Published July 2, 2015

Tillage and Crop Rotation Effects on Corn Agronomic Response and Economic Return at Seven Iowa Locations

Mahdi M. Al-Kaisi,* Sotirios V. Archontoulis, David Kwaw-Mensah, and Fernando Miguez

ABSTRACT

Corn yield (*Zea mays* L.) and economic return with different tillage systems and crop rotations are highly influenced by regional soil and climate conditions. This study was conducted at seven locations in Iowa from 2003 to 2013. The experiment design was split-plot with tillage as the main factor, which included five tillage systems (no-tillage, NT; strip-tillage, ST; chisel plow, CP; deep rip, DR; and moldboard plow, MP).Three crop rotations of corn–soybean (*Glycine max* L.), C–S; corn–corn–soybean, C–C–S; and corn–corn, C–C were subplots in a completely randomized block design in four replications. The objectives were to: (i) investigate seasonal variability in corn yield as affected by tillage and crop rotation, (ii) identify appropriate tillage for each crop rotation and location, and (iii) evaluate the magnitude of crop rotation effect on corn yield. Corn yields varied from 2.5 to 15.8 Mg ha^{-1} with no detectable increase over time. The results showed northern locations have yield of 1.9 Mg ha^{-1} and economic return of US\$329 ha^{-1} advantage over southern locations. Yield and economic returns for the three rotations were as follow: C–S > C–C–S > C–C. Yield and economic penalty were greater with NT than conventional tillage in the northern locations (poorly-drained soils) than locations with well-drained soils. The corn yield penalty associated with C–C was location specific and varied from 11 to 28%. The findings suggest a location specific adoption of tillage and crop rotation for achieving optimum yield.

Crop response to different tillage systems and crop rotations is highly influenced by soil conditions that include soil drainage class; soil texture; soil organic matter; water holding capacity; and weather variables, such as temperature, precipitation amount and distribution, and frost-free days (Licht and Al-Kaisi, 2005; DeFelice et al., 2006). The consideration of temporal and spatial variability effect on corn production and yield response is important in the adoption of location-specific management practices with certain crop rotations and tillage systems in each region (Machado et al., 2002; Smith et al., 2007; Kalfas et al., 2011; Sakurai et al., 2011). However, market (grain price) and the desire of producers to reduce production costs (i.e., equipment, chemicals, etc.) can affect the choice of rotation and tillage operations (DeFelice et al., 2006; Kumar et al., 2012). There are environmental implications associated with the choice of crop rotation and tillage systems adopted in a particular location as management choices can affect residue cover. Therefore, there is a potential for soil erosion, loss of nutrients, and soil organic C (Paustian et al., 1997; Stonehouse et al., 1988; Huggins et al., 2007).

Tillage and crop rotation influence crop productivity in the short-term through changes in soil water and N dynamics (Gentry et al., 2013) and in the long-term by affecting soil organic matter dynamics (Conant et al., 2007; Khan et al., 2007; Al-Kaisi et al., 2005). The magnitude of that effect is driven by soil properties (Al-Kaisi et al., 2013; Wang et al., 2006; Rasmussen, 1999; Lal and Kimble, 1997), the timing and frequency of tillage events (Griffith et al., 1988; Al-Kaisi and Yin, 2004), climate (Manley et al., 2005; DeFelice et al., 2006), and choice of crop (Shapiro et al., 2001; Wilhelm and Wortmann, 2004; Toliver et al., 2012). In general, areas in the United States with low annual rainfall and low soil water-holding capacity have demonstrated the advantages of conservation tillage over conventional tillage systems (Wang et al., 2006; Hansen et al., 2012). However, the effects of tillage and crop rotations on corn yield are highly variable across years and locations (Manley et al., 2005; Halvorson et al., 2006; Endale et al., 2008; Toliver et al., 20012), and may not be significant (Kapusta et al., 1996; Archer and Reicosky, 2009; Toliver et al., 2012). Research findings have shown that crop rotation has positive, but highly variable effects on corn yield response (corn–soybean rotation) from 3 to 30% as compared to C–C (Peterson and Varvel, 1989; Crookston et al., 1991; Gentry et al., 2013). This variation in yield response due to crop rotation effect is associated with the year-to-year variability in weather, which influences planting time and may limit the adoption of new management practices that involve different tillage systems (Ribera et al., 2004).

Dep. of Agronomy, Iowa State Univ., Ames, IA 50011. Received 2 Sept. 2014. Accepted 3 Mar. 2015. *Corresponding author (malkaisi@iastate.edu).

Published in Agron. J. 107:1411–1424 (2015)
doi:10.2134/agronj14.0470

Abbreviations: C–C, continuous corn; C–C–S, corn–corn–soybean; C–S, corn–soybean; CP, chisel plow; DR, deep rip; MP, moldboard plow; NT, no-tillage; ST, strip-tillage.

One way to address the year-to-year yield variability of rapidly changing agroecosystems is to evaluate crop performance in long-term studies (Richter et al., 2007; Karlen et al., 2013). This is particularly important when the evaluation of agronomic treatments includes crop rotations and tillage systems that require time for the biophysical interactions between soil, crops, and pests to reach stability (Drinkwater, 2002). Long-term studies are useful for demonstrating the cumulative effects of management strategies on crop yield, profitability, soil properties, and delineation of risks and stability of cropping systems (Mitchell et al., 1991; Stanger et al., 2008, Grover et al., 2009; Coulter et al., 2011). Evaluating the effects of tillage and crop rotation using long-term studies can provide a better understanding for adopting new management practices that are based on many parameters, such as physiological changes (e.g., glyphosate resistant crops), crop prices, and agribusiness and scientific advances (Coughenour and Chamala, 2000, Karlen et al., 2013). Agronomic assessments are more valuable when coupled with economic analysis to determine net economic returns and risks of different tillage and crop rotations (Meyer-Aurich et al., 2006; Stanger et al., 2008). Also, confidence in adopting a new management practice would be improved if economic benefits are coupled with both agronomic and environmental benefits (Vyn et al., 2000; Katsvairo and Cox, 2000; Vetsch et al., 2007; Stanger et al., 2008). In this study, a comprehensive data set of corn yields and the associated economic input costs will be analyzed from seven locations across Iowa addressing two important management practices: crop rotation and tillage systems. The specific objectives are to: (i) investigate the seasonal variability of corn yield as affected by five tillage systems and three crop rotations (and their interactions), at each location; (ii) identify appropriate tillage systems for each crop rotation and location by evaluating multiple criteria such as corn yield, input cost and economic return; and (iii) evaluate the magnitude of the rotation effect on corn yield and economic returns at each location.

MATERIALS AND METHODS

Experiment Locations and Weather Information

Experiments were conducted at seven research and demonstration farms of Iowa State University (ISU) that represent

Table 1. Summary of measured soil properties for the top 15-cm depth for each location.

Location†	Soil organic matter	Soil pH	Clay	Silt	Sand	Water holding capacity
	g kg^{-1}		———	%	———	cm^3 cm^{-3}
Ames	55	6.7	25	55	20	0.34–0.40
Crawfordsville	35	6.3	30	66	4	0.34–0.40
Kanawha	55	6.4	26	70	4	0.34–0.40
Armstrong	55	6.9	35	62	3	0.34–0.40
Nashua	35	6.3	20	65	15	0.34–0.40
McNay	37	6.4	48	47	5	0.34–0.40
Sutherland	47	6.5	48	49	3	0.34–0.40

† Ames (Central Iowa); Crawfordsville (Southeast Iowa); Kanawha (north central Iowa); Armstrong (Southwest Iowa); McNay (south central Iowa); Nashua (Northeast Iowa); Sutherland (Northwest Iowa).

Table 2. Major soil information by region across Iowa for all locations (USDA-NRCS, 2013).

Location† and Lat:Long‡	Soil association	Soil series	Classification	Soil texture	Drainage class
Ames (C) 42.0204 N, 93.7738 W	Clarion–Nicollet–Webster	Nicollet	fine-loamy, mixed, mesic Aquic Hapludoll	clay loam	poorly to very poorly drained
Crawfordsville (SE) 41.2033 N, 91.4860 W	Ottle–Mahaska–Taintor	Nira Taintor	fine-silty, mixed, superactive, mesic Aquic Argiudoll; fine, smectitic, Vertic Argiaquoll	silty clay loam	well-drained
Kanawha (NC) 42.9311 N, 93.5889 W	Clarion–Nicollet–Webster	Webster	fine-loamy, mixed, superactive, mesic Typic Endoaquoll	silty clay loam	somewhat poorly drained and moderately permeable
Armstrong (SW) 43.3101N, 95.1741W	Marshall	Marshall	fine-silty, mixed, superactive, mesic Typic Hapludoll	silty loam	poorly to very poorly drained
McNay (SC) 40.9733N, 93.4228W	Grundy–Haig	Grundy-Haig	fine, smectitic, mesic Aquertic Argiudolls fine, smectitic, mesic Vertic Argiaquoll	silty loam	somewhat poorly-drained
Nashua (NE) 42.9327N, 92.5632W	Kenyon–Floyd–Clyde	Kenyon	fine-loamy, mixed, mesic, Typic Hapludoll	loam	moderately well-drained
Sutherland (NW) 42.9246N, 95.5390W	Galva–Primghar–Sac	Galva Primghar	fine-silty, mixed, mesic Typic Hapludoll; fine-silty, mixed, mesic Aquic Hapludoll	silty clay loam	well-drained and moderately permeable

†Ames (Central Iowa); Crawfordsville (Southeast Iowa); Kanawha (north central Iowa); Armstrong (Southwest Iowa); McNay (south central Iowa); Nashua (Northeast Iowa); Sutherland (Northwest Iowa).

‡ Lat:Long = Latitude:Longitude.

different soil associations and precipitation distribution across Iowa. The names of the locations, the geographic locations, and soil type information are summarized in Tables 1 and 2. The locations of the ISU research farms cover the major soil associations in the state and capture landscape differences (Oschwald et al., 1965; Khanal et al., 2014). All locations top soils are characterized by high organic matter content in the range of 35 to 55 g kg^{-1} (Table 1). Weather data from local weather stations at each location that include precipitation and air temperature was used in determining precipitation and growing degree days (GDD). Growing degree days (base temperature of 10°C), cumulative annual precipitation, and growing season precipitation (from 1 June–15 September) were calculated for each season at all locations and presented in Fig. 1. On average 1253°C GDD and 397 mm of precipitation were recorded during the growing season for every year across locations. Approximately 42% of the annual precipitation occurred during the growing season (June–September).

