the smallest HKW (Table 3.2). Hundred-kernel weight increased linearly with increasing N fertilizer application ($r^2 = 0.92$; $P = 0.0062$) when averaged across years.

Nitrogen Uptake and Components of N Use

Response of sorghum to cropping systems differed with year ($P < 0.05$) and affected aboveground N uptake, grain N uptake, nitrogen utilization efficiency (NUtE), and nitrogen harvest index (NHI) (Fig. 3.2). In 2013, pigeon pea, sunn hemp, and double-cropped soybean cropping systems had aboveground N uptake similar to grain sorghum in fallow systems with 45 to 90 kg N ha^{-1} (Fig. 3.2e). In 2014, grain sorghum in any of the summer cover crop systems and double-cropped soybean cropping system did not differ in aboveground N uptake but were similar to grain sorghum in the fallow system with 45 kg N ha^{-1} (Fig. 3.2e). In both years, grain sorghum in the double-cropped grain sorghum cropping system had the least aboveground biomass N uptake. A linear response curve best described the response of aboveground N uptake ($r^2 = 0.96$; $P = 0.0015$) to N fertilizer application.

In 2013, grain N uptake in cowpea and pigeon pea cropping systems was significantly greater than that of sunn hemp and double-cropped soybean cropping systems. In 2014, grain N uptake in the cowpea cropping system was significantly greater than that of pigeon pea, sunn hemp, and double-cropped soybean systems (Fig. 3.2f). The least grain N uptake in both years was observed in the fallow system with 0 kg N ha^{-1} and the double-cropped grain sorghum cropping system (Fig. 3.2f). Grain N uptake linearly ($r^2 = 0.97$; $P = 0.0015$) responded to N fertilizer application. Overall, grain N uptake of grain sorghum in the various summer cover crops and double-cropped soybean cropping system over the years was similar to grain sorghum in fallow systems with 45 to 90 kg N ha^{-1}.

In 2013, NUtE of grain sorghum in any of the cover crop systems was greater than that of grain sorghum in the double-cropped soybean cropping system. (Fig. 3.2g). In 2014, NUtE of grain sorghum in cowpea or sunn hemp cropping systems was more than that of grain sorghum in pigeon pea and double-cropped soybean cropping systems. In both years, NutE was greatest in the double-cropped grain sorghum cropping system and similar to that of the fallow system with 0 kg N ha^{-1}. Nitrogen utilization efficiency of grain sorghum in fallow systems with N fertilizer application showed a decreasing trend with increasing N application in both years (2013: $r^2 = 0.89$; $P = 0.0102$; 2014: $r^2 = 0.97$; $P = 0.0008$). Nitrogen utilization efficiency in the various cover crops and double-cropped soybean cropping systems was generally similar to grain sorghum in fallow systems with 45 to 90 kg N ha^{-1} (Fig. 3.2g).

Nitrogen harvest index in cowpea and pigeon pea cropping systems was significantly greater than in sunn hemp and double-cropped soybean cropping systems in 2013 (Fig. 3.2h). The double-cropped grain sorghum cropping system and fallow system with 0 kg N ha^{-1} had the least NHI in 2013. In 2014, NHI for grain sorghum in the cowpea cropping system was the greatest, but NHI was relatively similar in pigeon pea, sunn hemp, and double-cropped soybean systems. The double-cropped grain sorghum system also had the lowest NHI in 2014 (Fig. 3.2h). The NHI increased with increasing N fertilizer application ($r^2 = 0.97$; $P = 0.0012$). Nitrogen harvest index in the cover crop systems and double-cropped soybean systems was similar to grain sorghum in the fallow system with 45 kg N ha^{-1} in both years. Nitrogen harvest index of grain sorghum in the fallow system with 0 kg N ha^{-1} and the double-cropped grain sorghum cropping system were similar over the years.

Site x Cropping System

Response of sorghum to cropping systems differed by site ($P < 0.05$) and affected leaf chlorophyll index, kernels $plant^{-1}$, and grain yield (Fig. 3.3). Leaf chlorophyll index in the various cover crop systems and double-cropped soybean system was similar at Ashland Bottoms and comparable to leaf chlorophyll index in the fallow system with 45 kg N ha^{-1}. A similar trend was observed for leaf chlorophyll index at ANF. Furthermore, leaf chlorophyll index was lowest in the double-cropped grain sorghum cropping system (Fig. 3.3a). The response of leaf chlorophyll index was linear at both sites ($r^2 = 0.99$, $P =0.0002$).

Kernels $plant^{-1}$ in any of the cover crop systems and double-cropped soybean system was similar at Ashland Bottoms (Fig. 3.3b), and kernels $plant^{-1}$ in double-cropped grain sorghum system was the lowest at Ashland Bottoms. A similar trend was observed for kernels $plant^{-1}$ at ANF. Kernels $plant^{-1}$ in fallow systems with N fertilizer application can be best described by a quadratic response curve ($r^2 = 0.94$; $P = 0.0272$) at both sites. Kernels $plant^{-1}$ in the various cover crop systems and double-cropped soybean cropping system was similar to fallow systems with either 45 or 90 kg N ha^{-1}, depending on the site (Fig. 3.3b).

The response of grain yield to the cover crop system was greater at Ashland Bottoms than at ANF (Fig. 3.3c). Cowpea and pigeon pea cropping systems had grain yield greater than those of sunn hemp and double-cropped soybean systems at Ashland Bottoms (Fig. 3.3c). Similar trends were observed for grain yield at ANF. Grain yield in double-cropped grain sorghum did not differ from that in the fallow system with 0 kg N ha^{-1} at both sites. Overall, grain yields in the various cover crop systems and double-cropped soybean cropping system were similar to grain yield in fallow system with 45 kg N ha^{-1}. Grain yield also had a quadratic response curve (r^2 = 0.96; P = 0.0183) to N fertilizer application at both sites (Fig. 3.3c).

Response of sorghum to cropping systems varied with site ($P < 0.05$) and affected aboveground N uptake, grain N uptake, total N uptake, NHI, and NUtE (Fig. 3.3). Aboveground N uptake was significantly greater at Ashland Bottoms than at ANF (Fig. 3.3d). At both sites, aboveground N uptake in any of the cover crop systems and double-cropped soybean cropping system was similar to fallow systems with 45 to 90 kg ha^{-1}. Aboveground N uptake response to N fertilizer application was quadratic (r^2 = 0.99; P = 0.007) at Ashland Bottoms and linear at ANF (r^2 = 0.96; P = 0.0020). Aboveground N uptake in double-cropped grain sorghum was similar to the fallow system with 0 kg N ha^{-1}.

Grain N uptake in any of the summer cover crop systems and double-cropped soybean system was significantly greater at Ashland Bottoms than at ANF (Fig. 3.3e). Grain N uptake in any of the cover crop systems at Ashland Bottoms was similar to the fallow system with 90 kg N ha^{-1}, but the double-cropped soybean cropping system was similar to the fallow system with 45 kg N ha^{-1}. At ANF, grain uptake in the various cover crop systems and double-cropped soybean cropping system was similar to the fallow system with 45 kg N ha^{-1}. Grain sorghum in the double-cropped grain sorghum system had the least grain N uptake at both sites (Fig. 3.3e).

Grain N uptake ($r^2 = 0.98$; $P = 0.0006$) responded linearly to N fertilizer application at Ashland Bottoms and ANF.

Total N uptake by sorghum in the cover crop systems was significantly greater than total N uptake in the double-cropped soybean cropping system at Ashland Bottoms. Similar trends for total N uptake were observed at ANF (Fig. 3.3f). In addition, total N uptake responded linearly ($r^2 = 0.93$; $P = 0.0050$) to N fertilizer application. Total N uptake in cowpea, pigeon pea, sunn hemp, and double-cropped soybean was comparable to fallow systems with either 45 or 90 kg N ha^{-1}, depending on the site.

Nitrogen harvest index in cover crop systems was greater than that of NHI in double-cropped soybean and double-cropped grain sorghum systems at Ashland bottoms. At ANF, grain sorghum NHI in cowpea, sunn hemp, and double-cropped soybean systems was greater than in pigeon pea and double-cropped grain sorghum cropping systems (Fig. 3.3g). The response of NHI at Ashland Bottoms was 0.153narte + 42.81, $r^2 = 0.94$, and $P = 0.0032$; at ANF, the response of NHI was 0.170nrate + 45.82, $r^2 = 0.96$, and $P = 0.0018$. Aboveground N uptake, grain N uptake, total N uptake, and NHI in double-cropped grain sorghum system was generally similar to that in fallow system with 0 kg N ha^{-1}.

Nitrogen utilization efficiency of grain sorghum in the various cover crop systems, double-cropped soybean, and double-cropped grain sorghum cropping systems was greater at ANF than at Ashland Bottoms (Fig. 3.3h). At Ashland Bottoms, NUtE in any of the summer cover crop systems and double-cropped soybean cropping system was similar to fallow systems with 90 to 135 kg N ha^{-1}. Nitrogen utilization efficiency in the various cover crop systems and double-cropped grain crops systems at ANF was similar to fallow systems with 0 to 45 kg N ha^{-1}.

Furthermore, NUtE decreased linearly with N fertilizer application ($r^2 = 0.93$; $P = 0.0052$) at both sites.

Relationship among Physiology Traits and Grain Yield

Photosynthetic rate was a linear function of leaf chlorophyll index, leaf nitrogen uptake, stomatal conductance, and C_i (Fig. 3.4). Leaf chlorophyll index and leaf N uptake effects on photosynthetic rate typically were more influenced by N fertilizer application in both years (Figs. 3.4a and b) than by stomatal conductance and C_i (Figs. 3.4c and d). Stomatal conductance explained more of the variability observed in photosynthetic rate than leaf chlorophyll index, leaf N uptake, or C_i (Figs. 3.4a, b, c, and d).

Positive linear relationships were observed when grain yield was plotted against photosynthetic rate, aboveground biomass, kernels plant^{-1}, and HKW (Fig. 3.4). The relationships were significantly driven by N fertilizer application. Aboveground biomass and kernels plant^{-1} were the traits that contributed most to the variability observed in grain yield compared with photosynthetic rate and HKW (Figs. 3.4e, f, g, and h).

Pearson Correlation among Physiology Traits, Growth Traits, Yield and Yield Components, and Components of N Use

Correlation coefficients were determined among physiological traits, growth traits; yield, yield components, and components of N use (Table 3.3). The correlation analysis among all the parameters generated 62 significant ($P < 0.05$) correlations from a total of 225 pairs. Leaf chlorophyll index and photosynthetic rate showed a positive correlation ($P < 0.05$) with transpiration rate, stomatal conductance, C_i, plant height, aboveground biomass, grain yield HKW, and kernels plant^{-1}. In contrast, the leaf chlorophyll index showed a negative correlation with NHI. Transpiration rate was positively correlated with stomatal conductance, C_i, plant height, aboveground biomass, kernels plant^{-1} aboveground biomass N uptake, grain N uptake, and total N uptake.

In contrast, transpiration rate was negatively correlated with grain yield. Stomatal conductance showed a negative correlation with plant height but was positively correlated with aboveground biomass and kernels plant^{-1}. Intercellular CO_2 concentration was significantly ($P < 0.05$) and positively correlated with plant height, aboveground biomass, and HKW but negatively correlated with aboveground biomass N uptake and NHI.

Plant height significantly ($P < 0.05$) showed a positive correlation with aboveground biomass, HKW, and kernels plant^{-1}. Aboveground biomass also was positively correlated with grain yield, HKW, kernels plant^{-1}, and total N uptake. In addition, grain yield showed a significant ($P < 0.05$) correlation with HKW and kernels plant^{-1}. Aboveground N uptake correlated positively with grain N uptake, total N uptake, and NHI but negatively correlated with NUtE. Furthermore, grain N uptake showed a positive correlation with total N uptake, NUtE, and NHI, whereas total N uptake negatively correlated with NUtE.

Economic Analyses

Economic analyses were calculated for fallow systems with N fertilizer application, cover crop systems, and double-cropped grain crop systems. The results are presented in Tables 3.4 and 3.5. Grain sorghum in fallow systems with N fertilizer application all had positive gross benefits averaged across site and years. Among the N fertilizer rates, 45, 90, 135, and 180 kg N ha^{-1} gave gross benefits that were greater than the fallow system with 0 kg N ha^{-1}. Averaged across site and years, 180 kg N ha^{-1} gave the greatest net benefit, followed by 135 kg N ha^{-1} and 90 kg N ha^{-}; however, the net benefit in fallow with 45 kg N ha^{-1} was greater than in the fallow system with 0 kg N ha^{-1}. The marginal rate of return (MRR) between the fallow with 0 kg N ha^{-1}

and 90 kg N ha^{-1} was greater than that of fallow systems with either 135 or 180 kg N ha^{-1} (Table 3.4).

The net economic benefit of including the summer cover crops, double-cropped soybean, and double-cropped grain sorghum is presented in Table 3.5. Among cover crops, the cowpea cropping system gave greatest net economic return, followed by the pigeon pea cropping system. In contrast, the sunn hemp cropping system gave a negative net economic return. The net return accrued from grain sorghum in the double-cropped soybean cropping system was greater than what was observed in the double-cropped grain sorghum cropping system. Both double-crop systems resulted in greater net returns than the cover crop systems.

DISCUSSION

Grain sorghum hybrid DKS54-00 varied in its response to N fertilizer and cover cropping system for all traits. Averaged across site years, the fallow system with application of N fertilizer increased leaf chlorophyll index and photosynthesis, grain yield, and kernels plant^{-1} and decreased the DTF by 10 d. Decreased leaf chlorophyll index and photosynthetic rates are good indicators of yield losses under N deficiency (Dwyer et al., 1995). The 2012-2013 and 2013-2014 growing seasons (April-October) were different. More rainfall in 2013, especially in the months of June through September, resulted in adequate soil moisture, particularly during the grain-filling period. In 2014, despite the high rainfall amount compared with 2013, the maximum amount of rainfall after N fertilizer application was less than 10 mm for a period of 42 d. This might have affected N uptake and resulted in the yield reduction in 2014 compared with 2013. In 2012, a long dry spell and high temperatures were observed, but this did not adversely affect the cover crops due to their drought tolerance characteristics.

Adaptability to specific soil and environmental conditions can influence the performance of summer cover crops. Among the summer cover crops, pigeon pea had greater aboveground biomass and N uptake both in the drier year, 2012 (338 mm rainfall during the crop season), and the wetter year, 2013 (539 mm of rainfall). It is generally held that residues with C/N ratios greater than 25 to 30 result in the net immobilization of N (Shaffer and Ma, 2001). Double-cropped grain sorghum was the only treatment with a C/N ratio greater than this threshold (Fig. 3.1).

A significant difference was observed among various cropping systems for leaf chlorophyll index when averaged across site-years. These findings are in agreement with other researchers (Schepers et al., 1992; Mahama et al., 2014) who have reported a significant variation in leaf chlorophyll index. Both field and laboratory investigations have demonstrated that increasing the supply of N fertilizer increases leaf chlorophyll index and photosynthesis, leading to increased growth and yield. Photosynthetic rate increased with increasing N rate, and the cover crop systems and double-cropped soybean cropping system had photosynthetic rates greater than fallow system with 0 kg N ha^{-1} and were comparable to fallow with 45 kg N ha^{-1} (Fig. 3.2b).

Across years and cropping systems, mean increases in grain yield as a result of including cowpea, pigeon pea, sunn hemp, double-cropped soybean, and double-cropped grain sorghum in the rotation over fallow with 0 kg N ha^{-1} were 56, 62, 43, 32, and 3%, respectively (Fig. 3.2d). Number of kernels plant^{-1} was the yield component most closely associated with grain yield response to N fertilizer application and various cover crops in both years. These results are consistent with Saeed et al. (1986), who found that the number of kernels per panicle was the major contributing factor to grain sorghum yield across dryland production environments and indicates that the responses to legumes observed in the current study were N rather than non-N effects. Consequently, we used the regression equations for grain sorghum responses to the cover crops and double-cropped grain crops to calculate N fertilizer replacement values following a procedure described by Hesterman et al. (1992).

Nitrogen fertilizer replacement values (NFRV) of cowpea, pigeon pea, sunn hemp, and double-cropped soybean in 2013 ranged from 30 to 75 kg N ha^{-1}, respectively. The corresponding values in 2014 were 23-52.3 kg N ha^{-1} for cowpea, pigeon pea, sunn hemp, and double-cropped soybean, respectively (Fig. 3.5a and b). Liebman et al. (2012) showed that including a legume cover crop in a cereal production system can help improve N availability, resulting in improved biomass accumulation and grain yield of maize. The N contribution from small grain crops generally is negative (Torbert and Reeves, 1991) due to the wide C/N ratio of the residue. In this study, the NFRV of the double-cropped grain sorghum over the years was -2.5 kg N ha^{-1}.

Correlation of grain yield with leaf chlorophyll was significant ($P = 0.007$), which is in agreement with Edmisten et al. (1992) and Wood et al. (1992), who both reported that SPAD readings and chlorophyll measurements were good for predicting grain yield. Increased N availability results in greater leaf N content, resulting in a strong positive correlation between photosynthesis and leaf N content for many C_4 and C_3 species (Connor et al., 1993; Huber et al., 1989). In our study, there was a strong correlation between photosynthesis and leaf chlorophyll index (Fig. 3.4a). A linear relationship between photosynthetic rate and leaf N uptake represents the contribution of leaf N content on photosynthetic CO_2 assimilation (Fig. 3.4c) as previously observed by (Muchow and Sinclair, 1994) in grain sorghum.

Cereal yield is determined by grain numbers per unit of land area, grain weight, and the proportion of filled grains. Kernels plant^{-1} is correlated with total plant N content because N is an important resource, both limiting yield and contributing to the determination of grain number (Sinclair and Jamieson, 2006). Nitrogen harvest index is a measure of N partitioning in grain sorghum that provides an indication of how efficiently the plant utilized the acquired N for grain production. The positive correlation of NHI and grain yield in this study shows the importance of this trait in grain sorghum (Table 3.3).

Results showed that fallow with 135 and 180 kg N ha^{-1} rates added to the cost of production but did not add significantly to output, as evidenced by the fact that the main effect of increasing N level from 90 to 135 and to 180 kg N ha^{-1} resulted in corresponding increase in grain yield and net benefits, but this increase did not merit extra costs to producers. Maximum economic grain yields for grain sorghum occurred at the N level of 90 kg N ha^{-1}. Double-cropping soybean or grain sorghum after wheat increases cropping intensity and results in extensive use of fixed resources, improved cash flow, and increased net returns (Kelley, 2003). In this study, grain sorghum in double-cropped soybean cropping system gave the greatest economic net return. Careful management is required for production of a profitable second crop after wheat. Soybean and grain sorghum planting date is critical in determining productivity of the system. At the time of wheat harvest, the potential yield of soybean and grain sorghum decreases each day that planting is delayed (Smith et al., 2014). Thus, every effort must be made to harvest wheat and seed soybean and grain sorghum as early as possible.

CONCLUSIONS

Grain sorghum hybrid DKS54-00 varied in its response to N fertilizer and various cover crops. Aboveground biomass, N uptake, and C accumulation varied among the summer cover crops and double-cropped grain crops. There were significant differences in physiological, growth, yield traits, and N use of grain sorghum in fallow systems with N fertilizer application and various cover crops. Summer leguminous cover crops improved soil N availability from the residues, which were subsequently used by the succeeding grain sorghum crop. This resulted in increased leaf chlorophyll index, photosynthetic rate, grain yield, kernels plant^{-1}, HKW, and grain N uptake. Across years and cropping systems, mean increases in grain yield as a result of including cowpea, pigeon pea, and sunn hemp, double-cropped soybean, and double-cropped grain sorghum in the rotation over fallow with 0 kg N ha^{-1} were 56, 62, 43, 32, and 3%, respectively. Furthermore, N fertilizer replacement values across years for cowpea, pigeon pea, sunn hemp, double-cropped soybean, and double-cropped grain sorghum were 53, 64, 36, 27, and -2.5 kg N ha^{-1}, respectively. Grain sorghum in the double-cropped soybean cropping system and fallow system with 90 kg N ha^{-1} gave profitable net returns.

