Published January 5, 2016

Cover Crops, Fertilizer Nitrogen Rates, and Economic Return of Grain Sorghum

George Y. Mahama, P. V. Vara Prasad,* Kraig L. Roozeboom, Jesse B. Nippert, and Charles W. Rice

ABSTRACT

Leguminous cover crop systems have been envisaged as a critical component of sustainable agriculture because of their potential to increase soil productivity by cycling C and N in agricultural systems. Our objectives were to: (i) determine the effects of including summer cover crops and N rates in the cropping system on the growth and yield of the succeeding grain sorghum [*Sorghum bicolor* (L.) Moench] crop, (ii) calculate the N fertilizer replacement value (NFRV) and evaluate economic returns, and (iii) determine the most cost-effective cropping system. Field experiments were conducted for two seasons in Kansas. Leguminous summer cover crops and double-cropped soybean [*Glycine max* (L.) Merr.] residues improved soil N availability; N was subsequently used by the succeeding crop. Across years and cropping systems, the mean increases in grain yield as a result of including cowpea [*Vigna unguiculata* (L.) Walp.], pigeonpea [*Cajanus cajan* (L.) Millsp.], sunn hemp (*Crotalaria juncea* L.), double-cropped soybean, 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 NFRVs across the years were 53, 64, 36, 27, and –3 kg N ha^{-1}, respectively. Across years, grain sorghum in a double-cropped soybean system and a fallow system with 90 kg N ha^{-1} gave profitable economic net returns. We conclude that including leguminous cover crops in a cropping system has the potential to reduce N requirements and improve the N availability and grain yield of the succeeding grain sorghum crop.

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 equal to 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 (including 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. The use of winter cover crops has been emphasized (Clark et al., 1995). Blackshaw et al. (2001) measured a 16 to 52 kg ha^{-1} increase in soil N following a sweetclover [*Melilotus officinalis* (L.) Pall.] cover crop compared with fallow treatments and wheat (*Triticum aestivum* L.) yields were 47 to 75% greater following sweetclover rather 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-till (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 the timeliness of planting, and saving labor and time (West and Marland, 2002). No-till sequesters C in the soil, thereby mitigating the negative impact of climate change (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

Published in Agron. J. 108:1–16 (2016)
doi:10.2134/agronj15.0135
Received 18 Mar. 2015
Accepted 17 July 2015
Available freely online through the author-supported open access option

G.Y. Mahama, P.V.V. Prasad, K.L. Roozeboom, and C.W. Rice, Dep. of Agronomy, Kansas State Univ., 2004 Throckmorton Plant Sciences Center, Manhattan, KS 66506; and J.B. Nippert, Division of Biology, Kansas State Univ., 116 Ackert Hall, Manhattan, KS 66506. *Corresponding author (vara@ksu.edu).

Abbreviations: ABS, Ashland Bottom site; ANF, Agronomy North farm; DTF, days to flowering; HKW, hundred-kernel weight; KSU, Kansas State University; MRR, marginal rate of return; NFRV, nitrogen fertilizer replacement value; NHI, nitrogen harvest index; NUE, nitrogen use efficiency; SOM, soil organic matter.

al., 2006). In addition, N accumulation in plant biomass can provide large amounts of mineralized N if all the residue is uniformly distributed onto the soil surface in an NT system. Summer cover crops such as cowpea, pigeonpea, and sunn hemp are considered to have greater N_2 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 and drought tolerance than some typical legumes that have been grown in the United States (soybean, clovers, etc.); for instance, pigeonpea can tolerate long-term stress during its growth cycle, especially the long-duration varieties (Subbarao et al., 2000). Pigeonpea's 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 temperatures for growth and development range from 15 to 25°C.

Biological N_2 fixation is the process that changes inert N_2 to biologically useful NH_3. This process is mediated in nature only by bacteria. Cultivating N_2–fixing plants is a valuable approach to curbing the increasing reliance on chemical inputs. The ability of legumes to fix atmospheric N_2 is dependent on microbial, soil, and environmental variables, many of which are influenced by agronomic practices (Giller, 2001). Thus, it cannot be assumed that legumes will always fix significant amounts of N (Peoples et al., 2009). Annual N_2 fixation capacity was estimated to range from 30 to 125 kg N ha^{-1} and 40 to 97 kg N ha^{-1} for cowpea and pigeonpea, respectively. Previous studies found that the total N_2 fixed in aboveground biomass ranged from 40 to 224 kg N ha^{-1} (Schipanski et al., 2010) for soybean. Furthermore, 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 United States.

Cropping sequence is important in determining the optimum N rate to the succeeding cereal crop. Legumes grown in rotation with grain sorghum can provide N credits. For example, the N credit of alfalfa (*Medicago sativa* L.), red clover (*Trifolium pratense* L.), sweetclover, and soybean in rotation with grain sorghum ranged from 44 to 135, 45 to 90, 67 to 134, and 45 to 51 kg N ha^{-1}, respectively (Leikam et al., 2007). The availability of N 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 the content of C, N, cellulose, lignin, and polyphenols (Fox et al., 1990; Varco et al., 1993).

Nitrogen nutrition is a critical component of any cereal production system. Nutrient inputs from chemical fertilizers are needed to replace the 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. The 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 crop production. Previous research has shown that application of N increased the aboveground biomass and grain yield of grain sorghum (Kaizzi et al., 2012; Mahama et al., 2014) without cover crops. Increases in sorghum grain yield were mainly associated with improved panicle number, grain number per panicle, and grain weight (Buah et al., 2012). Mahama et al. (2014) observed that applications of N up to 90 kg ha^{-1} increased grain number, grain yield, and harvest index in grain sorghum. Increases in leaf photosynthesis rates were observed under higher N levels in grain sorghum (Cechin, 1998). Greater yields and yield components with increases in N application were also observed in maize (*Zea mays* L.) and wheat (Demotes-Mainard and Jeuffroy, 2004; Ma et al., 2006).

Little research has been done on the responses of grain sorghum to summer leguminous cover crops. Another important need is to understand the responses of grain sorghum under varying rates of 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 the 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 the N availability and grain yield of the succeeding grain sorghum crop. Our objectives were: (i) to determine the effects of inclusion of summer cover crops and N rates in the cropping system on the growth and yield of the succeeding grain sorghum crop, (ii) to calculate the NFRV and evaluate economic returns, (iii) and to determine the most cost-effective cropping system.

MATERIALS AND METHODS

Site Description and Experimental Design

Field experiments were conducted on dryland conditions in the 2012 to 2013 and 2013 to 2014 growing seasons to evaluate the response of grain sorghum to varying N fertilizer rates and summer cover. The experimental design was a randomized complete block with four replications. Each block consisted of five N rates (0, 45, 90, 135, and 180 kg ha^{-1}), three cover crops (cowpea, pigeonpea, and sunn hemp) and two double-cropped grain crops (soybean and grain sorghum). Both sites for the study were located on Kansas State University (KSU) Department of Agronomy research facilities near Manhattan, KS. One site (Ashland Bottoms site, ABS) was situated on a Reading silt loam soil (a fine-silty mixed, superactive, mesic Pachic Argiudoll; 39°8′35.3″ N, 96°37′39.2″ W, 308 m asl) and the other (Agronomy North Farm, AFN) was on a well-drained Kennebec silt loam (a fine-silty, mixed, superactive, mesic Cumulic Hapludoll; 39°11′30″ N, 96°35′30″ W, 311 m asl). The experiments were implemented on sites that had not been tilled for at least the previous 6 yr. The previous crop at both sites was soybean.

Winter Wheat and Cover Crop Phase

Cover crops were seeded in the summer of 2012 and 2013 directly after winter wheat harvest. Winter wheat was drilled in October 2012 and September 2013 with a target seeding rate of 115 kg ha^{-1} and a 19-cm row spacing with no fertilizer applied at planting. Wheat was harvested in July in all site-years and the stubble was sprayed immediately after harvest with glyphosate-4 plus herbicide [*N*-(phosphonomethyl) glycine] at a rate of 1.67 a.i. kg L^{-1} to control weeds and volunteer wheat.

Three cover crops (cowpea, pigeonpea, and sunn hemp) and two double-cropped grain crops (grain sorghum and soybean) were established in the standing wheat stubble with a no-till planter (John Deere 1590, Deere & Co.) equipped with residue 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, pigeonpea, and sunn hemp seeds were treated with a commercial *Rhizobium* inoculant (*Rhizobia* sp.) and planted at a seeding rate of 57, 28, and 13 kg ha^{-1}, respectively. 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. Planting was performed on 19 June 2012 and 12 July 2013 at a depth of 1.3 to 2.5 cm.

Stand counts of the cover crops were made for all cover crops 20 d after plant emergence within an area of 4.5 m^2 in the two middle rows. Within the two middle rows (4.5 m^2 area), samples of aboveground biomass (everything above 10 cm) from all cover crop plots were hand-harvested in 2012 or rotary mower-harvested in 2013 in each plot. Cowpea, pigeonpea, and sunn hemp were terminated at the onset of flowering, which occurred at 67, 88, and 84 d after emergence in 2012 or 70, 90, and 88 d in 2013, respectively. In all site-years, aboveground subsamples from each plot of the cover crops were dried in a forced-air dryer at 60°C for 5 d, then weighed to obtain dry matter content. The dried samples were ground with a Wiley Mill (Model 4, Thomas Scientific) and analyzed for N and C by dry combustion (modified Dumas method) using an elemental analyzer (LECO CHN–2000, LECO Corp.) 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 the N concentration or C concentration, expressed as percentages. The remaining fresh plant material cut from the summer leguminous cover crop plots was then uniformly distributed on the harvested plots and left in the field to decompose.