Experiment Layout and Design

The study was established in 2003 at seven locations across Iowa including five tillage systems and three crop rotations. The experimental design was split-plot with tillage as the main factor and crop rotation as a subplot in a completely randomized block design with four replications at all locations. The five tillage systems NT, ST, CP, DR, and MP were randomly assigned within each replication as main treatments. Three crop rotations (subplots) of C–S, C–C–S, and C–C were randomly assigned within each tillage systems. The corn phase appearance each year was dictated by the type of rotation (i.e., in C–S, corn appeared every other year, in C–C–S, corn appeared in two consecutive years, and in C–C, corn appeared every year). However, at the Nashua location there were two sets of each of the C–S and C–C–S rotations, while there were only one set of C–S and two sets of C–C–S rotations at all other locations within each replication. The C–C treatment was added to all locations by converting one of the two sets of the C–C–S rotation in each replication to C–C in 2008. The plots' dimensions at all location ranged between 9.1 to 27.4 m long and 18.3 to 34.6 m wide depending on the orientation of corn rows at each location and replications separated by 8.3 to15.2 m borders.

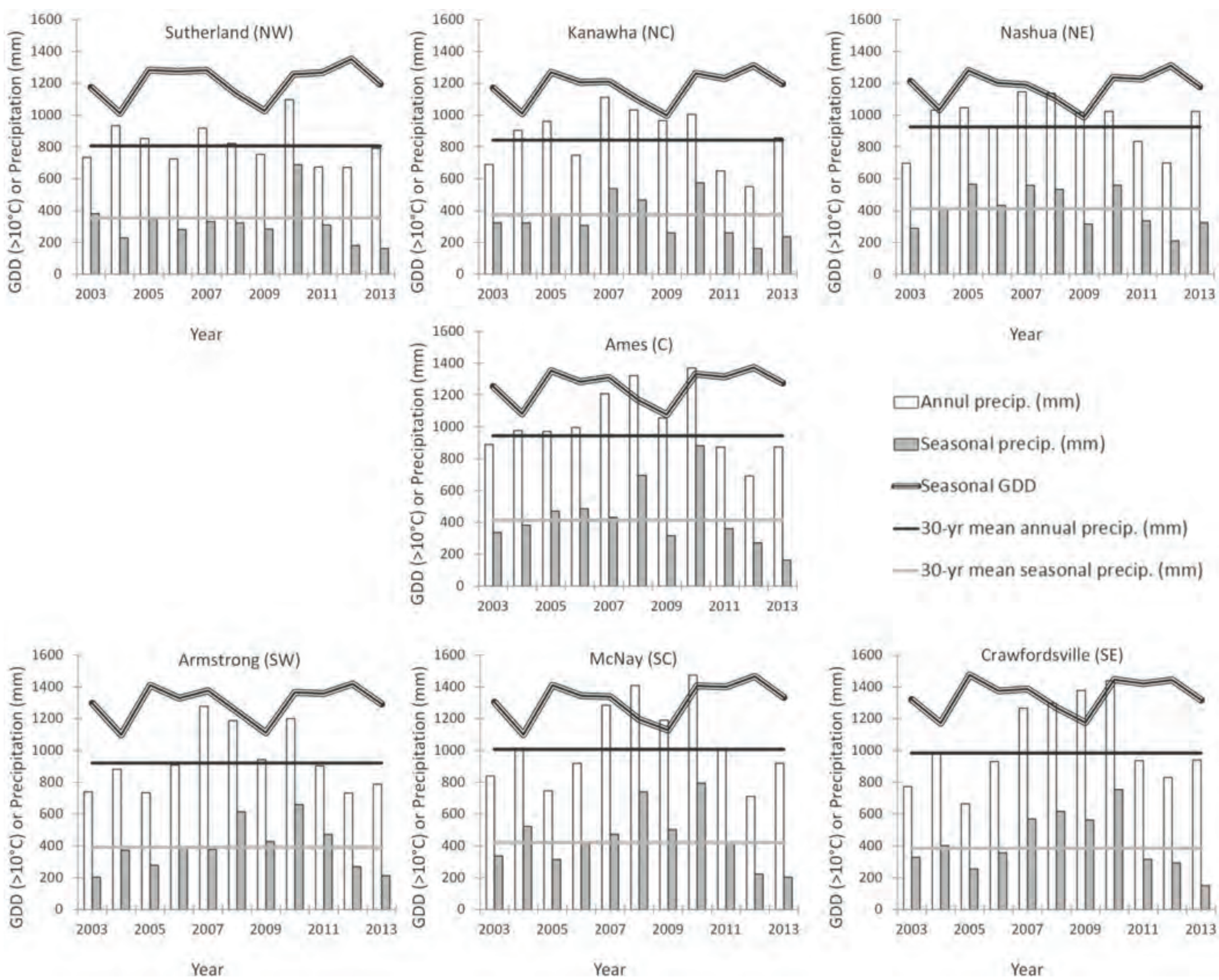

Fig. 1. Seasonal growing degree days (GDD, base temperature of 10°C from 1 June to 15 September), seasonal precipitation, annual precipitation, 30-yr mean annual precipitation, 30-yr mean seasonal precipitation for each location in Iowa.

Table 3. Summary of locations, years, corn hybrids, crop rotation, planting dates, and N rate for corn within each crop rotation of tillage and crop rotation study in Iowa.

Location†	Year	Corn hybrid‡	Rotation§	Planting date (DOY)¶	N rate#
					kg N ha^{-1}
Ames	2003	DeKalb DKC58-24	C–s, c–C–s	142	146,190
(C)	2005	Pioneer 34H31	C–s, C–c–s	116	146
	2006	ICIA Selections	c–C–s	139	190
	2007	Fontanelle 6T672	C–s	142	146
	2008	Fontanelle 7T668	C–c–s, C–C	140	146, 190
	2009	DeKalb5259VT3, Pioneer 35K33	All	139, 150	146, 190
	2010	Pioneer PO461	C–C	126	190
	2011	Pioneer PO448XR	All	125	146, 190
	2012	Pioneer PO448XR	c–C–s, C–C	136	190
	2013	Pioneer PO528 AMX	C–s, C–C	143	146, 190
Crawfordsville	2003	Garst 8481Bt	C–s, c–C–s	104	146, 190
	2004	Garst 8481 Bt	C–s	102	146
(SE)	2005	EX10-EP	C–s, C–c–s	94	146
	2006	DeKalb 0KC60-14	C–s, c–C–s	99	146, 190
	2007	Mycogen 2D673	C–s	113	146
	2008	DeKalb-DKC63-42	All	126, 140	146, 190
	2009	Mycogen 2W705 (triple)	c–C–s, C–C	125	190
	2010	Pioneer P1162XR (triple)	C–s, C–C	111	146, 190
	2011	DeKalbDK62-54(VT3)	C–c–s, C–C	111	146, 190
	2012	DeKalb DKC 62-97	All	98	146, 190
	2013	P036AMX	C–C	126	190
Kanawha	2003	GH8223	C–s	115	146
(NC)	2004	GH8223	C–s, C–c–s	119	146
	2005	DK53-32-Bt	C–s, c–C–s	123	146, 190
	2006	DK53-32-Bt	C–s	127	146
	2007	Pioneer 36W66	C–s, C–c–s	125	146
	2008	Pioneer 36W66	c–C–s, C–C	135	190
	2009	Pioneer 37Y14, 990	C–s, C–C	124	146,190
	2010	Pioneer 990	C–c–s, C–C	111	146,190
	2011	GH7254	All	126	146,190
	2012	P0488	C–C	117	190
	2013	P0528	All	139	146, 190
Armstrong	2003	P34G16	C–c–s	133	146
(SW)	2004	GH9164Bt	C–s, c–C–s	107	146, 190
	2006	P34A16	C–s, C–c–s	130	146
	2007	P34A18	c–C–s	120	190
	2008	NC+522VT3	C–s, C–C	126	146, 190
	2009	P33T59	C–c–s, C–C	114, 115	146, 190
	2010	NC+20929	All	119	146, 190
	2011	P33W84	C–C	123	190
	2012	DeKalb DKC63-42	All	114	146, 190
	2013	Golden Harvest 60-63	C–s, C–C	166	146,190
McNay	2003	Cropland 678RR	C–s, C–c–s, c–C–s	125	146, 190
	2004	Cropland 678RR	c–C–s	125	190
(SC)	2005	Cropland 678RR	C–s, C–c–s	125	146
	2006	FS–6873	C–c–s, c–C–s	111	146, 190
	2007	DK 6339	C–s, c–C–s	137	146, 190
	2008	NC5403VT3	C–c–s, C–C	139	146, 190
	2009	Pio33W84	All	152	146, 190
	2010	Agrigold 6309VT3	C–C	137	190
	2011	DK-6342	All	126	146, 190
	2012	Pioneer 1395AM	c–C–s, C–C	135	190
	2013	Pio1395AM1	C–s, C–C	157	146, 190

(continued)

Table 3 (continued).

