Published January 5, 2016

Response of Maize to Cover Crops, Fertilizer Nitrogen Rates, and Economic Return

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

ABSTRACT

Leguminous cover crops are considered part of sustainable agricultural systems. With the development of no-till cropping systems, cover crops have been recognized for their ability to provide N for succeeding crops. The objectives of this study were: (i) to determine the N contribution of summer cover crops and double-cropped grain crops following winter wheat (*Triticum aestivum* L.) and N rates to subsequent maize (*Zea mays* L.) crops' physiological traits and yield, (ii) to calculate the fertilizer N replacement value, and (iii) to perform economic analyses of the cropping systems. Field experiments were conducted during the 2012–2013 and 2013–2014 growing seasons in Kansas. The grain yield of maize in all the cover crop systems and the double-cropped soybean [*Glycine max* (L.) Merr.] system was similar to maize in the fallow system with 45 kg N ha^{-1}. The mean increase 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 [*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. Fertilizer N replacement values for cowpea, pigeonpea, sunn hemp, double-cropped soybean, and double-cropped grain sorghum were 53, 64, 43, 47, and –5 kg N ha^{-1}, respectively. We conclude that the inclusion of summer leguminous cover crops in a cropping system has the potential to reduce or supplement N requirements and increase the grain yield of subsequent maize crops.

Maize is the world's most widely grown cereal on the basis of Mg produced (FAO, 2014). Nitrogen fertilizer applied to cropland is a considerable portion of the cost and energy input associated with nonlegume crop production (Liebman et al., 2012). When N is lost from cropland, it represents both a financial loss to producers and has a potentially negative impact on the environment (Vetsch and Randall, 2004).

Leguminous cover cropping systems have been proposed as a method to reduce the reliance on fertilizer N and reduce environmental risks by decreasing N losses (Reinbott et al., 2004). Cover crops are steadily gaining adoption by producers across the Great Plains as a cultural practice to improve soil health and crop yields (Dagel et al., 2014). Previous studies have shown that apart from providing N, winter legume cover crops can improve physical soil 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 the asynchrony of cover crop planting windows and biomass accumulation with planting windows for summer cash crops (Janke et al., 2002). For example, to allow winter legume cover crops adequate growing time before cold temperatures occur, summer crops may need to be harvested before optimum conditions (Blanco-Canqui et al., 2012). A 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 the yields of summer cash crops (Blanco-Canqui et al., 2012).

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, pigeonpea, 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). Balkcom and Reeves (2005) reported that sunn hemp produced 7.6 Mg ha^{-1} of biomass with 144 kg ha^{-1} of N in the first 2 yr in Alabama. Cherr et al. (2006) observed

Published in Agron. J. 108:17–31 (2016)
doi:10.2134/agronj15.0136
Received 19 Mar. 2015
Accepted 25 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 Bottoms site; a.e., active equivalent; ANF, Agronomy North Farm; DTS, days to 50% silking; HKW, hundred-kernel weight; FNRV, fertilizer nitrogen replacement value; KSU, Kansas State University; MRR, marginal rate of return; NHI, nitrogen harvest index; NUE, nitrogen use efficiency.

that sunn hemp produced 8.0 Mg ha^{-1} of biomass with 146 kg N 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 pigeonpea conducted by Mafongoya et al. (2006) found that leaves dropping from pigeonpea can contribute up to 40 kg N ha^{-1} when used as a cover crop.

Leguminous summer cover crops influence subsequent crop yield primarily via their effects on N availability (Schomberg et al., 2007); however, effective cover crop N contribution depends on sufficient N uptake in the cover crop biomass and timely mineralization of the accumulated N, precipitation events, cover crop species, tillage management, and the length of cover crop management (Teasdale et al., 2008; Blanco-Canqui et al., 2012). 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 (Sainju et al., 2005). Previous research has found that residues with C/N ratios <25 generally result in net N mineralization, whereas residues with C/N ratios >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 pigeonpea 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 to be in the range of 60 to 80 kg N ha^{-1} (Sanginga et al., 2000), depending on how the residues were managed. Significant increases in yield for maize grown in crop rotation with soybean were also recorded in experiments where N, P, and K soil test levels were high and pest populations were managed (Copeland et al., 1993) compared to monocropping. Thus crop rotation effects can have a substantial positive influence on maize yields beyond the potential N contributions.

Many have studied the effect of cover crops and N addition on crop yields but few studies have compared the effects of summer leguminous cover crops and N on maize yield and various physiological traits under managed no-till cropping systems. A better understanding of the performance of maize 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 would result in increased benefit to the soil through N in the residue, which would improve the subsequent maize crop. The objectives of this study were: (i) to determine the N contribution of summer cover crops, double-cropped grain crops following winter wheat, and N rates to subsequent maize crops physiological traits and yield; (ii) to calculate fertilizer N replacement value (FNRV); and (iii) to perform an economic analysis of the cropping 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 to evaluate the response of maize to summer cover crops and fertilizer N 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, (a fine-silty mixed, superactive, mesic Pachic Argiudoll; 39°8′35.3″ N, 96°37′39.2″ W, 308 m asl) (Ashland Bottoms site, ABS); the other was on a Kennebec silt loam soil (a fine-silty, mixed, superactive, mesic Cumulic Hapludoll; 39°11′30″ N, 96°35′30″ W, 311 m asl) (Agronomy North Farm, ANF). The experiments were implemented on sites that had not been tilled for at least the previous 6 yr. Treatments were arranged in a randomized complete block design with four replications. The treatments were as follows: wheat rotated with maize plus 0 kg N ha^{-1}, wheat rotated with maize plus 45 kg N ha^{-1}, wheat rotated with maize plus 90 kg N ha^{-1}, wheat rotated with maize plus 135 kg N ha^{-1}, wheat rotated with maize plus 180 kg N ha^{-1}, cowpea rotated with maize after wheat, pigeonpea rotated with maize after wheat, sunn hemp rotated with maize after wheat, double-cropped soybean rotated with maize after wheat, and double-cropped grain sorghum rotated with maize after wheat.

Soil Sampling and Analyses

In 2013 and 2014, composite soil samples were taken at the time of planting from each replication to a depth of 60 cm. Sampling was done using a hand probe (Oakfield Soil-Probe, Forestry Suppliers, Inc.; 3.2 cm in 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, 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 NO_3–N and NH_4–N. All 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 mol L^{-1}, pH 7.0) extraction method (Thomas, 1982). The Walkley–Black method was used to determine organic matter (Combs and Nathan, 1998). Chloride was analyzed by calcium nitrate extraction (Combs and Nathan, 1998). The turbidimetric method was used to determine sulfate-S. Ammonia and NO_3–N were extracted from soil samples with 1 mol L^{-1} KCl (2 g in 20 mL, 30 min) and measured by an indophenol colorimetric reaction (Combs and Nathan, 1988).

Winter Wheat and Cover Crop Phase

Cover crops were evaluated in the 2011–2012 and 2012–2013 growing seasons after winter wheat. Each plot was 9.1 m long and 4.5 m wide (six rows). Winter wheat was drilled in October 2011 and September 2012 with a seeding rate of 115 kg ha^{-1} with 19-cm row spacing at a depth of 1.5 to 3.0 cm with no fertilizer applied at planting. The wheat was harvested in July in both years and the stubble was sprayed with glyphosate [*N*-(phosphonomethyl)glycine] at 1.67 kg active equivalent (a.e.) ha^{-1} to control weeds.

Three different cover crops (cowpea, pigeonpea, 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.) at a row spacing of 0.75 cm in both years and sites. A chemical fallow was used as a check treatment and double-cropped soybean and double-cropped grain sorghum were included as the cash double-crop alternatives following the 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 350,000 and 125,000 seeds ha^{-1}, respectively.

At physiological maturity of grain sorghum, the aboveground biomass of 10 plants from each plot planted was randomly sampled. Two rows 2.5 m long of soybean plants were sampled at the R7 stage (the beginning of maturity). Samples were dried at 60°C in a forced-air oven for 72 h and weighed. Based on the individual plot plant density, total aboveground biomass was determined and expressed per unit of area. The dried 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.) (Brown, 1997).

Leguminous cover crop performance was measured throughout the growing season. Stand counts were made for all cover crops 20 d after 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; however, in 2013 a rotary mower was used for harvesting. The remaining fresh aboveground biomass cut from the summer leguminous cover crop plots were then uniformly distributed on the harvested plots and left in the field to decompose. In both years, aboveground subsamples from each plot of the cover crops were dried in a forced-air dryer at 60°C for 5 d and weighed to obtain dry matter content. The dried samples were ground using a Wiley mill (Model 4, Thomas Scientific) and analyzed for N and C by dry combustion (modified Dumas method) using a LECO CHN-2000 elemental analyzer (LECO Corp.) at the KSU Soil Testing Laboratory. Nitrogen and C uptake of the various cover crops were determined by multiplying aboveground dry matter weight by the percentage of N or C concentration. Cowpea, pigeonpea, and sunn hemp cover crops were terminated at onset of flowering at 67, 88, and 84 d after planting, respectively, in 2012. Corresponding values in 2013 were 70, 90, and 88 d after planting, respectively.

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 Corp.). Grain moisture and test weight were estimated with a moisture meter (GAC 2000, DICKEY–John Corp.).

