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Tillage × Rotation × Management Interactions in Corn

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ABSTRACT

Although corn (*Zea mays* L.) yields following soybean [*Glycine max* (L.) Merr.] or wheat (*Triticum aestivum* L.) exceed yields of continuous corn, continuous corn is common in the northeastern USA because of demand for corn by the dairy industry. We evaluated corn under different tillage (moldboard plow, chisel, and ridge), rotation (continuous corn, soybean–corn, soybean–corn–corn, and soybean–wheat/red clover (*Trifolium pratense* L.)–corn), and management systems (high and low chemical input) for 6 yr to determine optimum cropping systems for corn. In moldboard plow, corn in soybean–wheat/red clover–corn (9.2 Mg ha^{-1}) and soybean–corn (8.5 Mg ha^{-1}) rotations under low chemical yielded greater than continuous corn under high chemical management (7.9 Mg ha^{-1}). In chisel tillage, corn in the soybean–corn rotation yielded greater under high chemical (8.9 Mg ha^{-1}) and similarly under low chemical (7.9 Mg ha^{-1}) compared with continuous corn under high chemical management (7.6 Mg ha^{-1}). In ridge tillage, corn in soybean–corn or first-year corn in soybean–corn–corn rotations yielded greater under high chemical (8.1 Mg ha^{-1}) but less under low chemical (6.3 and 6.8 Mg ha^{-1}, respectively) compared with continuous corn under high chemical management (7.5 Mg ha^{-1}). Growers under similar environmental conditions to this study can increase corn yields while reducing inputs by adopting soybean–wheat/red clover–corn and soybean–corn rotations in moldboard plow or a soybean–corn rotation in chisel tillage. In ridge tillage, growers could adopt soybean–corn or soybean–corn–corn rotations, which would increase corn yields but not reduce inputs when compared with continuous corn.

Corn grown in rotation with soybeans or wheat yields greater than continuous corn does (Lund et al., 1993; West et al., 1996). The corn yield response to crop rotation, however, can interact with years (Porter et al., 1997), tillage systems (Raimbault and Vyn, 1991), and management inputs (Riedell et al., 1998). The 1996 Federal Agriculture Improvement and Reform Act, which allows for planting flexibility by decoupling support payments from production, will result in increased corn acreage grown in rotation with other crops. Corn growers require more information on yield interactions with years, tillage, rotation, and management systems.

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Porter et al. (1997) reported that the yield advantage for corn in an annual soybean–corn rotation compared with continuous corn frequently exceeded 25% in low-yielding years, but averaged less than 15% in high-yielding years. Other researchers have also reported greater yields for rotated compared with continuous corn in dry vs. wet years (Peterson and Varvel, 1989; Raimbault and Vyn, 1991). Also, the corn yield response to crop rotation is usually greater under no-till or reduced tillage systems compared with moldboard plow tillage (Dick and Van Doren, 1985). For example, in Ontario, Canada, Raimbault and Vyn (1991) reported that rotated corn yielded 4% greater than continuous corn in moldboard plow tillage but 8% greater in chisel tillage. Likewise, West et al. (1996) reported that corn in an annual soybean–corn rotation yielded 6% greater than continuous corn in moldboard plow tillage but 10% greater in chisel and ridge tillage. Riedell et al. (1998) also reported that the level of inputs provided to corn can affect the crop rotation response. For example, corn following soybean compared with continuous corn under intermediate inputs (reduced tillage, no soil insecticide, reduced herbicide input, and ~50 kg N ha^{-1}) yielded 32% more, but yielded the same under high inputs (moldboard plow, soil insecticide, full herbicide inputs, and ~75 kg N ha^{-1}).

We conducted a 6-yr tillage × rotation × management study to determine optimum cropping systems for corn production in the northeastern USA. Previous studies, with the exception of the study by Riedell et al. (1998), did not vary management systems when evaluating different crop rotations. We were particularly interested in potential rotation × management interactions and wished to test the hypothesis that rotated corn with low chemical inputs could yield as well as continuous corn with high chemical inputs, a common cropping system in the northeastern USA.