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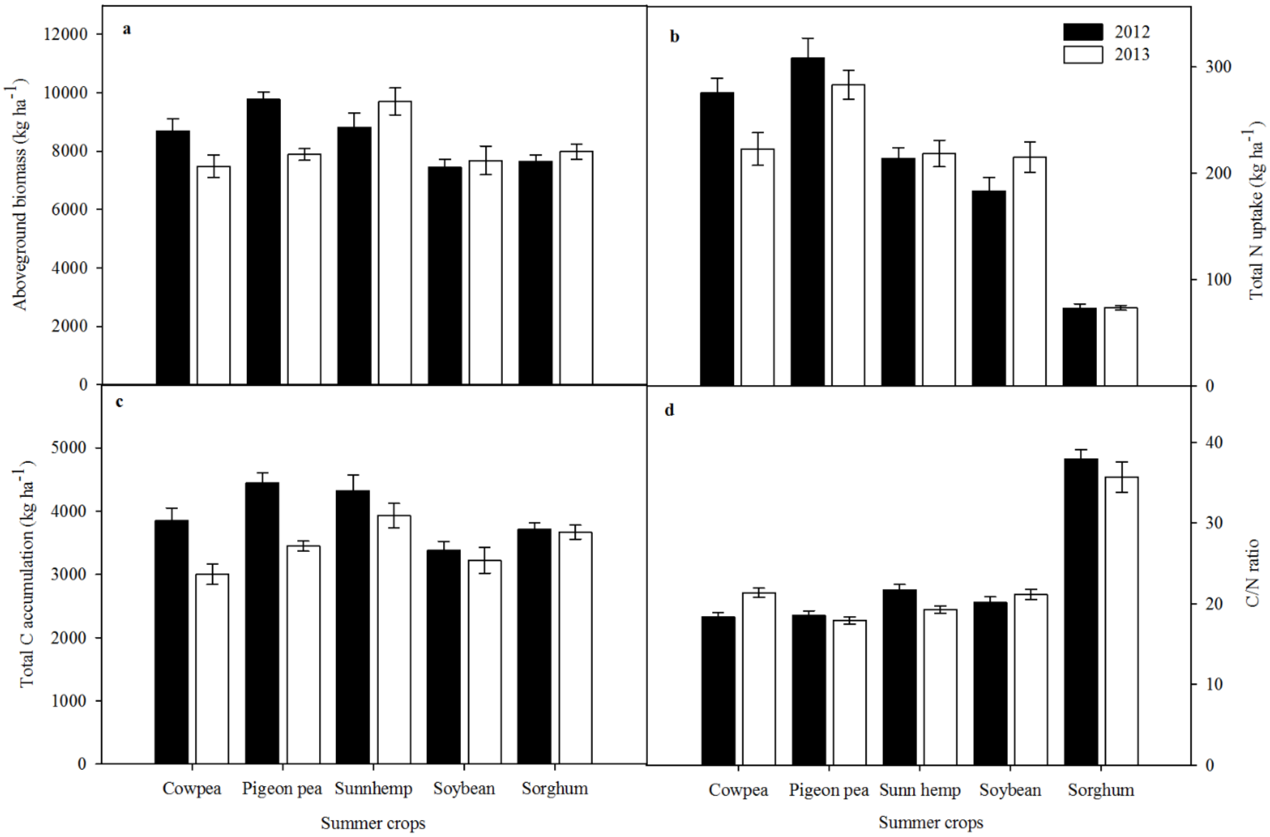

Figure 3.1. Crop and year effects on (a) aboveground biomass; (b) total N uptake, (c) total C accumulation, (d) C/N ratio of cover crops, double-cropped soybean, and double-cropped grain sorghum grown in 2012 and 2013.

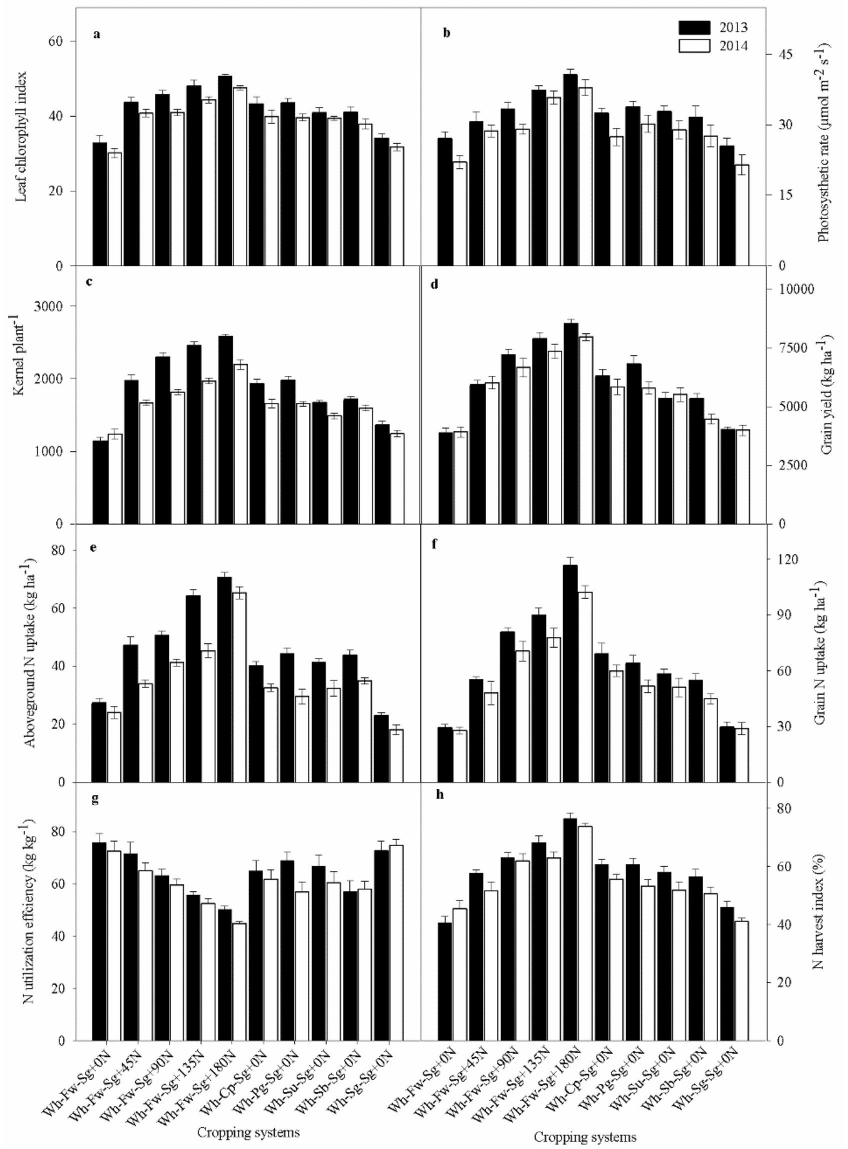

Figure 3.2. Cropping system and year effects on (a) leaf chlorophyll index, (b) photosynthetic rate, (c) kernels plant^{-1}, (d) grain yield, (e) aboveground N uptake at physiological maturity, (f) grain N uptake at physiological maturity, (g) N utilization efficiency, and (h) N harvest index of grain sorghum grown in 2013 and 2014.

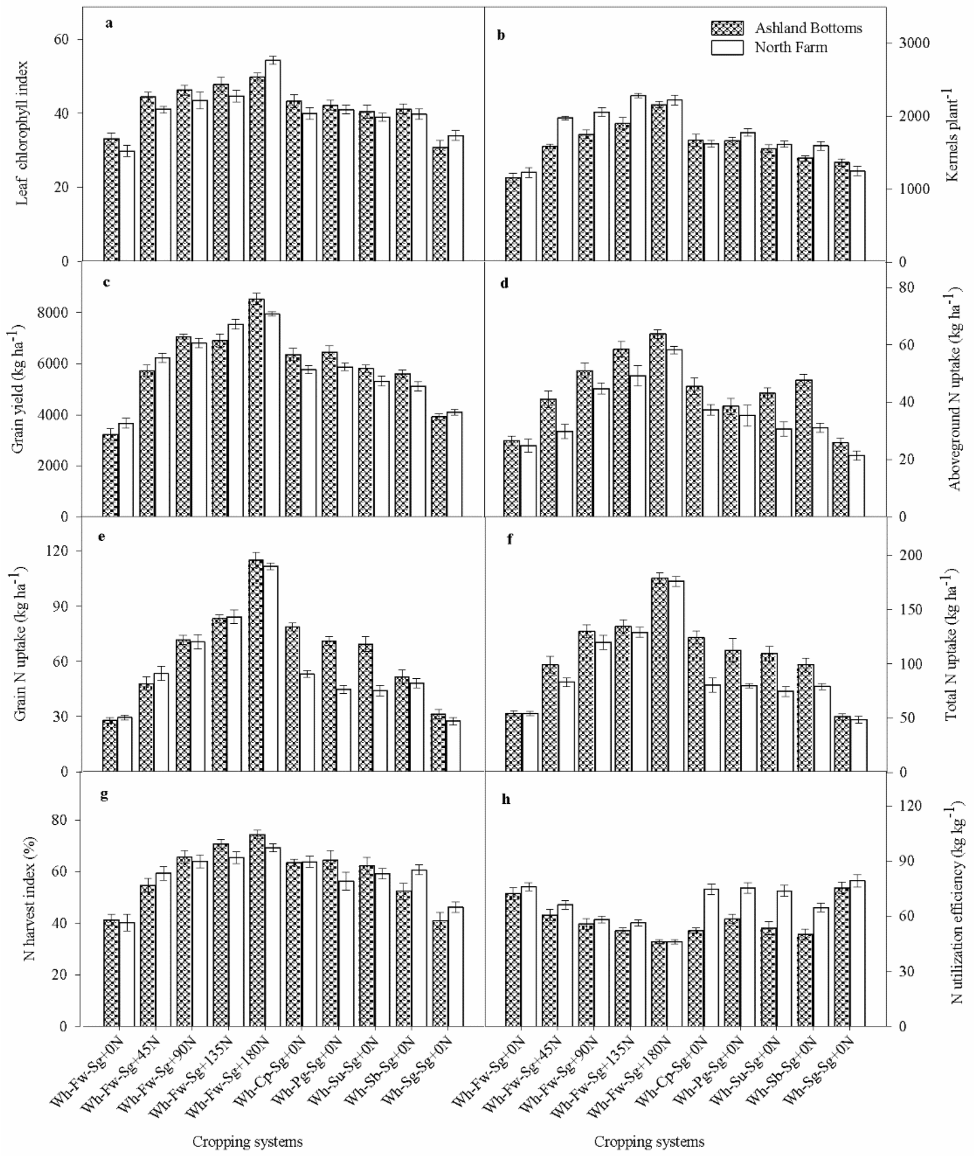

Figure 3.3. Cropping system and site effects on (a) leaf chlorophyll index, (b) kernels plant^{-1}, (d) grain yield, (e) aboveground N uptake at physiological maturity, (f) grain N uptake at physiological maturity, (g) total N uptake, and (h) N utilization efficiency of grain sorghum grown in 2013 and 2014.

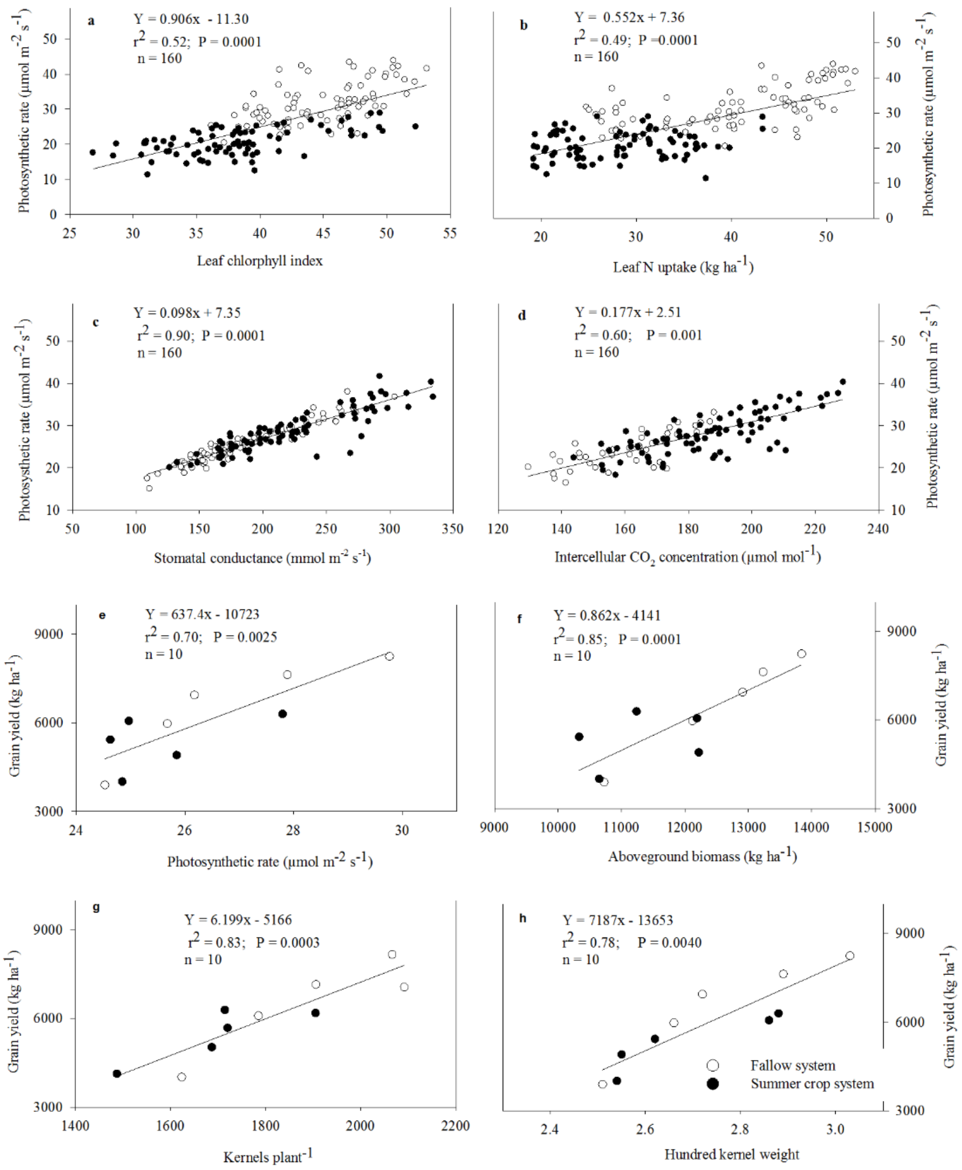

Figure 3.4. Relationship between photosynthetic rate and (a) leaf chlorophyll index; (b) leaf N uptake, (c) stomatal conductance, and (d) intercellular CO_2 concentration; relationship between grain yield and (e) photosynthetic rate, (f) aboveground biomass at physiological maturity, (g) kernels plant^{-1}, and (h) hundred kernel weight in 2013 and 2014.

Note: Open circle marker: Fallow system with 0, 45, 90, 135, and 180 kg N ha^{-1}.

Closed circle marker: Cover crops and double-cropped grain crops systems.

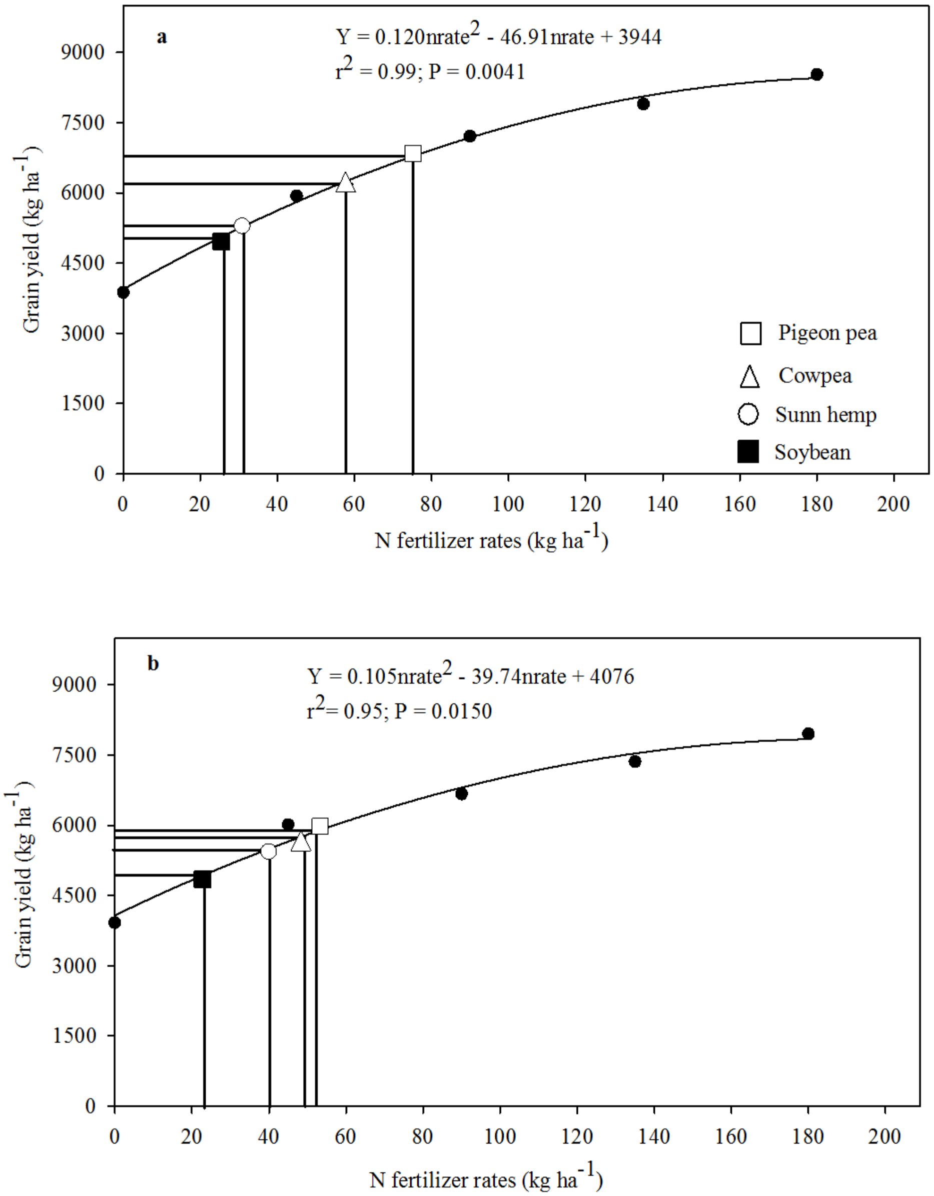

Figure 3.5. Nitrogen replacement value of leguminous summer cover crops and double-cropped soybean in (a) 2013, and (b) 2014.

Table 3.1. Physical and chemical characteristics of soil from the sites.

		2012-2013		2013-2014	
Parameters	Units	Ashland Bottoms	Agronomy North Farm	Ashland Bottoms	Agronomy North Farm
Sand	%	54.0	14.0	51.0	18.0
Silt	%	38.0	55.0	39.0	49.0
Clay	%	8.00	31.0	10.0	33.0
pH		5.80	8.00	5.80	6.30
Mehlich-3 P	mg kg^{-1}	41.2	30.2	75.5	32.5
K	mg kg^{-1}	140	221	196	207
Na	mg kg^{-1}	11.9	16.9	11.1	17.5
Cl^{-}	mg kg^{-1}	4.30	8.30	4.90	7.20
SO_4-S	mg kg^{-1}	1.30	1.90	0.35	2.60
SOM	%	0.50	3.00	0.86	2.90
NH_4-N	mg kg^{-1}	4.20	6.80	2.50	3.30
$N0_3$-N	mg kg^{-1}	3.55	5.50	2.30	4.50

Table 3.2. Cropping systems means averaged across site and years for phenology, physiology and growth traits, and yield component of grain sorghum grown in 2013 and 2014.

Cropping System	Stomatal conductance	Transpiration rate	Intercellular CO_2 concentration	Days to 50% flowering	Aboveground biomass	Plant height	Hundred-kernel weight
	mmol m^{-2} s^{-1}	mmol m^{-2} s^{-1}	µmol mol^{-1}	d	kg ha^{-1}	cm	g
Wh-Fw-Sg+0N	172.1bc	5.40c	159.6bc	78c	8995ef	110.4c	2.51d
Wh-Fw-Sg+45N	185.2b	5.98abc	160.9bc	72b	11482c	127.8ab	2.75bc
Wh-Fw-Sg+90N	185.8b	5.81abc	164.2bc	71a	13055b	128.6ab	2.72bc
Wh-Fw-Sg+135N	183.2bc	6.29a	159.9bc	69a	13586b	129.9ab	2.89a
Wh-Fw-Sg+180N	209.2a	6.21ab	180.7a	69a	14729a	132.3a	3.03a
Wh-Cp-Sg+0N	183.8bc	5.52bc	168.5b	73b	11310cd	128.9ab	2.86b
Wh-Pg-Sg+0N	187.1b	6.11abc	154.5c	73b	11685cd	129.0ab	2.66bc
Wh-Su-Sg+0N	186.8b	5.50bc	172.5a	73b	9795cd	127.1ab	2.62bc
Wh-Sb-Sg+0N	177.6bc	5.55bc	170.5a	74b	10605cd	125.8b	2.88b
Wh-Sg-Sg+0N	163.2c	5.58abc	158.9c	78c	8876f	116.0c	2.54d

For each parameter, means in the same column followed by same letter (s) are not significantly different at the 0.05 level by Tukey honest test.

Table 3.3. Pearson correlation of physiology and growth traits, yield and yield components, and N use components.

	SP	Pn	E	gs	C_i	PHT	BM	GY	HK	KN	BMN	GN	TN	NUtE	NHI
SP	1														
Pn	0.52***	1													
E	0.43***	0.83***	1												
gs	0.25**	0.49***	0.50***	1											
C_i	0.29**	0.21**	0.26**	0.10	1										
PHT	0.50***	0.41***	0.32***	-0.22**	0.30***	1									
BM	0.65***	0.36***	0.31***	0.15*	0.20*	0.52***	1								
GY	0.42**	-0.33***	-0.33***	-0.06	-0.12	-0.04	0.30***	1							
HKW	0.24**	0.16*	0.07	-0.06	0.168	0.27**	0.30***	0.55**	1						
KN	0.42***	0.58***	0.49***	0.24**	0.14	0.37***	0.46***	0.61**	-0.02	1					
BMN	-0.08	0.33***	0.28**	0.12	-0.17	-0.01	-0.127	-0.12	-0.17	0.26**	1				
GN	0.09	0.31***	0.28**	0.10	-0.01	0.13	0.055	-0.13	-0.10	0.24**	0.66***				
TN	-0.01	0.35***	0.31***	0.12	-0.12	0.04	-0.063	-0.137	-0.16	0.28**	0.94***	0.86***	1		
NUtE	0.06	-0.16*	-0.12	-0.01	0.08	-0.05	0.03	0.02	0.27	-0.21**	-0.59**	0.82***	-0.74***	1	
NHI	-0.21**	0.004	-0.01	0.01	-0.21**	-0.16*	-0.24**	-0.002	-0.08	-0.007	0.48***	0.46***	0.20*	0.24**	1

Abbreviations: SP, leaf chlorophyll; Pn, photosynthetic rate; E, transpiration rate; gs, stomatal conductance; C_i, intercellular CO_2 concentration; PHT, plant height; BM, aboveground biomass; GY, grain yield; HKW, hundred-kernel weight; KN, kernels plant^{-1}; BMN, aboveground N uptake; GN, grain N uptake; TN, total N uptake; NUtE, N utilization efficiency; NHI, N harvest index.