Maize Phase

Before planting maize (hybrid Dekalb DKC63-84), all plots were sprayed with glyphosate herbicides at 1.67 kg a.e. ha^{-1}. Maize was planted at 70,000 seeds ha^{-1} with a 76-cm row spacing with a no-till planter (John Deere 1590) equipped with residue managers 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. To ensure that N loss through ammonia volatilization of surface-applied N was minimal, N was applied when the soil was moist and drying conditions were not expected until all the N had dissolved. The fertilizer was hand-broadcast 10 to 14 d after emergence along the rows of each plot to ensure that N was evenly distributed. Acetochlor [2-chloro-*N*-(ethoxymethyl)-*N*-(2-ethyl-6methylphenyl)acetamide] was applied at a rate of 2.7 kg a.i. ha^{-1}. A postemergence herbicide, glyphosate, was applied at a rate of 1.2 kg a.e. ha^{-1} at the V6 stage (collar of the sixth leaf visible). 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 days to 50% silking (DTS), plant height, and physiological measurements. Plant height was recorded from tagged plants at dent stage by measuring the height from the ground surface to the tip of the tassels. Physiological measurements such as leaf chlorophyll index were measured using a soil plant analysis development chlorophyll meter (Model 502, Minolta Corp.). Readings were taken at five growth stages. At V7 (collar of the seventh leaf visible), readings were taken from the uppermost fully expanded middle portion of leaves from 10 different plants in each plot and averaged to one value per plot. At growth stages R1 (silking) through to R4 (dough), the ear leaf was used to measure the leaf chlorophyll index. Two representative plants were tagged at growth stage VT (tassel), R1 (silking), and R2 (blister) in each plot within each replication to measure gas exchange from 1100 to 1500 h on a clear day. After a steady state of gas exchange had been achieved, photosynthetic rate, intercellular CO_2 concentration (C_i), and stomatal conductance were measured using a handheld photosynthesis system (CI-340, CID Bio-Science) in an open system configuration. The chamber was connected directly to a CO_2 or H_2O differential gas analyzer (CI-340, CID Bio-Science).

The aboveground portion of 10 plants of the nonyield row from each maize plot were randomly sampled at physiological maturity. 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 Thomas-Wiley laboratory mill (Model 4, Thomas Scientific,) to pass through a 2.0-mm screen. The cobs were threshed in a stationary maize sheller (Model LDB, ALAMACO) and the grain was ground in a cyclone sample mill (Model 3010–030, Udy Corp.). Nitrogen concentration was analyzed by wet digesting samples with H_2SO_4 and H_2O_2. The total N in the digestion was analyzed by a colorimetric procedure (nitroprusside–sodium hypochlorite) using an RFA autoanalyzer (Alpkem Co.) (Combs and Nathan, 1988).

Plots planted to maize were mechanically harvested after physiological maturity using a modified two-row gleaner equipped with a weighing balance (Hege Plot Combine, Wintersteiger Inc.). Grain moisture and test weight were estimated with a GAC 2000 moisture meter (DICKEY–John Corp.). Yield was adjusted to 155 g kg^{-1} moisture content. Dried kernels per plant were counted with the aid of a Seedburo seed counter (Model 77, Inpack Systems).

Components of Nitrogen Use Calculations

Nitrogen use calculations were completed with 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, $\text{DM}_{\text{aboveground}}$ indicates aboveground dry matter, and $[N]_{\text{DM}}$ 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, $\text{DM}_{\text{aboveground}}$ indicates aboveground dry matter, and $[C]_{\text{DM}}$ 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 $\text{NUptake}_{\text{total}}$ 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, $\text{NUptake}_{\text{grain}}$ is the grain N uptake, and $\text{NUptake}_{\text{total}}$ is the total N uptake.

Fertilizer N replacements values were calculated following a procedure described by (Hesterman et al., 1992). Response of grain sorghum to urea-N was fitted to a linear model for each site and year. The intercept (yield of maize after fallow with no N) and slope (response of the maize to fertilizer N) of the model were used to estimate FNRV using

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

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

Economic Analyses

The economic analyses were based on statistically significant treatments of the experiment to determine which cropping systems gave acceptable net returns to producers (CIMMYT, 1988). Economic analyses were performed using current market prices (National Agricultural Statistics Service, 2013) for inputs at planting and for output at the time of harvest. All costs and benefits were calculated on a per-hectare basis in U.S. dollars (US\$). For the economic analyses, the mean grain yield of maize is the average yield of each treatment across years and sites. The revenue is the product of maize price and mean yield for each treatment. Total variable costs (*TVC*) is the sum of the costs for fertilizer and application, herbicides and application, seed, harvesting, and hauling cost. The net return (*NR*) for each is the difference between the revenue and the total variable costs. For each treatment, the 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 between Treatments 1 and 2 was generated by

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

where ΔNR is the change in net return ($\text{NR}_2 - \text{NR}_1$) and ΔTVC is the change in total variable costs ($\text{TVC}_2 - \text{TVC}_1$). Thus a MRR of 100% implies a return of US\$1 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 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 systems, site, and all interactions. Year, cropping system, and site were treated as fixed effects and block as a random effect. Leaf chlorophyll index, photosynthetic rate, stomatal conductance, transpiration rate, and C_i data were analyzed using the average value across all growth stages. Mean separation for significant effects was performed using Tukey's honestly significant difference test at $P < 0.05$. Regression analyses were based on individual plot data.

A quadratic model was used to describe the grain yield response to fertilizer N rates for both years by using regression analyses to compare the response of maize and grain sorghum to fertilizer N rates. The model is defined as: $y = aX + bX^2 + c$, 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. All regression responses were tested with linear, quadratic, linear plateau, and quadratic plateau models and were fitted to the model that had the lowest RMSE and the highest r^2 and best fitted the bias for the response.

RESULTS

Weather Conditions and Soil Test Results

Daily maximum and minimum temperatures and rainfall throughout the growing season (April to October) were obtained from the KSU digital weather data library. The amount and distribution of rainfall differed among the study years. Total rainfall during the growing season was greater in 2014 (576 mm) than in 2013 (539 mm) and the least rain fell in 2012 (338), although it was well distributed in 2013. Monthly mean daily maximum and minimum temperatures during the season did not vary greatly between 2013 and 2014. In contrast, the daily maximum temperature in July in 2012 was 4.6°C above the 30-yr average. The maximum air temperature during the early growing season (April) ranged from 16 to 22°C; in the middle of the season (June–July), temperatures peaked at up to 22 to 31°C; at the end of the growing seasons (August–October), it was around 20 to 33°C.

The results of the soil analyses presented in Table 1 show considerable differences in textural and chemical soil properties between the two experimental sites. The soil organic matter content of most agricultural soils in Kansas is 1 to 5%, with an average of 2.2% (Leikam et al., 2003). Soil organic matter is 5% N (Leikam et al., 2003). The soil at ABS consisted of >50% sand and <1% soil organic matter. At ANF, the soil consisted of <20% sand and >2.5% soil organic matter. Soil NH_4–N and NO_3–N were greater at ANF in both years. Soil test results from the sites were likely to have influenced the maize response to fertilizer N following cover crops and double-cropped grain crops (soybean and grain sorghum).

Cover Crop Dry Matter Yield and Carbon and Nitrogen Uptake

No significant three-way interactions were observed between site, year, and cropping system for all traits measured 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 the double-cropped grain crops' performance depended on year, it was similar at both sites.

The response of summer crops varied within year and was significant for aboveground biomass, plant C content, plant N content, and C/N ratio (Fig. 1). Pigeonpea had greater aboveground biomass than cowpea but there was no difference between sunn hemp and double-cropped grain sorghum after wheat in 2012. In 2013, sunn hemp had the greatest aboveground biomass and cowpea, pigeonpea, and double-cropped grain sorghum had similar aboveground biomass. The least aboveground biomass was observed in soybean in both years (Fig. 1a).

Carbon uptake was greater in 2012 than in 2013 for all cover crops and double-cropped grain crops (Fig. 1b). Double-cropped grain sorghum had greater C uptake than pigeonpea in 2012. Sunn hemp and double-cropped soybean had similar C uptake in 2012. Cowpea had the least C uptake in 2012. In 2013, double-cropped grain sorghum had the greatest C uptake, followed by sunn hemp. Carbon uptake was similar for cowpea, pigeon pea, and soybean in 2013 (Fig. 1b).

Pigeonpea had greater aboveground plant N uptake than cowpea, sunn hemp, and double-cropped soybean, but plant N uptake was least for double-cropped grain sorghum in 2012 (Fig. 1c). Similar trends were observed among summer cover crops and double-cropped soybean and double–cropped grain sorghum in 2013 (Fig. 1c). In 2013, the cover crops and double-cropped soybean had a similar C/N ratio but that for double-cropped grain sorghum was greater. In 2014, sunn hemp had a greater C/N ratio than cowpea, pigeonpea, and double-cropped soybean. Double-cropped grain sorghum again had the greatest C/N ratio of the summer crops in 2014. When averaged across years, the C/N ratio was greatest for grain sorghum (29:1); summer cover crops and double-cropped soybean averaged 19:1 (Fig. 1d).

Physiological Traits of Maize

The response of maize to cropping system differed within years and affected the leaf chlorophyll index and photosynthetic rate (Fig. 2a and 2b). The maize leaf chlorophyll index in the cover crop systems and in the double-cropped soybean system was similar to that 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. 2a). Leaf chlorophyll index increased linearly with increasing fertilizer N application in 2013 ($R^2 = 0.96$, $P = 0.002$) and 2014 ($R^2 = 0.99$, $P = 0.0002$) (Fig. 2a).