At physiological maturity, the aboveground portions of 10 plants from each plot planted to grain sorghum were randomly sampled. Two 2.5-m rows were sampled at the beginning of maturity 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 of area. The dry samples were ground with a Wiley mill (Model 4, Arthur H. Thomas Company) and analyzed for total N and C by dry combustion (modified Dumas method) using an elemental analyzer (LECO CHN–2000, LECO Corp.).

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 Corp.) equipped with a weighing balance. Grain moisture and test weight were measured with a calibrated moisture meter (GAC 2000, DICKEY-John Corp.).

Soil Sampling and Analyses

In both years, composite soil samples were taken at planting from each replication to a depth of 60 cm. Sampling was done using a hand probe (3.2 cm in internal 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 texture (sand, silt, and clay) was 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 NO_3^- and NH_4^+. Analyses were conducted by the KSU Soil Testing Laboratory.

The hydrometer method was used to determine soil texture. Soil samples were treated with $Na_6P_6O_{18}$ to break down 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 the density of the soil suspension was determined with a hydrometer (Model 6026Q20, Thomas Scientific) (Bouyoucos, 1962). 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 (Hanlon, 1984). Extractable (plant-available) K and Na were determined by the ammonium acetate (1 mol L^{-1}, pH 7.0) extraction method. The Walkley–Black method was used to determine organic matter (Combs and Nathan, 1998). Chloride was extracted by $CaNO_3$ and analyzed by mercury thiocyanate method (Gelderman et al., 1998). The turbidimetric method was used to determine sulfate-S (Combs et al., 1998). Soils were extracted with 1 mol L^{-1} KCl and NO_3–N and NH_4^+ measured by an indophenol colorimetric reaction (Gelderman et al., 1998). The soil test results are presented in Table 1.

Grain Sorghum Phase

Before planting grain sorghum (DKS54-00), all plots were sprayed with glyphosate-4 plus [*N*-(phosphonomethyl) glycine] herbicide (Alligare LLC) at 1.67 a.i. L ha^{-1} and 2,4-dichlorophenoxyacetic acid (Southern Agricultural Insecticides Inc.) at 2.4 a.i. L ha^{-1}. Grain sorghum was then planted on May 28 and May 20 in 2013 and 2014, respectively, at a target seeding rate of 125,000 seeds ha^{-1}. The standard spacing for grain sorghum (75 cm between rows) was used during planting in all site-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 [a.i.: mesotrione (2-[4-(methylsulfonyl)-2-nitrobenzoyl]-1,3-cyclohexanedione), 40%; other ingredients, 60%)] (Syngenta Crop Protection Inc.) at a rate of 0.177 a.i. L ha^{-1} and Bicep II Magnum [a.i.: atrazine (2-chloro-4-ethylamino- 6-isopropylamino-*S*-triazine) 33.0%; atrazine-related compounds 0.7%; *S*-metolachlor (2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-[(2*S*)-1-methoxy-2-propanyl]acetamide), 26.1%; other ingredients, 40.2%] (Syngenta Crop Protection Inc.) at a rate of 1.02 a.i. L ha^{-1} using a tractor-mounted boom sprayer (John Deere 1590, Deere & Co.). Hand-weeding was carried out

Table 1. Physical and chemical characteristics of soils from the study sites.

Parameter	2012–2013		2013–2014	
	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†, g kg^{-1}	0.50	3.00	0.86	2.90
NH_4–N, mg kg^{-1}	4.20	6.80	2.50	3.30
NO_3–N, mg kg^{-1}	3.55	5.50	2.30	4.50

† SOM, soil organic matter.

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 of area. The dried leaf and stem samples were ground in a Wiley mill (Model 4, Thomas Scientific) with a 2.0-mm screen. The panicles were threshed in a stationary thresher (Model LDB, ALMACO), and the grain was ground in a cyclone sample mill (Model 3010-030, Udy Corp.). Tissue N concentration was analyzed by wet-digesting samples with H_2SO_4 and H_2O_2. The total N in the digest was analyzed by a colorimetric procedure (nitroprusside–sodium hypochlorite) using a radiation field autoanalyzer (Alpkem Co.).

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 chlorophyll meter (Model 502, Minolta Corp.). Readings were taken at five growth stages (Vanderlip, 1993). At Growth Stage 3(head initiation), 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 6 to 9 (flowering through to physiological maturity), the fully expanded leaf below the flag leaf was used to measure the leaf chlorophyll index. Two representative plants were tagged at Growth Stages 5 to 7 in each plot within each replication, from which photosynthesis, transpiration, stomatal conductance, and intercellular CO_2 concentration (C_i) using a handheld photosynthesis system (CI-340, CID Bio-Science) were measured. All measurements were taken between 1100 and 1500 h on a clear-sky day.

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

Components of Nitrogen Use Calculations

Nitrogen use calculations were computed using the following equations:

$$\text{N uptake} = \text{DM}_{\text{aboveground}} \times \frac{[N]_{\text{DM}}}{100} \quad [1]$$

where N uptake is measured in kilograms per hectare, $DM_{aboveground}$ indicates aboveground dry matter, and $[N]_{DM}$ is the N concentration in dry matter;

$$\text{C uptake} = \text{DM}_{\text{aboveground}} \times \frac{[C]_{\text{DM}}}{100} \quad [2]$$

where C uptake is measured in kilograms per hectare, $DM_{aboveground}$ indicates aboveground dry matter, and $[C]_{DM}$ is the C concentration in dry matter;

$$\text{Grain N uptake} = \text{Yield} \times \frac{[\text{grain N}]}{100} \quad [3]$$

where grain N uptake is measured in kilograms per hectare, Yield indicates grain yield, and [grain N] indicates grain N concentration;

$$\text{NUE} = \frac{\text{Yield}}{\text{NUptake}_{\text{total}}} \quad [4]$$

where NUE is N use efficiency (kg kg^{-1}), Yield is grain yield, and $NUptake_{total}$ is the total N uptake; and

$$\text{NHI} = \frac{\text{NUptake}_{\text{grain}}}{\text{NUptake}_{\text{total}}} \times 100 \quad [5]$$

where NHI is the N harvest index, $NUptake_{grain}$ is the grain N uptake, and $NUptake_{total}$ is the total N uptake.

The NFRV was calculated following a procedure described by Hesterman et al. (1992) and Carsky et al. (2001). The response of grain sorghum to urea-N was fitted to a linear model for each site and year. The intercept (yield of grain sorghum after fallow with 0 N) and slope (response of grain sorghum to fertilizer N) of the model were used to estimate the NFRV using

$$\mathrm{NFRV} = \frac{\mathrm{Yield}_{\mathrm{summer}} - \mathrm{intercept}}{\mathrm{slope}} \quad [6]$$

where $\mathrm{Yield}_{\mathrm{summer}}$ indicates the yield after summer crops.

Data Analyses

Statistical analyses were performed using PROC MIXED, PROC CORR, and PROC REG in SAS version 9.1 (SAS Institute, 2003). The normality of the distribution of the studied traits was tested using the Shapiro–Wilk normality test. A three-way ANOVA was performed to determine the effects of years, cropping system, site, and the 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 the homogeneity of variances (Hartley, 1950) across sites showed that variances were homogenous. Data from all sites and years were therefore pooled.

Economic Analyses

Economic analyses were performed based on statistically significant treatments of the experiment to determine the fallow systems N rates, summer cover crop systems, double-cropped soybean, and double-cropped grain sorghum systems that gave acceptable net returns at low cost to producers (CIMMYT, 1988). Economic analyses were done using the current US market price (National Agricultural Statistics Service, 2013) for inputs at planting and for output at the time of harvest. All costs and returns were calculated on a per-hectare basis in US dollars. Concepts used in the economic analyses are defined as follows: The 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 the field price of grain sorghum and the mean yield for each treatment. The total variable cost (TVC) is the sum of the field cost of fertilizer and application, herbicides and application, seeds, harvesting, and hauling costs. The net benefit per hectare for each treatment is the difference between the gross benefit and the total variable cost. For each of the treatments, a marginal rate of return (MRR) was calculated and expressed as a percentage. The 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:

$$\mathrm{MRR} = \left(\frac{\Delta \mathrm{NR}}{\Delta \mathrm{TVC}}\right) \times 100 \quad [7]$$

where ΔNR is the change in net return ($NR_2 - NR_1$), and ΔTVC is the change in total variable costs ($TVC_2 - TVC_1$). Thus an MRR of 100% implies a return of US$1 on every dollar of expenditure for the given variable input.

RESULTS

Weather Conditions and Soil Test

Precipitation and temperature during the cropping season varied among the site-years of the study. The maximum temperature in July was 4.6°C above the 30-yr 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-yr average of 698 mm.

The results of the soil analyses presented in Table 1 document the substantial differences in textural and chemical soil properties between the two experimental sites. Soil texture probably exerts more influence on soil productivity and management requirements than any other physical soil characteristics (Kay and Angers, 1999). The soil texture at ABS consisted of >50% sand and <1 g kg^{-1} soil SOM. The SOM content of most agricultural soils in Kansas ranges from 1 to 5 g kg^{-1}, with an average of 2.2 g kg^{-1}. Soil organic matter has roughly 5 g kg^{-1} N. At ANF, the soil texture consisted of <20% sand and ~3 g kg^{-1} SOM. Soil NH_4^+ and NO_3^- were greater at ANF in both years. The differences between the two sites in texture and SOM could influence grain sorghum response to N fertilizer application, previous cover crops, and double-cropped grain crops (soybean and grain sorghum).