Location†	Year	Corn hybrid‡	Rotation§	Planting date (DOY)¶	N rate#
Nashua	2003	NK45-A6Bt	C–s, c–C–s	123	146, 190
(NE)	2004	DeKalb 5145RR,	C–s, C–c–s	123	146
	2005	DeKalb 50-20RR	C–s, c–C–s	120	146, 190
	2006	DeKalb C54-46RR/YG	C–s, C–c–s	111	146
	2007	Agrigold 6395RRBTRW(YG+)	C–s, C–c–s, c–C–s	114	146,190
	2008	Agrigold 6399RRVT3	All	129	146, 190
	2009	LGSEEDS 2540RRVT3	C–s, C–C	107	146, 190
	2010	LGSEEDS 2540RRVT3	All	108	146, 190
	2011	DeKalbC59-35RR/VT3	All	123	146, 190
	2012	DeKalb C59-37RR/RIB	C–s, C–C	116	146, 190
	2013	DeKalb C57-75 RR/RIB	All	133	146, 190
Sutherland	2003	DeKalb 53-33	c–C–s	141	190
(NW)	2004	DeKalb-53-34RR	C–s, C–c–s	123	146
	2005	Fidders Choice 7649	C–c–s, c–C–s	115	146, 190
	2006	Mycogen 2D545HXRW/C-C	C–s, c–C–s	114	146, 190
	2007	Kruger 6503TS	C–c–s	110	146
	2008	Agrigold 6325VT3	All	132	146, 190
	2009	Pioneer 37Y14HXX/LL/RR	c–C–s, C–C	124	190
	2010	Agrigold 6309VT3	C–s, C–C	121	146, 190
	2011	Agrigold Ag6323VT3	C–c–s, C–C	124	146, 190
	2012	Pioneer 33F44	All	124	146, 190
	2013	Agrigold 6319	C–C	134	190

† Ames (Central Iowa); Crawfordsville (Southeast Iowa); Kanawha (Northcentral Iowa); Armstrong (Southwest Iowa); McNay (Southcentral Iowa); Nashua (Northeast Iowa); Sutherland (Northwest Iowa).

‡ Hybrids for each year, location and rotation.

§ All means all rotations of C–C, C–C–S, C–S are in the same year. Upper case "C" means corn is growing in the rotation.

¶ Day of Year. Plant population for corn was 8 plants m^{-2}.

N rate for C–C in the range of 190–224 kg N $ha^{-1}$and for C–S in the range of 146–157 kg N ha^{-1}.

Field Operations

The same tillage operations were conducted every fall of each year at each location since the establishment of the study in 2003. No-tillage, in this study, is defined as the typical no pre-plant disturbance, except when corn was planted directly into soil with surface residue from the previous crop using a single coulter to cut through the residue along with a set of residue cleaners to remove residue to the side clearing 15-cm soil zone ahead of standard planting unit. The CP treatment was implemented with a commercially available model mounted on a tool bar with straight shanks and twisted chisel plow sweeps at the bottom. The shanks were mounted on four tool bars in a staggered order to ensure an effective spacing of 30 cm between shanks for 22- to 25-cm tillage depth. The ST treatment was 20-cm deep, established with an anhydrous mole knife centered between two cover disks 20 cm apart. The tilled zone was 20 cm wide and 10-cm deep in close proximity to the previous row. The DR treatment was established with a commercially available model with four straight shanks spaced at 76 cm apart on a 3-m long (three points) tool bar. The effective tillage depth of the DR treatment with the straight shanks was 46 cm. The MP treatment was also established with a commercially available model with four full bottoms, 46 cm wide and 25 cm deep. The MP treatment resulted in a complete inversion of the soil surface with nearly 100% incorporation of crop residue. All tillage treatments, except NT and ST received spring field cultivation 10-cm deep before planting.

Corn Management

Corn hybrids, planting dates, and N application rates for corn in each crop rotation and location are summarized in Table 3. The row spacing was 76 cm in all experiments and the planting density was approximately 8 plant m^{-2}. On average, across experiments locations and years, corn planting dates ranged between 94 and 141 day of year (DOY) depending on each year weather condition during planting season (Table 3). The corn relative maturity of hybrids ranged from 101 to 105 d in the northern locations to 109 to 112 d in the southern locations. The N fertilization applied rates for all experiments were determined by using the N-rate calculator (Sawyer et al., 2006) and ranged from 146 kg N ha^{-1} for corn following soybean in C-S and C-C-S rotations, to 190 kg N ha^{-1} for corn following corn in C–C–S and C–C rotations (Table 3). Corn grain was harvested from the center four rows of each plot with a commercial four-row combine equipped to determine harvested grain weight and moisture content simultaneously. The reported corn yields were adjusted to a moisture content of 155 g kg^{-1}.

Economic Analysis

The Ag Decision Maker (Duffy, 2014) was used to calculate economic returns of the various tillage systems and crop rotations in this study. Economic return is defined as the difference between gross income and input cost. Gross income was estimated by multiplying the obtained grain yield (for each treatment within each replication) by fixed corn price of $177.17 per metric tonne based on the USDA corn price in May 2014 of $0.18 kg^{-1} [$4.50 bu^{-1} (56 lb corn = 1 bu = 25.4 kg)]. The input costs included the following categories: (i) pre-planting operations (machinery), (ii) supplies (seeds, fertilizer, and chemicals), (iii) harvest (combine, haulage, drying, and handling), and (iv) labor. In this analysis the land cost, crop insurance cost, and the liming cost were not included. These costs are the same among different tillage and crop rotation treatments and locations based on farm records at individual farms that were kept by farm managers; therefore, they have no effect on the outcome of the analysis, which was aimed at comparing different treatments. The time required by each field operation was based on Hanna (2001), using machine sizes of intermediate field capacity. Farm labor cost for operating machinery, spraying, and harvesting used in the analysis are ($14.90 h^{-1}) and ($13.30 h^{-1}) for other operations based on the Ag Decision Maker (Duffy, 2014). The labor cost included the actual fieldwork, the time for maintenance, travel, and other activities related to corn production.

Statistical Analysis

Three different statistical analyses were implemented using the PROC mixed procedure of the SAS software version 9.3 (SAS Institute, 2011) to address the objectives of this study. The first analysis was conducted for corn yield response to year, location, tillage, and their interactions within each rotation separately (C–S, C–C–S, and C–C; Fig. 2, 3, and 4, respectively). The effects of year, location, and tillage were fixed. Years in this analysis were included in the REPEATED statement and the best structure for the variance–covariance matrix of the residuals was chosen from a set of reasonable options. For C–C–S and C–C we chose a banded heterogeneous structure and for C–S we chose a variance component structure. When differences among tillage systems were significant at $P < 0.05$ within a location and a specific year, we computed the standard error of the difference within a location and year and include this number multiplied by 2 to illustrate the variability (bars in Fig. 2–4). The second analysis was conducted for regional yields, input cost, and economic returns for each tillage system within each rotation separately (Tables 4 and 5). In this analysis location, tillage, and their interactions were fixed effects and years were considered random effects. To evaluate the effect of tillage within a location we used the slice option in LSMEANS in the MIXED procedure of SAS. The third analysis was conducted for the rotation effect on corn yields and economic returns for the years where corn was present in all rotations in the same year at each location (Fig. 5). Crop rotation, location, tillage, and their interactions were the fixed effects, and year was considered a random effect. To evaluate

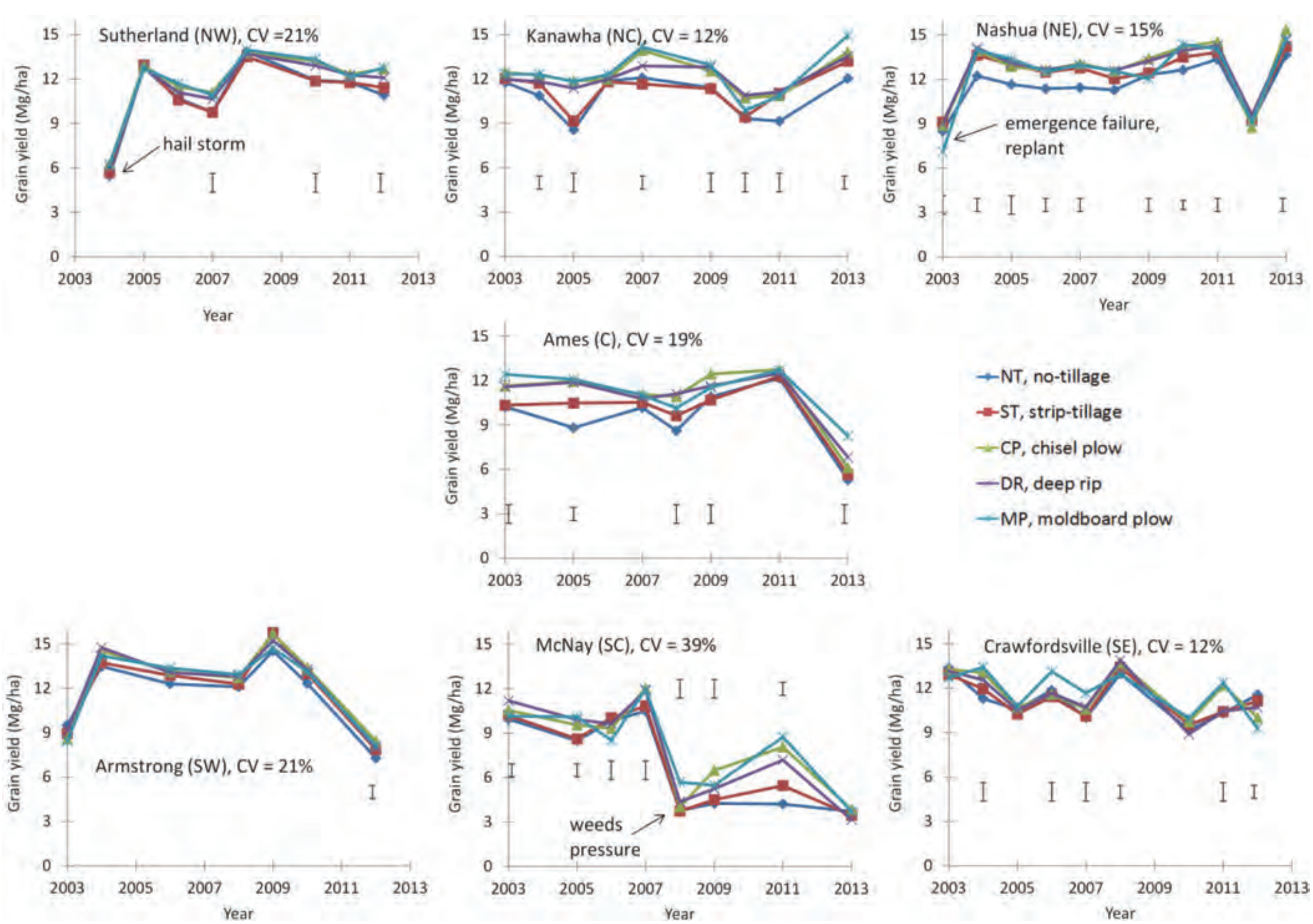

Fig. 2. Temporal variation in corn yield in a corn–soybean (C–S) rotation as affected by five tillage systems in seven locations across Iowa. Vertical bars (where visible) indicate the two times standard error of difference between tillage systems at $P < 0.05$. CV is the coefficient of variation.

the effect of rotation within a location we used the slice option in LSMEANS in the MIXED procedure of SAS. However, the corn yield in the second year of C–C–S rotation was treated as continuous corn, while corn following soybean in the same rotation (C–C–S) was treated as a C–S rotation during the various yield and economic analyses.