In 2013, the photosynthetic rate of maize in the pigeonpea cropping system was greater than that of cowpea, sunn hemp, and double-cropped soybean systems. The fallow system with 0 kg N ha^{-1} and the double-cropped grain sorghum system had the lowest photosynthetic rate in 2013 (Fig. 2b). Photosynthetic rate was greater in the pigeonpea, sunn hemp, and double-cropped soybean systems than in the cowpea cropping system in 2014. The photosynthetic rate was lowest in double-cropped grain sorghum in 2014 (Fig. 2b). Photosynthetic rate responded linearly to N fertilizer application in 2013 ($R^2 = 0.90$, $P = 0.008$) and 2014 ($R^2 = 0.98$, $P = 0.001$) (Fig. 2b). In both years, the photosynthetic rate of maize in the cover crop systems and the double-cropped soybean system was similar to the fallow system with a N fertilizer application of 45 to 90 kg N ha^{-1} but was less than that for fallow systems with 135 kg N ha^{-1} or more.

Table 1. Physical and chemical characteristics of soil from the research sites for the 0- to 60- cm depth.

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
Organic matter, %	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}	5.50	5.50	2.30	4.50

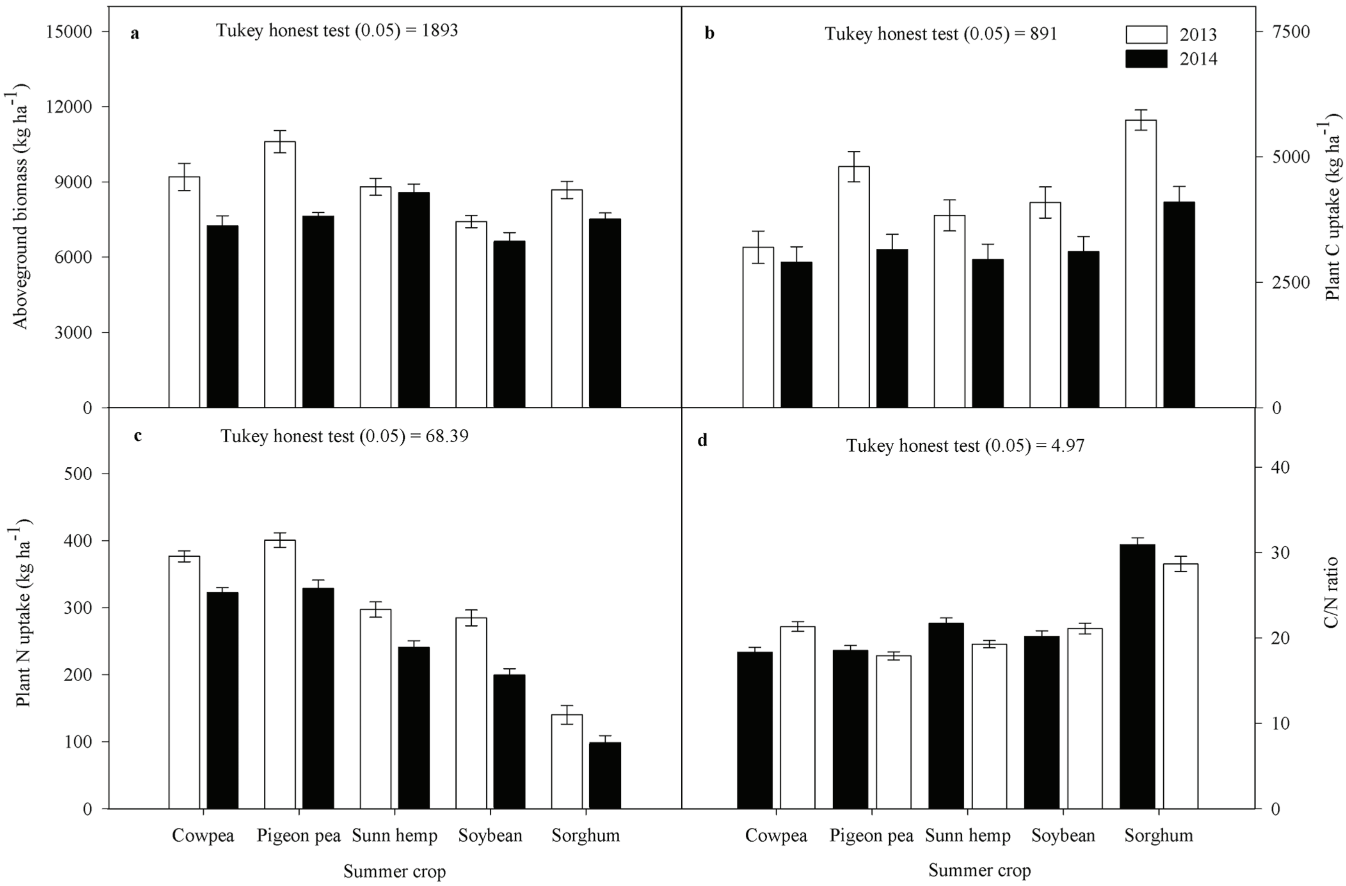

Fig. 1. Summer crop and year effects on (a) aboveground biomass, (b) plant C uptake, (c) plant N uptake, and (d) C/N ratio in maize in 2012 and 2013.

There was a significant effect of cropping system on stomatal conductance, transpiration rate, and C_i (Tables 2 and 3). 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 did not differ in stomatal conductance (Table 3).

Transpiration rate was greatest in the fallow system with 90 or 180 kg N ha^{-1}, followed by the fallow system with 135 kg N ha^{-1} (Table 3). Furthermore, transpiration rate was reasonably high for maize in the fallow system with 45 kg N ha^{-1}, cowpea, and sunn hemp. Transpiration rate was lowest in the fallow system with 0 kg N ha^{-1} and the cropping systems with pigeonpea, double-cropped soybean, and double-cropped grain sorghum (Table 3). Maize in the fallow system with 0 kg N ha^{-1} had the greatest C_i, but C_i was similar for maize in the fallow systems with a N fertilizer application of 90 to 180 kg N ha^{-1} and in the cowpea, pigeonpea, and double-cropped grain sorghum 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 systems (Table 3).

Phenology and Growth Traits of Maize

Cropping system had a significant effect on maize DTS and plant height (Table 3). For maize in the fallow systems with >90 kg N ha^{-1}, DTS was shorter than that for maize in the fallow system with 45 kg N ha^{-1}. Days to 50% silking ranged from 58 to 61 d among the cropping systems receiving fertilizer N applications. Maize with any of the cover crops and the double-cropped soybean systems had similar DTS but DTS in the fallow system with 0 kg N ha^{-1} and double-cropped grain sorghum was longer compared to the fallow systems with fertilizer N.

The plant height at the R5 stage (dent) was 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 with 45 and 90 kg N ha^{-1}, pigeonpea, and double-cropped soybean cropping systems. Maize plant height was shorter in the fallow system with 0 kg N ha^{-1} and in the double-cropped grain sorghum system (Table 3).

The response of maize to cropping system differed by year (Table 2) for aboveground biomass at physiological maturity. In 2013, the aboveground biomass of maize at physiological maturity in the cowpea and pigeonpea cropping systems was greater than that in the sunn hemp and double-cropped soybean systems (Fig. 2c). In 2014, aboveground biomass was similar in the cowpea, pigeonpea, and sunn hemp cropping systems. The aboveground biomass with the double-cropped soybean system was greater than that of the double-cropped grain sorghum system in 2014 (Fig. 2c).

There was a quadratic response of maize aboveground biomass at physiological maturity to fertilizer N in both years (2013: $y = -0.182x^2 + 74.99x + 9374$, $R^2 = 0.0093$, $P = 0.033$) and in (2014: $y = -0.198x^2 + 81.45x + 9718$, $R^2 = 0.98$, $P = 0.006$) (Fig. 2c). In both years, aboveground biomass at physiological maturity in the various cover crop systems and in the double-cropped soybean cropping system was similar to that in the fallow system with 45 kg N ha^{-1}.