Table 3.4. Economic analyses of N fertilizer application to grain sorghum grown in 2013 and 2014.

	N fertilizer rates (kg ha^{-1})				
Variables	0	45	90	135	180
Average yield (kg ha^{-1})	3897	5048	6941	7528	8342
Price (US$ kg^{-1})	0.176	0.176	0.176	0.176	0.176
Gross benefit (US$ ha^{-1})	686.00	888.00	1221.00	1325.00	1468.00
Variable inputs cost (US$ ha^{-1})					
Seeds	43.80	43.80	43.80	43.80	43.80
Planting	38.40	38.40	38.40	38.40	38.40
Urea (46% N) cost	0.00	85.83	171.60	257.50	343.30
Fertilizer application	0.00	15.20	15.20	15.20	15.20
Harvesting	64.43	72.59	82.33	84.07	88.88
Herbicides	123.70	123.70	123.70	123.70	123.70
Herbicides application	45.51	45.51	45.51	45.51	45.51
Hauling @$0.008 kg^{-1}	31.18	40.38	55.53	60.22	66.74
Total variable inputs cost	315.80	425.00	520.60	608.20	698.80
Net benefit (US$ ha^{-1})	370.10	463.40	701.00	716.80	769.40
Marginal rate of return (%)	-	85.39	248.60	18.01	58.03

Table 3.5. Economic analyses of grain sorghum after cover crops, double-cropped soybean, and grain sorghum grown in 2013 and 2014.

Variables	Cowpea	Pigeon pea	Sunn hemp	Soybean	Sorghum
Harvested yield (kg ha^{-1})	0.00	0.00	0.00	2919	2569
Grain price, (US$ kg^{-1})	0.00	0.00	0.00	0.411	0.176
Gross benefit (US$ ha^{-1})	0.00	0.00	0.00	1199.00	452.10
Variable cost (cover crops + double crops) (US$ ha^{-1})					
Seeds	62.20	306.20	380.80	150.50	43.80
Inoculants	42.90	42.90	42.90	42.90	0.000
Planting	38.40	38.40	38.40	38.40	38.40
Herbicides	123.70	123.70	123.70	123.70	123.70
Herbicides application	45.51	45.51	45.51	45.51	45.51
Mowing/harvesting	32.15	32.15	32.15	66.19	20.47
Total variable cost (cover crops + double crops)	344.80	588.80	663.40	467.20	271.80
Succeeding Crop (grain sorghum)					
Grain sorghum yield ha^{-1}	6063	6567	5562	5156	4170
Price $ kg^{-1}	0.186	0.186	0.186	0.186	0.186
Gross benefit (US$ ha^{-1})	1127.00	1221.00	1034.00	959.00	775.60
Variable cost (US$ ha^{-1})					
Seeds	43.80	43.80	43.80	43.80	43.80
Planting	38.40	38.40	38.40	38.40	38.40
Herbicides	123.70	123.70	123.70	123.70	123.70
Herbicides application	45.51	45.51	45.51	45.51	45.51
Harvesting	103.40	126.20	141.70	170.70	162.00
Hauling@ US$0.008 kg^{-1}	48.51	52.54	44.50	41.25	33.36
Total variable cost	403.30	430.10	437.60	463.30	446.80
Total cost (double crops + cover crops + sorghum)	748.20	1019.00	1101.00	930.50	718.60
Total income (double crops +cover crops + sorghum)	1127.00	1221.00	1034.00	2158.00	1227.00
Net Returns	379.60	202.40	-66.48	1228.00	509.00

Double-cropped grain crops: Soybean and grain sorghum

CHAPTER 4 - IMPACT OF COVER CROPS AND VARYING NITROGEN RATES ON GROWTH AND YIELD OF MAIZE IN NO-TILLAGE SYSTEM

ABSTRACT

Leguminous cover crops are pivotal part of sustainable agricultural systems. With the development of no-till cropping systems, cover crops have been recognized for their ability to provide moisture-conserving residues as well as nitrogen for the succeeding crop. The objective of this study was to determine nitrogen (N) contribution from summer cover crops following winter wheat (*Triticum aestivum* L.) and varying N rates to subsequent maize (*Zea mays* L.) crop growth and yield. Field experiments were conducted in 2012/2013 and 2013/2014 growing seasons in Kansas. Rotational benefit improved soil N availability from the residues of the legumes which was subsequently used by succeeding maize crop. Grain yield of maize in all the cover crops systems and double cropped soybean [*Glycine max* (L.) Merr.] system was similar to maize in the fallow system with 45 kg N ha^{-1}. Mean increase grain yield as a result of including cowpea [*Vigna unguiculata* (L.) Walp.], pigeon pea [*Cajanus cajan* (L.) Millsp], sunn hemp (*Crotalaria juncea* L.), double-cropped soybean, and double cropped grain sorghum [*Sorghum bicolor* (L.) Moench] in the rotation over the fallow system with 0 kg N ha^{-1} was 78, 91, 66, 72, and 12% respectively, and N fertilizer replacement values across years were 53, 64, 43, 47, and -4.8 kg N ha^{-1}, respectively. Maize in the fallow with 135 kg ha^{-1} and the double-cropped soybean systems gave economic and profitable net returns over the years.

INTRODUCTION

Maize is the world's most widely grown cereal on the basis of metric tonnes in production (FAOSTAT, 2014). Given the reliance on maize for food, feed, fiber, and fuel, it receives much more N fertilizer application in the United States than other cereal crops. Application of N fertilizers to cropland is a considerable portion of the cost and energy input associated with non-legume crop production (Liebman et al., 2012). When N is lost from cropland, it represents both a financial loss to producers and a potentially negative impact on the environment.

Leguminous cover cropping systems have been proposed as a method to reduce input costs by supplementing N and reducing environmental risks by decreasing N losses (Reinbott et al., 2004). Cover crops are steadily gaining adoption by numerous producers across the Great Plains as a cultural practice to improve soil health and crop yields. Previous studies have shown that, apart from furnishing N, winter legume cover crops can improve soil physical properties, reduce soil erosion, conserve soil water, recycle plant nutrients, and increase crop yield potential and soil productivity (Veenstra et al., 2007). The practical use of winter legume cover crops, however, is often limited by asynchrony of cover crop planting windows and biomass accumulation with planting windows for summer cash crops. For example, to allow winter legume cover crops adequate growing time before cold temperatures occur, summer crops may need to be harvested prior to optimum conditions. Delayed planting date of summer cash crops is also often necessary to allow winter legume cover crops adequate time to produce biomass and accumulate N. Early harvest and late planting may reduce yields of summer cash crops.

Challenges encountered in the use of winter cover crops can be overcome by using adapted tropical legumes. Under favorable climatic conditions, high-biomass producing and high-N fixing summer or tropical legume cover crops such as cowpea, pigeon pea, and sunn hemp may have more rapid and greater effects on increasing crop yields and improving soil properties than winter cover crops with low biomass input (Blanco-Canqui et al., 2012). Yadvinder et al. (1992) reported that tropical legumes produced 2.9 to 8.9 Mg dry matter ha^{-1} by 50 to 60 d after planting compared with winter legumes that produced 1.7 to 6.7 Mg dry matter ha^{-1} when grown November through May. Balkcom and Reeves (2005) reported that sunn hemp produced 7.6 Mg ha^{-1} of biomass with 144 kg ha^{-1} of N concentration in the first 2 yr in Alabama. Cherr et al. (2006) observed that sunn hemp produced 8.0 Mg ha^{-1} of biomass with 146 kg ha^{-1} of N in 12 wk in the first year and 12.2 Mg ha^{-1} of biomass with 172 kg ha^{-1} of N in 14 wk in the second year on a sandy soil in northern Florida. Estimates for pigeon pea conducted by Mafongoya et al. (2006) found that leaf-drops from pigeon pea can contribute up to 40 kg ha^{-1} of N when used as cover crop.

Leguminous summer cover crops can influence subsequent crop yield primarily via their effects on N availability (Schomberg et al., 2007); however, an effective cover crop N contribution depends on sufficient N accumulation in the cover crop biomass and timely mineralization of the accumulated N, precipitation events, cover crop species, tillage management, and length of cover crop management (Blanco-Canqui et al., 2012; Teasdale et al., 2008). The degree of synchrony between N supply from cover crop residues and crop N uptake can influence the efficiency of crop N use (Teasdale et al., 2008). Hence, C/N ratios of decomposing residues have been shown to influence soil N retention and N availability to crops (Fageria, 2007; Sainju et al., 2005). Although mineralization is also influenced by lignin and polyphenol content, residues with C/N ratios <25 generally result in net N mineralization, whereas residues with C/N ratios above 25 immobilize N (Accoe et al., 2004).

Soil improvement through the use of cover crops has been studied extensively, and the benefits are diverse. In West Africa, cropping systems involving grain legumes such as cowpea and pigeon pea in rotation with maize improved soil fertility and increased maize yields by about 50% (Osei-Bonsu and Asibuo, 2013). The benefits of cowpea to N supply in the savanna through biological N fixation have been estimated in the range of 60 to 80 kg ha^{-1} (Sanginga et al., 2000), depending on how the residues were managed. Significant increases in yield for maize grown in rotation were also recorded in experiments where N, P, and K soil test levels were high and pest populations were managed (Copeland and Crookston, 1992). Thus, rotation effects can have substantial positive influence on maize yields beyond potential N contributions.

Nitrogen plays a key role in several physiological, growth, and yield processes in maize. Previous studies have found that application of N up to 179 kg N ha^{-1} increased maize grain yield of 92% compared with 0 kg N ha^{-1} (Henry et al., 2010). Ciampiti and Vyn (2011) reported that at low N supply, plant growth and partitioning to reproductive structures was reduced during the bracketing silking period as a result of low N uptake rate. Low kernels plant^{-1} was also observed under N deficiency (Boomsma et al., 2009). Low N and C levels around the bracketing silking period can also exert a substantial impact on grain yield and its components (Ciampitti and Vyn, 2011).

Many have studied the effect of cover crops and N addition on crop yields, but few data are available comparing the effects of leguminous cover crops and N application on maize yield and various physiological traits under managed no-till cropping systems. Increased understanding of maize performance under summer cover crops, varying N rates, and the relationships among various traits is needed to develop improved and sustainable cropping systems. We hypothesized that the presence of a summer cover crop in a cropping system will result in increased benefit to soil through N in the residue that will improve the subsequent maize crop. The objective of this study was to determine the N contribution of summer cover crops following winter wheat and varying N rates to subsequent maize crop growth and yield.

MATERIALS AND METHODS

Site Description and Experimental Design

Field experiments were conducted at two sites in the 2012-2013 and 2013-2014 growing seasons on separate fields to evaluate the response of maize to summer cover crops and varying N fertilizer rates. Both sites for the study were located on Kansas State University (KSU) Department of Agronomy research facilities near Manhattan, KS. One experimental site was situated on a Reading silt loam soil, (fine-silty, mixed, mesic Typic Argiudolls; 39°08’35.3”N, 96°37’39.2”W), and the other was on a well-drained Kennebec silt loam (fine-silty, mixed, superactive, mesic Cumulic Hapludolls; 39°11’30”N, 96°35‘30”W) . The experiments were implemented on sites that had not been tilled for at least the previous six years. The treatments were coded as follows: Wh-Fw-Mz+0N, wheat rotated with maize plus 0 kg N ha^{-1}; Wh-Fw-Mz+45N, wheat rotated with maize plus 45 kg N ha^{-1}; Wh-Fw-Mz+90N, wheat rotated with maize plus 90 kg N ha^{-1}; Wh-Fw-Mz+135N, wheat rotated with maize plus 135 kg N ha^{-1}; Wh-Fw-Mz+180N, wheat rotated with maize plus 180 kg N ha^{-1}; Wh-Cp-Mz+0N, cowpea rotated with maize after wheat; Wh-Pg-Mz+0N, pigeon pea rotated with maize after wheat; Wh-Su-Mz+0N, sunn hemp rotated with maize after wheat; Wh-Sb-Sg+0N, double-cropped soybean rotated with maize after wheat; Wh-Sg-Mz+0N, double-cropped grain sorghum rotated with maize after wheat.

Soil Sampling and Analyses

In both years, composite soil samples were taken from each replication to a depth of 60 cm. Sampling was done using a hand probe (3.2 cm diameter), and samples consisted of 12 to 15 individual cores mixed to form individual composite samples. The soil was analyzed for pH, available P, exchangeable K, soil organic matter (SOM), S, and Cl^{-}. Soil physical properties such as sand, silt, and clay were also determined for each replication to a depth of 30 cm at both sites. Another set of soil samples for 30 to 60 cm were analyzed for soil nitrate and ammonium. Analyses were conducted by the Kansas State University Soil Testing Laboratory.

The hydrometer method was used to determine soil texture. Soil pH was estimated using a 1:1 slurry method with a 10-g scoop of soil and 10 mL of deionized water. Mehlich-3 P was analyzed by the HCl-ammonium fluoride extraction method. Extractable (plant-available) K and Na were determined by the ammonium acetate (1 M, pH 7.0) extraction method. The Walkley-Black method was used to determine organic matter. Chloride was analyzed by calcium nitrate extraction. The turbidimetric method was used to determine sulfate-S. Ammonia was extracted from soil samples with 1 M KCl (2 g in 20 mL, 30 min) and measured by an indophenol colorimetric reaction.

The results of soil analyses presented in Table 4.1 show considerable differences in soil textural and chemical properties between the two experimental sites. The SOM content of most agricultural soils in Kansas is 1 to 5%, with an average of 2.2%. Soil organic matter is roughly 5% N. The soil texture at Ashland Bottoms consisted of more than 50% of sand and <1% soil organic matter (SOM). At Agronomy North Farm (ANF), the soil texture consisted of <20% of sand and >2.5% SOM. Soil ammonium and nitrate were greater at ANF in both years. Soil test results from the sites greatly influence maize response to N fertilizer application after cover crops and double-cropped grain crops (soybean and grain sorghum).

Winter Wheat and Cover Crop Phase

Cover crops were evaluated in the 2011-2012 and 2012-2013 growing seasons after winter wheat. Plots were arranged in a randomized complete block design with four replications. Each plot was 9.1 m long and 4.5 m wide (6 rows). Winter wheat was drilled in October 2011 and September 2012 with a target-seeding rate of 115 kg ha^{-1} with 19-cm row spacing with no fertilizer applied at planting. The wheat was harvested in July in both years, and the stubble was sprayed immediately after harvest with 3.5 L ha^{-1} glyphosate 4 plus herbicide, (N-[(phosphonomethyl) glycine, to control weeds and volunteer wheat seedlings.

Three different cover crops, cowpea, pigeon pea, and sunn hemp, were established into the standing wheat stubble in July with a John Deere planter equipped with residue managers (Model 7200, Deere & Co., Moline, IL) in both years and sites. Chemical fallow was used as a check treatment, and double-cropped soybean and double-cropped grain sorghum were included as the most likely cash double-crop alternatives following winter wheat harvest. Cowpea, pigeon pea, and sunn hemp seeds were treated with a commercial rhizobium inoculant and planted at a seeding rate of 56, 28, and 12.5 kg ha^{-1}, respectively, on 19 June 2012 and 12 July 2013 at a depth of 1.3 to 2.5 cm. The double-cropped soybean (KS3406RR) and grain sorghum (DKS28-05) were planted at seeding rates of 350,000 and 125,000 seeds ha^{-1}, respectively.

At physiological maturity, the aboveground portion of 10 plants from each plot planted to grain sorghum were randomly sampled. Two rows of 2.5 m were sampled at R7 stage for soybean. Samples were dried at 60°C in a forced-air oven for 72 h and weighed. Based on the individual plot plant population, total aboveground biomass was determined and expressed per unit area. The dry samples were ground with a Wiley mill (Model 4, Arthur H. Thomas Company, Philadelphia, PA) and analyzed for total N and C by dry combustion (modified Dumas method) using a LECO CHN-2000 elemental analyzer (LECO Corp., St. Joseph, MI).

Leguminous cover crop performance was measured throughout the growing season. Stand counts were made for all cover crops 20 days after plant emergence within an area of 4.5 m^2. In 2012, two rows of 4.5-m^2 samples were hand-harvested from all cover crops plots, but in 2013 a portable rotary mower was used for harvesting. The fresh plant material cut from the summer leguminous cover crop plots were then uniformly distributed on the harvested plots and left in the field to decompose. Cowpea, pigeon pea, and sunn hemp cover crops were terminated at the beginning of flowering at 67, 88, and 84 days after planting, respectively, in 2012. Corresponding values in 2013 were 70, 90, and 88 days after planting, respectively. In both years, aboveground subsamples from each plot of the cover crops were dried in a forced-air dryer at 60°C until dry and weighed to obtain dry matter content. The dried samples were ground with a Wiley mill and analyzed for N and C by dry combustion (modified Dumas method) using a LECO CHN-2000 elemental analyzer at the KSU Soil Testing Laboratory. Nitrogen uptake and C accumulation of the various cover crops were determined by multiplying aboveground dry matter weight by percentage N concentration or percentage C concentration.

Double-cropped soybean and double-cropped grain sorghum were harvested in October in both years and sites using a modified two-row Gleaner (Model EIII; AGCO Corporation, Duluth, GA). Grain moisture and test weight were estimated with a DICKEY-John GAC 2000 (DICKEY-John Corp., Springfield, IL).

Maize Phase

Before planting maize (hybrid Dekalb DKC63-84), all plots were sprayed with glyphosate 4 plus herbicide, [N-(phosphonomethyl) glycine, at 3.5 L ha^{-1}. Maize was planted at a target seeding rate of 70,000 seeds ha^{-1} at standard 75-cm row spacing at both sites and years. Nitrogen fertilizer (urea 46% N) rates of 0, 45, 90, 135, and 180 kg N ha^{-1} were applied to maize in fallow system plots. The fertilizer was hand-broadcast 10 d to 14 d after emergence along the rows of each plot to ensure that N was evenly distributed. Acetochlor (2-chloro-2-methyl-6-ethyl-N-ethoxymethylacetanilide) was applied at a rate of 2.7 kg a.i. ha^{-1}. A postemergence herbicide, Buccaneer Plus (glyphosate N-(phosphomethyl) glycine, was applied at a rate of 2.5 L ha^{-1} at the 8-leaf growth stage. Hand-weeding was also done as and when necessary throughout the growing season to keep fields weed-free. The inside two rows were used for data collection to eliminate any border effects.

In both years and sites, 10 plants were tagged in the two middle rows for phenological measurement (days to 50 % silking), growth traits (plant height), and physiological traits. Physiological measurement such as leaf chlorophyll index was measured with the aid of a soil plant analysis development (SPAD) chlorophyll meter (Model 502, Minolta Corp. Tokyo, Japan). Readings were taken at 5 growth stages. At V7 growth stage, readings were taken from the uppermost fully expanded leaves from 10 different plants in each plot and averaged to one value per plot. At growth stages R1 through R4, the ear leaf was used to measure leaf chlorophyll index. Two representative plants were tagged at growth stage Vt, R1, and R2 in each plot within each replication from which photosynthesis, transpiration, stomatal conductance, and intercellular CO_2 concentration were measured using a handheld photosynthesis system (CI-340, CID Bio-Science, Camas, WA). All measurements were taken between 11:00 AM and 3:00 PM on a clear-sky day.

The aboveground portion of 10 plants from each maize plot were randomly sampled at R5. Samples were dried at 60°C in a forced-air oven for 72 h and weighed. Based on the individual plot plant population, total aboveground biomass was calculated and expressed per unit area. The dried leaf and stem samples were ground in a Thomas-Wiley laboratory mill to pass through a 2.0-mm screen. The cobs were threshed in a stationary maize sheller (Model LDB, ALAMACO, Nevada, IA), and the grain was ground in a cyclone sample mill (Model 3010-030, Udy Corporation, Fort Collins, CO). Nitrogen concentration was analyzed by wet-digesting samples with H_2SO4 and H_2O_2, and the total N in the digest was analyzed by a colorimetric procedure (nitroprusside-sodium hypochlorite) using an RFA autoanalyzer (Alpkem Co., Clackamas, OR).

Plots were mechanically harvested after physiological maturity using a modified two-row Gleaner equipped with a weighing balance. Grain moisture and test weight were estimated with a DICKEY-John GAC 2000. Yields at both sites and years were then corrected to 155 g kg^{-1} moisture content. Kernels plant^{-1} were counted with the aid of Seedburo seed counter (Model 77, Inpack Systems, Madison, WI).

Components of N Use Calculations

Nitrogen use calculations were completed with the following equations.

Nitrogen uptake (kg ha^{-1}) = [(Aboveground dry matter) x (N concentration in dry matter / 100)]

Carbon uptake (kg ha^{-1}) = [(Aboveground dry matter) x (C concentration in dry matter / 100)]

Grain N uptake (kg ha^{-1}) = [(Grain yield) x (grain N concentration / 100)]

Nitrogen utilization efficiency (kg kg^{-1}) = Grain yield / total N uptake

Nitrogen harvest index = [(Grain N uptake / total N uptake)] x 100

Nitrogen fertilizer replacement value was calculated based on the method described by Hesterman et al. (1992).