Aboveground Biomass Accumulation and 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, our discussion of the results will focus on two-way interactions and main effects as appropriate. Although the performance of the summer cover crops and double-cropped grain crops depended on year, it was similar at both sites. The response of cropping system differed with year ($P < 0.05$) (Table 2) for aboveground biomass, plant N uptake, total plant C, and the C/N ratio of the summer cover crops and the grain crops (double-cropped soybean and double-cropped grain sorghum) (Table 2; Fig. 1). Among the summer cover crops, pigeonpea 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 pigeonpea (Fig. 1a). Double-cropped grain sorghum and double-cropped soybean in both years had similar aboveground biomass but the aboveground biomass of cowpea and pigeonpea did not differ in 2014.

The total N uptake of cowpea and pigeonpea 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 pigeonpea (Fig. 1b). Double-cropped grain sorghum had the lowest total N uptake in both years (Fig. 1b).

Plant C accumulation was similar for pigeonpea and sunn hemp but that of these legumes was significantly greater than that of cowpea, double-cropped soybean, and double-cropped grain sorghum in 2012 (Fig. 1c). In 2013, sunn hemp had the greatest plant C accumulation, followed by double-cropped grain sorghum. Plant C accumulation was similar for pigeonpea and double-cropped soybean, whereas cowpea had the lowest level of plant C accumulation. Carbon/nitrogen ratios

Table 2. Significance (*P*-values) of the main effects of site (S), year (Y), and cropping system (CS) and their interactions of the ANOVA for the effect of cropping systems on cover crops, growth, physiological traits, grain yield, and yield components of grain sorghum grown in 2013 and 2014.

Parameter†	S	Y	CS	S × Y	S × CS	Y × CS	S × Y × CS
			Cover crops				
CBM	ns	ns	***	**	ns	**	ns
CTN	ns	ns	***	ns	ns	*	ns
CTC	ns	***	***	**	ns	**	ns
C/N	ns	***	***	ns	ns	*	ns
			Grain sorghum				
DTF	*	ns	**	ns	ns	ns	ns
Pn	ns	***	ns	ns	ns	**	ns
E	ns	***	**	ns	ns	ns	ns
g_s	**	***	**	ns	ns	ns	ns
C_i	*	***	***	*	ns	ns	ns
SPAD	***	***	***	***	*	**	ns
PHT	***	***	***	ns	ns	ns	ns
BM	ns	***	***	ns	ns	ns	ns
GY	ns	**	***	ns	*	**	ns
KN	***	***	***	***	*	**	ns
HKW	***	***	***	ns	ns	ns	ns
BMN	***	***	***	ns	**	*	ns
GRN	***	ns	***	ns	**	*	ns
TN	***	***	***	ns	***	ns	ns
NUE	***	*	***	ns	**	*	ns
NHI	ns	**	**	ns	**	**	ns

* Significantly different at $P = 0.05$; ns, not significantly different.

** Significantly different at $P = 0.01$.

*** Significantly different at $P = 0.001$.

† CBM, cover crop aboveground N uptake; CTN, cover crop aboveground total N uptake; CTC, cover crop aboveground total C accumulation; C/N, C/N ratio; DTF, days to 50% flowering; Pn, photosynthetic rate; *E*, transpiration rate; g_s, stomatal conductance; C_i, intercellular CO_2 concentration; SPAD, leaf chlorophyll index; PHT, plant height, BM, aboveground biomass, GY, grain yield; KN, kernels per plant; HKW, 100-kernel weight; BMN, aboveground N uptake; GN, grain N uptake; TN, total plant N uptake; NUE, N use efficiency; NHI, N harvest index.

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. 1d).

Physiological Traits of Grain Sorghum

The response of sorghum to cropping system differed by year ($P < 0.05$) (Table 2) for leaf chlorophyll index and photosynthetic rate (Fig. 2). The leaf chlorophyll index for cover crop systems and the double-cropped soybean system did not differ significantly in 2013 (Fig. 2a); a similar trend was observed in 2014. Grain sorghum in the fallow system with 0 kg N ha^{-1} and in the double-cropped grain sorghum system had the smallest leaf chlorophyll index in both years. The leaf chlorophyll index in all of the summer cover crop systems and the double-cropped soybean system in both years was equivalent to that in the fallow system with a N fertilizer application of 45 kg ha^{-1}. The 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 (8%) than in 2014 (Fig. 2a).

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

Cropping systems affected ($P < 0.05$) (Table 2), the stomatal conductance, transpiration rate, and C_i of the subsequent sorghum crop (Table 3). 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 system, and fallow systems with N fertilizer applications less than 180 kg N ha^{-1}. Grain sorghum in the double-cropped grain sorghum system had the lowest stomatal conductance.

The fallow system with 0 kg N ha^{-1} had the lowest transpiration rate but transpiration rate did not differ in pigeonpea and double-cropped grain sorghum systems and fallow systems with N fertilizer application. Furthermore, cowpea, sunn hemp, and double-cropped soybean systems had similar transpiration rates over the years. Intercellular CO_2 concentration

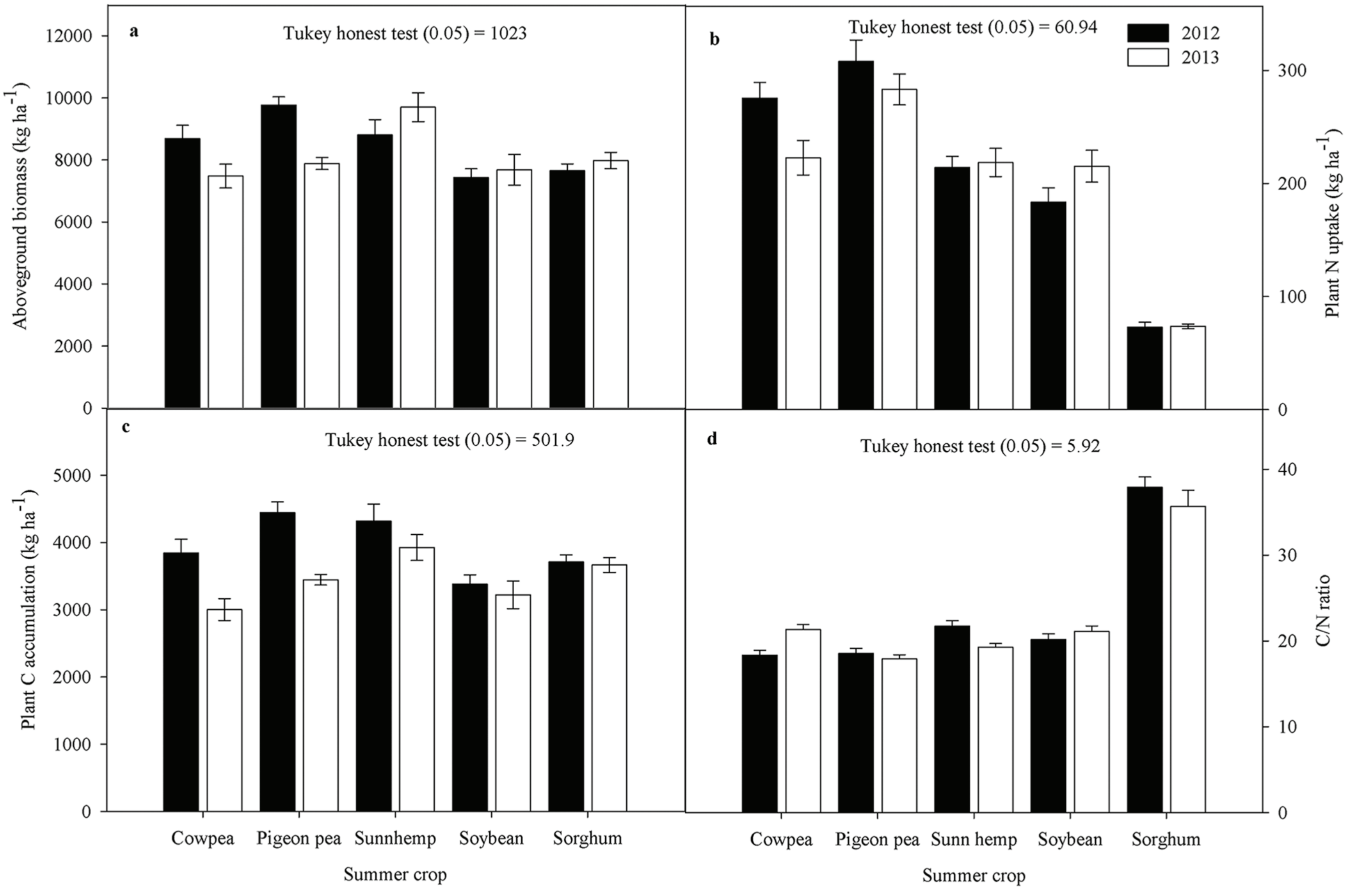

Fig. 1. Crop and year effects on (a) aboveground biomass, (b) total N uptake, (c) total C accumulation, and (d) C/N ratio of cover crops, double-cropped soybean, and double-cropped grain sorghum grown in 2012 and 2013.

was similar in the fallow system with 180 kg N ha^{-1}, the sunn hemp, and the double-cropped soybean systems. The cowpea cropping system had a similar C_i to that of fallow systems with 0 to 135 kg N ha^{-1}. Pigeonpea and double-cropped grain sorghum systems had the lowest C_i (Table 3).

Phenology and Growth Traits of Grain Sorghum

Cropping system had a significant ($P < 0.05$) (Table 2) effect on days to flowering (DTF) (Table 3). Fallow systems with a 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 system, DTF was similar to that for grain sorghum in the fallow system without N fertilizer application (Table 3).