RESULTS AND DISCUSSION

Temporal and Spatial Variability in Corn Yield

Within each rotation, there were significant interactions between years, locations, and tillage systems (Table 6). The results of corn yield are presented for each rotation and all locations in Fig. 2, 3, and 4. Over the study period (2003–2013) at seven locations across Iowa, corn yields ranged from 2.5 to 15.8 Mg ha^{-1}, with the lowest yield was always at the McNay location (Fig. 2–4). The low yield at the McNay location was primarily associated with soil constraints such as, poorly-drained soil, lack of drain tiles, and high clay content that made soil management challenging (Table 2). Because of these soil constraints in the south central region, row crop production comprises <25% of the total cropland, while in central and northern Iowa with less soil management challenges, row crop production accounts for approximately 75% of the total cropland in the state, according to a recent survey (Khanal et al., 2014).

The year-to-year variability in corn yield was evaluated by calculating the coefficient of variation (CV = standard deviation/mean value) for each location separately. The results are presented in Fig. 2 to 4. The yield variability observed in this study ranged from 11% for C–C–S rotation (Nashua, Fig. 3) to 39% for C–S rotation (McNay, Fig. 2). In the C–S and C–C–S rotations, the year-to-year yield variability was generally smaller compared to that for C–C rotation (Fig. 2–4). For example, in central Iowa (Ames location) the CV for C–C, C–C–S and C–S rotations were 37, 17, and 19%, respectively. Similar trends were observed for the southern locations of Crawfordsville and Armstrong (Fig. 2–4). In contrast in the northern locations (Sutherland, Kanawha, and Nashua), the annual variability in corn yield was approximately similar across three rotations (Fig. 2–4).

In the C–C rotation, Sutherland had the lowest CV (12%, Fig. 4) and Ames had the highest CV (37%, Fig. 4). The difference in CV between these two locations' yields was caused by the reduction in yield in the last 2 yr in the Ames location in 2012 and 2013. This reduction in yield was caused by a delay in planting by 10 d due to wet conditions in the springs of 2012 and 2013 (Table 3) and was not due to precipitation differences during the growing season (Fig. 1). Also, tillage had a significant effect on yield in 2013, where conventional tillage (CP, DR,

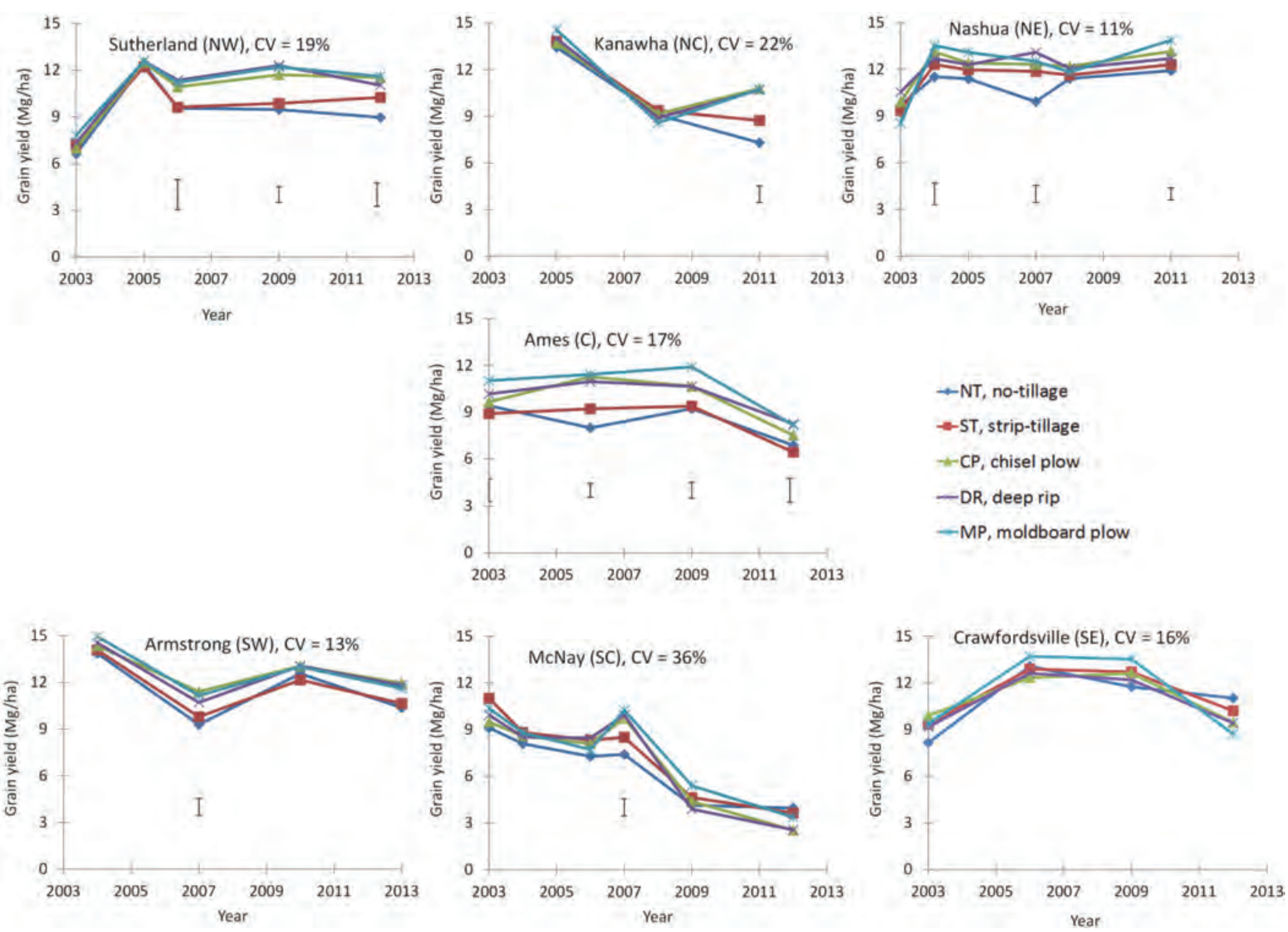

Fig. 3. Temporal variation in corn yield in a corn–corn–soybean (C–C–S) rotation as affected by five tillage systems in seven locations across Iowa. Vertical bars (where visible) indicate the two times standard error of difference between tillage systems at $P < 0.05$. CV is the coefficient of variation.

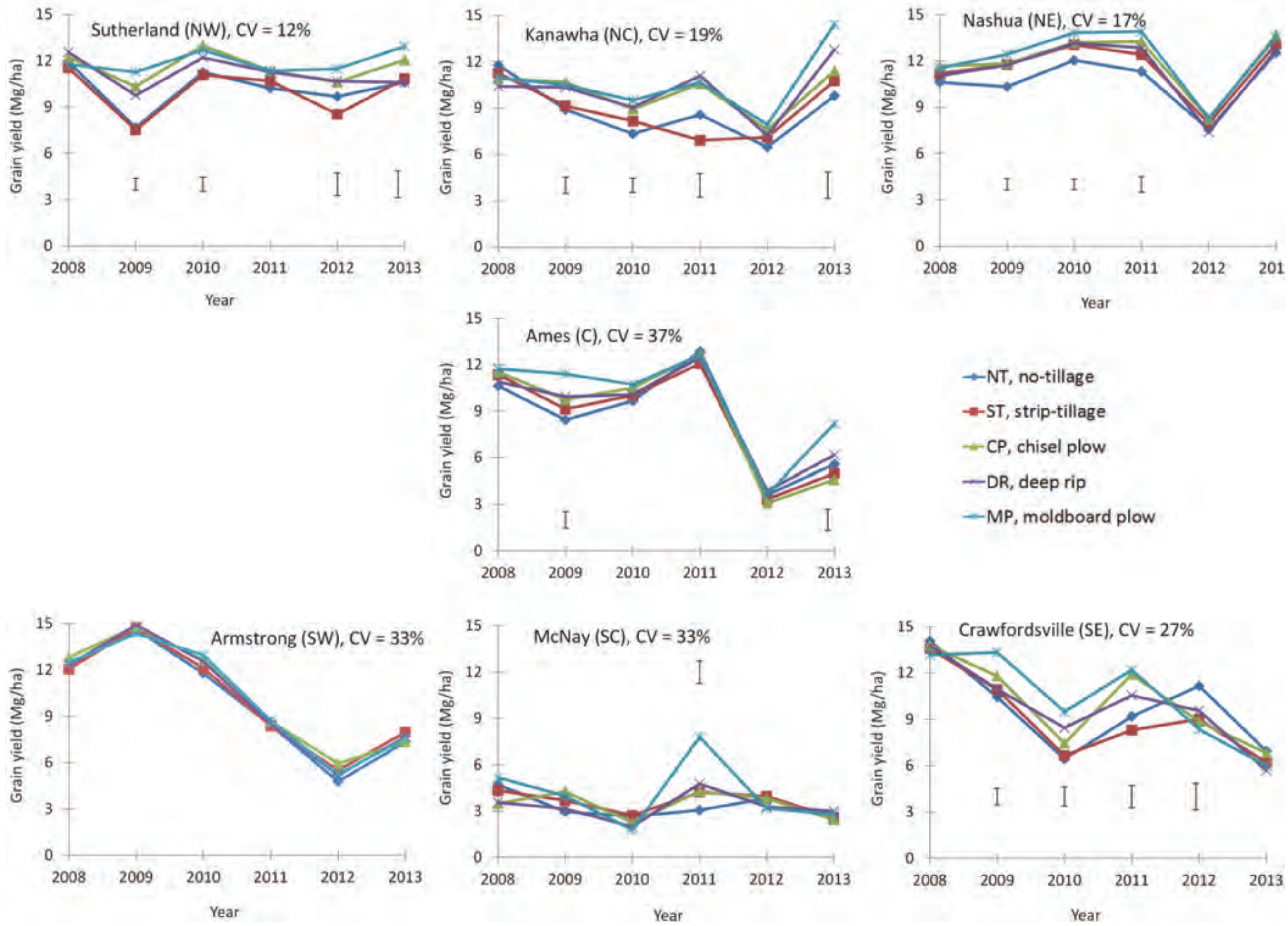

Fig. 4. Temporal variation in corn yield of a continuous corn (C–C) as affected by five tillage systems in seven locations across Iowa. Vertical bars (where visible) indicate the two times standard error of difference between tillage systems at $P < 0.05$. CV is the coefficient of variation.

