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ARTICLE

Row and forage crop rotation effects on maize mineral nutrition and yield

W.E. Riedell and S.L. Osborne

Abstract: Diverse crop rotations are an integral component of sustainable agriculture. The objectives were to investigate row and forage crop rotation effects on stover biomass, grain yield, and mineral nutrient concentrations of maize (*Zea mays* L.) grown under a maize–soybean [*Glycine max* (L.) Merr.] 2-yr rotation (C–S); maize–soybean–spring wheat (*Triticum aestivum* L.) 3-yr rotation (C–S–W); maize–soybean–oat/pea (*Avena sativa* L./*Pisum sativum* L.) hay 3-yr rotation (C–S–H); and maize–soybean–oat/pea hay underseeded with alfalfa (*Medicago sativa* L.) – alfalfa – alfalfa 5-yr rotation (C–S–H/A–A–A). Rotations were established in 1997 and maize plots were sampled in 2008–2011. Across the 4 yr of the study, grain yield was 10% greater (1.0 Mg ha^{-1}) in C–S–H/A–A–A and C–S–W rotations compared with C–S with C–S–H intermediate. Under C–S–H/A–A–A, kernel N concentration was 7% greater, kernel P was 17% less, and kernel K was 7% less compared with C–S–W. Kernel Zn concentration was 16% lower in C–S–H than in C–S and C–S–H/A–A–A. Thus, diversification of the C–S rotation with wheat (C–S–W) increased yield while conserving kernel P and K concentration, whereas diversification with oat/pea hay + alfalfa (C–S–H/A–A–A) increased grain yield and kernel N concentration but decreased both kernel P and kernel K concentration.

Key words: maize, alfalfa, wheat, rotation, mineral nutrition.

Résumé : Pour être durable, l'agriculture doit absolument reposer sur la diversification des cultures par l'assolement. Le but de l'étude était de voir quels effets l'assolement de cultures vivrières et fourragères aurait sur la biomasse de fourrage, le rendement grainier et la concentration de minéraux du maïs (*Zea mays* L.) dans un assolement maïs–soja [*Glycine max* (L.) Merr.] de deux ans (M–S), un assolement maïs–soja–blé de printemps (*Triticum aestivum* L.) de trois ans (M–S–B), un assolement maïs–soja–foin d'avoine/pois (*Avena sativa* L./*Pisum sativum* L.) de trois ans (M–S–F) et un assolement maïs–soja–foin d'avoine/pois avec sous-semis de luzerne (*Medicago sativa* L.) – luzerne – luzerne de cinq ans (M–S–F/L–L–L). Les assolements ont été démarrés en 1997 et les parcelles de maïs ont été échantillonnées de 2008 à 2011. Au cours des quatre années qu'a duré l'étude, le rendement grainier des assolements M–S–F/L–L–L et M–S–B dépassait celui de l'assolement M–S–F de 10 % (1,0 Mg ha^{-1}), le rendement de l'assolement M–S–F se situant entre les deux. Avec l'assolement M–S–F/L–L–L, la concentration de N dans le grain avait augmenté de 7 %, celle de P avait diminué de 17 % et celle de K, baissé de 7 % comparativement aux concentrations relevées avec l'assolement M–S–B. La concentration de Zn dans le grain de l'assolement M–S–F était de 16 % inférieure à celle observée avec l'assolement M–S et l'assolement M–S–F/L–L–L. On en déduit que l'ajout du blé à l'assolement M–S (M–S–B) accroît le rendement sans que la concentration de P et de K diminue dans le grain, alors que l'ajout de foin d'avoine/pois et du sous-semis de luzerne (M–S–F/L–L–L) augmente le rendement grainier et la concentration de N dans le grain, mais diminue la concentration de P et de K. [Traduit par la Rédaction]

Mots-clés : maïs, luzerne, blé, rotation, minéraux nutritifs.

Introduction

Cropping systems based upon diverse crop rotations are often characterized by enhanced soil quality, improved plant productivity, and sustained agricultural production (Vereijken 2002; Hobbs et al. 2008). In terms of soil quality, diverse crop rotations improved soil structure (Raimbault and Vyn 1991), increased soil organic matter levels (Bremer et al. 2008), and enhanced mycorrhizal associations (Plenchette et al. 2005). Rotation effects on plant productivity are thought to be mediated

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by increased crop nutrient use efficiency (Karlen et al. 1994), reduced grain yield variability (Varvel 2000), and improved grain quality (Kaye et al. 2007).