Cropping systems significantly ($P < 0.05$) (Table 2) affected aboveground biomass at physiological maturity (Table 3). Aboveground biomass at physiological maturity in cropping systems with any of the summer cover crops or the double-cropped soybean system was similar to aboveground biomass in the fallow system with 45 kg N ha^{-1}. The double-cropped grain sorghum system and the fallow system with 0 kg N ha^{-1} had the least aboveground biomass at physiological maturity (Table 3). The 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 ($P < 0.05$) (Table 2) 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 system (Table 3).

Components of Yield and Grain Yield

The response of sorghum to cropping system differed by year ($P < 0.05$) (Table 2) for kernels per plant and grain yield. The number of kernels per plant was greater in 2013 than in 2014 (Fig. 2c). In 2013, grain sorghum kernels per plant in the cowpea and pigeonpea cropping systems were relatively similar to the number of kernels per plant in the fallow system with 45 kg N ha^{-1}. Furthermore, grain sorghum in the sunn hemp cropping system had fewer kernels per plant than of grain sorghum in the double-cropped soybean system. However, the fallow system with 0 kg N ha^{-1} and the double-cropped grain sorghum system had the fewest kernels per plant (Fig. 2c). Grain sorghum kernels per plant in 2014 in the cowpea, pigeonpea, and double-cropped soybean systems were similar and comparable to the kernels per plant in the fallow system with 45 kg N h^{-1} (Fig. 2c). In addition, the sunn hemp cropping system had more kernels per plant than the double-cropped grain sorghum system. In both years, kernels per plant increased with increasing N fertilizer application (2013: $R^2 = 0.99$, $P = 0.0041$; 2014: $R^2 = 0.96$, $P = 0.0018$).

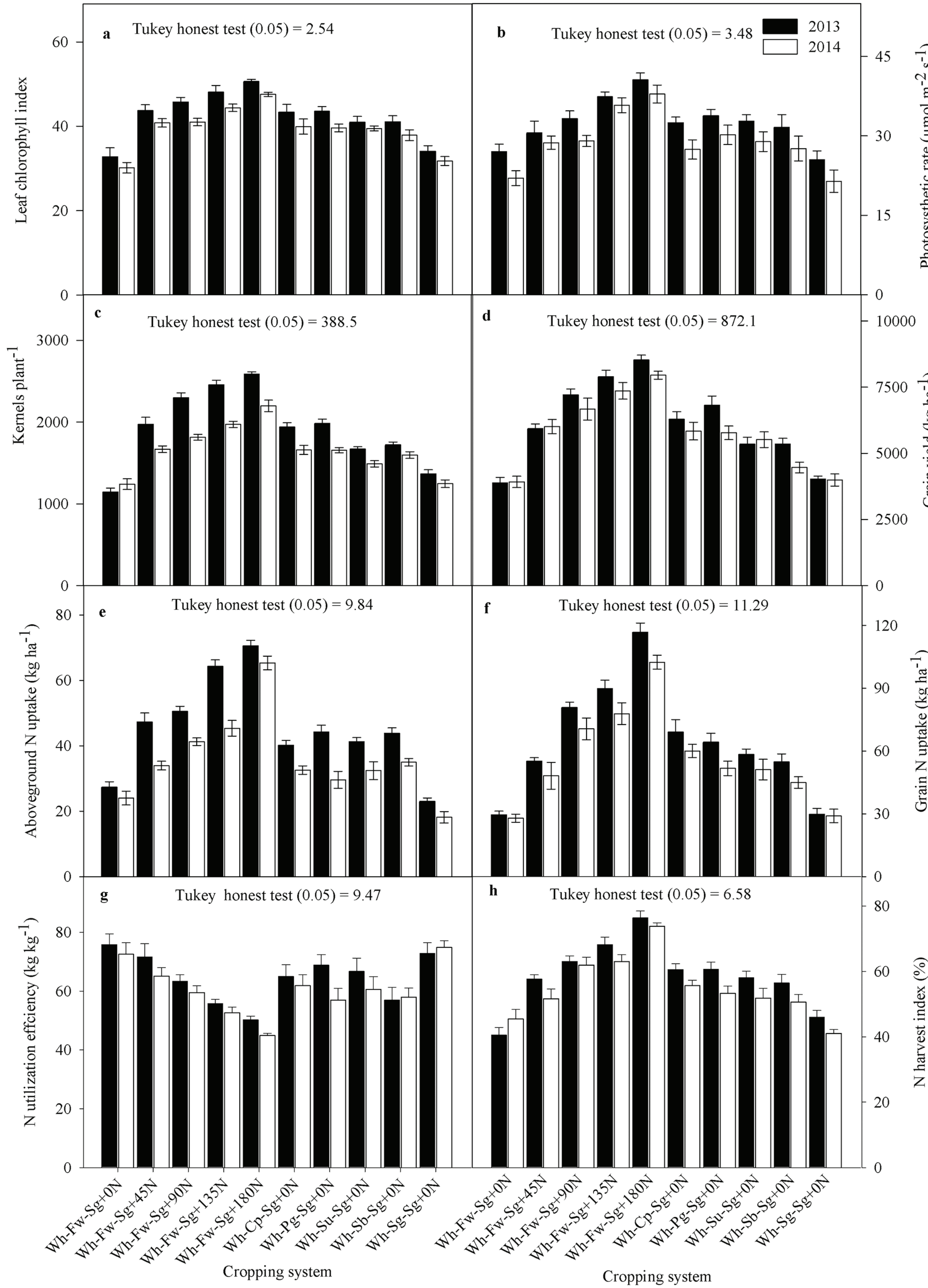

Fig. 2. Cropping system × year effects on (a) leaf chlorophyll index, (b) photosynthetic rate, (c) kernels per plant, (d) grain yield, (e) aboveground N uptake at physiological maturity, (f) grain N uptake at physiological maturity, (g) N use efficiency, and (h) N harvest index of grain sorghum grown in 2013 and 2014 (Wh, wheat; Fw, fallow; Sg, grain sorghum; Cp, cowpea; Pg, pigeonpea; Su, sunn hemp; Sb, soybean; 0N, 0 kg N ha^{-1}; 45 N, 45 kg N ha^{-1}; 90N, 90 kg N ha^{-1}; 135N, 135 kg N ha^{-1}; 180N, 180 kg N ha^{-1}).

Table 3. Cropping systems means averaged across sites and years for phenology, physiology, growth, and yield traits 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	100-kernel weight
	——— mmol m^{-2} s^{-1} ———		μmol mol^{-1}	d	kg ha^{-1}	cm	g
Wh–Fw–Sg+0N	172.1 bc‡	5.40 c	159.6 bc	78 c	8995 ef	110.4 c	2.51 d
Wh–Fw–Sg+45N	185.2 b	5.98 abc	160.9 bc	72 b	11482 c	127.8 ab	2.75 bc
Wh–Fw–Sg+90N	185.8 b	5.81 abc	164.2 bc	71 a	13055 b	128.6 ab	2.72 bc
Wh–Fw–Sg+135N	183.2 bc	6.29 a	159.9 bc	69 a	13586 b	129.9 ab	2.89 a
Wh–Fw–Sg+180N	209.2 a	6.21 ab	180.7 a	69 a	14729 a	132.3 a	3.03 a
Wh–Cp–Sg+0N	183.8 bc	5.52 bc	168.5 b	73 b	11310 cd	128.9 ab	2.86 b
Wh–Pg–Sg+0N	187.1 b	6.11 abc	154.5 c	73 b	11685 cd	129.0 ab	2.66 bc
Wh–Su–Sg+0N	186.8 b	5.50 bc	172.5 a	73 b	9795 cd	127.1 ab	2.62 bc
Wh–Sb–Sg+0N	177.6 bc	5.55 bc	170.5 a	74 b	10605 cd	125.8 b	2.88 b
Wh–Sg–Sg+0N	163.2 c	5.58 abc	158.9 c	78 c	8876 f	116.0 c	2.54 d

† Wh, wheat; Fw, fallow; Sg, sorghum; Cp, cowpea; Pg, pigeonpea; Su, sunn hemp; Sb, soybean; 0N, 0 kg N ha^{-1}; 45 N, 45 kg N ha+; 90N, 90 kg N ha^{-1}; 135N, 135 kg N ha^{-1}; 180N, 180 kg N ha^{-1}.

‡ Values within a column followed by the same letter are not significantly different at the $P = 0.05$ level by Tukey's honestly significant difference test.

Grain sorghum in the pigeonpea 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. 2d). Grain sorghum in the sunn hemp and double-cropped soybean system had similar grain yields. In 2014, grain yield was significantly greater in all the cover crops systems compared with the double-cropped soybean system (Fig. 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 quadratic (2013: $R^2 = 0.99$, $P = 0.0031$; 2014: $R^2 = 0.95$, $P = 0.0219$).

There was a significant ($P < 0.05$) (Table 2) effect of cropping system on 100-kernel weight (HKW) (Table 3). Grain sorghum in the various cover crop systems and the double-cropped soybean system had a HKW similar to that of grain sorghum in the fallow system with 45 to 90 kg ha^{-1}. Grain sorghum in the fallow system with 0 kg N ha^{-1} and the double-cropped system had the smallest HKW (Table 3). 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 Nitrogen Use

The response of sorghum to cropping system differed by year ($P < 0.05$) (Table 2) and affected aboveground N uptake, grain N uptake, NUE, and NHI (Fig. 2). In 2013, grain sorghum in the pigeonpea, sunn hemp, and double-cropped soybean systems had aboveground N uptake levels similar to that of grain sorghum in fallow systems with 45 to 90 kg N ha^{-1} (Fig. 2e). In 2014, grain sorghum in any of the summer cover crop systems and the double-cropped soybean system did not differ in aboveground N uptake, but all were similar to grain sorghum in the fallow system with 45 kg N ha^{-1} (Fig. 2e). In both years, grain sorghum in the double-cropped grain sorghum system had the lowest level of aboveground 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 for sorghum in the cowpea and pigeonpea cropping systems was significantly greater than in the sunn hemp and double-cropped soybean systems. In 2014, grain N uptake in the cowpea cropping system was significantly greater than that of the pigeonpea, sunn hemp, and double-cropped soybean systems (Fig. 2f). The lowest level of grain N uptake in both years was observed in the fallow system with 0 kg N ha^{-1} and the double-cropped grain sorghum system (Fig. 2f). Grain N uptake responded linearly ($R^2 = 0.97$, $P = 0.0015$) to N fertilizer application. Overall, the grain N uptake of grain sorghum in the various summer cover crops and the double-cropped soybean system over the years was similar to that of grain sorghum in fallow systems with 45 to 90 kg N ha^{-1}.