and MP) increased yield in Ames significantly ($P < 0.01$; Fig. 4). Another interesting finding from this analysis was that the northern locations had lower CV values than the southern locations (16 vs. 31%) and this may be attributed to a decline in corn yield over time in the Armstrong and Crawfordsville locations (Fig. 4). Neither weather conditions, nor soil properties, or crop/soil management could explain the yield decline in these two locations. Most likely, this decline in yield is related to the C–C cropping system, because the yield decline with the C–S and C–C–S rotations was less as compared to that for C–C (Fig. 2 and 3). Gentry et al. (2013) reported that among the factors that contribute to continuous corn yield penalty, the number of years under C–C system was an important factor, which appears to be in agreement with our findings. In the C–C rotation, a positive effect of conventional tillage on yields was more evident at northern locations and Crawfordsville (Fig. 4). At other locations (especially Armstrong) corn response to tillage was inconsistent, which indicates that a no-tillage system can be as effective as any other tillage systems in these locations.

On average across locations, the corn yield annual variability was 36.7, 24.7, and 23.1%, respectively for C–C, C–C–S and C–S (Fig. 2–4). These values for three rotations are in agreement with those obtained in similar environments in Iowa (Karlen et al., 2013) and different environments, such as in Pennsylvania (Grover et al., 2009).

The overall year-to-year variability in corn yield across locations, tillage systems, and rotations in this study was 28%. Examination of soil parameters (Tables 1 and 2), genotype information, management (Table 3), and weather variables (Fig. 1), individually could not explain satisfactorily the observed temporal variability in corn yield. For example, all soils had high levels of organic matter (above 35 g kg^{-1}) and water-holding capacity (Table 1). Weather variables such as growing season precipitation and GDD, though varied from year to year (Fig. 1), explained <10% of the year variability in corn yield (linear regression between rain or GDD and yield had an $r^2 < 0.10$; data not shown). On the other hand, we found a significant relationship between corn yield and heat stress. The results show that heat stress occurred when daily maximum temperature >34°C. The regression relationship between corn yield and heat stress was linear as defined by the following relationship: Corn yield = 175.62 – 4.18 × cumulative heat stress days, ($r^2 = 0.17$, $P < 0.01$). Therefore, the observed temporal variability in corn yield is a product of interactions between soil properties, field/crop management practices, and weather variables. There are a few studies relating yield variability to a single variable (e.g., precipitation; Grover et al., 2009), but in our multi-environment study such correlation was not found. The findings of this study are among a few studies in the literature (Griffith et al., 1988; Porter et al., 2003) that quantify and report spatial and

Table 4. Average corn yield across years as affected by tillage system for each crop rotation in Iowa. Significant interactions between tillage and rotation were found in C-S and C-C ($P < 0.05$).

Rotation†	Location‡	NT§	ST	CP	DR	MP	Average
		Grain yield					
		Mg ha^{-1}					
C–S	Sutherland (NW)	10.92a¶	10.96a	11.71b	11.44ab	11.72b	11.35
	Kanawha (NC)	10.78a	11.26ab	12.28b	12.02b	12.43b	11.76
	Nashua (NE)	11.59a	12.37b	12.76b	12.73b	12.47b	12.38
	Ames (C)	9.45a	9.96ab	10.99b	10.90b	11.17b	10.49
	Armstrong (SW)	11.64a	12.07a	12.37a	12.31a	12.15a	12.11
	McNay (SC)	6.80a	7.08ab	8.00b	7.86b	8.08b	7.56
	Crawfordsville (SE)	11.27a	11.27a	11.63a	11.42a	11.74a	11.47
C–C–S	Sutherland (NW)	9.45	9.88	10.78	10.97	11.13	10.44
	Kanawha (NC)	9.84	10.53	11.11	11.10	11.19	10.75
	Nashua (NE)	10.93	11.52	12.14	12.15	12.24	11.80
	Ames (C)	8.35	8.66	10.09	10.22	10.82	9.63
	Armstrong (SW)	11.43	11.57	12.61	12.43	12.58	12.12
	McNay (SC)	6.72	7.54	7.19	7.27	7.70	7.28
	Crawfordsville (SE)	11.05	11.72	11.68	11.39	12.27	11.62
	Means	9.68a	10.20ab	10.80b	10.79b	11.13b	
C–C	Sutherland (NW)	10.22a	10.03a	11.59b	11.17b	11.91b	10.99
	Kanawha (NC)	8.74a	8.85a	10.04bc	10.20bc	10.71c	9.71
	Nashua (NE)	10.71a	11.63b	11.96b	11.47b	12.29b	11.61
	Ames (C)	8.46a	8.48a	8.69a	8.90a	9.71b	8.85
	Armstrong (SW)	9.85a	10.13a	10.37a	10.19a	10.22a	10.15
	McNay (SC)	3.29a	3.58a	3.43a	3.30a	4.12a	3.55
	Crawfordsville (SE)	9.90a	9.17a	10.06a	9.81a	10.42a	9.87

† Rotation: C–C, continuous corn; C–C–S, corn–corn–soybean; C–S, corn–soybean.

‡ Ames (Central Iowa); Crawfordsville (Southeast Iowa); Kanawha (north central Iowa); Armstrong (Southwest Iowa); McNay (south central Iowa); Nashua (Northeast Iowa); Sutherland (Northwest Iowa).

§ Tillage system: NT, no-tillage; ST, strip-tillage; CP, chisel plow; DR, deep rip; MP, moldboard plow.

¶ Different lowercase letters within a row indicate statistical differences among different tillage systems ($P < 0.05$).

temporal variability of corn yields concurrently. Most of the long-term studies in the literature deal with temporal aspects in a specific location (Pedersen and Lauer, 2003; Karlen et al., 2013) or overlook the year-to-year variability (Pedersen and Lauer, 2002; Porter et al., 2003). Although explanation of the annual variability is challenging, the analysis of the temporal variability was helpful in this study to identify crop rotations that are associated with high and stable yields and/or low production risks. This is an important observation for providing guidelines for management recommendations (Stanger and Lauer, 2008; Grover et al., 2009).

The results of this study show no evidence of yield increase over time regardless of crop rotation across seven locations in Iowa (Fig. 2–4). Most likely, the time period was not long enough to allow for the establishment of a detectable trend. However, no yield increase was also reported in other long-term experiments, such as 12-yr experiments in Indiana and Wisconsin (Griffith et al., 1988), 25-yr experiment in Indiana (Vyn et al., 2000), and 14-yr experiment in Minnesota (Porter et al., 2003). In contrast, Grover et al. (2009) in a 15-yr experiment in Pennsylvania found a significant corn yield increase over time (slope of 0.21 Mg ha^{-1} yr^{-1} for the C–C rotation and 0.28 Mg ha^{-1} yr^{-1} for the C–S rotation), but the coefficient of determination was low ($r^2 < 0.22$). Results from a 32-yr experiment in Iowa showed a small yield increase over time along with a large year-to-year variability (Karlen et al., 2013). In general, analysis of historical county level records indicated that corn yield increased linearly over time by 1.7% yr^{-1} for Iowa (period: 1950–2005; Egli, 2008). Downscaling at field level, such an increase was not detectable in this study.

Regional Interaction of Tillage and Crop Rotation Effects on Corn Yield

Significant interactions were found between tillage and location for the C–S rotation ($P = 0.02$) and C–C rotation ($P = 0.04$), but not for the C–C–S rotation ($P = 0.15$). Average regional corn yields within each crop rotation and all tillage systems are summarized in Table 4. In the C–S rotation, corn yields associated with conventional tillage systems (CP, DR, and MP) were not significantly different from those of ST, but they were significantly different from NT yields in five out of the seven locations (Table 4). The two exceptions were two southern locations, Armstrong and Crawfordville, where all tillage systems performed the same.

In the C–C–S rotation (no interactions between locations and tillage), the conventional tillage systems yields were 11% greater than those of NT at all locations (Table 4). In the C–C rotation, yield response to different tillage systems was only

Table 5. Average input cost and economic return across years for corn production with different tillage systems and crop rotations in Iowa. Significant interactions between tillage and rotation were found in the corn–soybean (C–S) rotation only ($P < 0.05$).