Economic Analyses

Economic analyses based on statistically significant treatment of the experiment were performed to determine which cropping systems gave acceptable net returns to producers (CIMMYT, 1988). Economic analyses were done using prevailing market prices (USDA-NASS, 2013) for inputs at planting and for output at the time of harvest. All costs and benefits were calculated on hectare basis in US dollars (US $). The concepts used in the economic analyses are defined as follows: mean grain yield of maize is the average yield (kg ha^{-1}) of each treatment in both years and sites. The gross benefit per hectare is the product of field prices of maize and the mean yield for each treatment. The total variable cost (TVC) is the sum of field cost of fertilizer and application, herbicides and application, seeds, harvesting, and hauling cost. The net benefit per hectare (NB) for each treatment is the difference between the gross benefit and the total variable cost. For each of the treatments, percentage marginal rate of return (MRR) was calculated to denote the return per unit of investment in fertilizer expressed as a percentage of that investment. An estimate of these returns was generated by the formula:

MRR (between treatments, 1 and 2) = [(Change in net benefit (NB_1-NB_2) / (change in TVC (TVC_2-TVC_1)] x 100.

Thus a MRR of 100% implies a return of one dollar on every dollar of expenditure for the given variable input.

Comparison of Maize and Sorghum Response to Nitrogen Fertilizer

A quadratic model was fitted to grain yield response to varying N levels for both years by using regression analyses to compare the response of maize and grain sorghum to N fertilizer application. The model is defined as: $Y = a + bX + cX^2$

where Y is the yield of grain (kg ha^{-1}) and X is the rate of N application (kg ha^{-1}), a (intercept), b (linear coefficient), and c (quadratic coefficient) are constants obtained by fitting the model to the data.

Data Analyses

Statistical analyses were performed using PROC MIXED, PROC CORR, and PROC REG in SAS 9.1 (SAS Institute, 2003). The normality of distribution of the studied traits were tested using the Shapiro-Wilk normality test. A three-way analysis of variance was carried out to determine the effects of years (Y), cropping systems (CS), and site (S) and a combination of all interactions. Cropping system, site, and year were treated as fixed effects and block as a random effect. Mean separation for significant effects was performed using Tukey's honestly significant difference test at 0.05%.

RESULTS

Weather Conditions

Precipitation and temperature during the cropping season varied among site years of the study. Maximum temperature in July 2012 was 4.6°C above the 30-year average. Total precipitation (April-October) in 2012, 2013, and 2014 was 338 mm, 539 mm, and 576 mm, respectively. These were below the 30-year average of 698 mm (Source: KSU Weather Data Library).

Aboveground Biomass Accumulation, Carbon and Nitrogen Uptake by Cover Crops

No significant three-way interactions were observed between site, year, and cropping systems in this study. Hence, discussion of the results will focus on two-way interactions and main effects as appropriate. Although the summer cover crop and double-cropped grain crop performance depended on year, it was similar at both sites.

Response of summer crops varied with year ($P < 0.05$) and was significant for aboveground biomass, plant C accumulation, plant N uptake and C/N ratio (Fig. 4.1). Pigeon pea had significantly greater aboveground biomass followed by cowpea, but there was no significant difference between sunn hemp and double-cropped grain sorghum in 2012. In 2013, sunn hemp had the greatest aboveground biomass, and cowpea, pigeon pea, and double-cropped grain sorghum had similar aboveground biomass. The least aboveground biomass was observed for soybean in both years (Fig. 4.1a).

Carbon accumulation was significantly greater in 2012 than in 2013 for all cover crops and double-cropped grain crops (Fig. 4.1b). Double-cropped grain sorghum had the greatest C accumulation, followed by pigeon pea in 2012. But sunn hemp and double-cropped soybean were not statistically different for C accumulation in 2012. Cowpea had the least C accumulation in 2012. In 2013, double-cropped grain sorghum had the most C accumulation followed by sunn hemp. Carbon accumulation was relatively similar for cowpea, pigeon pea, and soybean in 2013 (Fig. 4.1b).

Pigeon pea had the most plant N uptake compared with cowpea, sunn hemp, and double-cropped soybean, but the least was found for double-cropped grain sorghum in 2012 (Fig. 4.1c). Similar trends were observed among summer cover crops and double-cropped soybean and double-cropped grain sorghum in 2013 (Fig. 4.1c). In 2013, the cover crops and double-cropped soybean, had similar C/N ratio, but significantly greater in double-cropped grain sorghum. In 2014, sunn hemp had a higher C/N ratio than cowpea, pigeon pea, and double-cropped soybean. Double-cropped grain sorghum again had the greatest C/N of the summer crops in 2014. When averaged across years, C/N ratio was greatest for grain sorghum (29:1); summer cover crops and double-cropped soybean averaged 19:1 (Fig. 4.1d).

Physiology Traits of Maize

Response of maize to cropping system differed with year ($P < 0.05$) and significantly affected leaf chlorophyll index and photosynthetic rate (Figs. 4.2a and b). Maize leaf chlorophyll index in the cover crops systems and in the double-cropped soybean cropping system was similar to the response of maize in the fallow system with 45 kg N ha^{-1}, but was lower in the double-cropped grain sorghum system in 2013. Similar trends were observed for leaf chlorophyll index in 2014 (Fig. 4.2a). Leaf chlorophyll index increased with increasing N fertilizer application in 2013 ($r^2 = 0.96$, $P = 0.0015$) and 2014 ($r^2 = 0.99$; $P = 0.0002$) (Fig. 4.2a).

In 2013, the photosynthetic rate of maize in the pigeon pea cropping system was greater than that of cowpea, sunn hemp, and double-cropped soybean cropping systems. The fallow system with 0 kg N ha^{-1} and the double-cropped grain sorghum system had the smallest photosynthetic rate in 2013 (Fig. 4.2a). Photosynthetic rate was greater in the pigeon pea, sunn hemp, and double-cropped soybean cropping systems than that of the cowpea cropping system in 2014. Photosynthetic rate was smallest in double-cropped grain sorghum in 2014 (Fig. 4.2b). Photosynthetic rate responded linearly to N fertilizer application in 2013 ($r^2 = 0.90$; $P = 0.0079$) and 2014 ($r^2 = 0.98$; $P = 0.0007$) (Fig. 4.2b). In both years, the photosynthetic rate of maize in the cover crop systems and double-cropped soybean cropping system was similar to the fallow system with N fertilizer application of 45 to 90 kg ha^{-1}.

Cropping systems affected ($P < 0.05$) stomatal conductance, transpiration rate, and intercellular CO_2 concentration (C_i) (Table 4.2). Stomatal conductance was similar for maize in the fallow systems with any N fertilizer application rate, the fallow system with 0 kg N ha^{-1}, the various cover crop systems, and the double-cropped soybean system. Maize in the fallow system with 45 kg N ha^{-1} and the double-cropped grain sorghum system was not statistically different in stomatal conductance (Table 4.2).

Transpiration rate was greatest in the fallow system with either 90 or 180 kg N ha^{-1} compared with the fallow system with 135 kg N ha^{-1} (Table 4.2). Furthermore, transpiration rate was greater for maize in the fallow system with 45 kg N ha^{-1}, cowpea, and sunn hemp. The least transpiration rate was recorded in the fallow system with 0 kg N ha^{-1}, the cropping system with pigeon pea, double-cropped soybean, and double-cropped grain sorghum (Table 4.2). Maize in the fallow system with 0 kg N ha^{-1} had the greatest C_i, but the C_i was similar for maize in the fallow systems with N fertilizer application of 90 to 180 kg ha^{-1} and in the cowpea, pigeon pea, and double-cropped grain sorghum cropping systems. Intercellular CO_2 concentration was lowest in the fallow system with 45 kg N ha^{-1} and the sunn hemp and double-cropped soybean cropping systems (Table 4.2).

Phenology and Growth Traits of Maize

Cropping systems had a significant ($P < 0.05$) effect on maize days to 50% silking (DTS) and plant height (Table 4.2). Maize in the fallow systems with 90 kg N ha^{-1} or more had similar DTS and were earlier than maize in the fallow system with 45 kg N ha^{-1}. Days to 50% silking ranged from 58-61 d among the cropping systems with N fertilizer application. Maize in any of the cover crops and double-cropped soybean cropping systems had similar DTS, but DTS in the fallow system with 0 kg N ha^{-1} and double-cropped grain sorghum was longer.

Plant height was significantly taller for maize in the fallow systems with 135 or 180 kg N ha^{-1}, the cowpea cropping system, and the sunn hemp cropping system. Furthermore, plant height did not differ for maize in the fallow systems 45 and 90 kg N ha^{-1}, pigeon pea, and double-cropped soybean cropping systems. Plant height was significantly shorter in the fallow system with 0 kg N ha^{-1} and maize in the double-cropped grain sorghum system (Table 4.2).

Response of maize to cropping systems differed with year ($P < 0.05$) for aboveground biomass at physiological maturity. In 2013, aboveground biomass at physiological maturity of maize in the cowpea and pigeon pea cropping systems was greater than aboveground biomass in sun hemp and double-cropped soybean (Fig. 4.3c). In 2014, aboveground biomass in the cowpea, pigeon pea, and sunn hemp cropping systems were similar. The double-cropped soybean system aboveground biomass was greater than that of the double-cropped grain sorghum system (Fig. 4.3c).

Aboveground biomass at physiological maturity response to N fertilizer application can best be described by a quadratic curve in both years (2013: $-0.182\text{nrate}^2 + 74.99\text{nrate} + 9374$; $r^2 = 0.093$; $P = 0.0331$) and in (2014: $-0.198\text{nrate}^2 + 81.45\text{nrate} + 9718$; $r^2 = 0.98$; $P = 0.0063$) (Fig. 4.3c). In both years, aboveground biomass at physiological maturity in the various cover crop systems and double-cropped soybean cropping system was similar to maize in the fallow system with 45 kg N ha^{-1}.

Components of Yield and Grain Yield

Response of maize to cropping systems varied with year ($P < 0.05$) and affected grain yield and kernels $plant^{-1}$ (Figs. 4.2d and e). Grain yield was significantly greater in 2013 than in 2014. Grain yield in the pigeon pea cropping system was significantly greater, followed by the cowpea and sunn hemp cropping systems, compared with the double-cropped soybean cropping system in 2013. Grain yield of maize in the fallow system with 0 kg N ha^{-1} and double-cropped grain sorghum were the least in 2013 (Fig. 4.2d). In 2014, grain yield of maize in the various cover crop systems was greater than that in the double-cropped soybean system (Fig. 4.2d). The double-cropped grain sorghum cropping system had the least grain yield in 2014. A quadratic response curve best described grain yield to N fertilizer application in 2013 ($r^2 = 0.97$; $P = 0.0245$) as well as in 2014 ($r^2 = 0.98$; $P = 0.0132$). Grain yield in the various cover crops and double-cropped soybean cropping systems was similar to fallow system with 45 kg N ha^{-1} in both years (Fig. 4.2d).

Kernels $plant^{-1}$ in any of the cover crops and double-cropped soybean cropping systems was similar to maize in the fallow system with 45 kg N ha^{-1} in 2013 (Fig. 4.2e). Maize in the double-cropped grain sorghum system had the fewest kernels $plant^{-1}$ in 2013. In 2014, Kernels $plant^{-1}$ followed trends similar to those observed in 2013. Kernels $plant^{-1}$ response to N fertilizer application was linear in 2013 (1.118nrate + 383.2; $r^2 = 0.99$; $P = 0.0002$). In contrast, kernels $plant^{-1}$ in 2014 was best described by a quadratic ($-0.004\text{nrate}^2 + 1.368\text{nrate} + 452.4$; $r^2 = 0.097$; $P = 0.0131$) response curve to N fertilizer application. Overall, kernels $plant^{-1}$ was greater in 2013 than in 2014 (Fig. 4.2e).

Cropping systems significantly ($P < 0.05$) affected hundred-kernel weight (HKW); Table 4.2). The fallow system with 135 and 180 kg N ha^{-1} had the greatest HKW. Hundred-kernel weight in the various cover crops systems and double-cropped soybean system was similar to the fallow systems with 45 and 90 kg N ha^{-1}.The smallest HKW was found in the fallow system with 0 kg N ha^{-1} and the double-cropped grain sorghum system.

Nitrogen Uptake and Components of N Use

Response of maize to cropping systems differed with year ($P < 0.05$) for grain N uptake, total N uptake, and N harvest index (NHI) (Fig. 4.2f, g and h). Maize in the cowpea cropping system had the greatest grain N uptake in 2013, but grain N uptake did not differ in the pigeon pea and double-cropped soybean systems in 2013. Grain N uptake in the sunn hemp cropping system was greater than grain N uptake in the double-cropped grain sorghum system (Fig. 4.2f) in 2013. Grain N uptake in the pigeon pea system was greater than grain N uptake in the cowpea, sunn hemp, and double-cropped soybean systems in 2014. In both years, the least grain N uptake was found in the double-cropped grain sorghum system. In 2013, the cover crop and double-cropped soybean systems had grain N uptake similar to the fallow system with 45 kg N ha^{-1} in both years (Fig. 4.2f). Grain N uptake in 2013 had a quadratic ($-0.002nrate^2 + 1.012x + 31.81$; $r^2 = 0.99$; $P = 0.0037$) response curve to N fertilizer application. In contrast, grain N uptake increased with increasing N fertilizer application ($0.429nrate + 30.92$; $r^2 = 0.98$; $P = 0.0007$) in 2014.

Total N uptake was similar in the various cover crops systems in 2013, but it was greater in the double-cropped soybean system than in the double-cropped grain sorghum cropping system. Similar trends were observed for total N uptake in 2014. Total N uptake increased with increasing N fertilizer application ($0.907nrate + 73.41$; $r^2 = 0.096$; $P = 0.00150$) (Fig. 4.2g). In both years, total N uptake for all the cover crop systems and double-cropped soybean system was similar to maize in the fallow system with 45 kg N ha^{-1}.

In 2013, NHI was similar in the cowpea and pigeon pea cropping systems, and no statistical difference was detected in the sunn hemp and double-cropped soybean systems. The smallest NHI was found in the double-cropped grain sorghum system (Fig. 4.2h). Similar trends were found for NHI in 2014. Nitrogen harvest index had a quadratic ($-3.661E{-}004nrate^2 + 0.142nrate + 41.63$, $r^2 = 0.097$; $P = 0.0108$) response curve to N fertilizer application. Over the years, all the cover crop systems and double-cropped soybean system had NHI equivalent to that of the fallow systems with 45 to 90 kg N ha^{-1}.

Site x Cropping System

Response of maize to cropping systems differed with site ($P < 0.05$) for leaf chlorophyll index, photosynthetic rate, and grain yield. At Ashland Bottoms, leaf chlorophyll index in the cover crop systems and double-cropped soybean system was similar that in the fallow system with 45 kg N ha^{-1} (Fig. 4.3a). Leaf chlorophyll index in the double-cropped grain sorghum cropping system was the lowest. Similar trends for leaf chlorophyll index were observed at ANF (Fig. 4.3a). Leaf chlorophyll index increased with increasing N fertilizer application (0.085nrate + 35.11; $r^2 = 0.85$; $P = 0.00162$).

At Ashland Bottoms, photosynthetic rate was greater for maize in the pigeon pea cropping system than in the cowpea, sunn hemp, and double-cropped soybean systems (Fig. 4.3b). Maize in the double-cropped grain sorghum system had the lowest photosynthetic rate at Ashland Bottoms. At ANF, maize in all the cover crop systems and the double-cropped soybean system had similar photosynthetic rates. Photosynthetic rate of maize in the double-cropped grain sorghum cropping system was the lowest. Photosynthetic rate also responded linearly (0.109nrate + 22.73; $r^2 = 0.99$; $P = 0.0003$) to N fertilizer application at both sites. Moreover, maize in all the cover crop systems and double-cropped soybean cropping system had photosynthetic rates similar to maize in the fallow system with 45 kg N ha^{-1} at both sites.

Maize in the cowpea and pigeon pea systems at Ashland Bottoms had greater grain yield than in the sunn hemp and double-cropped soybean systems. At ANF, grain yield of the cowpea and pigeon pea cropping systems was similar. At ANF, grain yield of maize in the sunn hemp system was greater than in the double-cropped soybean system. Maize in the double-cropped grain sorghum system had the lowest grain yield at both locations (Fig. 4.3c). Grain yield in the fallow systems with N fertilizer application at both sites was best described by a quadratic response curve ($-0.0170\text{nrate}^2 + 63.58\text{nrate} + 3642$; $r^2 = 0.99$; $P = 0.001$). Grain yield in the cropping systems with all the cover crops and the double-cropped soybean system was comparable to the fallow system with 45 kg N ha^{-1}.

Response of maize to cropping systems varied with site ($P < 0.05$) and affected aboveground N uptake, grain N uptake, total N uptake, NHI, and NUtE. Maize in the double-cropped soybean system had the greatest aboveground N uptake compared with the maize in all the cover crop systems at Ashland Bottoms (Fig. 4.2d). At ANF, maize in the cowpea system had the greatest aboveground N uptake. Aboveground N uptake was similar in the pigeon pea and sunn hemp cropping systems at ANF. Aboveground N uptake in double-cropped soybean was greater than that in the double-cropped grain sorghum system (Fig. 4.2 d). Aboveground N uptake at both sites responded linearly to N fertilizer application ($r^2 = 0.96$; $P = 0.0018$). All the cover crop systems and the double-cropped soybean system had aboveground N uptake similar to the fallow systems with 45 to 135 kg N ha^{-1}.

At Ashland Bottoms, maize in the cowpea and pigeon pea cropping systems had more grain N uptake compared with the sunn hemp and double-cropped soybean systems. The lowest grain N uptake was found in the double-cropped grain sorghum cropping system. Similar trends were observed for grain N uptake at ANF (Fig. 4.3e). A linear response curve best fit the response of grain N uptake (0.425nrate + 38.42; $r^2 = 0.88$; $P = 0.0018$) at Ashland bottoms and (0.571nrate + 35.12; $r^2 = 0.99$; $P = 0.0003$) at ANF to N fertilizer application. At both sites, maize in all the cover crops systems and the double-cropped soybean system had grain N uptake equivalent to the fallow system with 45 kg N ha^{-1}.

Total N uptake was greater at Ashland bottoms than at ANF. Total N uptake for maize in all the cover crop systems and the double-cropped soybean system was similar to maize in the fallow system, with 45 kg N ha^{-1} at Ashland Bottoms. Similar trends were observed at ANF for total N uptake (Fig. 4.3f). Total N uptake increased with increasing N fertilizer application (Ashland Bottoms: $r^2 = 0.98$; $P = 0.0004$; ANF: $r^2 = 0.93$; $P = 0.0042$). Total N uptake in the double-cropped grain sorghum system was generally similar to that of the fallow system with 0 kg N ha^{-1} at both sites.

Maize in the double-cropped grain sorghum system had the highest NUtE among the systems at Ashland Bottoms. Maize in the pigeon pea, double-cropped soybean, and double-cropped grain sorghum systems had similar NUtE compared with the maize in cowpea and sunn hemp systems at ANF (Fig. 4.3g). Nitrogen utilization efficiency decreased linearly ($r^2 = 0.93$; $P = 0.0050$) with increasing N application at both sites (Fig. 4.3g). All the cover crops systems and the grain crop systems had NUtE similar to the fallow systems with 0 to 180 kg N ha^{-1}.

Maize in the cowpea cropping system had the greatest NHI but was similar in pigeon pea and sunn hemp cropping systems in Ashland Bottoms. Furthermore, NHI in the double-cropped soybean system was greater than NHI in the double-cropped grain sorghum cropping system at Ashland Bottoms. At ANF, maize in the pigeon pea cropping system had the greatest NHI compared with maize in cowpea, sunn hemp, and double-cropped soybean systems. The double-cropped grain sorghum system had the lowest NHI, and the value was similar to the fallow system with 0 kg N ha^{-1}. Nitrogen harvest index increased with increasing N fertilizer application at both sites ($r^2 = 0.97$; $P = 0.0009$). Overall, NHI following all the cover crop systems and the double-cropped soybean system was similar to maize in the fallow system with 45 kg N ha^{-1} at both sites.

Relationship among Physiology Traits and Grain Yield

Photosynthetic rate showed linear relationships when plotted against leaf chlorophyll index, leaf N uptake, stomatal conductance, and intercellular CO_2 concentration (C_i) (Figs. 4.4a, b, c, and d). Stomatal conductance explained more of the variability associated with photosynthetic rate than other physiological traits (Figs. 4.4a, b, c, d), and photosynthetic rate, leaf chlorophyll index and leaf N uptake were influenced by N fertilizer application (Figs. 4a, b, c, d).

Linear relationships also were observed when grain yield was plotted against leaf chlorophyll, aboveground biomass, kernels plant^{-1}, and HKW (Fig. 4). All these parameters were affected by N fertilizer application (Figs. 4.2 and 4.3). Aboveground biomass explained more of the variability observed in grain yield than leaf chlorophyll index, kernels plant^{-1}, and HKW.

Pearson Correlation among Physiology Traits, Growth Traits, Yield and Yield Components, and Components of N Use

Correlation coefficients were determined among physiology traits, growth traits, yield, and yield components, and components of N use (Table 4.3). The correlation analysis among all the parameters generated 61 significant ($P < 0.05$) correlations from a sample size of 160 and a total of 225 pairs. Leaf chlorophyll index and photosynthetic rate showed a positive correlation ($P < 0.05$) with leaf chlorophyll index, transpiration rate, stomatal conductance, grain yield, HKW plant height, and grain N uptake. Grain yield significantly ($P < 0.05$) and positively correlated with aboveground biomass at physiological maturity, HKW, kernels plant^{-1}, and plant height. Aboveground biomass showed a positive correlation with HKW, kernels plant^{-1}, and NUtE. In contrast, aboveground biomass at physiological maturity correlated negatively with aboveground biomass N uptake, total N uptake, and NHI. Aboveground biomass N uptake and grain N uptake had the greatest correlation with total N uptake but were negatively correlated with NutE.