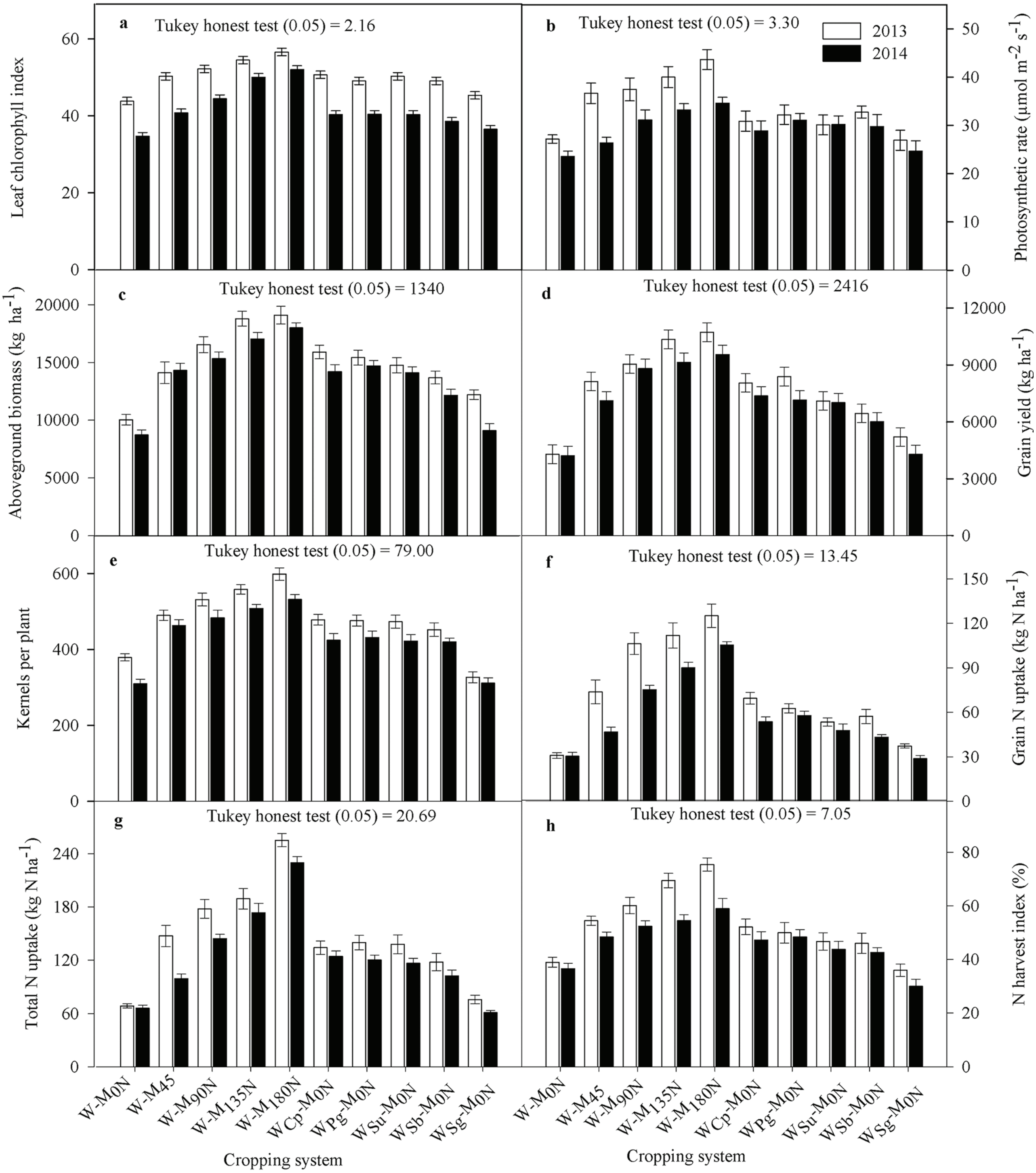

Fig. 2. Cropping system and year effects on (a) leaf chlorophyll content, (b) photosynthetic rate, (c) aboveground biomass at physiological maturity, (d) grain yield, (e) kernels per plant, (f) grain N uptake, (g) total N uptake at physiological maturity, and (h) N harvest index of maize grown in 2013 and 2014 averaged across sites.

Components of Yield and Grain Yield

The response of maize to cropping system varied by year and affected grain yield and kernels per plant (Fig. 2d and 2e). Grain yield was greater in 2013 than in 2014. Grain yield in the pigeonpea cropping system was greater than the cowpea, sunn hemp, and double-cropped soybean system in 2013. Grain yield of maize in the fallow system with 0 kg N ha^{-1} and double-cropped grain sorghum were the lowest in 2013 (Fig. 2d). In 2014, the grain yield of maize in the various cover crop systems was greater than that in the double-cropped soybean system (Fig. 2d). The double-cropped grain sorghum cropping system had the lowest grain yield in 2014. There was a quadratic response of grain yield to fertilizer N application in 2013 (R^2 = 0.97, P = 0.025) and in 2014 (R^2 = 0.98; P = 0.013). Grain yield in the various cover crop and double–cropped soybean cropping systems was similar to that in the fallow system with 45 kg N ha^{-1} in both years (Fig. 2d).

The number of kernels per plant in the cover crop and double-cropped soybean cropping systems was similar to maize in the fallow system with 45 kg N ha^{-1} in 2013 (Fig. 2e). Maize in the

Table 2. Significance of main effects of site (S), year (Y), and cropping system (CS) and their interactions from the ANOVA for the effect of cropping system on summer crop growth, physiological traits, grain yield, and yield components of maize grown in 2013 and 2014.

Parameter†	S	Y	CS	S × Y	S × CS	Y × CS	S × Y × CS
			Summer crop				
CBM	ns	***	***	***	ns	***	ns
CTN	ns	*	***	ns	ns	***	ns
CTC	ns	***	**	***	ns	***	ns
C/N	*	***	***	ns	*	*	ns
			Maize				
DTS	ns	ns	*	ns	ns	ns	ns
Pn	ns	***	ns	ns	*	***	ns
E	*	***	***	***	*	ns	ns
g_s	ns	***	***	***	ns	ns	ns
C_i	ns	***	*	***	ns	ns	ns
SPAD	***	***	***	***	*	*	ns
PHT	**	**	***	***	ns	ns	ns
BM	ns	ns	***	*	ns	*	ns
GY	ns	***	***	*	**	***	ns
KN	*	ns	***	**	ns	*	ns
HKW	**	***	***	**	ns	ns	ns
BMN	ns	ns	**	**	*	ns	ns
GRN	ns	**	***	ns	**	**	ns
TN	ns	**	***	***	***	*	ns
NHI	ns	**	***	***	*	*	ns
NUE	ns	ns	***	*	***	ns	ns

* Significantly different at $P = 0.05$.

** Significantly different at $P = 0.01$.

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

† CBM, cover crop aboveground biomass; CTN, cover crop aboveground N uptake; CTC, cover crop aboveground C uptake; C/N, C/N ratio; DTS, days to 50% silking; 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 N uptake; NUE, N use efficiency; NHI, N harvest index; ns, not significant.

double-cropped grain sorghum system had the fewest kernels per plant in 2013. In 2014, kernels per plant followed trends similar to those observed in 2013. There was a linear response of kernels per plant to fertilizer N application in 2013 ($y = 1.118x + 383.2$, $R^2 = 0.99$, $P = 0.0002$). In contrast, there was a quadratic response of kernels per plant in 2014 ($y = -0.004x^2 + 1.368x + 452.4$, $R^2 = 0.097$, $P = 0.013$). Overall, the number of kernels per plant was greater in 2013 than in 2014 (Fig. 2e).

Cropping system ($P < 0.05$) affected 100-kernel weight (HKW) (Tables 2 and 3). The fallow system with 135 and 180 kg N ha^{-1} had the greatest HKW. Hundred-kernel weight in the various cover crop systems and the double-cropped soybean system was similar to that with 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 caused by a lack of any N contribution in the system.

Table 3. Cropping system means averaged across site and years for stomatal conductance (g_s), transpiration rate (*E*), intercellular CO_2 concentration (C_i), days to 50% silking (DTS), plant height (PHT), and 100-kernel weight (HKW) of maize grown in 2013 and 2014.

Cropping system†	g_s	*E*	C_i	DTS	PHT	HKW
	mmol m^{-2} s^{-1}		µmol mol^{-1}	d	cm	g
W–M_{0N}	216.0 a‡	6.05 de	274.8 a	77 d	185.5 e	25.09 e
W–M_{45N}	192.9 bc	6.78 cd	182.3 d	60 b	212.1 bcd	28.32 c
W–M_{90N}	245.6 ab	8.02 ab	197.4 bcd	58 a	201.06 d	28.63 bc
W–M_{135N}	231.8 abc	7.16 bc	197.7 bcd	59 a	212.1 bcd	30.84 a
W–M_{180N}	255.8 a	8.09 a	221.5 bc	59 a	225.4 a	30.77 ab
W_{Cp}–M_{0N}	238.0 ab	7.06 c	188.6 cd	62 bc	216.8 ab	27.74 cd
W_{Pg}–M_{0N}	217.5 abc	6.19 de	195.6 bcd	62 bc	212.5 abcd	28.41 c
W_{Su}–M_{0N}	226.2 abc	6.72 cde	175.0 d	64 bc	215.1 abc	27.67 cd
W_{Sb}–M_{0N}	255.7 a	6.00 de	169.1 d	62 bc	211.6 bcd	27.13 cde
W_{Sg}–M_{0N}	173.3 c	5.86 e	226.3 b	77 d	203.1 cd	27.72 e

† WM_{0N}, wheat rotated with maize plus 0 kg N ha^{-1}; W–M_{45}, wheat rotated with maize plus 45 kg N ha^{-1}; W–M_{90}, wheat rotated with maize plus 90 kg N ha^{-1}; W–M_{135}, wheat rotated with maize plus 135 kg N ha^{-1}; W–M_{180}, wheat rotated with maize plus 180 kg N ha^{-1}; W_{Cp}–M_{0N}, cowpea rotated with maize after wheat; W_{Pg}–M_{0N}, pigeonpea rotated with maize after wheat; W_{Su}–M_{0N}, sunn hemp rotated with maize after wheat; W_{Sb}–M_{0N}, double-cropped soybean rotated with maize after wheat; W_{Sg}–M_{0N}, double-cropped grain sorghum rotated with maize after wheat.