Crop rotations used by farmers range from a strict maize–soybean rotation (which is common in southern Ontario, gaining popularity in southern Manitoba, and is nearly ubiquitous in the U.S. Corn Belt) to a 10- to 12-yr rotation used in Argentina which involves 4–6 yr of continuous grass–legume pasture followed by cash crops (Bullock 1992; Hamel and Dorff 2014). Soil N levels often increase when N-fixing forages are included as rotation crops (Raimbault and Vyn 1991; Carpenter-Boggs et al. 2000). Deep-rooted forage crops, such as alfalfa, can also scavenge deep residual soil N and thus increase N availability to subsequent shallow-rooted crops (Karlen et al. 1994). Under tilled soil management, inclusion of perennial forages in crop rotations not only increased soil N, but also increased maize yields achieved after alfalfa when compared with maize yields measured under rotations that included only row crops (Riedell et al. 2009). Under no-till soil management, increased soil N as well as greater yield and seed protein were observed in soybean planted after maize in a 5-yr rotation that contained oat/pea hay and alfalfa when compared with solely a maize–soybean rotation (Riedell et al. 2013).

Many farmers are interested in increasing the sustainability of their farming operations. Because understanding crop rotation effects on soils and crops is the first step towards the development of sustainable agricultural systems (Hobbs et al. 2008; Garnett and Godfray 2012), we designed a long-term experiment to examine diverse crop rotations that included row crops (maize, soybean, and spring wheat) as well as annual (oat/pea hay) and perennial forages (alfalfa) under no-till soil management. We were interested in documenting the effects of these diverse rotations on soil properties as well as on mineral nutrients and yields of crops common to all rotation treatments. A manuscript investigating the soybean phase has been published (Riedell et al. 2013). The current manuscript examines the impact of diverse rotations on maize yield, mineral nutrition as well as soil characteristics. For maize, the effects of management practices on plant mineral nutrients other than N, P, and K are relatively unknown (Ciampitti et al. 2013). Thus, our specific experimental objectives were to measure the effects of diverse rotations on soil NO_3-N, P, and K when sampled preceding the maize phase and to measure crop rotation effects on stover yield, grain yield, and mineral composition (N, P, K, Ca, Mg, S, Fe, and Zn) in maize plants sampled at crop maturity.

Materials and Methods

Study site characteristics

This experiment under no-till soil management and dryland conditions was initiated in 1997 on a Barnes loam soil (fine-loamy, mixed, superactive, frigid Calcic Hapludoll) with nearly-level topography at the Eastern South Dakota Soil and Water Research Farm near Brookings, SD (44°19′N, 96°46′W; 500 m elevation). Soil testing conducted before the start of the experiment indicated 16.5 g kg^{-1} organic matter, extractable ion concentrations of 14.8 mg kg^{-1} NO_3-N, 9.2 mg kg^{-1} Olsen P, 192 mg kg^{-1} K, and a pH of 7.4 in the top 26 cm (Ap1 horizon) of the soil profile (Maursetter et al. 1992). Additional information about the study site characteristics can be found in Riedell et al. (2013).

Rotation treatments and cultural practices

The four crop rotation treatments were arranged in a randomized complete block design with four replicates (Littell et al. 2006). Rotation treatments consisted of: a 2-yr maize–soybean rotation (C–S), a 3-yr rotation of maize–soybean–oat/pea hay (C–S–H), a 3-yr rotation of maize–soybean–spring wheat (C–S–W), and a 5-yr rotation of maize–soybean–oat/pea hay companion seeded with alfalfa–alfalfa–alfalfa (C–S–H/A–A–A). The experiment was designed to have all phases of crops grown in rotation to be present every year in plots that were 12 m long × 12 m wide. Data presented in this study were collected in the 2008–2011 growing seasons from plots in the maize phase of rotation treatments.

All rotational crops used in this study were established and managed using the agronomic methods as presented in Table 1. Maize was planted on 8 May 2008, 6 May 2009, 19 May 2010, and 18 May 2011. Fertilizer N rates applied to maize were calculated using preseason soil residual nitrate-N tests (0–60 cm depth; Gelderman et al. 1987), N credits from previous N-fixing crops (soybean, oat/pea hay, or alfalfa), and expected grain yields of 9.4 Mg ha^{-1} following the recommendations of Gerwing and Gelderman (1996). The total N prescription was split-applied as a planting-time banded (8 cm to the side and 8 cm deep) starter fertilizer treatment (170 kg ha^{-1} of 10–34–0) plus a broadcast treatment (ammonium nitrate, 34–0–0) applied to the soil surface with a drop spreader when maize reached the V6 (Abendroth et al. 2011) development stage (24 June 2008, 18 June 2009, 25 June 2010, and 1 July 2011). The broadcast method was used because it was not disruptive to the soil surface residues (as knifing would be) under no-till soil management. The ammonium nitrate (34–0–0) fertilizer product was used because of its low volatilization.

Across the 4 yr of the experiment, maize following soybean under the C–S treatment received N fertilizers (starter and broadcast) at an average rate of 168 kg N ha^{-1} (154, 145, 183, and 190 kg N ha^{-1} in 2008, 2009, 2010, and 2011, respectively), 210 kg N ha^{-1} following wheat under the C–S–W treatment (215, 186, 219, and 220 kg N ha^{-1} in 2008, 2009, 2010, and 2011, respectively), 196 kg N ha^{-1} following hay under the C–S–H treatment (213, 166, 200, and 205 kg N ha^{-1} in 2008, 2009, 2010, and 2011, respectively), and 124 kg N ha^{-1} following alfalfa

Table 1. Agronomic information for crops used during the 2008–2011 growing seasons in the crop rotation experiment conducted at the Eastern South Dakota Soil and Water Research Farm near Brookings, SD.