Economic Analyses

Economic analysis was conducted for grain yield of maize in fallow systems with N fertilizer application, cover crops, double-cropped soybean, and double-cropped grain sorghum cropping systems. The results are presented in Tables 4.4 and 4.5. Maize in fallow plots with N fertilizer application had positive gross benefits averaged across years. The marginal rate of return was the greatest between fallow with 0 and 135 kg N ha^{-1}. Among the cover/double-cropping systems, maize in the double-cropped soybean system gave the greatest economic net return, followed by the double-cropped grain sorghum system. In contrast, maize in the sunn hemp system gave a negative economic net return.

Comparison of Maize and Sorghum Response to Nitrogen Fertilizer

Response of maize and grain sorghum to N fertilizer application can be found in Fig. 4.5. Nitrogen fertilizer effects were highly significant for both maize and grain sorghum. Grain yield increased as N fertilizer level increased. Maize grain yield increased from 4,320 kg ha^{-1} in the unfertilized treatment to 10,387 kg ha^{-1} at 180 kg ha^{-1} N fertilizer level, and grain sorghum increased from 3,897 kg ha^{-1} to 8,342 kg ha^{-1} (Fig. 4.5). Grain yield of maize and grain sorghum at 180 kg N ha^{-1} were 154% and 114% higher that the unfertilized treatments, respectively. Both maize and grain sorghum had quadratic responses to increasing N fertilizer rates.

Nitrogen fertilizer replacement values (NFRV) of the cover crops and double-cropped soybean in 2013 ranged from 35 to 66 kg N ha^{-1}. The corresponding values in 2014 were 35 to 62 kg N ha^{-1} (Figs. 4.5a and b) when maize was the test crop. In contrast, the NFRV of double-cropped grain sorghum in 2013 was -8.9 kg N ha^{-1}, and in 2014 the value was -0.61 kg N ha^{-1}. Compared with grain sorghum, NFRV in 2013 for the cover crops and double-cropped soybean ranged from 30 to 75 kg N ha^{-1}. The corresponding values in 2014 were 23 to 52.3 kg N ha^{-1}

(Figs. 4.5c and d). Nitrogen fertilizer replacement values for double-cropped grain sorghum was -2.7 kg N ha^{-1} in 2013, and in 2014 the value was -2.2 kg N ha^{-1}. In both years and between maize and grain sorghum, the cropping system with pigeon pea had the greatest NFRV. Estimated economic maximum grain yield of maize and grain sorghum occurred at 90 kg N ha^{-1} and 135 kg N ha^{-1}, respectively.

DISCUSSION

The response of hybrid DKC63-84 to N fertilizer application and various cover crops varied for all measured traits. The summer cover crops varied in their contribution to aboveground biomass produced in both years. Pigeon pea had the greatest aboveground biomass, which was the factor that most determined the high plant C accumulation and plant N uptake observed compared with cowpea and sunn hemp. This result agrees with Tegegne et al. (2012), who reported that pigeon pea produced abundant organic matter and fixed more N than other legumes.

Weather conditions during the growing season (April-October) in 2013 and 2014 influenced crop performance. Rainfall was adequate in 2013, especially during silking and grain filling periods. In 2014, a long dry spell and high temperatures were recorded during silking and grain filling. Reproductive processes in maize are highly sensitive to high temperature stress (>32°C). The most sensitive stages in maize were identified 2 wk prior to and post-silking (Tollenaar and Lee, 2011). Drought during late vegetative growth and silking causes a significant reduction in grain yield and components of yield (Cicchino et al., 2010), which might explain the yield advantage of 2013 over 2014. High temperature stress can directly affect grain yield by influencing kernel-filling duration and rate, both of which are highly sensitive to high temperature stress (Uribelarrea et al., 2002). Kernels plant^{-1} and HKW were both affected by drought and high temperature stress in 2014. Although the amount of rainfall in 2014 was greater than in 2013, the rainfall distribution pattern in 2013 was more favorable for plant growth.

Leaf chlorophyll index and photosynthetic rate varied among the cropping systems, especially for maize in the fallow systems with N fertilizer application across site years. Nitrogen plays a key role in several crop physiological processes, so increased N levels led to increased photosynthetic rate and leaf chlorophyll index. These findings are in agreement with those of other researchers (Li et al., 2012; Tóth et al., 2002). Low-N supply negatively affects the amount or activity of photosynthetic components (Li et al., 2012); accordingly, it is believed that biochemical limitations primarily constrain photosynthesis in N-deficient plants. Leaf chlorophyll index and photosynthetic rate of maize following cover crops was greatest in the fallow system with 0 kg N ha^{-1} and in maize following double-cropped grain sorghum (Fig. 4.2).

The importance of N fertilizer in improving soil fertility status and sustainable maize production is demonstrated clearly in the increased grain yield across site years in this study. Grain yield and biomass were greatest in maize fallow system with 180 kg N ha^{-1}, followed by 135 kg N ha^{-1} and 90 kg N ha^{-1} (Fig. 4.2). Inclusion of cowpea, pigeon, sunn hemp, double-cropped soybean, and double-cropped grain sorghum in the rotation compared with the fallow system with 0 kg N ha^{-1} resulted in a mean increase in grain yield of 78, 91, 66, 72, and 12%, respectively, over the years (Fig. 4.2). Balkcom and Reeves (2005) found that using legume cover crops in a cereal production system can help improve N availability, resulting in improved biomass accumulation and grain yield of maize.

Over the years, mean N fertilizer replacement values (NFRV) for maize following cowpea, pigeon pea, sunn hemp, double-cropped soybean, and double-cropped grain sorghum years was 53, 64, 43, 47, and -4.8 kg N ha^{-1}, respectively (Figs. 4.5a and b). As a comparison, NFRV was 53.3, 64.0, 36.0, 27, and -2.5 kg N ha^{-1}, respectively (Figs. 4.5c and d), for grain sorghum. In our research, the response to N fertilizer application was greater for maize than for grain sorghum (Fig. 4.5). Balkcom and Reeves (2005) determined that the NFRV of sunn hemp residues for a following maize crop averaged 58 kg N ha^{-1} on Compass loamy sand under conventional tillage in Alabama. Although both maize and sorghum are C_4 plants, maize is physiologically more efficient at utilizing N (more yield per unit N accumulation) than most other cereal crops (Greenwood et al., 1990). A tremendous amount of research over the years has led to more efficient N uptake and utilization in maize than in other cereals, and the genetic gains in maize have been more pronounced than in other cereals grains.

Correlation analysis showed a positive ($P < 0.05$) relationship between leaf chlorophyll index and yield, and grain yield as function of photosynthetic rate, which demonstrated that chlorophyll index and photosynthetic rate play an indispensable role in determining yield. Strong positive correlations were also observed between photosynthetic rate and leaf N uptake. Li et al. (2012) reported that most leaf N is used for components of the photosynthetic apparatus and for synthesis of photosynthesis-related enzymes (Li et al., 2012), which indicates the valuable contribution of leaf N in photosynthetic rate of cereal crops. NHI represents the increased capacity of cereals to mobilize and translocate N from leaves and stems to grain. In this study, NHI was observed to increase with increasing N fertilizer application. This is consistent with other studies in maize (Caviglia et al., 2014; Manson and D'croz-Manson, 2002) that have indicated improved NHI with increasing N application.

Kernels plant^{-1} was the more important yield component than HKW in terms of grain yield changes in both years. These results are consistent with those of Bidinger and Raju (2000) in pearl millet [*Pennisetum glaucum* (L.) R. Br.] and Kamara et al. (2003) in maize. In several other cereals (rice and wheat) and grain legumes (soybean and peanut), most of the yield variation in different environments is described mainly by the response of grain numbers, rather than other physiological or reproductive traits.

Economic analysis showed that fallow with 180 kg N ha^{-1} rates added to the cost of production but did not add significantly to output. This is evidenced by the fact that the main effect of increasing N level from 135 to 180 kg N ha^{-1} resulted in a corresponding increase in grain yield, which shows net benefit, but the increase did not merit the extra cost to producers. Maize in fallow with N level of 135 kg N ha^{-1} gave maximum economic grain yield and profitable net return.

Double-cropped soybean and double-cropped grain sorghum after wheat increase cropping intensity, a means for improving cash flow, spreading risk, improving use of land and equipment, and achieving greater net returns on investment (Chen and Wiatrak, 2010). Maize in a double-cropped soybean system gave the greatest economic net return compared with double-cropped grain sorghum system and cover crop systems.

CONCLUSIONS

Maize hybrid DKC63-84 varied in its response to N fertilizer and various cover crops. Among the cover crops, pigeon pea had the greatest aboveground biomass accumulation and N uptake. Fallow with N fertilizer application had the greatest grain yield and leaf chlorophyll index. Mean increase in grain yield as a result of inclusion of cowpea, pigeon pea, sunn hemp, double-cropped soybean, and double-cropped grain sorghum in the rotation was greater than fallow with 0 kg N ha^{-1}, and the NFRV was greatest for pigeon pea. The response to N fertilizer application was greater for maize than for grain sorghum. A strong relationship was found between leaf chlorophyll index and photosynthetic rate and grain yield. The relationship between kernels plant^{-1} and grain yield, and between total aboveground biomass and grain yield, were significant. Kernels plant^{-1} was the most important factor for grain yield in this study. Maize in the fallow system with 135 kg N ha^{-1} and maize in the double-cropped soybean system gave profitable economic net returns.

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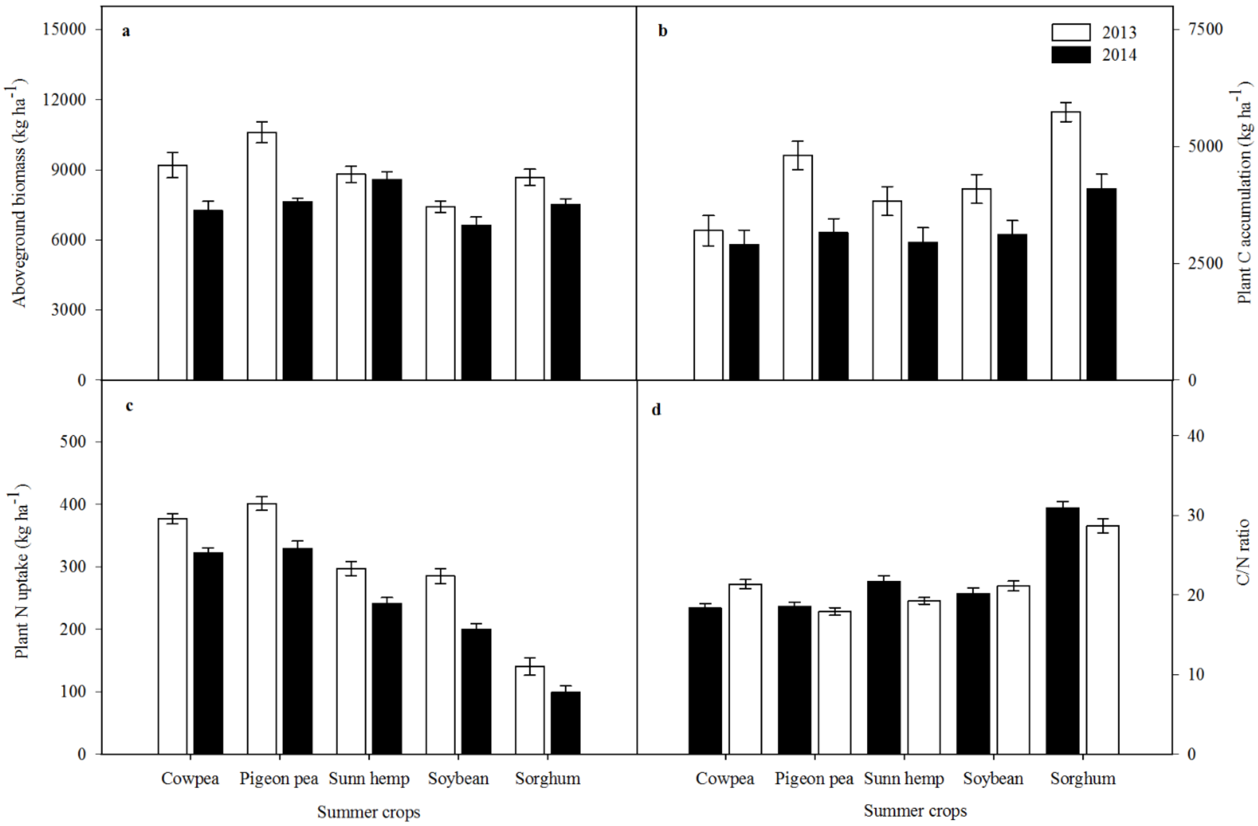

Figure 4.1. Summer crops and year effects on (a) aboveground biomass, (b) plant C accumulation, (c) plant N uptake, and (d) C/N ratio in 2012 and 2013.

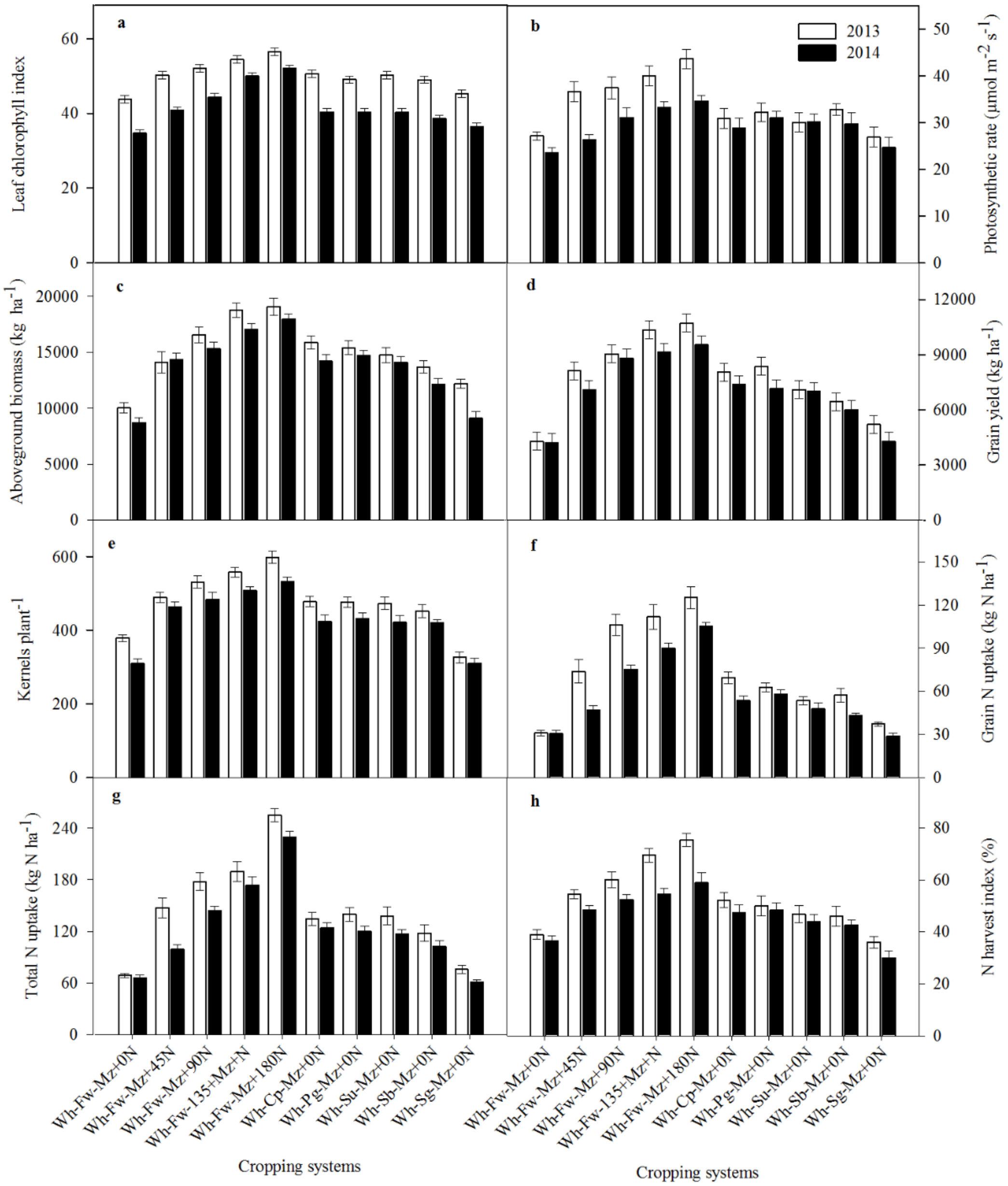

Figure 4.2. Cropping system and year effects on (a) leaf chlorophyll content, (b) photosynthetic rate, (c) aboveground biomass at physiological maturity, (d) grain yield, (e) kernels plant^{-1}, (f) grain N uptake, (g) total N uptake at physiological maturity, and (h) N harvest index of maize grown in 2013 and 2014.

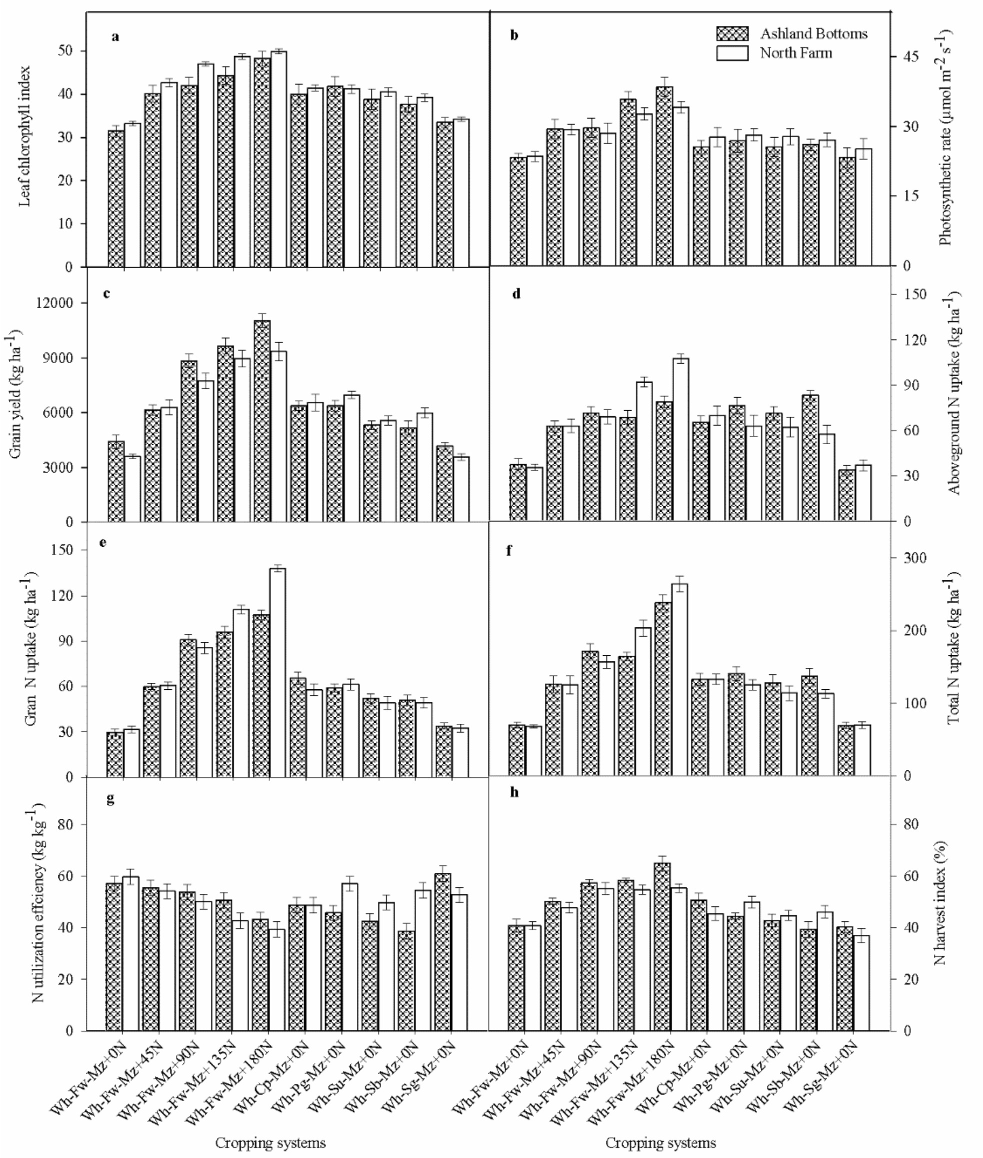

Figure 4.3. Cropping system and site effects on (a) leaf chlorophyll content, (b) photosynthetic rate, (c) grain yield, (d) aboveground N uptake, (e) grain N uptake, (f)) total N uptake (g) N utilization efficiency, and (h) N harvest index of maize grown in 2013 and 2014.