In 2013, the NUE of grain sorghum in all of the cover crop systems was greater than that of grain sorghum in the double-cropped soybean system (Fig. 2g). In 2014, the NUE of grain sorghum in cowpea or sunn hemp cropping systems was greater than that of grain sorghum in the pigeonpea and double-cropped soybean systems. In both years, NUE was greatest in the double-cropped grain sorghum system and similar to that of the fallow system with 0 kg N ha^{-1}. The NUE 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 use efficiency in the various cover crop and double-cropped soybean systems was generally similar to that of grain sorghum in fallow systems with 45 to 90 kg N ha^{-1} (Fig. 2g).

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

Site × Cropping System Interaction

The response of sorghum to cropping system differed by site-year ($P < 0.05$) and affected leaf chlorophyll index, kernels per plant, and grain yield (Fig. 3). The leaf chlorophyll index in the various cover crop systems and the double-cropped soybean system was similar at ABS and was comparable to leaf chlorophyll

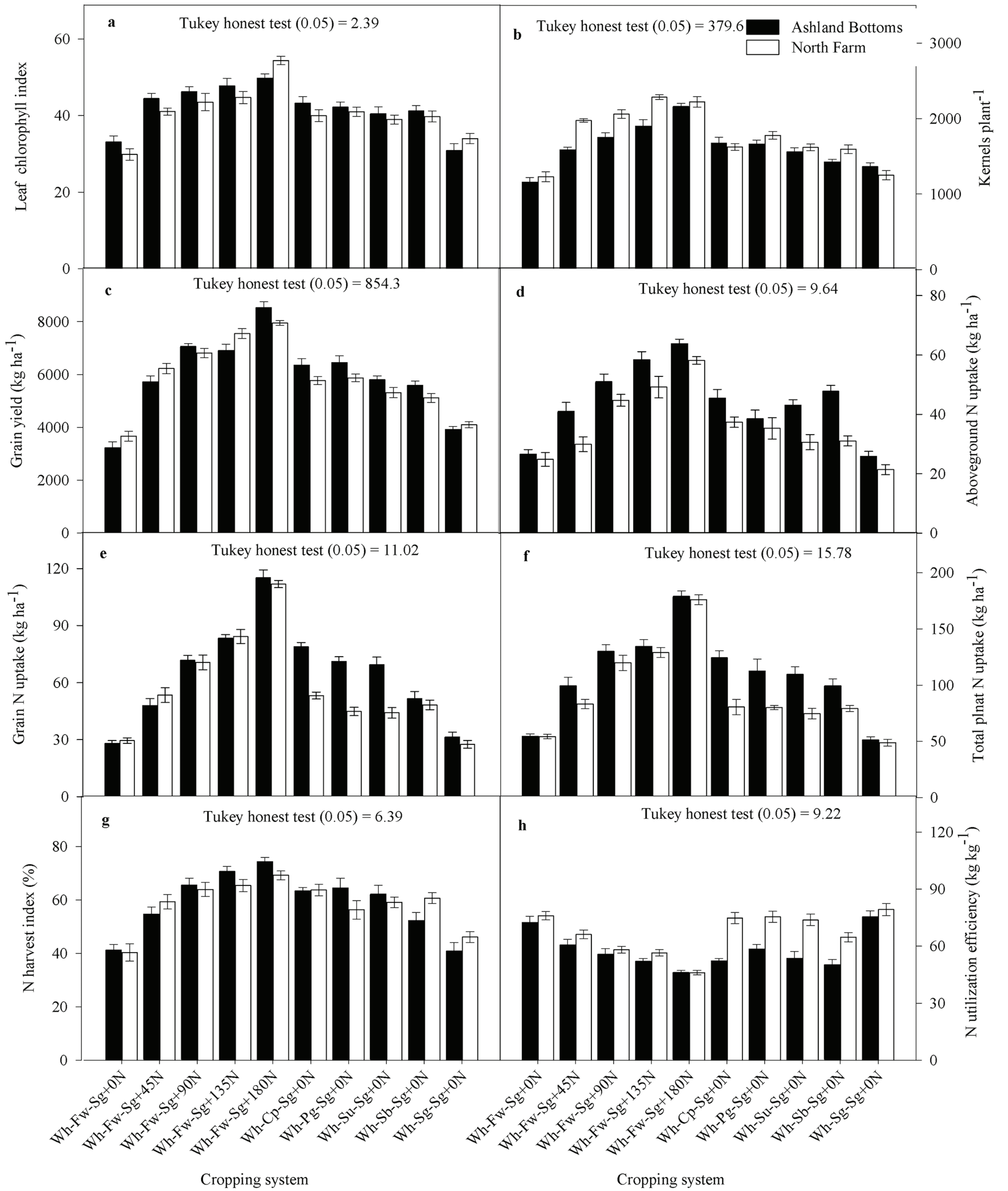

Fig. 3. Cropping system × site effects on (a) leaf chlorophyll index, (b) kernels per plant, (c) grain yield, (d) aboveground N uptake at physiological maturity, (e) grain N uptake at physiological maturity, (f) total N uptake, (g) N harvest index, and (h) N use efficiency of grain sorghum grown in 2013 and 2014 (Wh, wheat; Fw, fallow; Sg, grain sorghum; Cp, cowpea; Pg, pigeonpea; Su, sunn hemp; Sb, soybean; 0N, 0 kg N ha^{-1}; 45 N, 45 kg N ha^{-1}; 90N, 90 kg N ha^{-1}; 135N, 135 kg N ha^{-1}; 180N, 180 kg N ha^{-1}).

index in the fallow system with 45 kg N ha^{-1}. A similar trend was observed for leaf chlorophyll index at ANF. Furthermore, the leaf chlorophyll index was lowest in the double-cropped grain sorghum system (Fig. 3a). The response of leaf chlorophyll index was linear at both sites ($R^2 = 0.99$, $P = 0.0002$).

The number of kernels per plant in any of the cover crop systems and the double-cropped soybean system was similar at ABS (Fig. 3b) and the number of kernels per plant in the double-cropped grain sorghum system was the lowest at ABS. A similar trend was observed for kernels per plant at ANF. Kernels per plant in the fallow systems with N fertilizer applications can best be described by a quadratic response curve ($R^2 = 0.94$, $P = 0.0272$) at both sites. The number of kernels per plant in the various cover crop systems and the double-cropped soybean system was similar to that in fallow systems with either 45 or 90 kg N ha^{-1}, depending on the site (Fig. 3b).

The response of grain yield to the cover crop system was greater at ABS than at ANF (Fig. 3c). Cowpea and pigeonpea cropping systems had grain yields greater than those of sunn hemp and the double-cropped soybean systems at ABS (Fig. 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 the double-cropped soybean system were similar to grain yield in the 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. 3c).

The response of sorghum to cropping systems varied by site ($P < 0.05$) (Table 2) and affected aboveground N uptake, grain N uptake, total N uptake, NHI, and NUE (Fig. 3). Aboveground N uptake was significantly greater at ABS than at ANF (Fig. 3d). At both sites, aboveground N uptake in any of the cover crop systems and the double-cropped soybean system was similar to that of fallow systems with 45 to 90 kg ha^{-1}. The aboveground N uptake response to N fertilizer application was quadratic ($R^2 = 0.99$, $P = 0.007$) at ABS and linear at ANF ($R^2 = 0.96$, $P = 0.002$). Aboveground N uptake in the double-cropped grain sorghum was similar to that of the fallow system with 0 kg N ha^{-1}.

Grain N uptake in any of the summer cover crop systems and the double-cropped soybean system was significantly greater at ABS than at ANF (Fig. 3e). Grain N uptake in any of the cover crop systems at ABS was similar to the fallow system with 90 kg N ha^{-1} but that in the double-cropped soybean system was similar to that in the fallow system with 45 kg N ha^{-1}. At ANF, grain uptake in the various cover crop systems and the double-cropped soybean system was similar to that in the fallow system with 45 kg N ha^{-1}. Grain sorghum in the double-cropped grain sorghum system had the lowest level of grain N uptake at both sites (Fig. 3e). Grain N uptake ($R^2 = 0.98$, $P = 0.0006$) responded linearly to N fertilizer application at ABS and ANF.

Total N uptake by sorghum in the cover crop systems was significantly greater than total N uptake in the double-cropped soybean system at ABS. Similar trends for total N uptake were observed at ANF (Fig. 3f). In addition, total N uptake responded linearly ($R^2 = 0.93$; $P = 0.005$) to N fertilizer application. Total N uptake in cowpea, pigeonpea, sunn hemp, and double-cropped soybean was comparable to fallow systems with either 45 or 90 kg N ha^{-1}, depending on the site.