Rotation†	Location	NT‡	ST	CP	DR	MP	Average	NT	ST	CP	DR	MP	Average
		Input cost						Economic return					
		US$ha⁻¹											
C–S	Sutherland	973a§	990b	1052c	1052c	1052c	1023	983a	973a	1045a	998a	1046a	1009
	Kanawha	952a	975b	1037c	1033c	1039c	1007	975a	1040b	1159b	1114b	1184b	1094
	Nashua	969a	992a	1052b	1051b	1049b	1022	1109a	1228b	1237b	1232b	1187b	1199
	Ames	965a	986b	1051c	1050c	1052c	1021	730a	802a	922b	906b	952b	862
	Armstrong	977a	998a	1056b	1056b	1056b	1029	1106a	1162a	1158a	1146a	1121a	1139
	McNay	931a	950b	1015c	1014c	1016c	985	294a	327ab	428b	403b	441b	379
	Crawfordsville	978a	995b	1053c	1053c	1054c	1026	1043a	1026a	1031a	994a	1050a	1029
C–C–S	Sutherland	1007	1027	1091	1091	1091	1062	688	744	841	874	902	810
	Kanawha	1010	1032	1094	1094	1095	1065	753	856	898	896	912	863
	Nashua	1019	1040	1102	1102	1102	1073	940	1024	1074	1077	1091	1041
	Ames	998	1017	1085	1087	1091	1056	498	535	724	746	848	670
	Armstrong	1023	1041	1106	1104	1105	1076	1024	1033	1155	1124	1150	1097
	McNay	985	1008	1062	1063	1066	1037	219	344	227	240	314	269
	Crawfordsville	1020	1042	1098	1096	1103	1072	961	1058	995	946	1096	1011
	Means	1009a	1030b	1091c	1091c	1093c		726a	799ab	845b	843b	902b	
C–C	Sutherland	1063	1078	1147	1144	1149	1116	770	721	930	859	986	853
	Kanawha	1051	1068	1134	1135	1139	1106	515	517	665	693	781	634
	Nashua	1029	1052	1120	1108	1114	1085	892	1033	1024	949	1089	997
	Ames	1049	1065	1123	1125	1132	1099	469	456	434	470	609	488
	Armstrong	1060	1079	1137	1136	1136	1109	706	737	722	691	697	711
	McNay	1007	1026	1081	1081	1087	1057	–417	–384	–466	–489	–348	–421
	Crawfordsville	1006	1023	1083	1081	1085	1055	714	573	668	625	731	662
	Means	1038a	1056a	1118b	1116b	1120b		521a	522a	568a	543a	649b	

† Rotation: C–C–S, corn–corn–soybean; C–C, continuous corn.

‡ Tillage system: NT, no-tillage; ST, strip-tillage; CP, chisel plow; DR, deep rip; MP, moldboard plow.

§ Different letters within a row indicate statistical differences between different tillage systems ($P < 0.05$).

significant in the northern and central Iowa locations, where NT yields in most locations was lower than those with all conventional tillage systems, except for Ames location, where it was only lower than that with MP (Table 4). The yield reduction in a similar environment to northern Iowa under NT was also documented by other studies, where they found a yield reduction in NT as compared particularly to MP (Karlen et al., 2013), and other conventional tillage systems in Wisconsin (Pedersen and Lauer, 2003) and Indiana (Griffith et al., 1988).

In general, corn yield associated with all rotations in the southern locations under NT was not significantly different from that with conventional or ST systems, except in some locations (McNay with C–S). The observed yield decline in the NT system, especially in the northern part of the state is most likely attributed to soil condition (poorly-drained) and early spring wet and cold soil temperature conditions (Licht and Al-Kaisi, 2005). Under NT and ST systems the residue amount on the soil surface is significantly greater than that with conventional tillage systems. This high amount of residue with NT coupled with soil conditions (poorly-drained soil) that reduced soil temperature, delay seed germination, and emergence (Licht and Al-Kaisi, 2005; Halvorson et al., 2006; Hatfield, 2014; Karlen et al., 2013; Sindelar et al., 2013). Tillage systems effects on plant development can also be attributed to change in light interception, where it was found to be lower with a NT system than conventional system in Iowa (Hatfield, 2014). A lower light interception during early crop growth stages can affect crop growth rate and ultimately biomass and grain production.

Table 6. Summary of fixed effects tests to evaluate corn yield variability within each crop rotation in Fig. 2 to 4.

Effect	Corn–soybean df	Corn–soybean *P* value	Corn–corn–soybean df	Corn–corn–soybean *P* value	Continuous corn df	Continuous corn *P* value
Year (Y)	11	0.0787	10	<0.0001	5	<0.0001
Location(L)	6	0.0633	6	<0.0001	6	<0.0001
L×Y	42	0.0618	14	<0.0001	30	<0.0001
Tillage (T)	4	<0.0001	4	<0.0001	4	<0.0001
T×Y	44	<0.0001	40	<0.0001	20	<0.0001
L×T	24	<0.0001	24	<0.0001	24	<0.0001
L×T×Y	168	<0.0001	56	<0.001	120	<0.0001

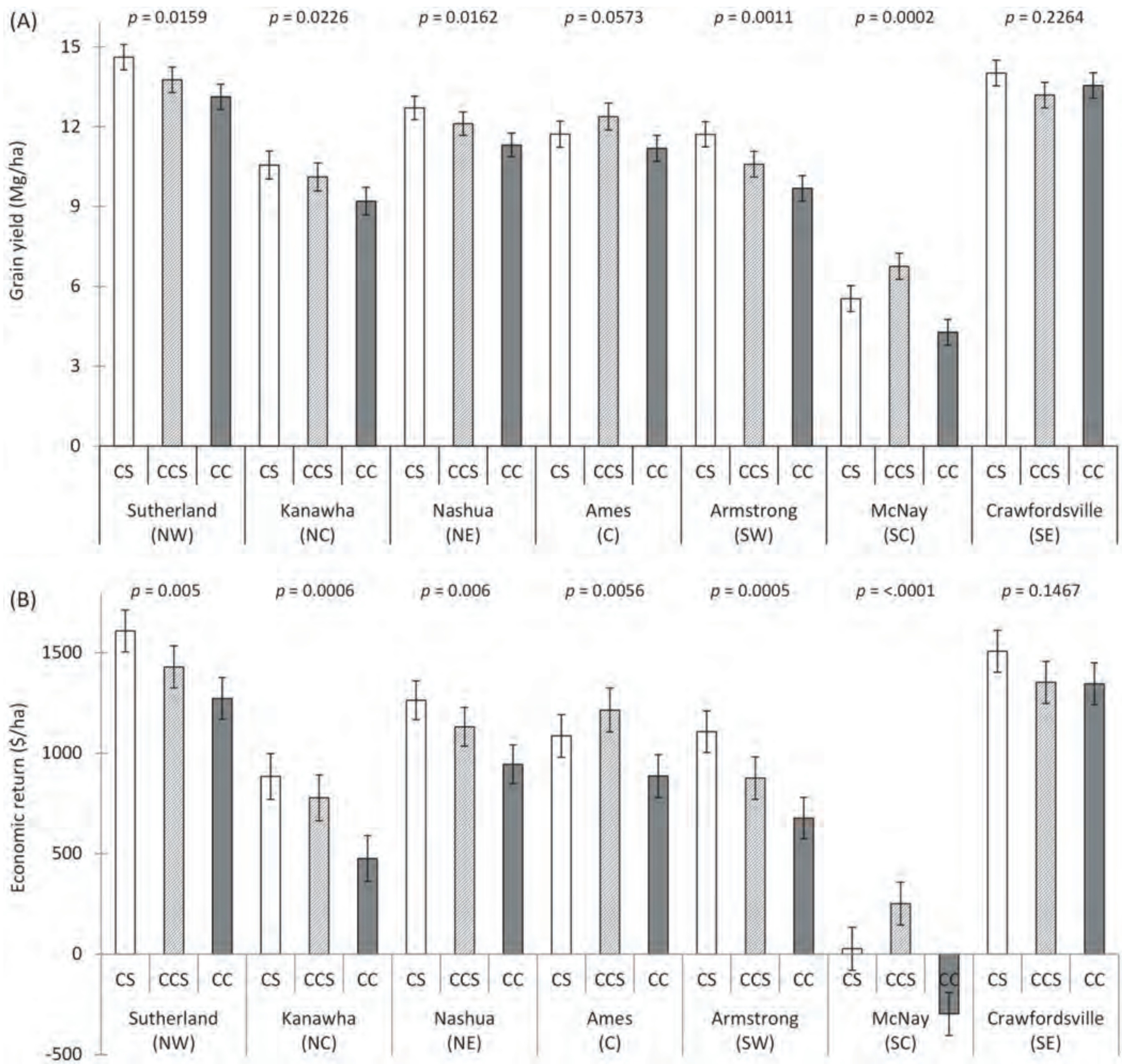

Fig. 5. (A) Regional corn yield and (B) economic return as affected by crop rotation at seven locations in Iowa. *P* values calculated for each location's crop rotations comparison is at $P < 0.05$. Vertical bars indicate the standard error of the mean values.

Economic Return as Influenced by Tillage and Crop Rotation

There was a significant interaction between tillage and location for regional input cost ($P = 0.01$) and economic returns ($P = 0.02$) in the C–S rotation. However, no interactions were found in the C–C–S and C–C rotations ($P > 0.05$) and therefore individual tillage and location effects were examined and were found statistically significant ($P < 0.05$). Table 5 shows corn economic returns and the associated input costs for each tillage system and crop rotation. As expected, input costs for conventional tillage systems (CP, DR, and MP) were higher than those for NT by 7.5% and 5.7% for the ST systems and this was consistent for all crop rotations and locations (Table 5).

In the C–S rotation, the economic return varied among locations (from \$379 to \$1199 ha^{-1}). The NT system economic return was significantly lower than that with conventional tillage (CP, DR, and MP) systems and ST, except at the NW, SW, and SE locations (Table 5). In the C–C–S rotation, the economic return was not significantly different among all tillage systems at all locations, except for the Ames location (central Iowa), where NT had the lowest economic return compared to those of other tillage systems, but it was not significantly different from that for ST.

The economic return with the C–C rotation was not significantly different for all tillage systems, except at the NW location, where both NT and ST economic returns were significantly lower than those with conventional tillage systems (CP, DR, and MP). In one location in particular, McNay (south central), the C–C economic return was negative, and the lowest among all locations due to low yield associated with all tillage systems (Tables 4 and 5 and Fig. 4). The McNay location is characterized by poorly-drained soil conditions, which led to serious management challenges during wet and dry periods.

The only viable crop rotation for the McNay location from an agronomic and economic return standpoint is C–S or C–C–S, where modest economic return was achieved.