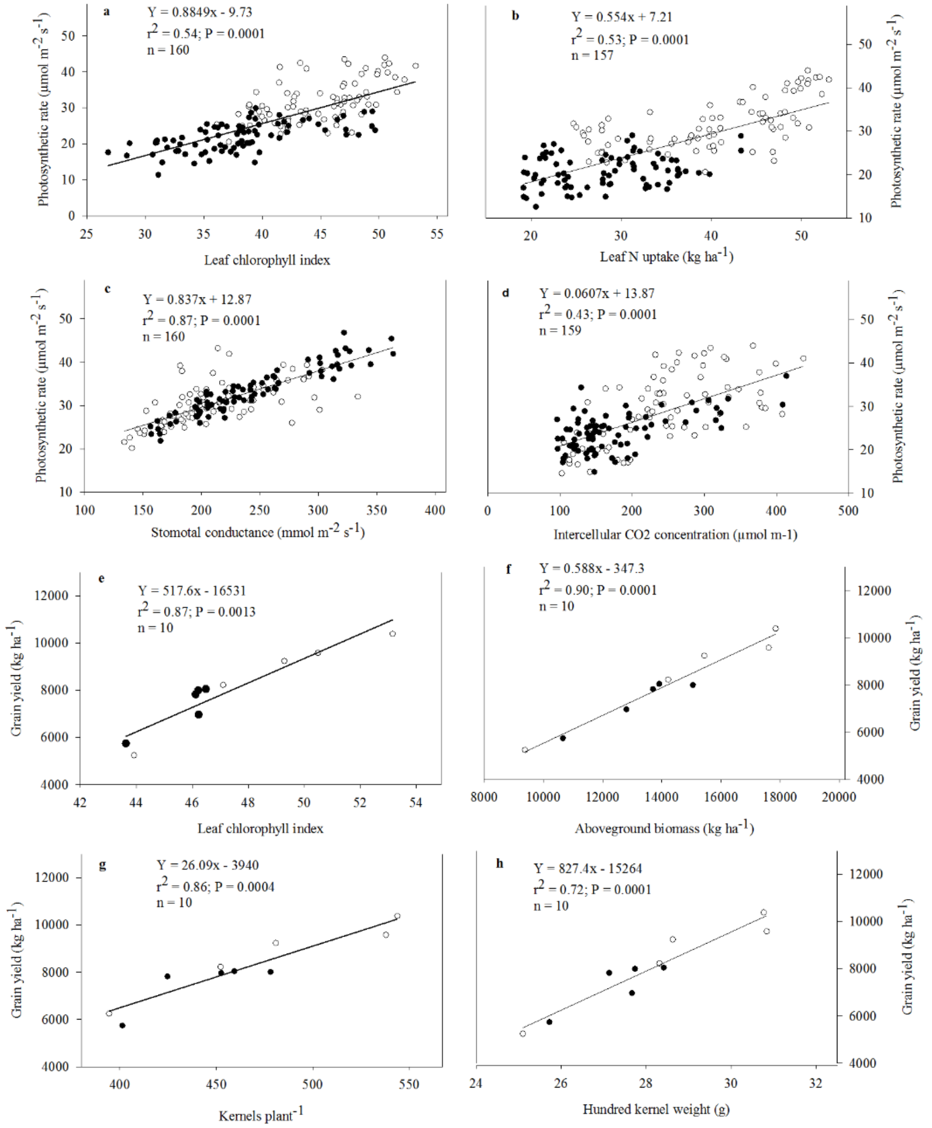

Figure 4.4. Relationship of photosynthetic rate and (a) leaf chlorophyll index, (b) aboveground biomass at leaf N uptake, (c) stomatal conductance, (d) intercellular CO_2 concentration; relationship of grain yield and (e) photosynthetic rate, (f) aboveground biomass at physiological maturity, (g) kernels $plant^{-1}$, (h) hundred kernel weight of maize grown in 2013 and 2014.

Note: Open circle marker: Fallow system with 0, 45, 90, 135, and 180 kg N ha^{-1}.

Close circle marker: Cover crops and double-cropped grain crops systems.

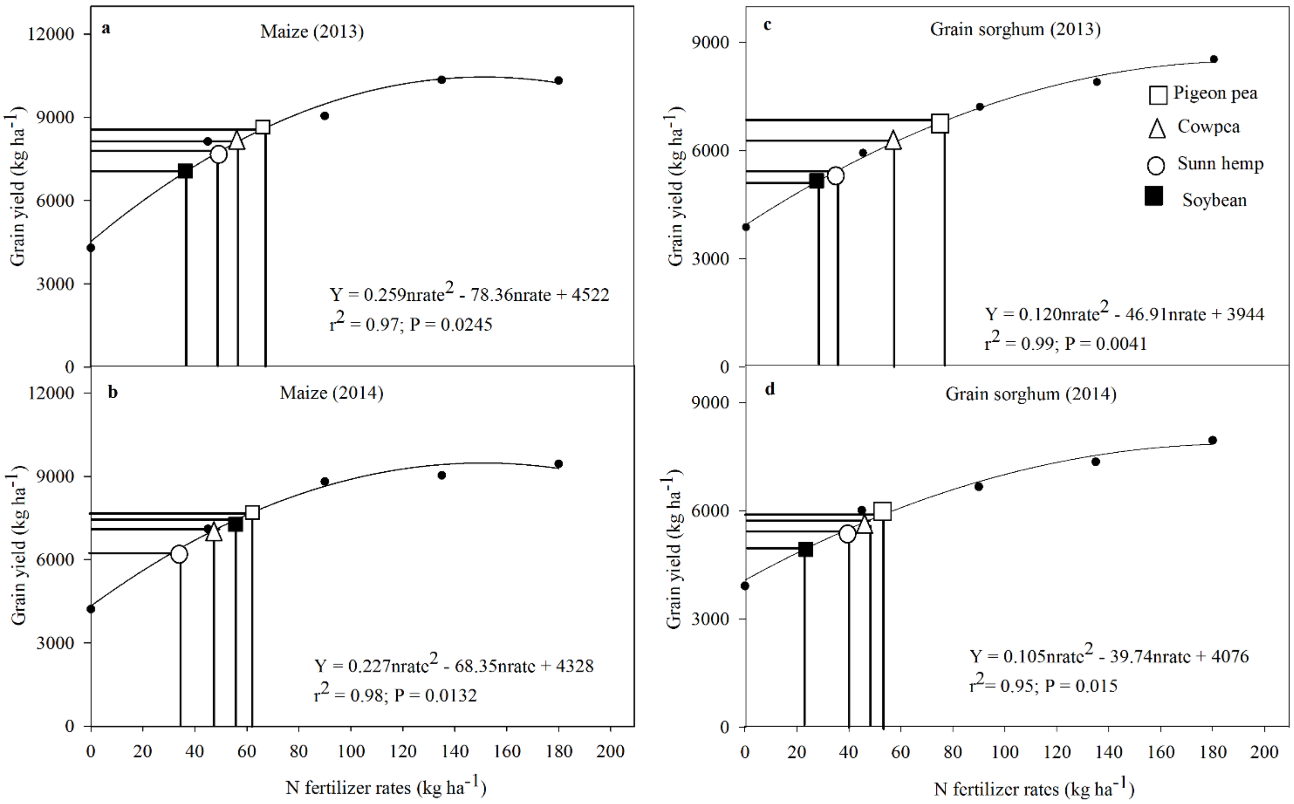

Figure 4.5. Nitrogen fertilizer replacement value of summer leguminous cover crops and double-cropped soybean of (a) maize in 2013, (b) maize in 2014, (c) grain sorghum in 2013, and (d) grain sorghum in 2014.

Table 4.1. Physical and chemical characteristics of soil from the sites.

		2012-2013		2013-2014	
Parameters	Units	Ashland Bottoms	Agronomy North Farm	Ashland Bottoms	Agronomy North Farm
Sand	%	54.0	14.0	51.0	18.0
Silt	%	38.0	55.0	39.0	49.0
Clay	%	8.00	31.0	10.0	33.0
pH		5.80	8.00	5.80	6.30
Mehlich-3 P	mg kg^{-1}	41.2	30.2	75.5	32.5
K	mg kg^{-1}	140	221	196	207
Na	mg kg^{-1}	11.9	16.9	11.1	17.5
Cl^-	mg kg^{-1}	4.30	8.30	4.90	7.20
SO_4-S	mg kg^{-1}	1.30	1.90	0.35	2.60
O.M.	%	0.50	3.00	0.86	2.90
NH_4-N	mg kg^{-1}	4.20	6.80	2.50	3.30
$N0_3$-N	mg kg^{-1}	5.50	5.50	2.30	4.50

Table 4.2. Cropping systems means averaged across site years for phenology, physiology and growth traits, and yield component of maize grown in 2013 and 2014.

Cropping system	Stomatal conductance	Transpiration rate	Intercellular concentration	Days to 50% silking	Plant height	100-kernel weight
	mmol m^{-2} s^{-1}	mmol m^{-2} s^{-1}	µmol mlo^{-1}	d	cm	g
Wh-Fw-Mz+0N	216.0a	6.05de	274.8a	77d	185.5e	25.09e
Wh-Fw-Mz +45	192.9bc	6.78cd	182.3d	60b	212.1bcd	28.32c
Wh-Fw-Mz+90	245.6ab	8.02ab	197.4bcd	58a	201.06d	28.63bc
Wh-Fw-Mz+135	231.8abc	7.16bc	197.7bcd	59a	212.1bcd	30.84a
Wh-Fw-Mz+180	255.8a	8.09a	221.5bc	59a	225.4a	30.77ab
Wh-Cp+Mz+0N	238.0ab	7.06c	188.6cd	62bc	216.8ab	27.74cd
Wh-Pg+Mz+0N	217.5abc	6.19de	195.6bcd	62bc	212.5abcd	28.41c
Wh-Su+Mz+0N	226.2abc	6.72cde	175.0d	64bc	215.1abc	27.67cd
Wh-Sb+Mz+0N	255.7a	6.00de	169.1d	62bc	211.6bcd	27.13cde
Wh-Sg+Mz+0N	173.3c	5.86e	226.3b	77d	203.1cd	27.72e

For each parameter, means in the same column followed by same letter (s) are not significantly different at the 0.05 level by Tukey honest test.

Table 4.3. Pearson correlation of physiology and growth traits, yield and yield components, and N use components.

	SP	Pn	E	gs	C_i	GY	BM	HKW	KN	PHT	BMN	GN	TN	NUtE	NHI
SP	1														
Pn	0.69***	1													
E	0.59***	0.71***	1												
gs	0.39***	0.50***	0.51***	1											
C_i	0.38***	0.56***	0.37***	0.28**	1										
GY	0.54***	0.23**	0.28**	0.13	-0.05	1									
BM	0.33***	0.11	0.30***	0.10	-0.24**	0.49***	1								
HKW	0.61***	0.64**	0.48***	0.19*	0.39***	0.41***	0.33***	1							
KN	0.43***	0.24**	0.34***	0.16*	-0.03	0.43***	0.51***	0.26**	1						
PHT	0.48***	0.34**	0.31***	0.33**	0.14	0.40***	0.11	0.25**	0.27**	1					
BMN	0.05	0.06	-0.06	0.16*	0.32***	-0.03	-0.36**	-0.01	-0.05	0.03	1				
GN	0.16*	0.26**	0.01	0.22**	0.43***	-0.02	-0.43***	0.15	-0.10	0.15	0.59***	1			
TN	0.125	0.192	-0.02	0.21**	0.42***	-0.01	-0.45***	0.08	-0.08	0.11	0.89***	0.91***	1		
NUtE	-0.014	0.083	0.03	-0.07	-0.082	-0.04	0.23**	0.14	0.04	0.03	-0.74**	-0.28**	-0.56**	1	
NHI	0.09	0.23**	-0.01	0.107	0.32***	-0.02	-0.22**	0.17	-0.12	0.16*	-0.01	0.63***	0.39***	0.35**	1

Abbreviations: SP, leaf chlorophyll; Pn, photosynthetic rate; E, transpiration rate; gs, stomatal conductance; C_i, intercellular CO_2 concentration; PHT, plant height; BM, aboveground biomass; GY, grain yield; HKW, hundred-kernel weight; KN, kernels plant^{-1}; BMN, aboveground N uptake; GN, grain N uptake; TN, total N uptake; NUtE, N utilization efficiency; NHI, N harvest index.

Table 4.4. Economic analyses of N fertilizer application to maize grown in 2013 and 2014.

Variables	N fertilizer levels (kg ha^{-1})				
	0	45	90	135	180
Gross benefit					
Average yield (kg ha^{-1})	4320	6009	7811	10285	10994
Price (US$ kg^{-1})	0.186	0.186	0.186	0.186	0.186
Gross benefit (US$ ha^{-1})	803.60	1118.00	1453.00	1913.00	2044.00
Variable inputs cost (US$ ha^{-1})					
Seeds	215.70	215.70	215.70	215.70	215.70
Planting	37.40	37.40	37.40	37.40	37.40
Fertilizer	0	85.83	171.60	257.50	343.30
Fertilizer application	15.20	15.20	15.20	15.20	15.20
Harvesting	52.05	83.77	87.80	114.20	121.90
Herbicides	113.70	113.70	113.70	113.70	113.70
Herbicides application	45.51	45.51	45.51	45.51	45.51
Hauling @US$0.008 kg^{-1}	34.56	48.07	62.48	82.28	87.95
Total variable inputs cost	479.50	597.10	686.90	799.20	892.70
Net benefit (US$ ha^{-1})	324.00	520.60	765.80	1113.00	1152.00
Marginal rate of return (%)	-	167.20	272.80	309.80	40.98

Table 4.5. Economic analyses of maize after cover crops, double-cropped soybean, and grain sorghum grown in 2013 and 2014.

Variable	Cowpea	Pigeon pea	Sunn hemp	Soybean	Sorghum
Harvested yield (kg ha^{-1})	-	-	-	2897	2549
Grain price (US$ kg^{-1})	-	-	-	0.411	0.176
Gross benefit (US$)	-	-	-	1190	448.6
Variable cost (cover crops + double crops) (US$ ha^{-1})					
Seed	62.20	306.20	380.80	150.50	43.80
Inoculants	42.90	42.90	42.90	42.90	-
Planting	38.40	38.40	38.40	38.40	38.40
Herbicides	123.70	123.70	123.70	123.70	123.70
Herbicides application	45.51	45.51	45.51	45.51	45.51
Mowing/harvesting	32.15	32.15	32.15	66.19	20.47
Total variable cost (cover crops + double cropped)	344.80	588.80	663.40	467.20	271.80
Succeeding crop (Maize)					
Maize yield (kg ha^{-1})	6217	6485	5257	5209	3815
Price (US$ kg^{-1})	0.186	0.186	0.186	0.186	0.186
Gross benefit (US$)	1156.00	1206.00	977.80	968.00	709.00
Variable cost (US$ ha^{-1})					
Seeds	215.70	215.70	215.70	215.70	215.70
Planting	38.40	38.40	38.40	38.40	38.40
Herbicides	123.70	123.70	123.70	123.70	123.70
Herbicides application	45.51	45.51	45.51	45.51	45.51
Harvesting	103.40	126.20	141.70	170.70	162.00
Hauling@ US$0.008 kg^{-1}	49.74	51.88	42.05	41.67	30.52
Total variable cost	576.40	601.30	607.00	635.60	615.80
Total cost variable (double cropped + cover crops + maize)	921.3.00	1190.00	1270.00	1102.00	887.70
Total income (double crops + cover crops + maize)	1156.00	1206.00	977.8.00	2159.00	1158.00
Net Returns	235.10	15.99	-292.60	1056.00	270.50

Double-cropped grain crops: Soybean and grain sorghum

CHAPTER 5 - IMPACT OF COVER CROPS ON SOIL AGGREGATE STABILITY, ASSOCIATED CARBON, AND NITROGEN POOLS

ABSTRACT

Measurement of soil aggregate stability is important because it can give general information about soil conditions. Cover crops can influence soil aggregation and associated carbon (C) and nitrogen (N) pools, thereby affecting soil quality and productivity. The objective of this study was to assess the contribution of different cover crops and double-cropped grain crop systems on soil aggregate stability and aggregate-associated C and N pools. Six different cropping systems were evaluated in 2013 and 2014: Wheat (*Triticum aestivum* L.) was rotated with three cover crops [*Vigna unguiculata* (L.) Walp.]; [*Cajanus cajan* (L.) Millsp]; (*Crotalaria juncea* L.); two double-cropped grain crops [*Glycine max* (L) Merr.]; [*Sorghum bicolor* (L.) Moench], and chemical fallow. Maize was planted after terminating the cover crops at flowering and after double-cropped harvest. Soil samples were taken at 0-15 cm depth in October after maize harvest in both years. Water-stable aggregates (WSA) were separated using a wet sieving method. Total C and N contents were determined by dry combustion method. Sand free WSA was more in the intermediate aggregates size fractions than in the macroaggregates, whereas, aggregate-associated C and N were more in the macroaggregate fraction than the microaggregates in all the cropping systems. Furthermore, double-cropped grain sorghum system increased aggregate-associated C and whole soil total C. All the cover crops and double-cropped soybean systems increased aggregate-associated N and whole soil total N. The use of summer cover crops and double-cropped grain crops systems in no-tillage system has proven to be important in increasing soil aggregate stability and aggregate-associated C and N pools.

INTRODUCTION

Management strategies to maintain and improve soil quality and enhance agricultural production has been stressed as a way to address increasing world population and climate change (Lal, 2009; Komatsuzaki and Ohta, 2007). In recent times, sustainable agriculture has been promoted as an integrated management tool to meet these and other challenges (Verhulst et al., 2010). One of the components of sustainable agriculture is the use of conservation agriculture concepts that include conservation tillage, diverse crop rotations, residue management, and cover crops as key elements. These management practices can help improve soil structure and soil health if employed effectively.

Soil structure is considered as a key factor in the functioning of soil, especially its ability to support plant and animal life and provide ecosystem services with particular emphasis on soil C sequestration and water quality. Aggregate stability is used as an indicator of soil structure (Six et al., 2000). Poorly structured soils are characterized by reduced infiltration, increased bulk density, increased soil strength and low water retention capacity, mainly due to aggregate breakdown upon wetting. Good soil structure is important for maintaining favorable soil physical conditions for plant growth (Krzic, 1997). Aggregation results from the rearrangement of particles, flocculation and cementation. Aggregation is mediated by soil organic carbon (SOC), biota, ionic bridging, clay, and carbonates (Duiker et al., 2003).

Soil organic matter (SOM) is responsible in the formation of aggregates by acting as a nucleus for the formation of aggregates. Also, SOM is responsible for the stabilization of aggregates by lowering their wettability and increasing the cohesion of aggregates through the binding of mineral particles by organic polymers or through the physical enmeshment of particles (Chenu et al., 2000). Apart from SOM, texture, clay mineralogy, aluminum and iron oxides also influence aggregate stability. However, SOM plays a more crucial role in aggregate stability because its characteristics can be modified by agronomic practices like no tillage and cover cropping systems (Abiven et al., 2009; Simmons and Coleman, 2008).

Improving aggregate stability on cropland typically involves cover and green manure crops, animal manure, residue management, sod-based rotations, and decreased tillage and soil disturbance. Madari et al. (2005) found that aggregate stability declines rapidly in soil planted to a clean-tilled crop. It has been found that cover cropping systems can maintain or improve organic C and N in the soil by providing additional crop residues, reducing soil erosion, and promote nutrient cycling (Sainju et al., 2000), but their impacts on soil structure deserve further research.

Understanding impacts of cover crops on soil quality is essential to the development of sustainable cover cropping systems. The impacts of cover crops on subsequent soil physical properties most likely depend on precipitation input, cover crop species, growing season (summer vs. winter cover crops), amount of biomass return, tillage management, and duration of cover crops growth (Blanco-Canqui et al., 2011). Under favorable climatic conditions, high-biomass producing and high-N fixing summer or tropical legume cover crops such as pigeon pea, cowpea, and sun hemp may have more rapid and greater effects on improving soil properties than most winter leguminous cover crops (Carof et al., 2007). Blanco-Canqui et al. (2011) reported that sunn hemp and late maturing soybean when used as summer cover crops reduced soil's susceptibility to compaction and increased wet aggregate stability, water infiltration, earthworm (*Lumbricus terrestris*) population, and SOC.

Furthermore, plant species can indirectly affect aggregation by the amount of plant residue returned to the soil, its biochemical composition, and C released from the growing roots, thus affecting microbial composition and activity (Bronick and Lal, 2005; Rice and Angle, 2004;

Rillig et al., 2002). Martens (2000) found differences in aggregation after soybean, compared to maize and native prairie (ecosystems considered part of the temperate grasslands, savannas, and shrub lands biome). After soybean, aggregation decreased compared with corn and native prairie, which the author attributed to a lower phenolic acid content of soybean and a lower amount of residue returned to the soil.

Previous research has found that switching from continuous wheat or corn to a cover crop system resulted in a 23-40% increase in aggregate stability over 100 year rotation study on the Sanborn Field, University of Missouri, Columbia (Rachman et al., 2003). Villamil et al. (2006) found a significant increase in water aggregate stability in corn/soybean rotation compared to winter fallow. Cover crops also have been shown to increase aggregate size distribution by protecting aggregates from the impact of raindrops (Delgado et al., 1999). Not all studies have shown that cover crops increase average aggregate size. Mendes et al. (1999) found no significant difference in aggregate size distribution with or without a cover crop in a vegetable crop rotation; nonetheless, significant increases in soil microbial carbon and enzymatic activity were found in the cover crop treatment. Wright et al. (1999) found that several compounds produced by fungi, glycoproteins including glomalin, are essential to the stability of aggregates, however, active root growth and no-tillage (NT) management are necessary for maximum effect.