Crop	Variety	Seeding rate[a]	Row spacing (cm)	Starter fertilizer[b] (kg ha^{-1})			Broadcast fertilizer (ammonium nitrate)
				N	P	K	
Maize	DKC 46-60[c]	79 000	51	17	25	0	34–0–0[d]
Soybean	91M70[e]	407 000	51	17	25	0	N/A
Spring wheat	Briggs[f]	340	19	15	17	12	34–0–0
Oat/pea hay	Jerry/Arvika[f]	200/100	19	15	17	12	N/A
Alfalfa	54V54[e]	20	19	N/A	N/A	N/A	N/A

Note: Additional information about rotational crop agronomic methods can be found in Riedell et al. (2013); N/A, not applicable.

[a]Seeding rate is in seeds ha^{-1} for maize and soybean, in seeds m^{-2} for spring wheat and oat/pea hay, and in kg ha^{-1} for alfalfa.

[b]For maize and soybean, ammonium polyphosphate (10–34–0) was applied at 170 kg ha^{-1}. Urea, triple super phosphate, and potassium chloride (14–36–13) were applied at 110 kg ha^{-1} for spring wheat and oat/pea hay.

[c]DeKalb Genetics Corporation maize seed, DeKalb, IL.

[d]Across the 4 yr of the experiment, an average of 168 kg ha^{-1} N was applied to the C–S treatment, 210 kg ha^{-1} to the C–S–W treatment, 196 kg ha^{-1} to the C–S–H treatment, and 124 kg ha^{-1} to the C–S–H/A–A–A treatment.

[e]DuPont Pioneer soybean or alfalfa seed, Johnston, IA.

[f]Available from Millborn Seeds, Brookings, SD.

under the C–S–H/A–A–A treatment (131, 95, 125, and 145 kg N ha^{-1} in 2008, 2009, 2010, and 2011, respectively). Herbicide [glyphosate; *N*-(phosphonomethyl)glycine] was applied as needed to manage weeds in the maize phase.

Soybeans were seeded in mid- to late-May while spring wheat and oat/pea in early to mid-April. Soybean seeds were treated with *Bradyrhizobium japonicum* (Kirch.) Jordan inoculant (Precision Laboratories, Waukegan, IL) prior to planting. Alfalfa was companion seeded with oat/pea in the C–S–H/A–A–A rotation. Alfalfa seeds were treated with *Sinorhizobium meliloti* (Dange.) De Lajudie inoculant (Novozymes BioAg Inc., Brookfield, WI) prior to planting. Soybeans were harvested in late-September to early October. Wheat was harvested in early to mid-August. Oat/pea crops for C–S–H and C–S–H/A–A–A were harvested from early to late July. Volunteer wheat was present in C–S–W plots after wheat harvest while C–S–H plots were relatively weed-free following oat/pea annual forage harvest. Alfalfa was cut two to three times each growing season for hay in the 4th and 5th yr of this rotation treatment. To terminate alfalfa prior to the corn phase, the last cutting of the 5th yr was omitted and the remaining plants were treated with a mixture of glyphosate (4.6 L ha^{-1}), dicamba (1.7 L ha^{-1}), and 2,4-D (1.2 L ha^{-1}).

Pre-season soil analysis

A stainless steel probe (3.2 cm diameter) was used to take preseason soil samples from non-wheel-track areas between crop rows during late fall (1 Nov. 2007, 30 Oct. 2008, 18 Nov. 2009, and 8 Nov. 2010). Two separate cores were taken from each plot. Soil cores from the 0 to 60 cm depth were analyzed for soil nitrate-N [0.01 M $Al_2 (SO_4)_3$, 0.02 M H_3BO_3 extraction; Gelderman et al. 1987]. Soil Olsen P (0.5 M $NaHCO_3$ extraction) and soil K (1 N NH_4OAc extraction) were measured on cores from the 0 to 15 cm depth (Gelderman et al. 1987).

One week after planting, soil moisture sensors (Watermark Model 200SS, Irrometer Company, Riverside, CA) were placed within the maize row in the center of each experimental plot. Three sensors were installed per plot, one each at 10, 30, and 45 cm deep in the soil profile, using a 2.5 cm diameter soil core sampler. Sensors were allowed to equilibrate for 48 h after which soil matric potential was measured using a digital readout meter (Watermark Model 30-KTCD-NL).