MATERIALS AND METHODS

A 6-yr tillage × rotation × management study was initiated in the fall of 1991 on a tile-drained Kendaia-Lima silt loam soil (fine-loamy, mixed, nonacid, mesic Aeric Haplaquept) at

Abbreviations: GDD, growing degree days; V*n*, *n*th leaf stage.

Table 1. Crop rotations and their different phases from 1992 to 1997. The data presented in this paper are from the corn crops in italics.

Crop rotation	1992	1993	1994	1995	1996	1997
Continuous corn	corn	*corn*	*corn*	*corn*	*corn*	*corn*
Soybean–corn	soybean	*corn*	soybean	*corn*	soybean	*corn*
	corn	soybean	*corn*	soybean	*corn*	soybean
Soybean–corn–corn	corn	*corn*	soybean	*corn*	*corn*	soybean
	soybean	*corn*	*corn*	soybean	*corn*	*corn*
	corn	soybean	*corn*	*corn*	soybean	*corn*
Soybean–wheat/red clover–corn	wheat/red clover	*corn*	soybean	wheat/red clover	*corn*	soybean
	soybean	wheat/red clover	*corn*	soybean	wheat/red clover	*corn*
	corn	soybean	wheat/red clover	*corn*	soybean	wheat/red clover

the Robert B. Musgrave Farm near Aurora, NY (42°45′ N, 76°35′ W). The 2-ha experimental site had been under chisel tillage since 1988 and had been planted to soybean in 1991. Soil tests in the fall of 1991 indicated a pH of 7.8 and medium soil P and K concentrations.

Experimental design was a randomized complete block in a split-split plot treatment arrangement with four replications. Main plots, 55 m wide by 30 m long, consisted of three tillage systems (chisel, moldboard plow, and ridge). Moldboard and chisel tillage operations occurred in the fall of 1991 but during the spring in all subsequent years. Subplots, 6.1 m wide (8 rows of corn) by 30 m long, consisted of four crop rotations. Crop rotations included continuous corn, soybean–corn in both phases, soybean–corn–corn in all three phases, and soybean–wheat/red clover–corn in all three phases (Table 1). We will report only the corn results in this paper. Soybean and wheat yields are reported in a companion paper (Katsvairo and Cox, 2000). Sub-subplots, 6.1 m wide by 15 m long, consisted of high and low chemical input management of all three crops in the four rotations.

'Pioneer Brand 9162' soybean was planted in May and harvested in early October in each year of the study in the soybean–corn, soybean–corn–corn, and soybean–wheat/red clover–corn rotations. Soybeans did not receive any starter fertilizer. After disking in the soybean residue in chisel and moldboard tillage systems, 'Geneva' winter wheat was drilled at 0.18 m row spacing in all tillage systems during the second week of October in the soybean–wheat/red clover–corn rotation. Wheat received starter fertilizer at a rate of 13, 53, and 53 kg ha^{-1} of N, P, and K, respectively. 'Mammouth' red clover was frost-seeded into the wheat crop in March of each year as a green manure crop. After wheat harvest in July, the wheat straw was baled. Red clover then grew rapidly in the late summer and early fall. In 1993, red clover in the moldboard plow and chisel tillage plots was incorporated via tillage operations a day before planting. Clover in the ridge tillage plots received 1.12 kg ha^{-1} a.i. of glyphosate [*N*-(phosphonomethyl) glycine isopropylamine salt] 3 d before planting in 1993. Because of clover regrowth in corn in both chisel and ridge tillage in 1993, clover under both tillage systems in high and low chemical management plots received 0.56 kg ha^{-1} a.i. of glyphosate and 1.12 kg ha^{-1} a.i. of dicamba [3,6-dichloro-*o*-anisic-acid] in the late fall in all subsequent years to eliminate clover regrowth in corn during the following growing season.