No-tillage practices have increased recently in the central Great Plains because of agronomic and environmental advantages including increased stored water, decreased wind and water erosion susceptibility, increased C storage, and improvements in soil physical properties (Blanco and Lal, 2008; Reicosky and Saxton, 2007). Soil organic carbon storage in the surface layer is commonly greater under NT than conventional tillage (West and Post, 2002). Changes in soil physical properties such as water stable aggregates are affected by management practices, especially tillage (Pikul et al., 2006), and water stable aggregates is one of the most sensitive variables to the reduction of tillage (Stone and Schlegel, 2010; Blanco and Lal, 2008). No-till generally has been observed to produce more (and larger) water stable aggregates compared with more intensive tillage methods (McVay et al., 2006; Angers et al., 1993). Vetch (*Vicia orobus* L.) and rye (*Secale cereal* L.) cover crops grown as either monocultures or as bicultures under a no tillage system improved aggregate stability by an average of 13% compare to the weedy fallow control after a 5 year rotation (Villamil et al., 2006).

Although cover crops may not always improve soil physical properties in all soils (Olson et al., 2010; Andraski and Bundy, 2005), we hypothesized that inclusion of leguminous summer covers in no-tillage system will provide additional biomass, increase SOC and soil N which will subsequently improve aggregate-associated C and N compared with no cover crop system. The objective of this study was to assess the contribution of different cover crops and double-cropped grain crop systems on soil aggregate stability and aggregate-associated C and N pools.

MATERIALS AND METHODS

Site Description and Experimental Design

Soil samples were collected from fields located on research facilities of department of Agronomy at Kansas State University (KSU) near Manhattan, KS in 2013 and 2014. The sites were situated on a well-drained Kennebec silt loam (fine-silty, mixed, superactive, mesic Cumulic Hapludolls; 39°11’30”N, 96°35‘30”W). The soil had a pH of 7.2 and soil nitrate, soil ammonium, and Mehlich-III extractable P (Mehlich) in the 0- to 30 cm soil were 5.00, 5.10, and 31.4 mg kg^{-1}, respectively. Soil organic matter was 2.95%, and sand, silt and clay fractions were 16, 52, and 32%, respectively. Sites used for this study had not been tilled for the previous six years. Six cropping systems were used in this study: Wh-Fw-Mz+0N; wheat rotated with maize plus 0 kg N ha^{-1}; Wh-Cp-Mz+0N; cowpea rotated with maize after wheat; Wh-Pg-Mz+0N; pigeon pea rotated with maize after whaet ; Wh-Su-Mz-0N; sunn hemp rotated with maize after wheat ; Wh-Sb-Mz+0N; double-cropped soybean rotated with maize after wheat; and Wh-Sg-Mz+0N; double-cropped grain sorghum rotated with maize after wheat. The experimental design was a randomized complete block with four replications. Each experimental unit was 40 m^2.

Maximum temperature was 31.1°C in July 2013 and 33.0°C in August 2014. Total precipitation (April-October) in 2013 and 2014 was 539 mm and 576 mm, respectively. These were below the 30-year average of 698 mm (Source: KSU Weather Data Library).

Soil Sampling and Analyses

Thirty random soil samples were collected from each plot using a 2-cm diameter soil auger (Oakfield soil-probe, Forestry Suppliers, Inc., Jackson, MS) to15 cm depth in sterile polypropylene bags (3.78 L). Each 15 cm soil core was cut into depth increments of 0-5 and 5-15 cm lengths and each depth composited for each plot. Soil samples were transported to the laboratory immediately. The soil samples were then passed through a 4 mm sieve, air dried for 7d and stored at room temperature until use. Samples were collected in October after maize harvest in each of the two years.

Aggregate Stability and Aggregate Associated C and N

Water-stable aggregate size distribution was assessed for 2013 and 2014 by wet sieving two replicates of 50 g air-dried soil through 0.020, 0.053, 0.25 and >2.00 mm sieves with a Yoder-type apparatus as described by (Mikha and Rice, 2004). Air dried soil samples were placed over stacked 0.25 and >2.00 mm sieves and submersed in water for 10 min (slaking phase) and then subjected to 10 min of 4 cm length oscillations at a frequency of 0.5 Hz. The soil remaining on the sieves was collected and allowed to settle prior to drying. The soil that passed both sieves was filtered through the 0.053 and 0.020 mm sieves. The soil from each aggregate fraction dried at either 60°C or 105°C for 2d. The dried soil was weighed and used for estimating percentage aggregate size fraction of soil and later used for sand correction determination. Sand-free WSA was measured using a subsample of intact aggregates (5 g) and combined with fivefold volume (25 mL) of 5 g L^{-1} sodium hexametaphosphate, left overnight and shaken on an orbital shaker at 350 RPM for 4h. The dispersed organic matter and sand was collected on a 0.053 mm mesh sieve, washed with deionized water, and dried at 105ºC for 24 h, and the aggregate weights were recorded for estimating the sand-free correction. Sub-samples of the aggregate-size fraction that had been dried at 60°C, were later ground with mortar and pestle and analyzed for aggregate-associated C and N. Calculations for total C and N in different aggregate-size fractions were adjusted for sand-free water stable aggregates. The proportion of water-stable aggregates in each size fraction (WSA*i*) was calculated from $WSA_i = (\mathbf{Aggregate}_i - \mathbf{Sand}_i) / \{[\mathbf{Soil}/(1 + \mathbf{Moisture})] - \Sigma\, \mathbf{Sand}_i\}$

where *i* is the *i*th size fraction, Aggregate is the oven-dry mass of water-stable aggregates collected on each sieve, sand is the oven-dry mass of sand collected on each sieve, soil is the oven-dry mass of total 0.053-2.00 mm aggregates sieved, and moisture is the gravimetric moisture content (Liu et al., 2005).

Soil organic C and total N

Soil organic C and total N (TN) was assessed for all samples. A subsample (10 g) of the bulk soil samples was air-dried, ground to a fine powder, and analyzed for SOC and TN by dry combustion using a gas chromatograph with thermal conductivity detection (GC-TCD) (Thermo Finnegan Flash EA1112, Milan, Italy). Total soil N (TON) and C (TOC) were calculated as follows:

$\text{Mg N ha}^{-1} = \text{TON (\%)} \times \text{bulk density (mg/m}^{-3}) \times \text{sampling depth (cm)}$

Mg C ha^{-1} = SOC (%) x bulk density (mg/m^{-3}) x sampling depth (cm)

Data Analyses

The analysis of variance was conducted using PROC GLM in SAS version 9.3 (Cary, N.C.) to assess differences in TOC and TON of soil, mass of soil aggregate fractions, C and N concentration in aggregate fractions. Analysis was performed separately by soil depth. Means separation were applied within each aggregate fraction and considered statistically significant at $P < 0.05$ except when indicated otherwise. Means were compared using LSD.

RESULTS

Sand-Free Water Stable Aggregates at 0-to 5 cm Depth

Aggregate size fractions varied with cropping systems ($P < 0.05$) for the 0-to 5 cm and 5-to 15 cm depth for sand-free WSA in 2013 and 2014 (Fig. 5.1).

Sand-free WSA of the 0.020-0.053 mm and 0.053-0.25 mm size fraction in the fallow system with 0 kg N ha^{-1} was greater compared with all the cover crops systems and the double-cropped grain crops in 2013 (Fig. 5.1a). Sunn hemp and double-cropped grain sorghum had more sand-free WSA for the 0.25-2.00 mm than in the fallow system with 0 kg N ha^{-1}, cowpea, pigeon pea and double-cropped soybean systems. Sand-free WSA of the >2.00 mm size fraction in double-cropped grain sorghum system was more than all the cover crops and double-cropped soybean systems and fallow with 0 kg N ha^{-1} in 2013 (Fig. 5.1a).

In 2014, sand-free WSA for the 0.020-0.053 mm and 0.053-0.25 mm size fraction was more in the fallow system with 0 kg N ha^{-1} compared with all the cover crops and double cropped grain crops systems (Fig. 5.1b). Among all the systems, double cropped grain sorghum and pigeon pea had more sand-free WSA in the 0.25-2.00 mm size fraction (Fig. 5.1b). Sand-free WSA for the >2.00 mm size fraction was greatest in the pigeon pea, sunn hemp and double-cropped grain sorghum system than in the fallow with 0 kg N ha^{-1}, cowpea, and double-cropped soybean systems in 2014 (Fig. 5.1b).

Sand-Free Water Stable Aggregates at 5-15 cm Depth

In 2013, sand-free WSA in the cowpea, sunn hemp and double-cropped grain sorghum systems was greater than fallow with 0 kg N ha^{-1}, pigeon pea and the double-cropped soybean systems for the 0.020-0.053 mm size fraction. Fallow system with 0 kg N ha^{-1} had the greatest sand-free WSA for aggregates for the 0.053-0.25 mm size fraction among all the systems in 2013 (Fig. 5.1c). Furthermore, sand-free water stable aggregates in the double-cropped grain sorghum system was more among all the systems for the 0.25-2.00 mm size fraction in 2013 (Fig. 5.1c). Whereas, for the >2.00 mm size fraction, sand-free WSA in the sunn hemp and double-cropped grain sorghum systems was more than fallow with 0 kg N ha^{-1}, cowpea, and double-cropped soybean systems (Fig. 5.1c).

In 2014, sunn hemp and double-cropped soybean systems increased more sand-free WSA than fallow with 0 kg N ha^{-1}, cowpea, and pigeon pea and double cropped grain sorghum systems for the 0.020-0.053 mm size fraction (Fig. 5.1d). Furthermore, cowpea and double-cropped grain crops systems had the greatest sand-free WSA for the 0.053-0.25 mm size fraction compared to fallow with 0 kg N ha^{-1}, pigeon pea and sun hemp systems (Fig. 5.1d). In addition, sunn hemp system had more sand-free WSA for the 0.25-2.00 mm size fraction among all the systems (Fig. 5.1d). But sunn hemp and double-cropped grain sorghum systems had the greatest sand-free WSA for the >2.00 mm size fraction among all the systems (Fig. 5.1d).

Aggregate-Associated Total Carbon Concentration in 0-5 cm Depth

Aggregate size fractions varied with cropping systems ($P < 0.05$) at the 0-5 cm and 5-15 cm depth for total C and N concentration in 2013 and 2014.

In 2013, total C in the 0.020-0.053 mm size fraction was relatively similar in the fallow with 0 kg N ha^{-1}, pigeon pea, and double-cropped soybean systems, but significantly greater in the doubled-cropped grain sorghum system. Cowpea and sunn hemp systems had the least total C for the 0.020-0.053 mm size fraction in 2013 (Fig. 5.2a). Total C in the 0.053-0.25 mm size fraction was greatest in the pigeon pea, sunn hemp, double-cropped grain crops systems, while. fallow with 0 kg N ha^{-1} and cowpea systems had the least total C in the 0.020-0.053 mm size fraction in 2013 (Fig. 5.2a).

Total C concentration for the 0.25-2.00 mm size fraction was greatest in the double-cropped grain sorghum system than in the fallow with 0 kg N ha^{-1}, all the cover crops and double cropped soybean system in 2013 (Fig. 5.2a). Total C in the >2.00 mm size fraction was greater in double-cropped grain sorghum system, but less in the cowpea system compared with the fallow with 0 kg N ha^{-1}, pigeon pea, sunn hemp and double cropped soybean systems (Fig. 2a).

In 2014, double-cropped grain sorghum system total C was more than fallow with 0 kg N ha^{-1}, all the cover crops, and double-cropped soybean systems for the 0.020-0.053 mm size fraction (Fig. 5.2b). Whereas, total C was greatest in all the cover crops systems and double-cropped grain crops systems, but significantly less in fallow system with 0 kg N ha^{-1} for the 0.053-0.25 mm size fraction (Fig. 5.2b).

Furthermore, total C was greatest in the double-cropped grain sorghum system compared to fallow with 0 kg N ha^{-1}, all the cover crops and double-cropped soybean systems for the 0.25-2.00 mm size fraction in 2014 (Fig. 5.2b). Total C increased in the sunn hemp system, but was relatively similar in the fallow with 0 kg N ha^{-1} and double-cropped grain sorghum systems for the >2.00 mm size fraction (Fig. 5.2b). Cowpea, pigeon pea and double-cropped soybean systems had less total C for the >2.00 mm size fraction in 2014 (Fig. 5.2b).

Aggregate-Associated Total Carbon Concentration in 5-15 cm Depth

In 2013, total C was greater in the sunn hemp system compared to double-cropped grain sorghum system for the 0.020-0.053 mm size fraction. Total carbon was less in the fallow system with 0 kg N ha^{-1}, but relatively similar in the cowpea, pigeon pea, and double cropped soybean systems for the 0.020-0.053 mm size fraction (Fig. 5.2c). In the 0.053-0.25 mm size fraction, total C was greatest in the sunn hemp and double-cropped grain crops systems than fallow with 0 kg N ha^{-1}, cowpea and pigeon pea systems for the 0.053-0.25 mm size fraction (Fig. 5.2c). Sunn hemp and double-cropped soybean systems total C was greatest compared with cowpea, pigeon pea and double-cropped soybean systems for the 0.25-2.00 mm size fraction (Fig. 5.2c). The least total C was recorded in the fallow system with 0 kg N ha^{-1} for the 0.25-2.00 mm size fraction (Fig. 5.2c). Furthermore, sunn hemp had more total C for the >2.00 mm size fraction compared with cowpea, pigeon pea and double-cropped grain crops systems. The least total for the >2.00 mm size fraction was found in the fallow with 0 kg N ha^{-1} (Fig. 5.2c).

In 2014, total C for the 0.020-0.053 mm size fraction was the greatest in the fallow with 0 kg N ha^{-1}, pigeon pea and double-cropped grain crops systems, while cowpea and sunn hemp systems had the least total C (Fig. 2d). However, double-cropped grain sorghum had more total C for the 0.053-0.25 mm size fraction compared with fallow with 0 kg N ha^{-1}, all the cover crops and double-cropped soybean systems (Fig. 2d). Also, total C in the 0.25-2.00 mm size fraction was significantly greater in the sun hemp and double-cropped grain sorghum systems than cowpea, pigeon pea and double-cropped soybean system. The least total was found in the fallow system with 0 kg N ha^{-1} for the 0.25-2.00 mm size fraction. In addition, total C in double-cropped soybean systems was greater for the >2.00 mm size fraction then all the cover crops and double-cropped soybean systems (Fig. 5.2d). Whereas, fallow system with 0 kg N ha^{-1} had less total C for the >2.00 mm size fraction (Fig. 5.2d).

Aggregate-Associated Total Nitrogen Concentration in 0-5 cm Depth

Total N in the 0.020-0.053 mm size fraction was the greatest in the pigeon pea and double-cropped soybean systems compared with cowpea, sunn hemp, and double-cropped grain sorghum system in 2013 (Fig. 5.3a). Fallow with 0 kg N ha^{-1} had less total N for the 0.020-0.053 mm size fraction in 2013 (Fig. 5.3a). Pigeon pea and sun hemp system had more total N compared with fallow with 0 kg N ha^{-1}, cowpea and double-cropped grain crops systems for the 0.053-0.25 mm size fraction (Fig. 5.3a). Total N concentration for the 0.25-2.00 mm size fraction was greater in the pigeon pea system than cowpea, sunn hemp and double-cropped grain crops systems (Fig. 5.3a). Fallow system with 0 kg N ha^{-1} had less total N for the 0.25-2.00 mm size fraction in 2013. Pigeon pea and sunn hemp had the greatest total N compared with cowpea and double-cropped grain crops for the >2.00 mm size fraction (Fig. 5.3a). Whereas fallow system with 0 kg N ha^{-1} had the least total N for the >2.00 mm size fraction in 2013 (Fig. 5.3a).

In 2014, among the cropping systems, pigeon pea system had more total N, compared with cowpea, sunn hemp, and double-cropped grain crops systems for the 0.020-0.053 mm size fraction. Total N in the fallow system with 0 kg N ha^{-1} was the least for the 0.02-0.053 mm size fraction (Fig. 5.3b). Furthermore, total N for the 0.053-0.25 mm size fraction in the cowpea and pigeon pea systems was the greatest than sunn hemp and double-cropped soybean systems. Whereas fallow with 0 kg N ha^{-1} and double cropped grain sorghum systems had the least total N for the 0.053-0.25 mm size fraction. Similar trends were observed for total N among the various cropping systems for the 0.25-0.2000 mm and >2.00 mm size fraction (macroaggregates) in 2014 (Fig. 5.3b).

Aggregate-Associated Total Nitrogen Concentration in 5-15 cm Depth

In 2013, total N for the 0.020-0.053 mm size fraction was greater in the sunn hemp system compared with the fallow with 0 kg N ha^{-1}, cowpea, pigeon pea, and the double-cropped grain crops systems (Fig. 5.3c). In addition, double-cropped soybean increased more total N than all the cover crops and double grain sorghum systems for the 0.053-0.25 mm size fraction (Fig. 5.3c). Whereas fallow with 0 kg N ha^{-1} had the reduced total N for the 0.053-0.25 mm size fraction in 2013. Similar trends were observed among the various systems for total N for the 0.25-2.00 mm size fraction in 2013 (Fig. 5.3c). Total C in the >2.00 mm size fraction was greatest in the cowpea and double-cropped soybean compared with pigeon pea and sunn hemp systems. While fallow with 0 kg N ha^{-1} and double-cropped grain sorghum systems had the least total N for the >0.2.00 mm size fraction in 2013 (Fig. 5.3c).

In 2014, for the 0.020-0.053 mm size fraction, N was more in the double cropped soybean system compared with fallow with 0 kg N ha^{-1}, all the cover and double-cropped grain sorghum systems (Fig. 5.3d). However, cowpea, sunn hemp and double-cropped grain crops had more total N for the 0.053-0.25 mm size fraction than fallow with 0 kg N ha^{-1} and pigeon pea systems (Fig. 5.3d). The greatest total N for the 0.25-2.00 mm size fraction was found in the pigeon pea, sunn hemp, and double-cropped soybean systems compared with cowpea system. But fallow with 0 kg N ha^{-1} and double-cropped grain sorghum had less total N for the 0.25-2.00 mm size fraction. Furthermore, total N was greatest in the pigeon pea and sunn hemp systems than in the cowpea and double-cropped soybean systems for the >2.00 mm size fraction. Whereas fallow with 0 kg N ha^{-1} and double-cropped grain sorghum systems had the least total N for the 0.25-2.00 mm size fraction (Fig. 5.3d).

Total Soil Nitrogen and Carbon

There was significant ($P < 0.05$) effect of cropping systems on total soil N (TON) and total soil C (TOC) in 2013 and 2014 at the 0-15 cm depth (Table 5.1). Total soil N was greater in the sunn hemp system compared with cowpea, pigeon pea and double-cropped grain crops in 2013. Whereas, TON was similar in the cowpea, pigeon pea, and double-cropped soybean systems. Fallow with 0 kg N ha^{-1} and double-cropped grain sorghum systems had the least TON in 23013. Similar trends for TON were observed in 2014 (Table 5.1). Total soil C was greatest for the sunn hemp and double-cropped grain sorghum compared with cowpea, pigeon pea and double cropped soybean systems in 2013. Fallow with 0 kg N ha^{-1} had the least TOC in 2013.

In 2014, TOC was greater in the double-cropped grain sorghum, but similar in fallow system with 0 kg N ha^{-1} and all the cover crops system. Double-cropped soybean had the least TOC in 2014 (Table 5.1). Overall, total soil N and C was greater in 2014 than 2013.

DISCUSSION

Aggregate stability, associated C, and N varied among the cropping systems in both years. The amount of macroaggregates >0.25 mm increased in the double cropped grain sorghum in both years with corresponding decrease in the <0.25 mm size fraction (Fig. 5.1). Greater WSA in the double-cropped grain sorghum system is consistent with other research reporting increased WSA with rotations with cereals crops that have more fibrous root system (Weil and Magdoff, 2004). Grain sorghum has been known to produce greater root biomass and root length density than legume cover crops (Sainju et al., 1998; Kuo et al., 1997a, b). The increased enmeshing action of grain sorghum roots may also have improved soil aggregation (Tisdale and Oades, 1979). Root residue can improve soil aggregation better than shoot residue (Puget and Drinkwater, 2001).

The relationship between soil aggregation and associated C and N pools is complex. In cover cropped and fallow system soils, Mendes et al. (1999) did not find significant difference in the amount of soil present between aggregate-size classes, but Schutter and Dick (2002) observed increased amounts of soil present in aggregates with increasing size class. Both studies, however, observed greater C and N pools in intermediate size (2.00-0.25 mm) aggregates than in micro-or macroaggregates. In our study, the two largest aggregate sizes exhibited the greatest SOC storage across the systems in the 0-5 cm. The lowest concentrations of aggregate C were found in the 0.02-0.053 mm range (Fig. 5.2). Organic C in the aggregate fractions collected at the 5-15 cm depth (Fig. 5. 2) reveals generally lower concentrations than in the corresponding fractions from the 0- 5 cm depth for all the systems.

The increased organic C and total N, in the 0.25-2.0 mm than in >2.0 mm aggregate-size class, regardless of treatments (Figs. 5.2 and 5.3), suggests that C and N sequestrations and N mineralization may be greater in small and medium aggregates than in large aggregates. These results were similar to those reported by others (Schutter and Dick, 2002; Miller and Dick, 1995; Seech and Beauchamp, 1988) showing that increased substrate availability may have increased microbial activity and N mineralization in small and intermediate size aggregates.

The stabilization of SOC in aggregates is an important mechanism which has been recognized to influence SOC sequestration in different management practices. The double cropped grain sorghum system had greater TOC as would be expected with a larger estimated C input (Jokela et al., 2011) than all the summer cover crops systems (Table 5.1) in the 0-15 cm depth. The similar or greater levels of soil organic C, with double cropped grain sorghum suggest that non-legume cereal crops may be more effective than legume cover crops in increasing soil C pools, probably due to increased C input (Table 5.1) and its higher C/N ratio, which may have resulted in slower decomposition of its residue in the soil.