Crop stover, yield, and seed measurements

Maize shoots were randomly sampled (five $plot^{-1}$) for biomass dry weight and mineral nutrient concentration when plants reached the physiological maturity (R6; Abendroth et al., 2011) developmental stage. Grain was removed from the cob prior to analysis. Stover samples were dried to constant weight at 60 °C in a forced air oven and weighed. The average stover biomass dry weight $plot^{-1}$ was calculated and then multiplied by the number of plants ha^{-1} to yield the stover dry weight in kg ha^{-1}. Stover biomass was ground to pass a 1 mm screen in a Wiley mill (Thomas Scientific, Swedesburo, NJ). Ground biomass samples were analyzed for N concentration using the dry combustion method in a C/N analyzer (model CN2000, LECO Corp., St. Joseph, MI). An inductively coupled plasma atomic emission spectroscope (model Vista-MPX, Varian Instruments, Walnut Creek, CA) was used to measure P, K, Ca, Mg, S, Fe, and Zn concentrations on ground tissue after it was digested in nitric acid (Mars-X Extraction Unit, CEM Corporation, Matthews, NC). Total stover mineral nutrient uptake was calculated as the product of stover biomass and mineral nutrient concentration.

A research plot combine (MF 8-XP, Kincaid Equipment Manufacturing, Haven, KS) equipped with an electronic weigh bucket was used to measure maize grain yields on four 12-m-long rows plot^{-1}. Grain was harvested on 20 Oct. 2008, 17 Nov. 2009, 19 Oct. 2010, and 30 Sept. 2011. A grain analysis computer (model GAC 2000, DICKEY-john Corp., Auburn, IL) was used to measure seed moisture at harvest. Grain yields were then mathematically adjusted to 150 g kg^{-1} moisture content. After grinding in a sample mill (Udy Cyclone, Seedburo Equipment Company, Chicago, IL), seed N, P, K, Ca, Mg, S, Fe, and Zn concentrations and total nutrient uptake were measured and calculated using the same methods as described for stover.

Data analysis

PROC GLIMMIX procedures (SAS version 9.2; $\alpha = 0.05$; SAS Institute Inc. 2008) were used to analyze soil, stover, and seed data sets. Rotation, year, and their interactions were considered as fixed effects whereas replications nested within years were considered as random effects. Statistical results were presented on data pooled across years in the absence of year × rotation interactions. Means were separated using Tukey–Kramer grouping for least square means ($\alpha = 0.05$) with the occurrence of a significant test for rotation effects.

Results and Discussion

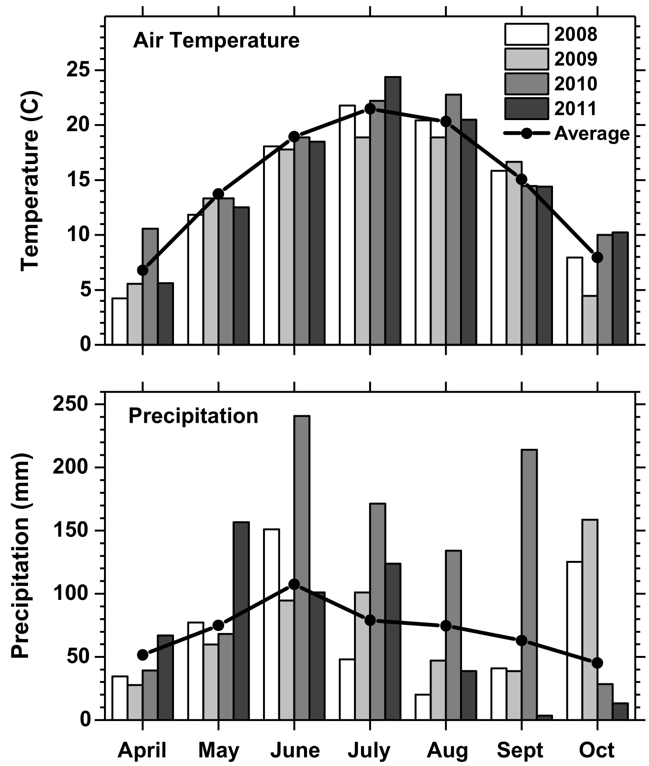
Growing season environmental conditions

The 2008 growing season had below normal air temperatures in spring and near or above normal temperatures in summer (Fig. 1). Rainfall was near or above normal in spring and below normal in summer. The 2009 growing season had below normal air temperatures in late spring and summer. Rainfall was below normal in spring and late summer. During the 2010 growing season, above normal air temperatures recorded in early spring and late summer were accompanied by near normal temperatures in late spring and early summer. Rainfall was below normal in early spring and considerably above normal from late spring through summer. The 2011 growing season had below normal air temperatures in early spring and above normal temperatures in summer. Rainfall was above normal in early spring and mid-summer but was below normal in late summer.

Preseason soil NO_3-N, P, and K

Analysis of soil data indicated significant crop rotation treatment effects on preseason soil NO_3-N levels (Table 2; $P = 0.001$). Statistical analysis revealed that soil NO_3-N was greater under the C–S–H/A–A–A rotation (about 38 kg ha^{-1}) than in the other rotation treatments (about 28 kg ha^{-1}). The consistent increase across years in soil NO_3-N level following the alfalfa phase was likely the result of N mineralization from organic matter residues of alfalfa (Carpenter-Boggs et al. 2000). The lack of significant increases in soil NO_3-N in the C–S or the C–S–H rotations suggests that these preceding crops did not provide enough N-rich organic residues to support large N mineralization.