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

Nitrogen Uptake and Components of Nitrogen Use

The response of maize to cropping system differed by year for grain N uptake, total N uptake, and NHI (Fig. 2f–2h). Maize in the cowpea cropping system had the greatest grain N uptake in 2013 but grain N uptake did not differ in the pigeonpea 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. 2f) in 2013. Grain N uptake in the pigeonpea system was greater than that in the cowpea, sunn hemp, and double-cropped soybean systems in 2014. In both years, the lowest level of 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 levels similar to those of the fallow system with 45 kg N ha^{-1} but less than that for 90 kg N ha^{-1} in both years (Fig. 2f). Grain N uptake in 2013 had a quadratic ($y = -0.002x^2 + 1.012x + 31.81$, $R^2 = 0.99$, $P = 0.004$) response to fertilizer N application. In contrast, grain N uptake increased linearly with increasing N fertilizer application ($y = 0.429x + 30.92$, $R^2 = 0.98$, $P = 0.001$) in 2014.

Total N uptake by maize was similar in the various cover crop systems in 2013, but was greater in the double-cropped soybean system than in the double-cropped grain sorghum system. Similar trends were observed for total N uptake in 2014. Total N uptake increased with increasing fertilizer N in both years ($y = 0.907x + 73.41$, $R^2 = 0.096$, $P = 0.002$) (Fig. 2g). In both years, total N uptake for all the cover crop systems and the double-cropped soybean system was similar to that in the fallow system with 45 kg N ha^{-1} but was less than that for fallow systems with 90 kg N ha^{-1} or more.

In 2013, NHI was similar in the cowpea and pigeonpea cropping systems but there was no difference between the sunn hemp and double-cropped soybean systems. The smallest NHI was found in the double-cropped grain sorghum system (Fig. 2h). Similar trends were found for NHI in 2014. Nitrogen harvest index had a quadratic ($y = -3.661 \times 10^{-4}x^2 + 0.142x + 41.63$, $R^2 = 0.097$, $P = 0.011$) response to fertilizer N rate in both years. Over the years, all of the cover crop systems and the double-cropped soybean system had a NHI equivalent to that of the fallow systems with 45 to 90 kg N ha^{-1} but was less than that for the fallow systems with 135 and 180 kg N ha^{-1}.

Site × Cropping System Interaction

The response of maize to cropping systems differed by site (Table 2) for leaf chlorophyll index, photosynthetic rate, and grain yield. At ABS, leaf chlorophyll index in the cover crop systems and double-cropped soybean system was similar to that in the fallow system with 45 kg N ha^{-1} but was less than that for the fallow system with 90 kg N ha^{-1} or more (Fig. 3a). Leaf chlorophyll index was lowest in the double-cropped grain sorghum cropping system. Similar trends for leaf chlorophyll index were observed at ANF (Fig. 3a). Leaf chlorophyll index increased linearly with increasing fertilizer N application ($y = 0.085x + 35.11$, $R^2 = 0.85$, $P = 0.0016$).

At ABS, the photosynthetic rate was greater for maize in the pigeonpea cropping system than in the cowpea, sunn hemp, and double-cropped soybean systems (Fig. 3b). Maize in the double-cropped grain sorghum system had the lowest photosynthetic rate at ABS. At ANF, maize in all of the cover crop systems and the double-cropped soybean system had similar photosynthetic rates. The photosynthetic rate of maize in the double-cropped grain sorghum cropping system was the least. Photosynthetic rate responded linearly ($y = 0.109x + 22.73$, $R^2 = 0.99$, $P = 0.0003$) to fertilizer N application across years and sites. Moreover, maize in all cover crop systems and the double-cropped soybean 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 pigeonpea systems at ABS had greater grain yield than that in the sunn hemp and double-cropped soybean systems. At ANF, the grain yield of the cowpea and pigeonpea cropping systems was similar. At ANF, the 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. 3c). Grain yield in the fallow systems had a quadratic response to fertilizer N application at both sites ($y = -0.0170x^2 + 63.58x + 3642$, $R^2 = 0.99$, $P = 0.001$). Grain yield in the cropping systems with all cover crops and the double-cropped soybean system was comparable to that in the fallow system with 45 kg N ha^{-1}.

The response of maize to cropping systems varied with site for aboveground N uptake, grain N uptake, total N uptake, NHI, and NUE. Maize in the double-cropped soybean system had the greatest aboveground N uptake compared with the maize in all cover crop systems at ABS (Fig. 3d). At ANF, maize in the cowpea system had the greatest aboveground N uptake. Aboveground biomass N uptake was similar in the pigeonpea 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. 3d). Aboveground biomass N uptake at both sites responded linearly to N fertilizer application ($R^2 = 0.96$, $P = 0.002$). All cover crop systems and the double-cropped soybean system had aboveground N uptake levels similar to the fallow systems with 45 to 135 kg N ha^{-1}.

At ABS, maize in the cowpea and pigeonpea cropping systems had more grain N uptake compared with the sunn hemp and double-cropped soybean systems (Fig. 3e). 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. 3e). There was a linear response of grain N uptake to fertilizer N rate ($y = 0.425x + 38.42$, $R^2 = 0.88$, $P = 0.0018$) at ABS and ($y = 0.571x + 35.12$, $R^2 = 0.99$, $P = 0.0003$). At both sites, maize in all the cover crops systems and the double-cropped soybean system had grain N uptake levels equivalent to that in the fallow system with 45 kg N ha^{-1} but was less than that in the fallow system with 90 kg N ha^{-1} or more.

Total N uptake was greater at ABS than at ANF. The total N uptake for maize in all cover crop systems and the double-cropped soybean system was similar to that in the fallow system with 45 kg N ha^{-1} at ABS. Similar trends were observed at ANF for total N uptake (Fig. 3f). Total N uptake increased with increasing N fertilizer application

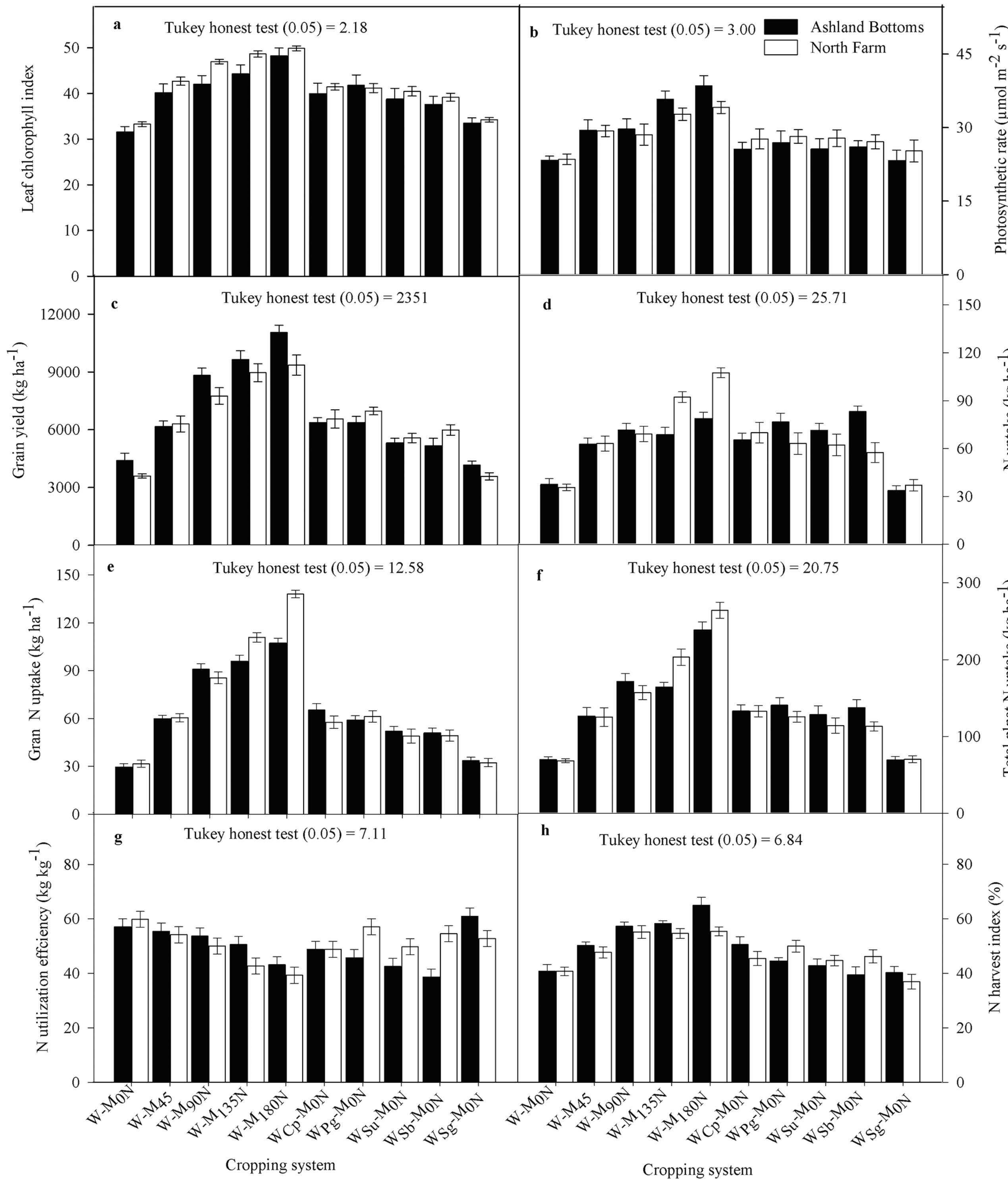

Fig. 3. Cropping system and site effects on (a) leaf chlorophyll content, (b) photosynthetic rate, (c) grain yield, (d) N uptake, (e) grain N uptake, (f) total N uptake, (g) N use efficiency, and (h) N harvest index of maize grown in two sites, averaged across years.