Total soil N was similar or greater with all the cover crops and double cropped soybean than with double cropped grain sorghum and fallow system with 0 kg N ha^{-1}. This suggest that legumes may be more effective than non-legume cereal crops in increasing soil N pools, probably due to increased N input via fixation.

Although C and N contents in cover crop and double cropped grain crops roots were not measured, studies have shown that roots can contribute as much as 40% of the aboveground C and N contents of cover crops (Kuo et al. 1997a, b). The amount, kind, and rate of decomposition of plant residues can influence soil C and N pools (Kuo et al. 1997a, b). Considering the amount of C input from both below and aboveground biomass of cover crops and double-cropped grain crops, cropping system with these crops have the potential to increase organic C levels and N pools in agricultural soils.

CONCLUSIONS

The use of summer crops and double-cropped grain crops systems in no-tillage system has proven to be important in soil chemical and physical characteristics such as aggregate stability. While many studies found the improving effects of cover crops on soil aggregation to be limited to long term rotations, our study showed that summer crops and double-cropped grain crops systems have the potential to improve soil structure in short term rotation in no-tillage system.

In this current study we found out that sand-free WSA was more in the intermediate (0.053-0.25 mm) aggregates size fractions than the macroaggregates. Aggregate-associated C and N were greater in the macroaggregate fraction (0.25-2.00 and >2.00 mm) than in the microaggregates in all the cropping systems. While the aggregate-associated N and total N pools were higher with the all the cover crops and double-cropped soybean system, the double cropped grain sorghum system was effective in increasing aggregate-associated C and total soil C. Both micro- and macro aggregates associated C and N were least affected by fallow with 0 kg N ha^{-1}. The results from this research suggests that cereal grain crops can be more effective in increasing soil aggregation and C pools, whereas leguminous cover crops and legume grain crops can be more effective in increasing labile N pools, thereby increasing soil productivity by sequestering atmospheric N and increasing soil N mineralization which can lead to crop yields. It would be interesting to continue examination of the aggregate and SOC dynamic in these soils to assess how long it could take for SOC to reach equilibrium in the different cropping systems.

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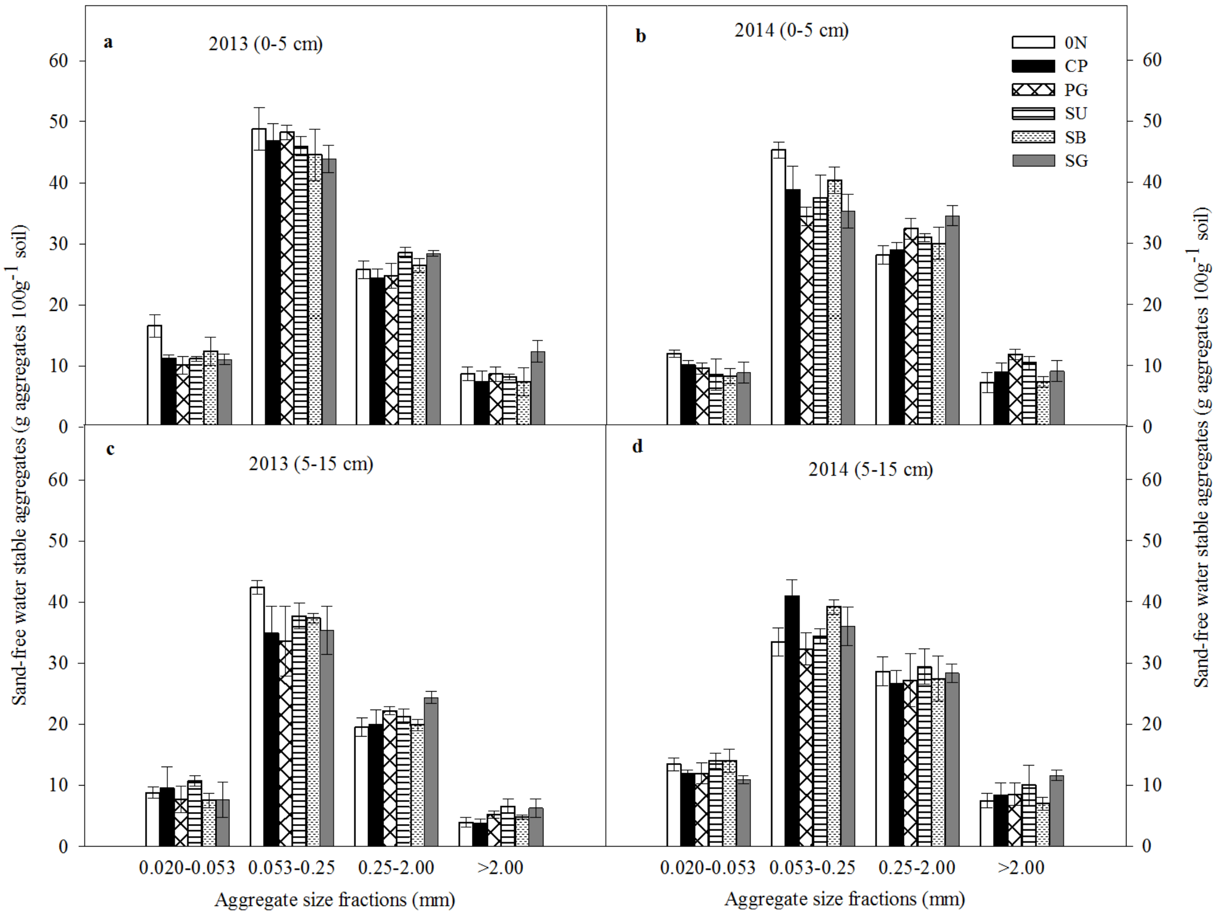

Figure 5.1. Distribution of sand-free water stable aggregates in wheat rotated with maize plus 0 kg N ha^{-1} (0N); cowpea rotated with maize after wheat (CP); pigeon pea rotated with maize after wheat (PG); sunn hemp rotated with maize after wheat (SU); double-cropped soybean rotated with maize after wheat (SB); double-cropped grain sorghum rotated with maize after wheat (SG) in the (a) 0-to 5-cm depth in 2013 (b) 0-to-5-cm depth in 2014, (c) 5-to 15-cm depth in 2013, and (d) 5-to 15-cm depth in 2014. Error bars represent the standard error of the mean (n=4).

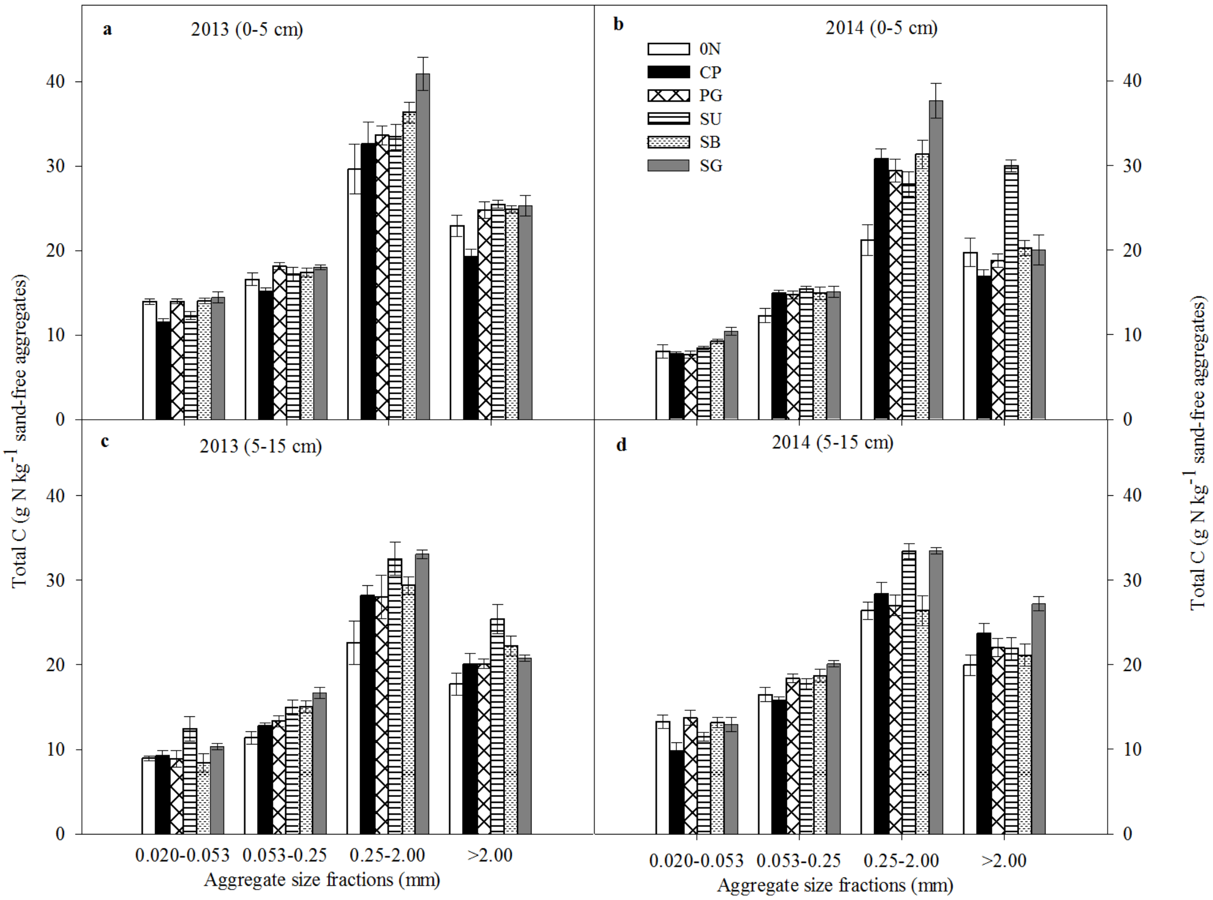

Figure 5.2. Total C normalized to sand-free basis in each water stable aggregates in wheat rotated with maize plus 0 kg N ha^{-1} (0N); cowpea rotated with maize after wheat (CP); pigeon pea rotated with maize after wheat (PG); sunn hemp rotated with maize after wheat (SU); double-cropped soybean rotated with maize after wheat (SB); double-cropped grain sorghum rotated with maize after wheat (SG) in the (a) 0-to 5-cm depth in 2013 (b) 0-to 5-cm depth in 2014, (c) 5-to 15-cm depth in 2013, and (d) 5-to 15-cm depth in 2014. Error bars represent the standard error of the mean (n=4).

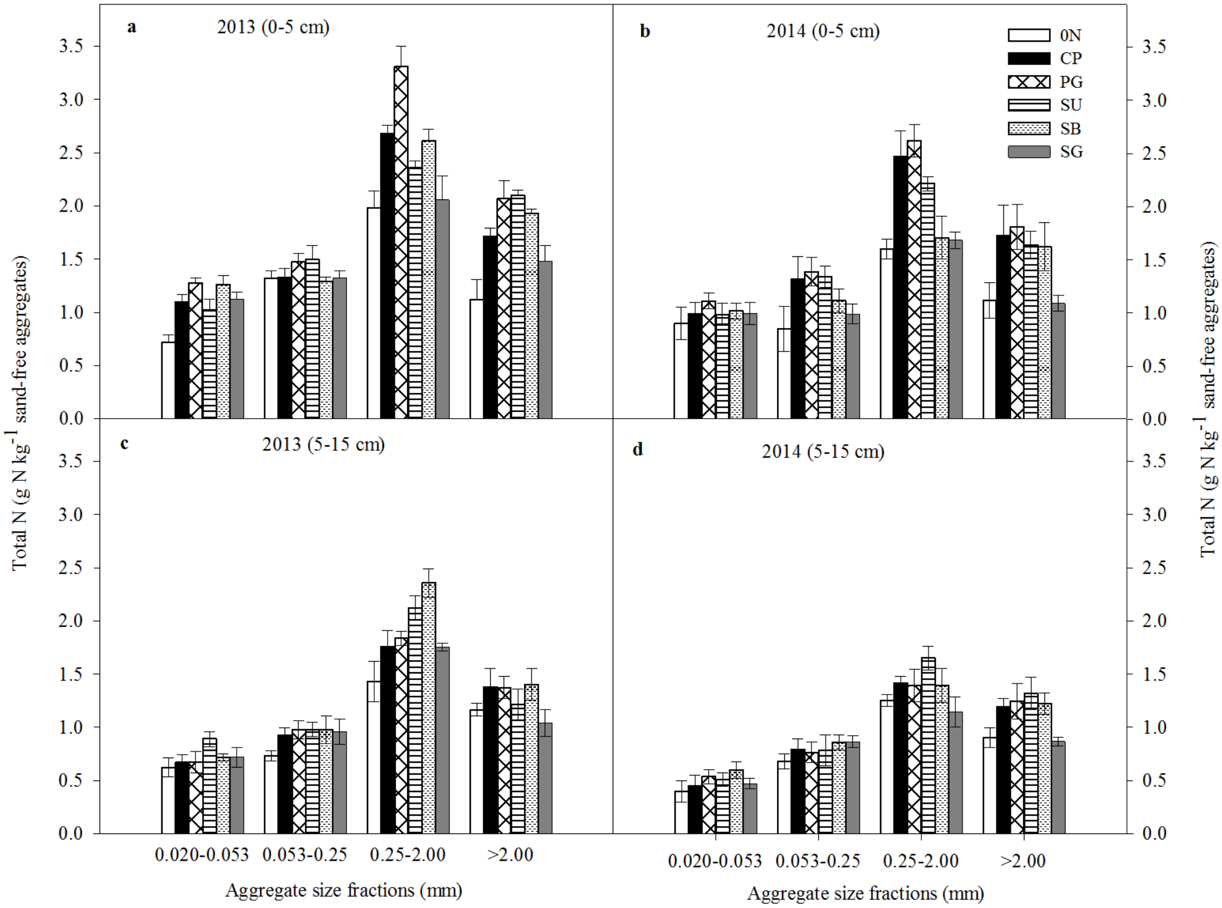

Figure 5.3. Total N normalized to sand-free basis in each water stable aggregates in wheat rotated with maize plus 0 kg N ha^{-1} (0N); cowpea rotated with maize after wheat (CP); pigeon pea rotated with maize after wheat (PG); sunn hemp rotated with maize after wheat (SU); double-cropped soybean rotated with maize after wheat (SB); double-cropped grain sorghum rotated with maize after wheat (SG) in the (a) 0-to 5-cm depth in 2013 (b) 0-to 5-cm depth in 2014, (c) 5-to 15-cm depth in 2013, and (d) 5-to 15-cm depth in 2014. Error bars represent the standard error of the mean (n=4).

Table 5.1. Total soil N and C in the 15 cm depth in 2013 and 2014.

	2013	2014	2013	2014
Cropping Systems	Total soil N Mg N ha^{-1}		Total soil C Mg C ha^{-1}	
Wh-Fw-Mz+0N	2.12c	2.65c	28.79c	38.16b
Wh-Cp-Mz+0N	2.92b	3.38b	33.24bc	40.01b
Wh-Pg-Mz+0N	2.62b	3.41b	32.95bc	38.97b
Wh-Su-Mz+0N	3.76a	4.15a	37.36ab	40.01b
Wh-Sb-Mz+0N	2.97b	3.16bc	34.64bc	34.66c
Wh-Sg-Mz+0N	2.13c	2.48c	42.77a	46.79a

For each parameter, means in the same column followed by same letter (s) are not significantly different at the 0.05 level by LSD.

CHAPTER 6 - GENERAL SUMMARY AND FUTURE DIRECTION

Mineral nutrition is one of the most important factors affecting crop productivity, and N is the most important nutrient in production systems, especially in developing countries due to high cost and scarcity of supply. Nitrogen fertility is becoming an increasing important component in gauging the economic and environmental variability of agro-ecosystems. Hence, leguminous cover crops systems have been envisaged as a critical component of sustainable agriculture due to their potential to increase soil productivity through cycling of carbon and N in agricultural systems.

The objectives of this research were to (1) evaluate the performance of leguminous cover crops and double-cropped grain crops for aboveground biomass production, N uptake and carbon accumulation following winter wheat (Chapter 2); (2) to quantify the effects of cover crops and N fertilizer application on N_2O emissions in no-tillage system (Chapter 2); (3) to determine the effects of inclusion of summer cover crops and varying N rates in the cropping system on growth and yield of the succeeding grain sorghum or maize crop (Chapter 3 and 4); (4) evaluate N fertilizer replacement values of (NFRVs) of summer cover crops and double-cropped grain crops (Chapter 3 and 4); (5) to identify the cropping system that results in profitable and economic net returns (Chapter 3 and 4); and (6) assess the contribution of different cover crops and double-cropped grain crop systems on soil aggregate stability and aggregate-associated C and N pools (Chapter 5).

In the study which evaluated various summer covers, double-cropped grain crops and varying N rates under no-tillage system on the effects of nitrous oxide emissions, yield of grain sorghum and maize, soil aggregate stability, aggregate-associated C, and N pools found that:

Pigeon pea and sunn hemp produced more aboveground biomass and accumulated more C than cowpea and the double-cropped grain crops. However, pigeon pea and cowpea had relatively more N uptake than sunn hemp and the double-cropped grain crops. The C/N ratio over the years for the cover crops and double-cropped soybean was <19:1, while the double-cropped grain sorghum was >25:1.

The study also observed that fallow systems with either 90 or 180 kg N ha^{-1} emitted significantly the greatest N_2O fluxes than cropping systems with all the cover crops and the fallow system with 0 kg N ha^{-1}. Nitrous oxide emissions were relatively similar between the various cover crops systems and the fallow system with 0 kg N ha^{-1}. The most determinant factors in N_2O emission in this study were water filled pore space, soil inorganic nitrate, and soil inorganic ammonium.

Fallow systems with N fertilizer application had the greatest leaf chlorophyll index, photosynthetic rate, grain yield kernel plant^{-1}, and HSW. Leguminous summer cover crops and double-cropped soybean residues improved soil N availability, which was subsequently used by the succeeding crops. Consequently, this resulted in increased leaf chlorophyll index, aboveground biomass, and grain yield. Leaf chlorophyll index, aboveground biomass, and grain yield of sorghum or maize in all the cover crops systems and double cropped soybean system was similar to sorghum or maize in the fallow system with 45 kg N ha^{-1}.

Mean increase in grain yield as a result of including the cover crops and double- cropped grain crops in the rotation over fallow system with 0 kg N ha^{-1} ranged from 3-62% and 12-91% for grain sorghum and maize respectively. Furthermore, N fertilizer replacement values across years for the cover crops and double-cropped grain crops ranged from -2.5-64 kg N ha^{-1} and was greater for pigeon pea. Grain sorghum or maize in the double-cropped soybean cropping system and fallow system with 90 kg N ha^{-1} or 135 kg N ha^{-1} gave profitable economic net returns over the years.

Sand-free WSA was more in the intermediate (0.053-0.25 mm) aggregates size fractions than the macroaggregates. Aggregate-associated C and N were greater in the macroaggregate fraction (0.25-2.00 and >2.00 mm) than in the microaggregates in all the cropping systems. While the aggregate-associated N and total N pools were higher with the all the cover crops and double-cropped soybean system, the double cropped grain sorghum system was effective in increasing aggregate-associated C and total soil C. Both micro- and macro aggregates associated C and N were least affected by fallow with 0 kg N ha^{-1}.

Overall, we conclude that inclusion of leguminous cover crops without inorganic N fertilizer addition reduces N_2O emissions compared to fallow system without inorganic N. This approach also provides additional C accumulation and N uptake contributing to increased grain yield of the following cereal grain crop. Increasing N rate beyond 90 and 135 kg N ha^{-1} did not merit the extra cost incurred by producers in northeast Kansas for these grain sorghum and maize hybrids used in this study.

FUTURE DIRECTION

The benefits of crop rotation and leguminous cover crops systems are well established and serve as pivotal component of sustainable agriculture. Unless a practice is economically viable, there is no incentive for producers especially small land holders to adopt it. Therefore, future efforts may be focused on the following items:

- Develop economic risk analyses for crop rotations and cover crops. Although some work has been done in this area, more work is needed and the transfer of this information is critical for decision making by producers.

- Determine the economic value of the indirect, long-term benefits of rotations and cover crops, i.e., increased soil productivity, decreased erosion, and potential value in improving or maintaining environmental quality. Improve the transfer of information regarding the monetary value of these effects to producers, action agencies, and policy makers.
- Development of expert systems that facilitate the selection of cover crops and management schemes based on cover crop adaptability, soil type, and climatic data would aid in managing environmental risk as well as economic risk by producers who use cover.
- In this study we found that grain yield after the cover crops only was equivalent to 45 kg N ha^{-1} for maize and grain sorghum. It is recommended that this study should be repeated with varying N rates in multi-locations.
- In addition, it was observed that N_2O oxide emissions in the cover crop systems were relatively similar to the fallow system with 0 kg N ha^{-1}. In future, it is recommended that the study should focus on the interaction of cover crops and various N fertilizer rates on N_2O oxide emissions.
- Future research in the Guinea Savanna zone of Ghana is to establish a long term cereal-legume based crop rotation. The purpose is to assess the rotational benefit on yield and soil physical properties such bulk density, water use, aggregates stability, and aggregate-associated C and N pools.
- Furthermore, this current study will be replicated in Northern Ghana with some of the existing cover crops such as *Mucuna pruriens, Callopogonium mucunoides, Stylosanthes guianensis,* and *Canavalia ensiformis.* This is for the reason that, in poor rural communities of Ghana, farmers expect immediate benefit from any farm operation as

they are largely concerned about short term survival. Therefore there is need to develop a system of introducing and integrating cover cropping into the smallholder farming system in a manner that addresses this concern.