Fig. 1. Air temperature and precipitation data recorded at a weather station near Brookings, SD. Columns represent average monthly air temperature and rainfall for the 2008–2011 growing seasons. Solid lines with circular symbols represent long-term (30-yr) averages of air temperature and rainfall for this location. Weather data were obtained from annual climatological data summaries of South Dakota provided by the National Oceanic and Atmospheric Administration National Climatic Data Center (http://www.ncdc.noaa.gov/cdo-web/).



Soil P ($P = 0.002$) and K ($P = 0.0001$) was also significantly affected by crop rotation (Table 2). The highest level of Olsen P was consistently observed across years in soils under the C–S–W rotation, whereas the lowest was found under the C–S–H and C–S–H/A–A–A rotations. Soil K levels were also consistently greater across years under the C–S–W and C–S rotations than under the C–S–H and C–S–H/A–A–A rotations. Soils under rotations that included forage crops were shown to have lower extractable soil P concentrations compared with soils under rotations that included only grain crops with tilled soil management (Riedell et al. 2009). Compared with grain harvested from row crops, harvest of forage crop residues can remove greater amounts of soil P and K (Karlen et al. 2006; Smith 1975) which, in turn, can reduce the soil extractable P and K concentrations. In

Table 2. Residual soil NO_3-N, P, and K under different crop rotation treatments.

Rotation[c]	NO_3-N (kg ha^{-1})[a]					P (mg kg^{-1})[b]					K (mg kg^{-1})[b]				
	2007	2008	2009	2010	Mean[d]	2007	2008	2009	2010	Mean[d]	2007	2008	2009	2010	Mean[d]
C–S[d]	27.9	28.0	31.4	20.7	26.7b[e]	12.2	5.5	7.2	23.7	12.2ab	120.5	129.7	106.0	126.2	120.6a
C–S–W	31.4	27.2	31.6	23.0	28.4b	17.2	10.5	15.5	25.2	17.1a	129.2	126.2	122.5	138.7	129.2a
C–S–H	27.4	25.8	32.8	24.1	27.5b	9.5	7.5	10.7	10.5	9.6b	107.0	118.2	103.7	99.0	107.0b
C–S–H/A–A–A	38.1	43.7	42.6	28.0	38.1a	6.0	3.2	12.2	3.0	6.1b	108.2	121.5	107.5	95.7	108.2b

Note: Soil samples were taken in the late fall of the year preceding the maize phase of the rotation.
[a]Residual soil NO_3-N was measured on cores taken from 0–60 cm soil depth.
[b]Soil P and K were measured on cores taken from soil depths of 0–15 cm.
[c]Rotation treatments: C–S, maize–soybean, 2-yr rotation; C–S–W, maize–soybean–spring wheat, 3-yr rotation; C–S–H, maize–soybean–oat/pea hay, 3-yr rotation; C–S–H/A–A–A-C, maize–soybean–oat/pea hay underseeded with alfalfa–alfalfa–alfalfa, 5-yr rotation.
[d]Values represent data averaged within rotations across all years of the study. Means followed by the same letter within columns are not significantly different (Tukey–Kramer grouping for least square means, $\alpha = 0.05$).

the current study, P and K starter fertilizers were soil-applied to maize, soybean, spring wheat, and oat/pea hay crops used in the rotation treatments (Table 1) while the alfalfa phase of the C–S–H/A–A–A rotation did not receive any starter fertilizer. Thus, greater P and K removal by the annual and perennial forage crops as well as fewer applications of P and K fertilizer to the soil in the rotation containing alfalfa likely caused the observed reductions of extractable P and K in the C–S–H and C–S–H/A–A–A rotations.

Residual soil matric potential

Soil matric potential was estimated from sensors placed in the plots one week after planting. Readings at the 10, 30, and 45 cm soil depth were significantly affected by year ($P = 0.0002$ for 10 cm, $P = 0.0001$ for 30 and 45 cm depth). Soil had the least negative soil matric potential in 2008 (−7 kPa at 10 cm, −2 kPa at 30 cm, and −3 kPa at 45 cm), while 2009 had the most negative levels (−21 kPa at 10 cm, −19 kPa at 30 cm, and −18 kPa at 45 cm). Matric potential readings taken in 2010 and 2011 were intermediate (data not shown). Crop rotation treatments had no significant effect on soil matric potential as measured at the three soil depths nor were there any significant rotation × year interactions (data not shown). Thus, residual soil water availability likely was not a factor in affecting biomass and yield productivity across rotation treatments.