While the NT system can provide conservation benefits in the northern Corn Belt (Al-Kaisi and Yin, 2004; Archer and Reicosky, 2009; Karlen et al., 2013) adoption has been low due to concerns about potential yield reduction and economic risk. The results of this study show that differences between conventional tillage systems and NT or ST in economic returns in Iowa were in the range of 5.2 to 15.9%. Specifically, conventional tillage systems (CP, DR, and MP) were superior to NT and ST by 9.8 and 5.2%, respectively, under C–S rotation, 15.9 and 7.4% under C–C–S rotation, and 11.1 and 11.0% under C–C rotation, respectively. It appears that the adoption of NT or ST practices in combination with a C–S rotation has lower risk for yield and economic return losses as compared to C-C-S or C-C rotation. Moreover, the results of this study shows that in the southern locations, the use of NT and ST practices are feasible, where economic returns losses were very small as compared to conventional tillage systems across all rotations (Table 5). However, the economic return losses with NT and ST compared to conventional tillage systems was 14 and 8%, respectively, in the northern locations across all rotations. In another study on corn economic performance near Morris, MN (Archer and Reicosky, 2009), they found higher economic return for NT compared to conventional tillage systems.

The average economic returns for the C–S, C–C–S, and C–C rotations were \$959, \$823 and \$561ha^{-1}, respectively (Table 5). Karlen et al. (2013) found similar trend with greater economic returns in the C–S as compared to C–C, though their findings indicated even higher economic returns than our findings. This difference is most likely attributable to different management practices and assumptions made in the calculations of input costs in the two studies (corn price, cost of herbicides etc.).

Rotation Effects on Corn Yield and Economic Return

The effect of crop rotation on yield and economic return was determined using a subset of data, where corn was present in three rotations (C–S, C–C–S, and C–C) in the same year at each location (Fig. 5). In this analysis, the rotation × tillage × location interaction was not significant ($P = 0.06$ for yield and $P = 0.09$ for economic return), the rotation × tillage interaction was not significant either ($P = 0.09$ for yield and $P = 0.10$ for economic return), but the rotation × location interaction was highly significant ($P < 0.001$ for both variables). Therefore, we presented the results by rotation within each location (Fig. 5). Significant differences in yields were found between crop rotations in six out of the seven study locations. The order of yield and economic returns benefit was: C–S > C–C–S > C-C (Fig. 5). The results of this study indicate that the C–S rotation was consistently superior ($P < 0.05$) to C–C–S and C–C by 5 and 11% in yields and 11 and 31% in economic returns, respectively, in Sutherland, Kanawha, and Nashua (northern locations). In central Iowa (Ames), there was a marginal ($P = 0.06$) yield increase, but a significant economic return ($P = 0.006$) benefit with the C–C–S rotation over the C–C, while both C–C–S and C–S rotations did not differ from each other. In the southern locations, the effects of crop rotation were not consistent (P values in Fig. 5). In Southwest Iowa, C–S rotation was superior to C–C–S and C–C in terms of yield and economic return ($P < 0.05$). In the south central location, a region which is characterized by poorly-drained soil leading to field management challenges, corn yield under C–C was significantly lower, which led to negative economic returns compared to C–S and C–C–S rotations (Fig. 5). According to our results, corn yield below 5.5 Mg ha^{-1} in that region is associated with negative economic return. In southeast Iowa, all rotations performed similarly ($P > 0.05$).

In general, the results of the rotation effect agree with those found in Illinois (Gentry et al., 2013), Minnesota (Porter et al., 1997; Porter et al., 2003), Wisconsin (Pedersen and Lauer, 2003), Pennsylvania (Grover et al., 2009), Iowa (Liebman et al., 2008; Karlen et al., 2013), Nebraska (Peterson and Varvel, 1989), and Indiana (Vyn et al., 2000). In a recent study in Illinois, Gentry et al. (2013) found that 84% of the rotation effect is due to nitrogen availability. Although the N rates were adjusted in this study for corn in C–S, C–C–S and C–C rotations as recommended by the regional N rate calculator (Sawyer et al., 2006), the rotation effect was still evident in most of the study locations (Fig. 5). In general, our study confirms that there is a significant corn yield reduction under continuous corn as compared to C–S, and also highlights that yield reduction is location specific (latitude) and generalization regarding the magnitude of yield reduction across Iowa or the Midwest should be avoided (Fig. 5).

CONCLUSIONS

The results show specific regional soil and weather conditions effects on corn yield and economic return with different tillage and crop rotations. The corn yield response to different tillage systems within each crop rotation was similar with a few exceptions, where NT yield was significantly lower than conventional tillage systems, especially in the northern locations in Iowa. Our results confirm the general trend in yield decline for corn yield under C–C as compared to that under C–S rotation. Corn yield and economic return decline with C–C are location specific as influenced by location latitude and soil formation characteristics within Iowa. The range of yield decline under C–C was from 11 to 28%, but greater decline was observed under poorly-drained soils and during drought condition in south central Iowa (53%). The input cost for corn production was greater with conventional tillage systems over NT and ST by 7.5 and 5.7%, respectively. However, the economic return for conventional tillage systems was higher than that for NT and ST systems by 9.8 and 5.2%, respectively, in a C–S rotation, 15.9 and 7.4% in a C–C–S rotation, and11.1 and 11.0% in a C–C rotation, respectively. The results of this study suggest that at locations with well-drained soils, NT and ST can be competitive in terms of yield and economic return as compared to conventional tillage systems. Corn production in a C–C system regardless of the tillage system led to a significant decline in yield and economic return. This decline in corn yield in C–C is highly related to rotation effect regardless of tillage system or location in the state.

REFERENCES

Al-Kaisi, M., R.W. Elmore, J.G. Guzman, H.M. Hanna, C.E. Hart, M.J. Helmers et al. 2013. Drought impact on crop production and soil environment: 2012 experience from Iowa. Soil Water Cons. J. 68(1):19–24.

Al-Kaisi, M.M., and X. Yin. 2004. Stepwise time response of corn yield and economic return to no tillage. Soil Tillage Res. 78:91–101. doi:10.1016/j.still.2004.02.011

Al-Kaisi, M.M., X. Yin, and M.A. Licht. 2005. Soil carbon and nitrogen changes as affected by tillage system and crop biomass in a corn-soybean rotation. Applied Soil Ecol. 30:174–191. doi:10.1016/j.apsoil.2005.02.014

Archer, D.W., and D.C. Reicosky. 2009. Economic performance of alternative tillage systems in the northern corn belt. Agron. J. 101:296–304. doi:10.2134/agron j 2008.0090x.

Conant, R.T., M. Easter, K. Paustian, A. Swan, and S. Williams. 2007. Impacts of periodic tillage on soil C stocks: A synthesis. Soil Tillage Res. 95:1–10. doi:10.1016/j.still.2006.12.006

Coughenour, C.M., and S. Chamala. 2000. Conservation tillage and cropping innovation: Constructing the new culture of agriculture. Iowa State Univ. Press, Ames.

Coulter, J.A., C.C. Sheaffer, D.L. Wyse, M.J. Haar, P.M. Porter, S.R. Quiring, and L.D. Klossner. 2011. Agronomic performance of cropping systems with contrasting crop rotations and external inputs. Agron. J. 103:182–192. doi:10.2134/agronj2010.0211

Crookston, R.K., J.E. Kurle, P.J. Copeland, J.H. Ford, and W.E. Lueschen. 1991. Rotational cropping sequence affects yield of corn and soybean. Agron. J. 83:108–113. doi:10.2134/agronj1991.00021962008300010026x

DeFelice, M.S., P.R. Carter, and S.B. Mitchell. 2006. Influence of tillage on corn and soybean yield in the United States and Canada. www.plantmanagementnetwork.org/cm/. Crop Manage. doi:10.1094/CM-2006-0626-01-RS.

Drinkwater, L.E. 2002. Cropping systems research: Reconsidering agricultural experimental approaches. Horttechnology 12(3):355–361.

Duffy, M. 2014. Estimated costs of crop production in Iowa–2014. Ag Decision Maker, File A1-20. Iowa State Univ. Ext. and Outreach. http://www.extension.iastate.edu/agdm/crops/pdf/a1-20.pdf (accessed 11 June 2014).

Egli, D.B. 2008. Comparison of corn and soybean yields in the United States: Historical trends and future prospects. Agron. J. 100:S-79–S-88. doi:10.2134/agronj2006.0286c

Endale, D.M., H.H. Schomberg, D.S. Fisher, M.B. Jenkiins, R.R. Sharpe, and M.L. Cabrera. 2008. No-till corn productivity in southeastern United States Ultisols amended with poultry litter. Agron. J. 100:1401–1408. doi:10.2134/agronj2007.0401

Gentry, L.F., M.L. Ruffo, and F.E. Below. 2013. Identifying factors controlling the continuous corn yield penalty. Agron. J. 105:295–303. doi:10.2134/agronj2012.0246

Griffith, D.R., E.J. Kladivko, J.V. Mannering, T.D. West, and S.D. Parsons. 1988. Long-term tillage and rotation effects on corn growth and yield on high and low organic matter, poorly drained soils. Agron. J. 80:599–605. doi:10.2134/agronj1988.00021962008000040011x

Grover, K.K., H.D. Karsten, and G.W. Roth. 2009. Corn grain yields and yield stability in four long-term cropping systems. Agron. J. 101:940–946. doi:10.2134/agronj2008.0221x

Halvorson, A.D., A.R. Mosier, C.A. Ruele, and W.C. Bausch. 2006. Nitrogen and tillage effects on irrigated continuous corn yields. 2006. Agron. J. 98:63–71. doi:10.2134/agronj2005.0174.

Hanna, M. 2001. Estimating field capacity of farm machines. PM 696. Revised April 2001. Iowa State Univ. Ext., Ames.