The NHI in cover crop systems was greater than that of the NHI in the double-cropped soybean and double-cropped grain sorghum systems at ABS. At ANF, grain sorghum NHI in the cowpea, sunn hemp, and double-cropped soybean systems was greater than in the pigeonpea and double-cropped grain sorghum systems (Fig. 3g). The response of NHI at ABS was $0.153x + 42.81$ ($R^2 = 0.94$, $P = 0.0032$); at ANF, the response of NHI was $0.170x + 45.82$($R^2 = 0.96$, $P = 0.0018$). Aboveground N uptake, grain N uptake, total N uptake, and NHI in the double-cropped grain sorghum system was generally similar to that in the fallow system with 0 kg N ha^{-1}.

The NUE of grain sorghum in the various cover crop systems, double-cropped soybean, and double-cropped grain sorghum systems was greater at ANF than at ABS (Fig. 3h). At ABS, the NUE in any of the summer cover crop systems and the double-cropped soybean system was similar to that of fallow systems with 90 to 135 kg N ha^{-1}. The NUE in the various cover crop systems and the double-cropped grain crop systems at ANF was similar to fallow systems with 0 to 45 kg N ha^{-1}. Furthermore, NUE decreased linearly with N fertilizer application ($R^2 = 0.93$, $P = 0.0052$) at both sites.

Relationship among Physiological Traits and Grain Yield

Photosynthetic rate was a linear function of leaf chlorophyll index, leaf N uptake, stomatal conductance, and C_i (Fig. 4). The effects of leaf chlorophyll index and leaf N uptake on photosynthetic rate typically were more influenced by N fertilizer application in both years (Fig. 4a and 4b) than by stomatal conductance or C_i (Fig. 4c and 4d). Stomatal conductance explained more of the variability observed in photosynthetic rate than leaf chlorophyll index, leaf N uptake, or C_i (Fig. 4a–4d).

Positive linear relationships were observed when grain yield was plotted against photosynthetic rate, aboveground biomass, kernels per plant, and HKW (Fig. 4). The relationships were significantly driven by N fertilizer application. Aboveground biomass and kernels per plant were the traits that contributed most to the variability observed in grain yield compared with photosynthetic rate and HKW (Fig. 4e–4h).

Economic Analyses

Economic analyses were calculated for fallow systems with N fertilizer applications, the cover crop systems, and the double-cropped grain systems. The results are presented in Tables 4 and 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^{-1}; the net benefit of the fallow system with 45 kg N ha^{-1} was greater than that of the fallow system with 0 kg N ha^{-1}. The MRR between the fallow with 0 kg N ha^{-1} and the fallow with 90 kg N ha^{-1} was greater than that of fallow systems with either 135 or 180 kg N ha^{-1} (Table 4).

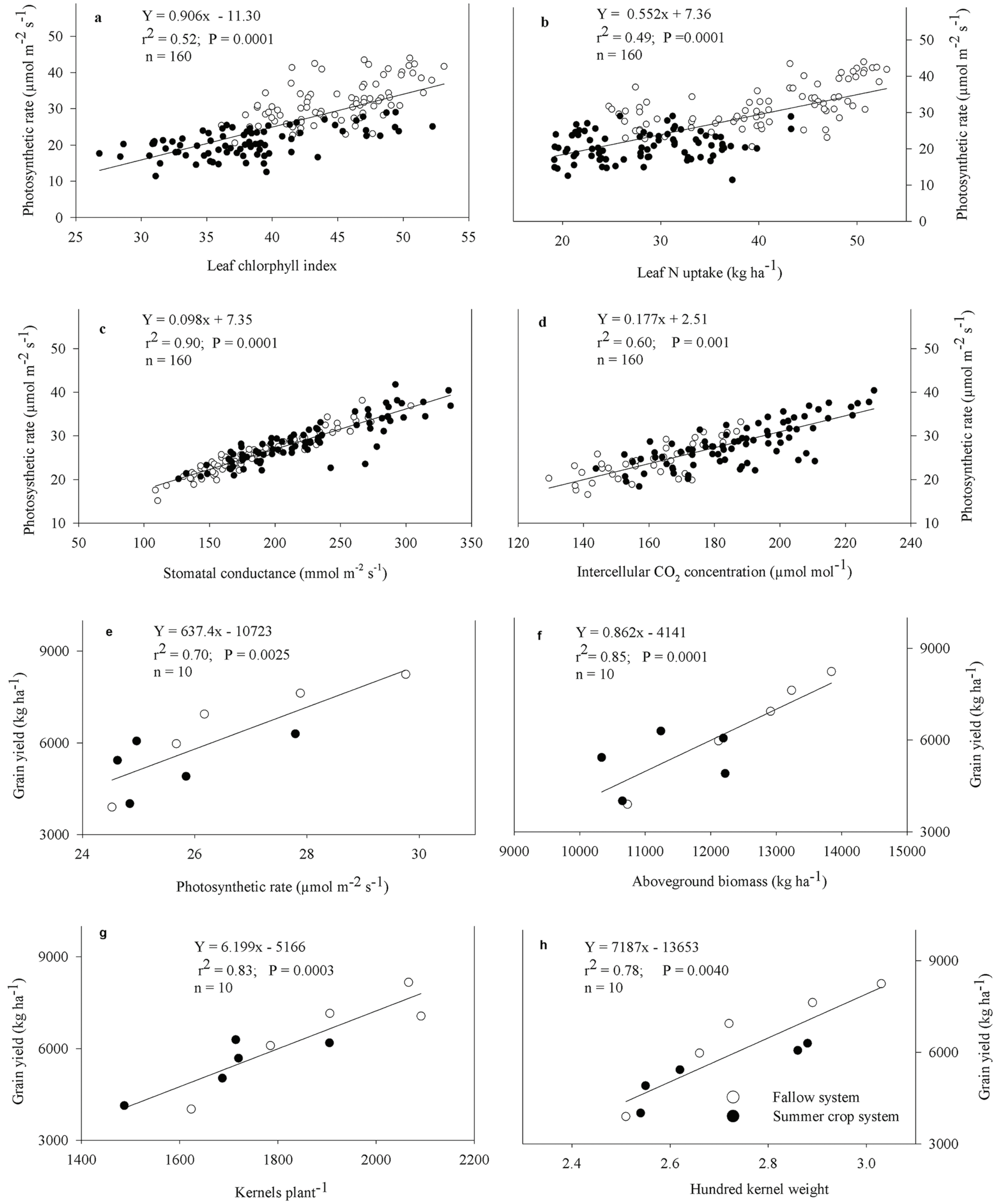

Fig. 4. Relationships between photosynthetic rate and (a) leaf chlorophyll index, (b) leaf N uptake, (c) stomatal conductance, and (d) intercellular CO_2 concentration and between grain yield and (e) photosynthetic rate, (f) aboveground biomass at physiological maturity, (g) kernels per plant, and (h) 100-kernel weight in 2013 and 2014.

The net economic benefits of including the summer cover crops, double-cropped soybean, and double-cropped grain sorghum are presented in Table 5. Among cover crops, the cowpea cropping system gave the greatest net economic return, followed by the pigeonpea cropping system. In contrast, the sunn hemp cropping system produced a negative net economic return. The net return accrued from grain sorghum in the double-cropped soybean system was greater than what was observed in the double-cropped grain sorghum system. Both double-cropping systems resulted in greater net returns than the cover crop systems.

Table 4. Economic analysis of N fertilizer applied to grain sorghum at rates from 0 to 180 kg ha^{-1} grown in fallow plots in 2013 and 2014.

Variable	N fertilizer rates				
	0 kg ha^{-1}	45 kg ha^{-1}	90 kg ha^{-1}	135 kg ha^{-1}	180 kg ha^{-1}
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 return, US$ ha^{-1}	686.0	888.0	1221	1325	1468
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	171.6	257.5	343.3
Fertilizer application	0.00	15.20	15.20	15.20	15.20
Harvesting	64.43	72.59	82.33	84.07	88.88
Herbicides	123.7	123.7	123.7	123.7	123.7
Herbicide application	45.51	45.51	45.51	45.51	45.51
Hauling at US$0.008 kg^{-1}	31.18	40.38	55.53	60.22	66.74
Total variable inputs cost	315.8	425.0	520.6	608.2	698.8
Net return, US$ ha^{-1}	370.1	463.4	701.0	716.8	769.4
Marginal rate of return, %	0.00	85.39	248.6	18.01	58.03

DISCUSSION

The grain sorghum hybrid DKS54-00 varied in its response to N fertilizer and cover cropping systems for all traits. Averaged across site years, the fallow system with applications of N fertilizer increased leaf chlorophyll index, photosynthesis, grain yield, and kernels per plant and decreased the DTF by 10 d. Decreased leaf chlorophyll indices and photosynthetic rates are good indicators of yield losses under N deficiency (Dwyer et al., 1995). The 2012 to 2013 and 2013 to 2014 growing seasons (April–October) were different. More rainfall in 2013, especially in the months of June to September, resulted in adequate soil moisture, particularly during the grain–filling period. In 2014, despite the high amount of rainfall 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

Table 5. Economic analysis of grain sorghum after cover crops and double-cropped soybean and grain sorghum grown in 2013 and 2014.