Maize stover biomass and mineral concentration

Stover biomass harvested at the R6 physiological maturity stage was significantly affected by year (Table 3). Detailed analysis (data not shown) indicated that maize had greater stover biomass in 2009 (13 552 kg ha^{-1}), a growing season that was characterized by near-average precipitation (Fig. 1), than in the much dryer 2008 growing season (7662 kg ha^{-1}). Stover biomass accumulations in 2010 (10 089 kg ha^{-1}) and 2011 (11 142 kg ha^{-1}) were intermediate between the levels recorded in 2008 and 2009. With the exception of S, nutrient concentrations and total nutrient uptake of all stover mineral elements were significantly affected by year (Table 3). This is understandable considering the differences in yearly weather patterns and the large differences in stover biomass recorded during the 4 yr of the experiment. Despite differences in growing season temperature and precipitation (Fig. 1), there was no significant year × rotation interaction for all these specific parameters (Table 3), suggesting that stover biomass or mineral elements as measured across rotation treatments did not respond differently to environmental conditions.

Rotation treatments did not significantly affect maize stover biomass (Tables 3 and 4). Peterson and Varvel (1989) also found that maize stover biomass was not affected by rotational treatments that included 2-yr maize-soybean and 4-yr maize-soybean-sorghum-oat/clover rotations. In contrast, rotation treatments significantly affected stover N, K, Mg, and Zn concentrations as well as the total uptake of K and Mg (Table 3). Maize stover N concentration was greater in the C–S–H/A–A–A rotation than in the C–S–W and C–S–H rotations (Table 5). Because stover N concentration increases linearly as fertilizer N rate is increased (Sindelar et al. 2013), the increased soil residual NO_3-N in the C–S–H/A–A–A rotation (Table 2), as well as in-season mineralization of N from alfalfa crop residues (Carpenter-Boggs et al. 2000), may have promoted N uptake from the soil which in turn may have increased stover N concentrations in this rotation treatment.

Stover harvested from the C–S–W rotation had greater K concentrations than any other rotation treatment while total uptake of K in stover was greater in the C–S–W rotation than C–S–H (Table 5). Maize has long been known to have luxury consumption of K (Koch et al. 1970). Maize also responds to increasing levels of soil K by accumulating K in stover (Mallarino and Higashi 2009). Increased preseason soil K level in the C–S–W rotation plots (Table 2) may have promoted

Table 3. Analysis of variance of year, rotation, and year × rotation (Year × Rot) interactions for stover biomass yield, stover mineral nutrient concentrations, and total stover mineral nutrient uptake when harvested at maturity (R6), as well as combine-harvested grain yield, seed mineral nutrient concentrations, and total seed mineral nutrient uptake of maize grown under four rotation treatments near Brookings, SD, in the 2008–2011 growing seasons.

		Pr >*F*								
Effect	df	Yield	N	P	K	Ca	Mg	S	Fe	Zn
Stover biomass yield and mineral nutrient concentrations										
Year	3	0.0001	0.002	0.0001	0.0001	0.005	0.0001	0.410	0.001	0.0001
Rotation	3	0.869	0.001	0.710	0.0001	0.194	0.0006	0.137	0.308	0.0006
Year × Rot	9	0.814	0.073	0.557	0.063	0.359	0.466	0.592	0.342	0.495
Total stover mineral nutrient uptake										
Year	3		0.001	0.0003	0.0001	0.0005	0.0005	0.001	0.0001	0.0001
Rotation	3		0.252	0.826	0.025	0.262	0.004	0.459	0.463	0.042
Year × Rot	9		0.572	0.386	0.151	0.198	0.143	0.781	0.191	0.934
Grain yield and seed mineral nutrient concentrations										
Year	3	0.0001	0.0002	0.006	0.0001	0.0003	0.0001	0.509	0.0001	0.002
Rotation	3	0.004	0.001	0.025	0.047	0.713	0.209	0.576	0.394	0.0009
Year × Rot	9	0.540	0.605	0.706	0.566	0.435	0.281	0.336	0.581	0.076
Total grain mineral nutrient uptake										
Year	3		0.0001	0.0003	0.0003	0.0003	0.012	0.067	0.0001	0.109
Rotation	3		0.002	0.017	0.029	0.449	0.087	0.063	0.409	0.0009
Year × Rot	9		0.774	0.831	0.730	0.611	0.800	0.398	0.614	0.267

Table 4. Stover biomass and grain yield of maize harvested from plots managed under different crop rotation treatments.

Rotation[a]	Stover biomass (kg ha^{-1})	Grain yield (kg ha^{-1})
C–S	10 391ns	9 366b
C–S–W	10 523	10 315a
C–S–H	10 836	10 055ab
C–S–H/A–A–A	10 694	10 366a

Note: Stover was harvested when grain reached physiological maturity (R6) just prior to grain harvest. Values represent data combined across all years of the study. Means followed by the same letter within columns are not significantly different (Tukey–Kramer grouping for least square means, $\alpha = 0.05$). ns, not significant.