'Pioneer Brand 3525' hybrid corn was planted in early May of all years except 1996, when planting was delayed until late May because of wet conditions, at a row spacing of 0.76 m and a planting rate of 72 000 kernels ha^{-1} with a Buffalo Till Planter (Fleisher Manufacturing Co., Columbus, NE).[1] Sweeps were mounted on the planter for a one-pass tillage planting operation in ridge tillage, which had average residue counts (Sloneker and Moldenhauer, 1977) at planting of about 80% when corn followed corn or wheat/red clover and about 40% when corn followed soybean (data not shown). Sweeps were removed from the planter for moldboard plow and chisel tillage plots. Crop residue counts in moldboard plow tillage, which was followed by a single cultimulch operation, averaged less than 10%, regardless of the previous crop (data not shown). Crop residue counts in chisel tillage, which was followed by a disking–cultipacker operation in all rotations, averaged about 35% when corn followed corn or wheat/red clover and about 20% when corn followed soybean (data not shown).

Starter fertilizer was applied in a band at planting in all corn plots at a rate of 28, 56, and 56 kg ha^{-1} of N, P, and K, respectively. The high chemical management plots received a broadcast application of 2.5 kg ha^{-1} a.i. of cyanazine (2-[4-chloro-6-(ethylamino)-*S*-triazin-2-yl] amino]-2-methlypropanenitrile] and 2.2 kg ha^{-1} a.i. of metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl) acetamide] immediately afer planting for weed control. The low chemical management plots received the same rate per hectare in a 0.25-m band over the row at planting. The high chemical management treatment also received 1.12 kg ha^{-1} a.i. of the soil-applied insecticide terbufos [*S*-[(1,1-dimethylethyl) thio] methyl] 0,0-diethyl phosphorodithoidle] at planting for corn rootworm control. When corn was at the 4-leaf stage of development (V4, Ritchie et al., 1993) in 1994 and 1997, the high chemical management treatment in moldboard plow and chisel tillage plots received a 0.56 kg ha^{-1} a.i. application of dicamba for broadleaf weed control, specifically field bindweed (*Convolvulus arvensis* L.) and velvetleaf (*Abutilon theophrasti* Medik.). In ridge tillage plots, the high chemical treatment received a 1.12 kg ha^{-1} a.i. application of glyphosate in the fall of 1993 and 1996 for control of perennial weeds, specifically quackgrass [*Agropyron repens* (L.) P. Beauv.] and yellow nutsedge (*Cyperus esculentus* L.). The low chemical management treatment in all tillage systems received one cultivation or ridge reconstruction at the V4 stage in 1993 and 1995 and two cultivations at the V3 and V6 stages in 1994, 1996, and 1997. We cultivated only once in 1993 and 1995 because dry conditions during May and the first half of June limited weed emergence and growth before the V6 stage of corn growth. The ridges were reconstructed in the high chemical treatment in ridge tillage at the same time as in the low chemical treatment. At the V5 stage, the high chemical management plots received 135 kg N ha^{-1}, the recommended N rate for continuous corn at this site (Cornell Recommends for Integrated Field Crop Management, 1998), as a 32% solution of urea and NH_4NO_3 (injected 0.1 m deep between rows). Low chemical management plots received 67 kg N ha^{-1} because previous studies indicated that preceding soybean and red clover crops could provide between 50 and 90 kg N ha^{-1} to the subsequent corn crop (Bruulsema and Christie, 1987; Bundy et al., 1993).

Plant densities were determined by counting the number of plants along the entire length (15 m) of the two harvest rows in each sub-subplot at the V7 stage. Also, weed densities

[1]Mention of a trademark, proprietary product, or vendor does not constitute a guarantee of warranty for the product, and does not imply its approval to the exclusion of other products or vendors that may be suitable.

Table 2. Significance of plant densities (PD), weed densities (WD), grain yield (GY), and grain moisture (GM) of corn in a combined analysis of the 1993 to 1997 data and soil pH, soil P, and soil K concentrations at the conclusion of the study in 1997.