Hansen, N.C., L.A. Brett, R.L. Baumhardt, and D.J. Lyon. 2012. Research achievements and adoption of no-till, dryland cropping in the semi-arid U.S. Great Plains. Field Crops Res. 132:196–203. doi:10.1016/j.fcr.2012.02.021

Hatfield, J.L. 2014. Radiation use efficiency: Evaluation of cropping and management systems. Agron. J. 106(5):1820–1827. doi:10.2134/agronj2013.0310

Huggins, D.R., R.R. Allmaras, C.E. Clapp, J.A. Lamb, and G.W. Randall. 2007. Corn-soybean sequence and tillage effects on soil carbon dynamic-s and storage. Soil Sci. Soc. Am. J. 71:145–154. doi:10.2136/sssaj2005.0231

Kalfas, J.L., X. Xiao, D.X. Vanegas, S.B. Verma, and A.E. Suyker. 2011. Modeling gross primary production of irrigated and rain-fed maize using MODIS imagery and CO_2 flux tower data. Agric. For. Meteorol. 151(12):1514–1528. doi:10.1016/j.agrformet.2011.06.007

Kapusta, G., R.F. Krausz, and J.L. Mathews. 1996. Corn yield is equal in conventional, reduced, and no tillage after 20 years. Agron. J. 88:812–816. doi:10.2134/agronj1996.00021962008800050021x

Karlen, D.L., J.L. Kovar, C.A. Cambardella, and T.S. Colvin. 2013. Thirty-year tillage effects on crop yield and soil fertility indicators. Soil Tillage Res. 130:24–41. doi:10.1016/j.still.2013.02.003

Katsvairo, T.W., and W.J. Cox. 2000. Economics of cropping systems featuring different rotations, tillage and management systems. Agron. J. 92:485–493. doi:10.2134/agronj2000.923485x

Khan, S.A., R.L. Mulvaney, T.R. Ellsworth, and C.W. Boast. 2007. The myth of nitrogen fertilization for soil carbon sequestration. J. Environ. Qual. 36:1821–1832. doi:10.2134/jeq2007.0099

Khanal, S., R.P. Anex, B.K. Gelder, and C. Wolter. 2014. Nitrogen balance in Iowa and the implications of corn-stover harvesting. Agric. Ecosyst. Environ. 183:21–30. doi:10.1016/j.agee.2013.10.013

Kumar, S., A. Kadono, R. Lal, and W. Dick. 2012. Long-term no-till impacts on organic carbon and properties of two contrasting soils and carbon yields in Ohio. Soil Sci. Soc. Am. J. 76:1798–1809. doi:10.2136/sssaj2012.0055

Lal, R., and J.M. Kimble. 1997. Conservation tillage for carbon sequestration. Nutr. Cycl. Agroecosyst. 49:243–253. doi:10.1023/A:1009794514742

Licht, M.A., and M. Al-Kaisi. 2005. Strip-tillage effect on seedbed soil temperature and other soil physical properties. Soil Tillage Res. 80:233–249. doi:10.1016/j.still.2004.03.017

Liebman, M., L.R. Gibson, D.N. Sundberg, A.H. Heggenstaller, P.R. Westerman, C.A. Chase et al. 2008. Agronomic and economic performance characteristics of conventional and low-external-input cropping systems in the central Corn Belt. Agron. J. 100(3):600–610. doi:10.2134/agronj2007.0222

Machado, S., E.D. Bynum, Jr., T.L. Archer, R.J. Lascano, L.T. Wilson, J. Bordovsky et al. 2002. Spatial and temporal variability of corn growth and grain yield: Implications for site-specific farming. Crop Sci. 42:1564–1576. doi:10.2135/cropsci2002.1564

Manley, J., G. Cornelis van Kooten, K. Moeltner, and D.W. Johnson. 2005. Creating carbon offsets in agriculture through no-till cultivation: A meta-analysis of costs and carbon benefits. Clim. Change 68:41–65. doi:10.1007/s10584-005-6010-4

Meyer-Aurich, A., A. Weersink, K. Janovicek, and B. Deen. 2006. Cost efficient rotation and tillage options to sequester carbon and mitigate GHG emissions from agriculture in eastern Canada. Agric. Ecosyst. Environ. 117:119–127. doi:10.1016/j.agee.2006.03.023

Mitchell, C.C., R.L. Westerman, J.R. Brown, and T.R. Peck. 1991. Overview of long-term agronomic research. Agron. J. 83:24–29. doi:10.2134/agronj1991.00021962008300010010x

Oschwald, W.R., F.F. Riecken, R.I. Dideriksen, W.H. Scholtes, and F.W. Schaller. 1965. Principal soils of Iowa. Spec. Rep. 142. Iowa State Univ. of Science and Technol., Coop. Ext. Serv., Ames.

Paustian, K., H.P. Collins, and E.A. Paul. 1997. Management controls on soil carbon. In: E.A. Paul et al., editors, Soil organic matter in temperate agroecosystems: Long-term experiments in North America. CRC Press, Boca Rotan, FL. p. 15–50.

Pedersen, P., and J.G. Lauer. 2002. Influence of rotation sequence on the optimum corn and soybean plant population. Agron. J. 94:968–974. doi:10.2134/agronj2002.0968

Pedersen, P., and J.G. Lauer. 2003. Corn and soybean response to rotation sequence, row spacing and tillage system. Agron. J. 95:965–971. doi:10.2134/agronj2003.0965

Peterson, T.A., and G.E. Varvel. 1989. Crop yield as affected by rotation and N rate. III. Corn. Agron. J. 81:735–738. doi:10.2134/agronj1989.00021962008100050007x

Porter, P.M., R.K. Crookston, J.H. Ford, D.R. Huggins, and W.E. Lueschen. 1997. Interrupting yield depression in monoculture corn: Comparative effectiveness of grasses and dicots. Agron. J. 89(2):247–250. doi:10.2134/agronj1997.00021962008900020015x

Porter, P.M., D.R. Huggins, C.A. Perillo, S.R. Quiring, and R.K. Crookston. 2003. Organic and other management strategies with two- and four-year crop rotations in Minnesota. Agron. J. 95(2):233–244. doi:10.2134/agronj2003.0233

Rasmussen, K.J. 1999. Impact of ploughless soil tillage on yield and soil quality: A Scandinavian review. Soil Tillage Res. 53:3–14. doi:10.1016/S0167-1987(99)00072-0

Ribera, L.A., F.M. Hons, and J.W. Richardson. 2004. An economic comparison between conventional and no-tillage farming systems in Burleson County, Texas. Agron. J. 96:415–424. doi:10.2134/agronj2004.0415

Richter, D. deB.,Jr., M. Hofmockel, M.A. Callaham, D.S. Powlson, and P. Smith. 2007. Long-term soil experiments: Keys to managing Earth's rapidly changing ecosystems. Soil Sci. Soc. Am. J. 71:266–279. doi:10.2136/sssaj2006.0181

Sakurai, G., T. Iizumi, and M. Yokozawa. 2011. Varying temporal and spatial effects of climate on maize and soybean affect yield prediction. Clim. Res. 49:143–154. doi:10.3354/cr01027

SAS Institute. 2011. The SAS system for Windows. Release 9.3. SAS Inst., Cary, NC.

Sawyer, J., E.D. Nafziger, G.W. Randall, L. Bundy, G. Rehm, and B. Joern. 2006. Concepts and rationale for regional nitrogen rate guidelines. Ext. Publ. PM 2015. Iowa State Univ., Ames.

Shapiro, C.A., D.L. Holshouser, W.L. Kranz, P.D. Sheldon, J.F. Witkowski, K.J. Jarvi et al. 2001. Tillage and management alternatives for returning Conservation Reserve Program land to crops. Agron. J. 93:850–862. doi:10.2134/agronj2001.934850x

Sindelar, A.J., J.A. Coulter, J.A. Lamb, and J.A. Vetsch. 2013. Agronomic responses of continuous corn to stover, tillage and nitrogen management. Agron. J. 105(6):1498–1506. doi:10.2134/agronj2013.0181

Smith, R.G., F.D. Menalled, and G.P. Robertson. 2007. Temporal yield variability under conventional and alternative management systems. Agron. J. 99:1629–1634. doi:10.2134/agronj2007.0096

Stanger, T.F., and J.G. Lauer. 2008. Corn grain yield response to crop rotation and nitrogen over 35 years. Agron. J. 100(3):643–650. doi:10.2134/agronj2007.0280

Stanger, T.F., J.G. Lauer, and J.P. Chavas. 2008. The profitability and risk of long-term cropping systems featuring different rotations and nitrogen rates. Agron. J. 100(1):105–113. doi:10.2134/agrojnl2006.0322

Stonehouse, D.P., B.D. Kay, J.K. Baffoe, and D.L. Johnston-Drury. 1988. Economic choices of crop sequences on cash-cropping farms with alternative crop yield trends. J. Soil Water Conserv. 43(3):266–270.

Toliver, D.K., J.A. Larson, R.K. Roberts, B.C. English, D.G. DeLa Torre Ugarte, and T.O. West. 2012. Effects of no-till on yields as influenced by crops and environmental factors. Agron. J. 104(2):530–541. doi:10.2134/agronj2011.0291

USDA-NRCS. 2013. Published soil surveys for Iowa. NRCS. http://www.nrcs.usda.gov/wps/portal/nrcs/surveylist/soils/survey/state/?stateId=IA (accessed February 2015).

Vetsch, J.A., G.W. Randall, and J.A. Lamb. 2007. Corn and soybean production as affected by tillage system. Agron. J. 99:952–959. doi:10.2134/agronj2006.0149

Vyn, T.J., T.D. West, and G.C. Steinhardt. 2000. Corn and soybean response to tillage and rotation systems on a dark prairie soil: 25 year review. No. 196 (p. 1–10) in Proceedings, 15th Conference of International Soil Tillage Research Organization, Fort Worth, TX. 2–6 July 2000. http://www.agry.purdue.edu/staffbio/ISTROConf.2000Manuscript.pdf (accessed 18 Mar. 2014).

Wang, X.B., D.X. Cai, W.B. Hoogmoed, O. Oenema, and U.D. Perdok. 2006. Potential effect of conservation tillage on sustainable land use: A review of global long-term studies. Pedosphere 16(5):587–595. doi:10.1016/S1002-0160(06)60092-1

Wilhelm, W.W., and C.S. Wortmann. 2004. Tillage and rotation interactions for corn and soybeans grain yield as affected by precipitation and air temperature. Agron. J. 96:425–432. doi:10.2134/agronj2004.0425