[a]Rotation treatments: C–S, maize–soybean, 2-yr rotation; C–S–W, maize–soybean–spring wheat, 3-yr rotation; C–S–H, maize–soybean–oat/pea hay, 3-yr rotation; C–S–H/A–A–A-C, maize–soybean–oat/pea hay underseeded with alfalfa–alfalfa–alfalfa, 5-yr rotation.

uptake of K from the soil to be stored in the stover of maize grown in this rotation.

Maize grown in the C–S–H/A–A–A rotation treatment also had greater stover Mg and Zn concentrations as well as total nutrient uptake compared with the other rotation treatments (Table 5). Increased root activity of the preceding alfalfa crop may have acted on the soil to increase the concentration of the plant-available Mg and Zn pools for the subsequent maize crop. This is consistent with the observations of Cakmak (2008), who found that low levels of plant-available Zn in soils was the major reason for the widespread occurrence of Zn deficiency in crop plants. Thus, increased stover Zn concentration may simply reflect the higher plant-available Zn concentrations found in the soil following alfalfa (Catlett et al. 2002). Another possibility could be that the perennial root system present during the alfalfa phase of the C–S–H/A–A–A rotation increased mycorrhizal associations in the subsequent maize crop (Plenchette et al. 2005), leading to increased root Zn uptake and translocation to maize stover (Lehmann et al. 2014).

Maize grain yield and mineral concentrations

Maize yield across rotation treatments was influenced by year-to-year variability in climatic conditions (Table 3). Cooler spring and near-average summer temperatures combined with well-below-average precipitation resulted in an average maize grain yield of 8846 kg ha^{-1} in 2008. Cooler air temperatures and near-average rainfall during the growing season in 2009 resulted in a maize grain yield of 11 219 kg ha^{-1}. Near-average air temperature and above-average precipitation recorded during the 2010 growing season combined to produce a maize grain yield of 11 170 kg ha^{-1}. Above-average summer air temperatures and below-average summer precipitation resulted in a maize grain yield of

Table 5. Stover concentrations and total uptake of N, K, Mg, and Zn in maize biomass harvested from plots managed under different crop rotation treatments.

	Stover mineral nutrient concentrations				Total stover mineral nutrient uptake			
Rotation[a]	N (g kg^{-1})	K (g kg^{-1})	Mg (g kg^{-1})	Zn (mg kg^{-1})	N (kg ha^{-1})	K (kg ha^{-1})	Mg (kg kg^{-1})	Zn (g kg^{-1})
C–S	7.57ab	6.20b	2.29ab	11.73ab	79.45ns	65.32ab	23.51ab	132.3ab
C–S–W	7.16b	7.44a	2.12b	10.11b	75.95	77.31a	22.29b	115.1b
C–S–H	6.96b	5.62b	2.50a	10.03b	75.96	61.34b	27.31a	118.6b
C–S–H/A–A–A	8.07a	6.31b	2.51a	14.52a	86.59	67.04ab	26.71a	161.9a

Note: Stover was harvested when grain reached physiological maturity (R6) just prior to grain harvest. Values represent data combined across all years of the study. Means followed by the same letter within columns are not significantly different (Tukey–Kramer grouping for least square means, $\alpha = 0.05$). ns, not significant.

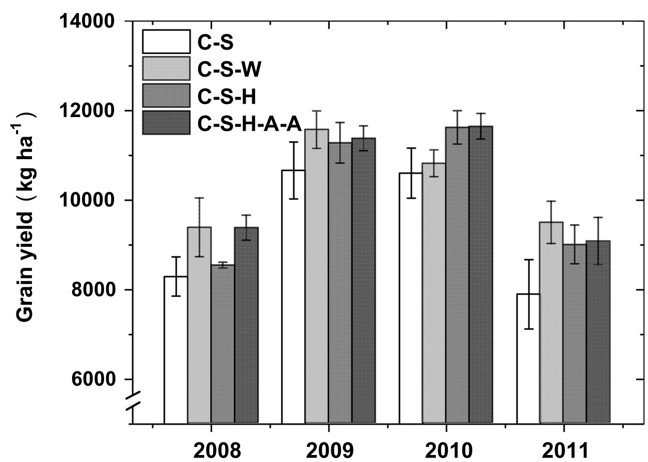
[a]Rotation treatments: C–S, maize-soybean, 2-yr rotation; C–S–W, maize–soybean–spring wheat, 3-yr rotation; C–S–H, maize–soybean–oat/pea hay, 3-yr rotation; C–S–H/A–A–A, maize–soybean–oat/pea hay underseeded with alfalfa–alfalfa–alfalfa, 5-yr rotation.

8866 kg ha^{-1} in 2011. Maize grain yields recorded across rotation treatments in 2009 and 2010 were significantly greater than those recorded in 2008 and 2011 (data not shown). The lack of significant year × rotation interaction (Table 3) suggests that maize grain yield responded similarly to rotation treatments across all years of the study (Fig. 2).