Variable	Cowpea	Pigeonpea	Sunn hemp	Soybean	Sorghum
Harvested yield, kg ha^{-1}	0	0.00	0.00	2919	2569
Grain price. US$ kg^{-1}	0.00	0.00	0.00	0.411	0.176
Gross return, US$ ha^{-1}	0.00	0.00	0.00	1199	452.1
Variable costs (cover crops + double crops), US$ ha^{-1}					
Seeds	62.20	306.2	380.8	150.5	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	123.7	123.7	123.7	123.7	123.7
Herbicide application	45.51	45.51	45.51	45.51	45.51
Mowing and harvesting	32.15	32.15	32.15	66.19	20.47
Total variable cost (cover crops + double crops)	344.8	588.8	663.4	467.2	271.8
Succeeding crop (grain sorghum)					
Grain sorghum yield, kg ha^{-1}	6063	6567	5562	5156	4170
Price, US$ kg^{-1}	0.186	0.186	0.186	0.186	0.186
Gross return, US$ ha^{-1}	1127	1221	1034	959.0	775.6
Variable costs, 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	123.7	123.7	123.7	123.7	123.7
Herbicide application	45.51	45.51	45.51	45.51	45.51
Harvesting	103.4	126.2	141.7	170.7	162.0
Hauling at US$0.008 kg^{-1}	48.51	52.54	44.50	41.25	33.36
Total variable costs	403.3	430.1	437.6	463.3	446.8
Total cost (double crops + cover crops + succeeding crop), US$ ha^{-1}	748.2	1019	1101	930.5	718.6
Total income, US$ ha^{-1}	1127	1221	1034	2158	1227
Net return, US$ ha^{-1}	379.6	202.4	–66.48	1228	509.0

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 because of their drought tolerance characteristics.

Adaptability to specific soil and environmental conditions can influence the performance of summer cover crops. Among the summer cover crops, pigeonpea 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. 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 the double-cropped soybean system had photosynthetic rates greater than that of the fallow system with 0 kg N ha^{-1} and were comparable to that of the fallow with 45 kg N ha^{-1} (Fig. 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 that of the fallow with 0 kg N ha^{-1} were 56, 62, 43, 32, and 3%, respectively (Fig. 2d). The number of kernels per plant 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 to calculate NFRVs following a procedure described by Hesterman et al. (1992) and Carsky et al. (2001)

The NFRVs of cowpea, pigeonpea, sunn hemp, and double-cropped soybean in 2013 ranged from 30 to 75 kg N ha^{-1}. The

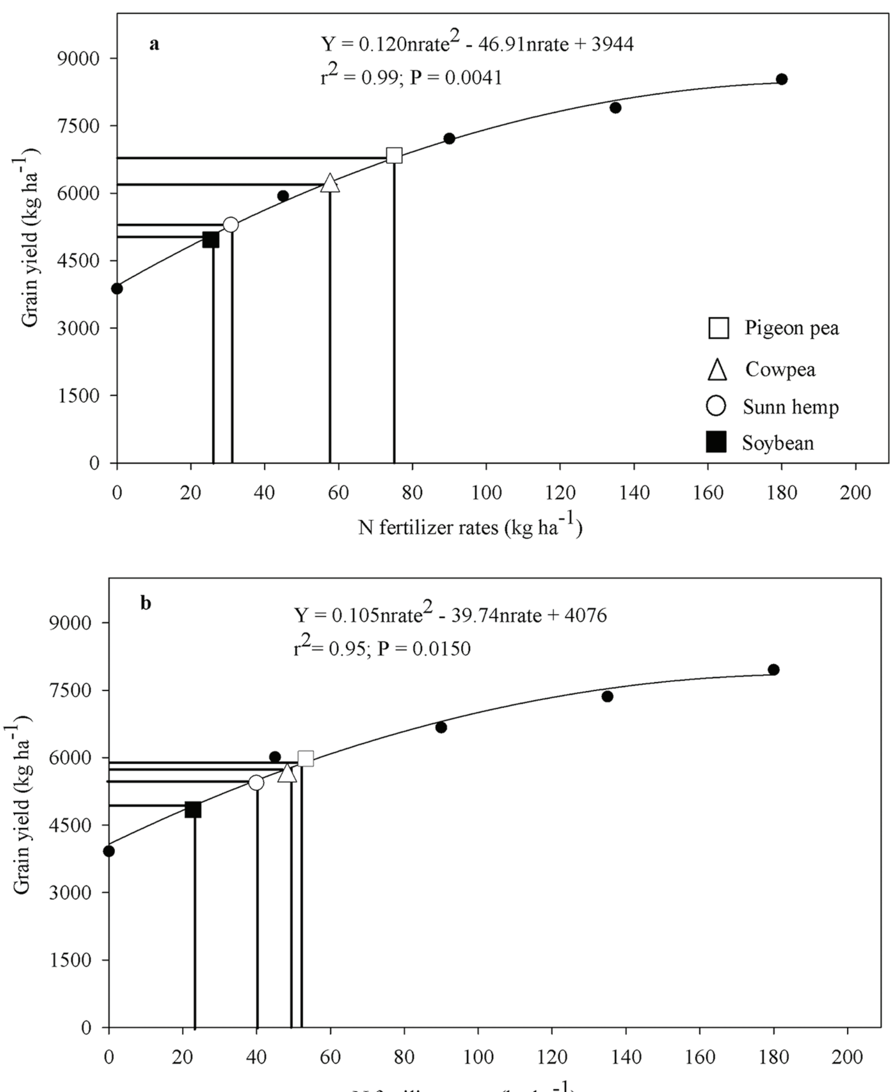

Fig. 5. Nitrogen replacement value of summer leguminous cover crops and double-cropped soybean in (a) 2013 and (b) 2014.

corresponding values in 2014 were 23 to 52.3 kg N ha^{-1} for cowpea, pigeonpea, sunn hemp, and double-cropped soybean (Fig. 5a and 5b). 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 in maize. The N contribution from small grain crops generally is negative (Torbert and Reeves, 1991) because of the wide C/N ratio of the residue. In this study, the NFRV of double-cropped grain sorghum over the years was −3 kg N ha^{-1}.

Correlation of grain yield with leaf chlorophyll was significant ($P = 0.007$), which is in agreement with Wood et al. (1992a, 1992b), who reported that soil plant analysis development 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 (Huber et al., 1989; Connor et al., 1993). In our study, there was a strong correlation between photosynthesis and leaf chlorophyll index (Fig. 4a). A linear relationship between photosynthetic rate and stomatal conductance represents the contribution of stomatal conductance to photosynthetic CO_2 assimilation (Fig. 4c) as previously observed by (Zhao et al., 2005) in grain sorghum.

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 shown by the fact that the main effect of increasing the N level from 90 to 135 to 180 kg N ha^{-1} resulted in a corresponding increase in grain yield and net benefits but this increase did not merit extra costs to producers. The 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 the double-cropped soybean system gave the greatest economic net return. Careful management is required for production of a profitable second crop after wheat. The soybean and grain sorghum, planting date is critical in determining the 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 sow soybean and grain sorghum as early as possible.

CONCLUSIONS

The 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 a physiological, growth, yield traits, and N use of grain sorghum in fallow systems with N fertilizer application and various cover crops. Leguminous summer 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 per plant, HKW, and grain N uptake. Across years and cropping systems, the mean increases in grain yield as a result of including cowpea, pigeonpea, and sunn hemp, double-cropped soybean, and double-cropped grain sorghum in the rotation over the fallow with 0 kg N ha^{-1} were 56, 62, 43, 32, and 3%, respectively. Furthermore, the NFRVs across years for cowpea, pigeonpea, sunn hemp, double-cropped soybean, and double–cropped grain sorghum were 53, 64, 36, 27, and −3 kg N ha^{-1}, respectively. Grain sorghum in the double-cropped soybean system and the fallow system with 90 kg N ha^{-1} gave profitable net returns. Overall, summer cover crops can reduce or supplement fertilizer N requirements for grain sorghum production. This research provides vital information for producers, especially in developing countries, where, because of high costs and the unavailability of fertilizer N, producers are unable to use fertilizer N for grain sorghum production.

ACKNOWLEDGMENTS

Financial assistance from the former USAID Collaborative Research Support Programs of Sustainable Agricultural and Natural Resource Management, the USAID Feed the Future Sustainable Intensification Innovation Lab (Grant no. AID-OAA-L-14-00006), and the K-State Center for Sorghum Improvement is appreciated. This is Contribution no. 15-344-J from the Kansas Agricultural Experiment Station. G.Y. Mahama thanks Savanna Agricultural Research Institute of the Council for Scientific and Industrial Research, Ghana, for providing study leave to pursue a doctoral degree at KSU.

REFERENCES

Amato, G., P. Ruisi, A.S. Frenda, G. Di Miceli, S. Saia, and A. Plaia. 2013. Long-term tillage and crop sequence effects on wheat grain yield and quality. Agron. J. 105:1317–1327. doi:10.2134/agronj2013.0019

Balkcom, K.S., and D.W. Reeves. 2005. Sunn hemp utilized as a legume cover crop for corn production. Agron. J. 97:26–31. doi:10.2134/agronj2005.0026

Blackshaw, R.E., J.R. Moyer, R.C. Doram, A.L. Boswall, and E.G. Smith. 2001. Suitability of undersown sweetclover as a fallow replacement in semiarid cropping systems. Agron. J. 93:863–868. doi:10.2134/agronj2001.934863x

Bouyoucos, G.J. 1962. Hydrometer method improved for making particle size analyses of soils. Agron. J. 54:464–465. doi:10.2134/agronj1962.00021962005400050028x

Buah, S.S.J., J.M. Kombiok, and L.N. Abatania. 2012. Grain sorghum response to NPK fertilizer in the Guinea savanna of Ghana. J. Crop Improv. 26:101–115. doi:10.1080/15427528.2011.616625

Carsky, R.J., B.B. Singh, and B. Oyewole. 2001. Contribution of early season cowpea to late season maize in the savanna zone of West Africa. Biol. Agric. Hortic. 18:303–315. doi:10.1080/01448765.2001.9754894

Cechin, L. 1998. Photosynthesis and chlorophyll fluorescence in two hybrids of grain sorghum under different nitrogen and water regimes. Photosynthetica 35:233–240. doi:10.1023/A:1006910823378

Cherr, C.M., J.M.S. Scholberg, and R. McSorley. 2006. Green manure approaches to crop production: A synthesis. Agron. J. 98:302–319. doi:10.2134/agronj2005.0035

Chikowo, R., P. Mapfumo, P. Nyamugafata, and K.E. Giller. 2004. Woody legume fallow productivity, biological N_2–fixation and residual benefits to two successive maize crops in Zimbabwe. Plant Soil 262:303–315. doi:10.1023/B:PLSO.0000037053.05902.60

CIMMYT. 1988. Agronomic data to farmer recommendations: An economics training manual. Rev. ed. CIMMYT, Mexico City.