(ABS: $R^2 = 0.98$, $P = 0.0004$; ANF: $r^2 = 0.93$, $p = 0.004$). 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 greatest NUE among the systems at ABS. Maize in the pigeonpea, double-cropped soybean, and double-cropped grain sorghum systems had similar NUE levels to the cowpea and sunn hemp systems at ANF (Fig. 3g). Nitrogen use efficiency decreased linearly ($R^2 = 0.93$, $P = 0.005$) with increasing N application at both sites (Fig. 3g). All cover crop systems and the grain crop systems had NUE levels that were similar to those of the fallow systems with 0 to 180 kg N ha^{-1}.

Maize in the cowpea cropping system had the greatest NHI and this was similar to that in the pigeonpea and sunn hemp cropping systems in ABS. Furthermore, NHI in the double-cropped soybean system was greater than that in the double-cropped grain sorghum cropping system at ABS. At ANF, maize in the pigeonpea cropping system had greater NHI than maize in the cowpea, sunn hemp, and double-cropped soybean systems (Fig. 3h). The double-cropped grain sorghum system had the lowest NHI and this value was similar to that of the fallow system with 0 kg N ha^{-1}. Nitrogen harvest index increased linearly with increasing fertilizer N rates at both sites (R^2 = 0.97, P = 0.0009). Overall, NHI for all the cover crop systems and the double-cropped soybean system was similar to that of maize in the fallow system with 45 kg N ha^{-1} at both sites but was less than that for fallow systems with 90 kg N ha^{-1} or more (Fig. 3h).

Relationship among Physiological Traits and Grain Yield

There was a linear relationship between photosynthetic rate and leaf chlorophyll index, leaf N uptake, stomatal conductance, and C_i (Fig. 4a–4d). Stomatal conductance accounted for more of the variability associated with photosynthetic rate than other physiological traits (Fig. 4a–4d) and photosynthetic rate, leaf chlorophyll index, and leaf N uptake were influenced by fertilizer N rates (Fig. 4a–4d). Linear relationships were also observed between grain yield and leaf chlorophyll, aboveground biomass, kernels per plant, and HKW (Fig. 4). All of these parameters were affected by fertilizer N rate (Fig. 4e–4h). Aboveground biomass explained more of the variability observed in grain yield than did leaf chlorophyll index, kernels per plant, or HKW.

Comparison of Maize and Sorghum Response to N Fertilizer

Nitrogen fertilizer effects were highly significant for both maize and grain sorghum. Grain yield increased as the N fertilizer level increased. Maize grain yield increased from 4320 kg ha^{-1} in the nonfertilized treatment to 10,390 kg ha^{-1} with 180 kg N ha^{-1}; grain sorghum increased from 3900 kg ha^{-1} to 8340 kg ha^{-1} respectively (Fig. 5). The grain yield of maize and grain sorghum at 180 kg N ha^{-1} were 154 and 114% greater, respectively, than the nonfertilized treatments. Both maize and grain sorghum had quadratic responses to increasing fertilizer N rates.

Fertilizer N replacement values 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} (Fig. 5a and 5b) when maize was the test crop. In contrast, the FNRV of double-cropped grain sorghum in 2013 was –8.9 kg N ha^{-1}; in 2014, the value was –0.61 kg N ha^{-1}. Compared with grain sorghum, FNRV 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 kg N ha^{-1} (Fig. 5c and 5d). The FNRV for double-cropped grain sorghum was –2.7 kg N ha^{-1} in 2013; in 2014, the value was –2.2 kg N ha^{-1}. In both years and for both maize and grain sorghum, the cropping system with pigeonpea had the greatest FNRV. The estimated economic maximum grain yields of maize and grain sorghum occurred at 135 kg N ha^{-1} and 90 kg N ha^{-1}, respectively.

Economic Analyses

The results of the economic analyses are presented in Tables 4 and 5. Maize in the fallow plots with N fertilizer application had positive gross returns averaged across years. The marginal rate of return was greatest with fallow and 0 to 135 kg N ha^{-1} (Table 4). Among the cover and double-cropping systems, 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 produced a negative economic net return (Table 5).

DISCUSSION

The response of maize to N fertilizer application and various cover crops varied for all measured traits. The summer cover crops and double-cropped grain crops varied in their contribution to the amount of aboveground biomass produced in both years. Pigeonpea had the greatest aboveground biomass, which was most closely associated with high plant C uptake and plant N uptake compared with cowpea and sunn hemp. This agrees with Tegegne et al. (2012), who reported that pigeonpea produced more 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 the silking and grain-filling periods. In 2014, a long dry period with high temperatures occurred during the silking and grain-filling stages of maize. Reproductive processes in maize are highly sensitive to high temperature stress (>32°C) (Ciampitti and Vyn, 2011). The most sensitive stages in maize are the 14 d before and after 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 greater yields in 2013 than 2014. High temperature stress can directly affect grain yield by influencing the kernel-filling duration and rate, both of which are highly sensitive to high temperature stress (Uribelarrea et al., 2002). Kernels per plant 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. Nitrogen plays a key role in several crop physiological processes and increased N levels were associated with greater photosynthetic rate and leaf chlorophyll index. These findings are in agreement with those of other researchers (Tóth et al., 2002; Li et al., 2012). 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. The 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. 2).

The importance of N fertilizer in improving soil fertility status and sustainable maize production was demonstrated clearly in the increased grain yield across site years in this study. Grain yield and biomass were greatest in the maize fallow system with 180 kg N ha^{-1}, followed by the systems with 135 and 90 kg N ha^{-1} (Fig. 2). Inclusion of cowpea, pigeonpea, sunn hemp, double-cropped soybean, and double-cropped grain

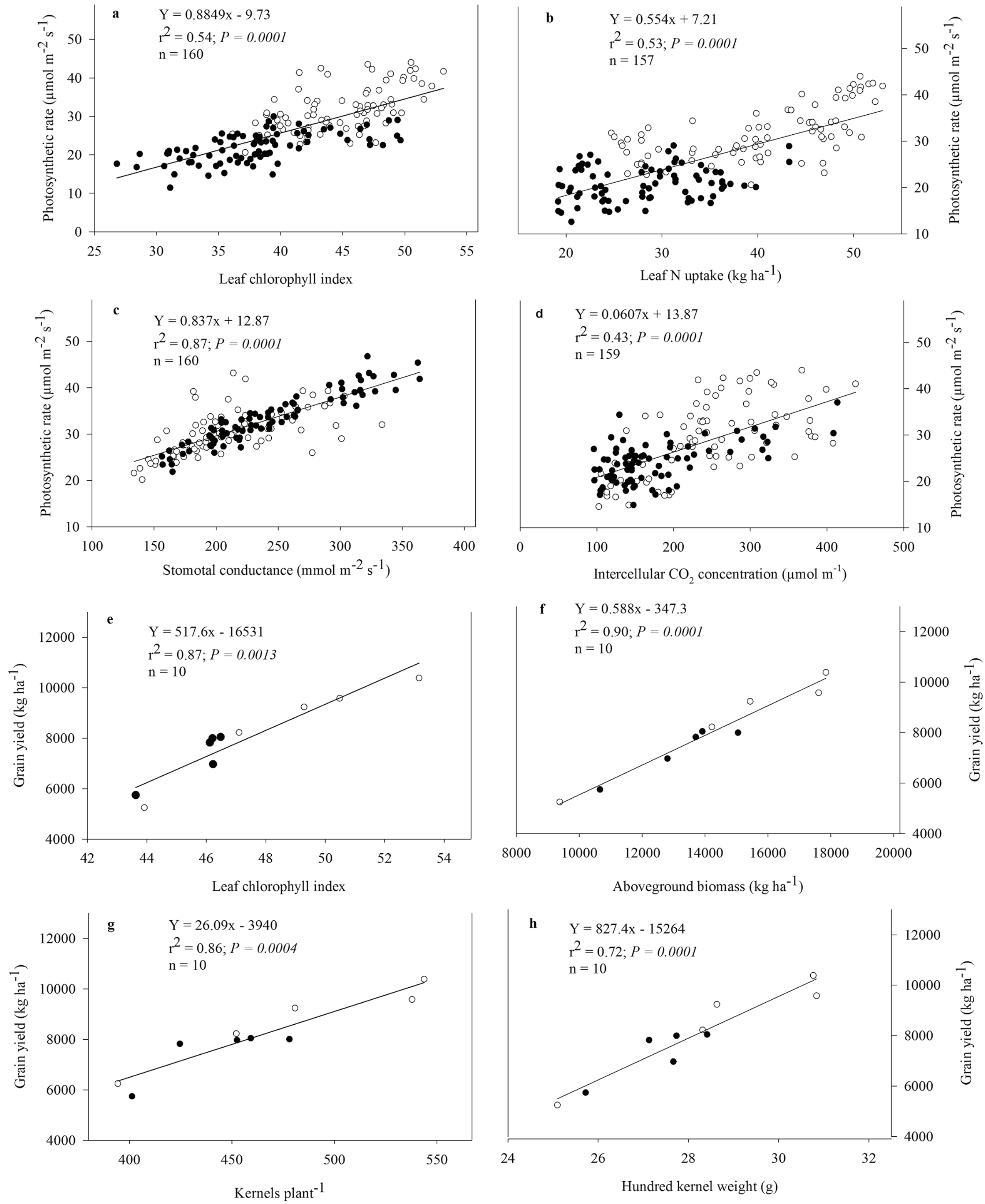

Fig. 4. Relationships between photosynthetic rate and (a) leaf chlorophyll index, (b) leaf N uptake, (c) stomatal conductance, and (d) intercellular CO_2 concentration of maize and the relationships between grain yield and (e) leaf chlorophyll index, (f) aboveground biomass at physiological maturity, (g) kernels per plant, and (h) 100-kernel weight of maize, averaged across sites and years.