Maize grain yield was about 10% greater in the C–S–W and the C–S–H/A–A–A rotation treatments compared with the C–S rotation, while yields for the C–S–H rotation were intermediate (Table 4). Porter et al. (1997) also found that rotations that included a perennial forage (maiz–soybean–oat/alfalfa–alfalfa) had greater maize grain yields than rotation with maize–soybean. Seed concentrations and total uptake of N, P, K, and Zn were significantly affected by rotation treatments (Table 3). While both the C–S–W and C–S–H/A–A–A rotation treatments produced greater yields, only maize grown under the C–S–H/A–A–A rotation had significantly greater seed N concentration and total N uptake (Table 6). Nutrient synergisms have been defined as those yield–nutrient relationships where yield, seed nutrient concentration, and total nutrient uptake all increase in a concurrent manner (Jarrell and Beverly 1981). Increased yield as well as greater seed N concentration and total N uptake for maize grown under the C–S–H/A–A–A rotation compared with the C–S rotation fits this synergistic relationship definition. Synergistic increases for N under the C–S–H/A–A–A rotation (Table 6) likely resulted from the higher concentrations of soil N (Table 2) available to the maize grown after alfalfa in the C–S–H/A–A–A rotation. Conversely, maize grown under the C–S–W rotation, which had greater grain yield but similar seed N concentration and total uptake as the C–S rotation (Table 6), did not show this synergistic relationship.

Grain P and K concentrations were greatest in the 3-yr C–S–W rotation and lowest in the C–S–H/A–A–A (Table 6). This increase in grain K and P concentration was consistent with the observation of increased K

Fig. 2. Maize grain yield from the 2008–2011 growing seasons. Vertical bars and error bars represent mean ± standard error for grain yield within year and rotation treatments.



concentration in maize stover at the R6 stage of development (Table 5) and pre-season increases in soil P and K levels (Table 2). Taken together, these data suggest that greater P and K removal by alfalfa and reduced fertilizer P and K applications to the alfalfa phase combined to reduce soil P and K under the C–S–H/A–A–A rotation, which caused the reduction of grain P and K concentrations.

Grain Zn concentration and total Zn uptake were lowest in the C–S–H rotation and greatest in the C–S–H/A–A–A rotation (Table 6). Root activity of the preceding alfalfa crop may have increased plant-available Zn in the soil (Catlett et al. 2002). Additionally, because arbuscular mycorrhizae have been shown to have positive impacts on Zn concentrations in shoots and grain (Lehmann et al. 2014), the lower Zn concentration and total Zn uptake in grain from the C–S–H rotation may have been because of suppression of mycorrhizal associations in maize plots

Table 6. Grain concentrations and total uptake of N, P, K, and Zn in maize seed harvested from plots managed under different crop rotation treatments.

	Grain mineral nutrient concentrations				Total grain mineral nutrient uptake			
Rotation[a]	N (g kg^{-1})	K (g kg^{-1})	Mg (g kg^{-1})	Zn (mg kg^{-1})	N (kg ha^{-1})	K (kg ha^{-1})	Mg (kg kg^{-1})	Zn (g kg^{-1})
C–S	13.61b	2.84ab	3.70ab	14.1a	127.59b	25.57b	33.80b	128.5bc
C–S–W	13.54b	3.17a	3.77a	13.4ab	139.74ab	31.03a	38.90a	136.1ab
C–S–H	14.02ab	2.80ab	3.65ab	12.0b	140.54ab	27.30ab	36.69ab	117.8c
C–S–H/A–A–A	14.48a	2.63b	3.49b	14.5a	150.09a	26.23b	35.92ab	146.3a

Note: Values represent data combined across all years of the study. Means followed by the same letter within columns are not significantly different (Tukey–Kramer grouping for least square means, $\alpha = 0.05$).

[a]Rotation treatments: C–S, maize–soybean, 2-yr rotation; C–S–W, maize–soybean–spring wheat, 3-yr rotation; C–S–H, maize–soybean–oat/pea hay, 3-yr rotation; C–S–H/A–A–A, maize–soybean–oat/pea hay underseeded with alfalfa–alfalfa–alfalfa, 5-yr rotation.

following the oat/pea hay phase. In this rotation, oat/pea hay was harvested from early to mid-July across the 4 yr after which land was left in fallow and relatively weed-free. Periods of fallow can reduce mycorrhizal propagules and hyphae (Harinikumar and Bagyaraj 1988; Plenchette et al. 2005), which may have reduced mycorrhizal associations in the subsequent maize phase of the rotation, leading to decreased Zn uptake and translocation to the grain. However, such a contention would need to be substantiated through additional research.

Conclusion

Data presented in this study indicate that diversification of the C–S rotation with wheat (C–S–W) increased maize grain yield while conserving soil P and K levels. Diversification with oat/pea hay + alfalfa (C–S–H/A–A–A) increased soil NO_3-N, maize grain yield, kernel N concentration, but decreased both soil and kernel P and K. Diversification with oat/pea hay only (C–S–H) did not increase yield over that obtained with C–S. These findings suggest that diversification of the ubiquitous maize–soybean rotation with spring wheat or alfalfa forage crops may improve sustainability of crop production.

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