Clark, A.J., A.M. Decker, J.J. Meisinger, F.R. Mulford, and M.S. McIntosh. 1995. Hairy vetch kill dates effects on soil water and corn production. Agron. J. 87:579–585. doi:10.2134/agronj1995.00021962008700030031x

Combs, S.M., and M.V. Nathan. 1998. Soil organic matter. In: J.R. Brown, editor, Recommended chemical soil test procedure for the North Central Region. NCR Publ. 221 (revised). Missouri Agric. Exp. Stn., Columbia. p. 57–58.

Combs, S.M., J.L. Denning, and K.D. Frank. 1998. Sulfate-sulfur. In: J.R. Brown, editor, Recommended chemical soil test procedures for the North Central Region. NCR Publ. 221 (revised). Missouri Agric. Exp. Stn., Columbia. p. 35–40.

Connor, D.J., A.J. Hall, and V.O. Sadras. 1993. Effect of nitrogen content on the photosynthetic characteristics of sunflower leaves. Aust. J. Plant Physiol. 20:251–263. doi:10.1071/PP9930251

Demotes-Mainard, S., and M.H. Jeuffroy. 2004. Effects of nitrogen and radiation on dry matter and nitrogen accumulation in the spike of winter wheat. Field Crops Res. 87:221–233. doi:10.1016/j.fcr.2003.11.014

Dwyer, L.M., A.M. Anderson, B.L. Ma, D.W. Steward, M. Tollenaar, and E. Gregorich. 1995. Quantifying the non-linearity and chlorophyll meter response to corn leaf nitrogen concentration. Can. J. Plant Sci. 75:179–182. doi:10.4141/cjps95-030

Fox, R.H., R.J.K. Myers, and I. Vallis. 1990. The nitrogen mineralization rate of legume residues in soil as influenced by their polyphenol, lignin, and nitrogen contents and soil. Plant Soil 129:251–259. doi:10.1007/BF00032420

Gelderman, R.H., J. L. Denning, and R. J. Goos. 1998. Chlorides. In: J.R. Brown, editor, Recommended chemical soil test procedures for the North Central Region. NCR Publ. 221 (revised). Missouri Agric. Exp. Stn., Columbia. p. 53–56.

Giller, K.E. 2001 Nitrogen fixation in tropical cropping systems. 2nd ed. CAB Int., Wallingford, UK.

Hanlon E.A. and G.V. Johnson. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Commun. Soil Sci. Plant Anal. 15:277–294. doi:10.1080/00103628409367475

Hartley, H.O. 1950. The use of range in analysis of variance. Biometrika 37:271–280. doi:10.1093/biomet/37.3-4.271

Hesterman, O.B., T.S. Griffin, P.T. Williams, G.H. Harris, and D.R. Christenson. 1992. Forage legume–small grain intercrops: Nitrogen production and response of subsequent corn. J. Prod. Agric. 5:340–348. doi:10.2134/jpa1992.0340

Huang, W., W. McBride, and U. Vasavada. 2009. Recent volatility in U.S. fertilizer prices. Amber waves, March 2009. USDA Econ. Res. Serv., Washington, DC.

Huber, S.C., T. Sugiyama, and R.S. Alberte. 1989. Photosynthetic determinants of growth in maize plants: Effects of nitrogen nutrition on growth, carbon fixation and photochemical features. Plant Cell Physiol. 30:1063–1072.

Kaizzi, C.K., J. Byalebeka, O. Semalulu, I. Alou, W. Zimwanguyizza, A. Nansamba, et al. 2012. Maize response to fertilizer and nitrogen use efficiency in Uganda. Agron. J. 104:73–82. doi:10.2134/agronj2011.0181

Kay, B. D. and D.A. Angers. 1999. Soil structure. In M.E. Sumner, editor, Handbook of soil science. CRC Press, Boca Raton, FL. p. A-229–A-276.

Kelley, K.W. 2003. Double-cropping winter wheat and soybean improves net returns in the eastern Great Plains. Crop Manage. 2: 1–7. doi:10.1094/CM-2003-1112-01-RS

Leikam, D., R.E. Lamond, L.C. Bonczkowski, J.S. Hickman, and D.W. Whitney. 2007. Using legumes in crop rotation. Kansas State Univ., Manhattan.

Liebman, M., R. Graef, D. Nettleton, and C.A. Cambardella. 2012. Use of legume green manures as nitrogen sources for corn production. Renew. Agric. Food Syst. 27:180–191. doi:10.1017/S1742170511000299

Liu, X.B., J. Jin, G.H. Wang, and S.J. Herbert. 2008. Soybean yield physiology and development of high-yielding practices in Northeast China. Field Crops Res. 105:157–171. doi:10.1016/j.fcr.2007.09.003

Ma, B.L., K.D. Subedi, D.W. Stewart, and L.M. Dwyer. 2006. Dry matter accumulation and silage moisture changes after silking in leafy and dual purpose corn hybrids. Agron. J. 98:922–929. doi:10.2134/agronj2005.0299

Mahama, G.Y., P.V.V. Prasad, D.B. Mengel, and T.T. Tesso. 2014. Influence of nitrogen fertilizer on growth and yield of grain sorghum hybrids and inbred lines. Agron. J. 106:1623–1630. doi:10.2134/agronj14.0092

National Agricultural Statistics Service. 2013. Custom rates. NASS, Washington, DC. http://www.nass.usda.gov/Statistics_by_State/Kansas/Publications/Custom_Rates/custom13.pdf (accessed 28 Aug. 2015).

Peoples, M.B., J. Brockwell, D. F. Herridge, I.J. Rochester, B.J.R. Alves, S. Urquiaga, et al. 2009. Review article. The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems. Symbiosis 48:1–17. doi:10.1007/BF03179980

Saeed, M., C.A. Francis, and M.D. Clegg. 1986. Yield component analysis in grain sorghum. Crop Sci. 26:346–351. doi:10.2135/cropsci1986.0011183X002600020028x

SAS Institute. 2003. SAS release 9.1 for Windows. SAS Inst., Cary, NC.

Schepers, J.S., D.D. Francis, M. Vigil, and F.E. Below. 1992. Comparison of corn leaf nitrogen concentration and chlorophyll meter readings. Commun. Soil Sci. Plant Anal. 23:2173–2187. doi:10.1080/00103629209368733

Schipanski, M.E., L.E. Drinkwater, and M.P. Russelle. 2010. Understanding the variability in soybean nitrogen fixation across agroecosystems. Plant Soil 329:379–397. doi:10.1007/s11104-009-0165-0

Shaffer, M.J., and L. Ma. 2001. Carbon and nitrogen dynamics in upland soils. In: M.J. Shaffer et al., editors, Modeling carbon and nitrogen dynamics for soil management. CRC Press, Boca Raton, FL. p. 11–26.

Smith, F., K.R. Brye, E.E. Gbur, P. Chen, and K. Korth. 2014. Long-term residue management effects on soil respiration in a wheat–soybean double-crop system. Soil Sci. 179:118–129. doi:10.1097/SS.0000000000000053

Subbarao, G.V., Y.S. Chauhan, and C. Johansen. 2000. Patterns of osmotic adjustment in pigeon pea– its importance as a mechanism of drought resistance. Eur. J. Agron. 12:239–249. doi:10.1016/S1161-0301(00)00050-2

Torbert, H.A., and D.W. Reeves. 1991. Benefits of a winter legume cover crop to corn: Rotation versus fixed-nitrogen effects. In: W.L. Hargrove, editor, Cover crops for clean water: Proceedings of an international conference, Jackson, TN. 9–11 Apr. 1991. Soil Water Conserv. Soc., Ankeny, IA. p. 99–100..

Unkovich, M.J., and J.S. Pate. 2000. An appraisal of recent field measurements of symbiotic N_2 fixation by annual legumes. Field Crops Res. 65:211–228. doi:10.1016/S0378-4290(99)00088-X

Vanderlip, R.L. 1993. How a sorghum plant develops. Kansas State Univ., Manhattan.

Varco, J.J., W.W. Frye, M.S. Smith, and C.T. MacKown. 1993. Tillage effects on legume decomposition and transformation of legume and fertilizer nitrogen. Soil Sci. Soc. Am. J. 57:750–756. doi:10.2136/sssaj1993.03615995005700030021x

West, T.O., and G. Marland. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91:217–232. doi:10.1016/S0167-8809(01)00233-X

Wood, C.W., D.W. Reeves P.W. Tracy, and K.L. Edmisten. 1992a. Determination of cotton nitrogen status with a hand-held chlorophyll meter in Alabama and Missouri. J. Plant Nutr. 15:1435–1448. doi:10.1080/01904169209364409

Wood, C.W., D.W. Reeves, R.R. Dufield, and K.L. Edmisten. 1992b. Field chlorophyll measurement for evaluation of maize N status. J. Plant Nutr. 15:487–500. doi:10.1080/01904169209364335

Zhao, D.L., K.R. Reddy, V.G. Kakani, and V.R. Reddy. 2005. Nitrogen deficiency effects on plant growth, leaf photosynthesis, and hyperspectral reflectance properties of sorghum. Eur. J. Agron. 22:391–403. doi:10.1016/j.eja.2004.06.005