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. 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 uptake and grain yield of maize.

Across years and locations, the mean FNRV for maize following cowpea, pigeonpea, sunn hemp, double-cropped

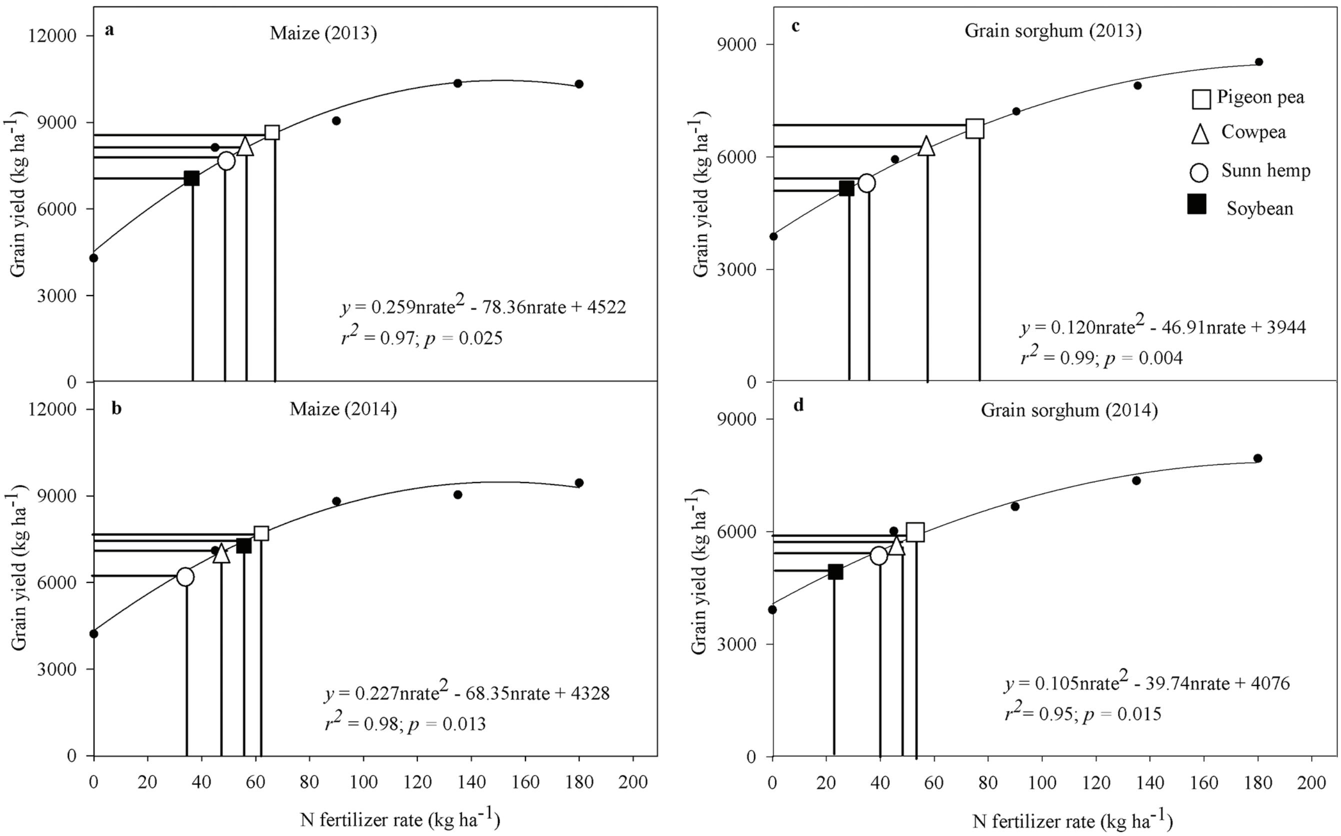

Fig. 5. Fertilizer N replacement value of summer leguminous cover crops and double-cropped soybean of (a) maize in 2013 averaged across sites, (b) maize in 2014 averaged across sites, (c) grain sorghum in 2013 averaged across sites, and (d) grain sorghum in 2014 averaged across sites.

soybean, and double-cropped grain sorghum years was 53, 64, 43, 47, and −5 kg N ha^{-1}, respectively (Fig. 5a and 5b). In comparison, the FNRVs for grain sorghum were 53, 64, 36, 27, and −3 kg N ha^{-1}, respectively (Fig. 5c and 5d). In our research, the response to fertilizer N rates was greater for maize than for grain sorghum (Fig. 5). Balkcom and Reeves (2005) determined that the FNRV of sunn hemp to a following maize crop averaged 58 kg N ha^{-1} under conventional tillage in Alabama. Although both maize and sorghum are C_4 plants, maize is physiologically more efficient at using N (more yield per unit N uptake) 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 use in maize than in other cereals, and the genetic gains in maize have been more pronounced than in other cereals grains (Ciampitti and Vyn, 2012).

There was a positive linear association between leaf chlorophyll index and grain yield and between grain yield and photosynthetic rate, demonstrating that chlorophyll index and photosynthetic rate are associated with grain yield determination. 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 to the photosynthetic rate of cereal crops. Nitrogen harvest index represents the increased capacity of cereals to mobilize and translocate N from leaves and stems to grain. In this study, NHI increased with increasing N fertilizer application. This is consistent with other studies in maize (Mason and D'croz-Mason, 2002; Caviglia et al., 2014) that have indicated improved NHI with increasing N application.

Kernels per plant was a more important component of grain yield than HKW 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 (*Oryza sativa* L.) and wheat] and grain legumes [soybean and peanut (*Arachis hypogaea* L.)], yield variation among environments is more closely associated with grain number than other physiological or reproductive traits.

Economic analysis showed that fallow with 180 kg N ha^{-1} added to the cost of production but did not add to grain yield. This is demonstrated by the fact that the main effect of increasing the N level from 135 to 180 kg N ha^{-1} resulted in a corresponding increase in grain yield, but the increase did not merit the extra cost to producers. As a guide, a MRR of below 100% is considered low and unacceptable to producers (CIMMYT, 1988). This is because such a return would not offset the cost of capital and other related transactions cost while still giving an attractive profit margin to serve as an incentive. Maize in fallow with 135 kg N ha^{-1} gave the maximum economic grain yield and a profitable net return.

Double-cropped soybean and double-cropped grain sorghum after wheat increased 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

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

Variable	0 kg ha^{-1}	45 kg ha^{-1}	90 kg ha^{-1}	135 kg ha^{-1}	180 kg ha^{-1}
Gross return					
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 return, US$ ha^{-1}	803.60	1118.00	1453.00	1913.00	2044.00
Variable input costs, US$ ha^{-1}					
Seed	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
Herbicide	113.70	113.70	113.70	113.70	113.70
Herbicide application	45.51	45.51	45.51	45.51	45.51
Hauling (US$ per 0.008 kg)	34.56	48.07	62.48	82.28	87.95
Total variable input costs	479.50	597.10	686.90	799.20	892.70
Net return, US$ ha^{-1}	324.00	520.60	765.80	1113.00	1152.00
Marginal rate of return, %	0.00	167.20	272.80	309.80	40.98

Wiatrak, 2010). Maize in a double-cropped soybean system gave the greatest economic net return compared with the double-cropped grain sorghum system and cover crop systems.

This research was conducted in Kansas where farmers use fertilizers for cereal grain crops. Similar research on estimating the value of summer cover crops and the potential to reduce or supplement the N requirement for maize or sorghum production in developing countries (particularly in Africa) where small-holder farmers rarely use fertilizer N due to high costs and unavailability will be critical and needed.

CONCLUSIONS

The maize hybrid DKC63-84 varied in its response to various summer crops and fertilizer N rates. Overall, pigeonpea had the greatest aboveground C and N uptake, whereas a fallow with N fertilizer application had the greatest grain yield and leaf chlorophyll index. The mean increase in grain yield as a result of the inclusion of cowpea, pigeonpea, 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 FNRV was greatest for pigeonpea. The summer crops were

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

Variable	Cowpea	Pigeonpea	Sunn hemp	Soybean	Sorghum
Harvested yield, kg ha^{-1}	–	–	–	2897	2549
Grain price, US$ kg^{-1}	–	–	–	0.411	0.176
Gross return, US$ ha^{-1}	–	–	–	1190.00	448.60
Variable costs (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
Herbicide	123.70	123.70	123.70	123.70	123.70
Herbicide application	45.51	45.51	45.51	45.51	45.51
Mowing or harvesting	32.15	32.15	32.15	66.19	20.47
Total variable costs (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 return, US$ ha^{-1}	1156.00	1206.00	977.80	968.00	709.00
Variable costs, US$ ha^{-1}					
Seed	215.70	215.70	215.70	215.70	215.70
Planting	38.40	38.40	38.40	38.40	38.40
Herbicide	123.70	123.70	123.70	123.70	123.70
Herbicide application	45.51	45.51	45.51	45.51	45.51
Harvesting	103.40	126.20	141.70	170.70	162.00
Hauling, US$ per 0.008 kg	49.74	51.88	42.05	41.67	30.52
Total variable costs, US$ ha^{-1}	576.40	601.30	607.00	635.60	615.80
Total variable costs (double-cropped + cover crops + maize), US$ ha^{-1}	921.3	1190.00	1270.00	1102.00	887.70
Total revenue (double-cropped + cover crops + maize), US$ ha^{-1}	1156.00	1206.00	977.80	2159.00	1158.00
Net return, US$ ha^{-1}	235.10	15.99	–292.60	1056.00	270.50

comparable to fallow with 45 to 90 kg N ha^{-1} but was less than that for fallow 135 kg N ha^{-1} or more for grain yield, leaf chlorophyll index, and components of N use. Kernels per plant was the most important factor influencing 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. Cover crops have the potential to reduce and/or supplement the fertilizer N requirement for maize production.

ACKNOWLEDGMENTS

Financial assistance from the former USAID Collaborative Research Support Programs of Sustainable Agricultural and Natural Resource Management, USAID Feed the Future Sustainable Intensification Innovation Lab (Grant no. AID-OAA-L-14-00006), and 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

Accoe, F., P. Boeckx, J. Busschaert, G. Hofman, and O. Van Cleemput. 2004. Gross N transformation rates and net N mineralization rates related to the C and N contents of soil organic matter fractions in grassland soils of different age. Soil Biol. Biochem. 36:2075–2087. doi:10.1016/j.soilbio.2004.06.006

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

Bidinger, F.R., and D.S. Raju. 2000. Mechanisms of adjustment by different pearl millet plant types to varying plant population densities. Crop Sci. 40:68–71. doi:10.2135/cropsci2000.40168x

Blanco-Canqui, H., M.M. Claassen, and D.R. Presley. 2012. Summer cover crops fix nitrogen, increase crop yield, and improve soil–crop relationships. Agron. J. 104:137–147. doi:10.2134/agronj2011.0240

Brown, J.R. 1997. Recommended chemical soil test procedure for the North Central region. North Central Regional Res. Publ. 221. Univ. of Missouri Exp. Stn., Columbia.

Caviglia, O.P., R.J.M. Melchiori, and V.O. Sadras. 2014. Nitrogen utilization efficiency in maize as affected by hybrid and N rate in late-sown crops. Field Crops Res. 168:27–37. doi:10.1016/j.fcr.2014.08.005

Chen, G., and P. Wiatrak. 2010. Soybean development and yield are influenced by planting date and environmental conditions in the southeastern Coastal Plain, United States. Agron. J. 102:1731–1737. doi:10.2134/agronj2010.0219

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

Ciampitti, I.A., and T.J. Vyn. 2011. A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. Field Crops Res. 121:2–18. doi:10.1016/j.fcr.2010.10.009

Ciampitti, I.A., and T.J. Vyn. 2012. Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review. Field Crops Res. 133:48–67. doi:10.1016/j.fcr.2012.03.008

Cicchino, M.J.I., M.R. Edreira, M. Uribelarrea, and M.E. Otegui. 2010. Heat stress in field-grown maize: Response of physiological determinants of grain yield. Crop Sci. 50:1438–1448. doi:10.2135/cropsci2009.10.0574

CIMMYT. 1988. Agronomic data to farmer recommendations: An economics training manual. Completely revised ed. CIMMYT, Mexico, DF.

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. North Central Region Res. Publ. 221 (revised). Missouri Agric. Exp. Stn., Columbia. p. 57–58.

Copeland, P.J., R.R. Allmaras, R.K. Crookston, and W.W. Nelson. 1993. Maize–soybean rotation effects on soil water depletion. Agron. J. 85:203–210. doi:10.2134/agronj1993.00021962008500020008x

Dagel, K.J., L.O. Shannon, and T.E. Schumacher. 2014. Improving soybean performance in the Northern Great Plains through the use of cover crops. Commun. Soil Sci. Plant Anal. 45:1369–1384. doi:10.1080/00103624.2014.884108

FAO. 2014. FAOSTAT: Food and agriculture commodities production, 2014. FAO, Rome. http://faostat3.fao.org/home/E (accessed 21 Aug. 2015).

Greenwood, D.J., G. Lemaire, G. Gosse, P. Cruz, A. Draycott, and J.T. Neetson. 1990. Decline in the percentage of N of C_3 and C_4 crops with increasing plant mass. Ann. Bot. 66:425–436.

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

Janke, R.R., M.M. Claassen, W.F. Heer, J. Jost, S. Freyenberger, and D. Norman. 2002. The use of winter annual legume cover crops in a wheat–grain sorghum rotation in South Central Kansas. J. Sustain. Agric. 20:69–88. doi:10.1300/J064v20n02_08

Kamara, A.Y., A. Menkir, B. Badu-Apraku, and O. Ibikunle. 2003. The influence of drought stress on growth, yield and yield components of selected maize genotypes. J. Agric. Sci. 141:43–50. doi:10.1017/S0021859603003423

Li, G., Z.S. Zhang, H.Y. Gao, P. Liu, S.T. Dong, and J.W. Zhang. 2012. Effects of nitrogen on photosynthetic characteristics of leaves from two different stay-green maize varieties at the grain-filling stage. Can. J. Plant Sci. 92:671–680. doi:10.4141/cjps2012-039

Liebman, M., R.L. 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

Leikam, D.F., R.E. Lamond, and D.B. Mengel. 2003. Soil test interpretations and fertilizer recommendations. MF-2586. Dep. of Agronomy, Kansas State Univ., Manhattan.

Mafongoya, P.L., A. Bationo, J. Kihara, and B.S. Waswa. 2006. Appropriate technologies to replenish soil fertility in southern Africa. Nutr. Cycling Agroecosyst. 76:137–151. doi:10.1007/s10705-006-9049-3

Mason, S., and N. D'croz-Mason. 2002. Agronomic practices influence maize grain quality. J. Crop Production. 5:75–91. doi:10.1300/J144v05n01_04

National Agricultural Statistics Service. 2013. Custom rates: Topeka, Kansas. USDA–NASS, Washington, DC.

Osei Bonsu, P., and J.Y. Asibuo. 2013. Rotational effects of legumes on maize yield. Int. J. Sci. Technol. Res. 2(4):222–227.

Reinbott, T.M., S.P. Conley, and D.G. Blevins. 2004. No-tillage corn and grain sorghum response to cover crop and nitrogen fertilization. Agron. J. 96:1158–1163. doi:10.2134/agronj2004.1158

Sainju, U.M., W.F. Whitehead, and B.P. Singh. 2005. Biculture legume–cereal cover crops for enhanced biomass yield and carbon and nitrogen. Agron. J. 97:1403–1412. doi:10.2134/agronj2004.0274

Sanginga, N., O. Lyasse, and B.B. Singh. 2000. Phosphorus use efficiency and nitrogen balance of cowpea breeding lines in a low P soil of the derived savanna zone in West Africa. Plant Soil 220:119–128. doi:10.1023/A:1004785720047

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

Schomberg, H.H., N.L. Martini, J.C. Diaz-Perez, S.C. Phatak, K.S. Balkcom, and H.L. Bhardwaj. 2007. Potential for using sunn hemp as a source of biomass and nitrogen for the Piedmont and Coastal Plains regions of the southeastern USA. Agron. J. 99:1448–1457. doi:10.2134/agronj2006.0294

Teasdale, J.R., A.A. Abdul-Baki, and Y.B. Park. 2008. Sweet corn production and efficiency of nitrogen use in high cover crop residue. Agron. Sustainable Dev. 28:559–565. doi:10.1051/agro:2008029

Tegegne, F., S.P. Singh, D. Duseja, E. Ekanem, and R. Bullock. 2012. Pigeon pea as a niche crop for small farmers. J. Food Distribution Res. 43:90–95.

Thomas, G.W. 1982. Exchangeable cations. In: A.L. Page et al. editors, Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI. p. 159–165.

Tollenaar, M., and E.A. Lee. 2011. Strategies for enhancing grain yield in maize. Plant Breed. Rev. 34:37–83.

Tóth, V.R., I. Mészáros, S. Veres, and J. Nagy. 2002. Effects of the available nitrogen on the photosynthetic activity and xanthophyll cycle pool of maize in field. J. Plant Physiol. 159:627–634. doi:10.1078/0176-1617-0640

Uribelarrea, M., J. Carcova, M.E. Otegui, and M.E. Westgate. 2002. Pollen production, pollination dynamics, and kernel set in maize. Crop Sci. 42:1910–1918. doi:10.2135/cropsci2002.1910

Veenstra, J.J., W.R. Horwath, and J.P. Mitchell. 2007. Tillage and cover cropping effects on aggregate–protected carbon in cotton and tomato. Soil Sci. Soc. Am. J. 71:362–371. doi:10.2136/sssaj2006.0229

Vetsch, J.A., and G.W. Randall. 2004. Corn production as affected by nitrogen application timing and tillage. Agron. J. 96:502–509. doi:10.2134/agronj2004.0502