Source	df	PD	WD	GY	GM	pH	P	K
Year	4	***	*	***	***	–	–	–
Error a	15	–	–	–	–	–	–	–
Tillage (Till)	2	***	**	***	***	NS	NS	NS
Year × Till	8	***	NS	NS	**	–	–	–
Error b	30	–	–	–	–	–	–	–
Rotation (Rot)	4	**	***	***	***	NS	NS	*
Year × Rot	16	NS	***	***	***	–	–	–
Till × Rot	8	NS	NS	***	***	NS	NS	NS
Year × Till × Rot	32	NS	*	NS	***	–	–	–
Error c	180	–	–	–	–	–	–	–
Management (Mgt)	1	***	***	***	***	NS	NS	**
Year × Mgt	4	***	***	***	***	–	–	–
Till × Mgt	2	NS	***	**	*	**	***	NS
Year × Till × Mgt	8	NS	***	*	***	–	–	–
Rot × Mgt	4	NS	NS	***	NS	NS	*	NS
Year × Rot × Mgt	16	NS	NS	NS	*	–	–	–
Till × Rot × Mgt	8	NS	NS	NS	**	NS	NS	NS
Year × Till × Rot × Mgt	32	NS	NS	NS	NS	–	–	–
Error d	225	–	–	–	–	–	–	–
CV (%)	–	5.8	54.1	11.4	3.3	2.0	17.7	13.0

*, **, *** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively. NS, not significant.

were determined at the V7 stage by counting all the weeds greater than 5 mm in height in a 1.5-m width straddling the entire length of the two center harvest rows. Weeds that were less than 5 mm in height were not counted because we did not believe that they would interfere with the growth and yield of corn.

Two rows of each sub-subplot were harvested for grain yield with a plot combine fitted with a two-row corn head in late October or early to mid-November of each year. Because of cool growing conditions in 1997, corn was harvested in mid-November, when grain moistures averaged close to 350 g kg^{-1} of water. Corn samples were collected from each sub-subplot to determine grain moisture. Corn yields were then adjusted to 155 g kg^{-1} of water.

After corn harvest in 1997, four soil samples were taken from each corn sub-subplot from the 0- to 0.20-m depth to determine soil pH, P, and K concentrations. Soil pH was measured in a 1:1 soil–water suspension. Soil P and K concentrations were determined using Morgan's solution (pH 4.8), as described by Lathwell and Peech (1965). Soil pH in the fall of 1991 averaged 7.8 across tillage and management plots at the experimental site. Soil P concentrations averaged 4.4 mg kg^{-1}, which is on the cusp of the medium (2–4.5 mg kg^{-1}) and high ranges (4.5–20 mg kg^{-1}) for the soil type at the experimental site (Cornell Recommends for Integrated Field Crop Management, 1998). Soil K concentrations averaged 43 mg kg^{-1}, which is in the medium soil test range (33–47 mg kg^{-1}).

Air temperature and precipitation were recorded hourly at a weather station located at the experimental site. Growing degree days (GDD) were calculated from daily maximum and minimum temperatures as GDD = $[(T_{max} + T_{min})/2] - 10$, where T_{max} = daily maximum (if $T_{max} > 30°C$, then $T_{max} = 30°C$) and T_{min} = daily minimum (if $T_{min} < 10°C$, then $T_{min} = 10°C$).

All data were analyzed by analysis of variance procedures using the SAS Statistical Software Package (SAS Inst., 1991). The rotations were not in place until 1993, so we will present data only from 1993 to 1997. A combined analysis showed numerous interactions with years for plant densities, weed densities, grain yield, and grain moisture (Table 2), so a separate analysis is also presented for each year. Mean separation for main effects and interactions were obtained by Fisher's protected LSD, as described by Little and Hills (1978). Effects were considered significant in all statistical calculations if $P \leq 0.05$.

RESULTS AND DISCUSSION

Weather conditions differed markedly among the five growing seasons (Table 3). The 1993, 1995, and 1997 growing seasons had less than normal precipitation, and the 1994 and 1996 growing seasons had above-normal precipitation. The 1993 and 1995 growing seasons also had above-average GDD, especially during July. In contrast, the 1997 growing season had less than normal GDD, especially in July and August. The 1993 and 1995 growing seasons can thus be characterized as warm and dry, and the 1997 growing season can be characterized as cool and dry. The 1994 and 1996 growing seasons, which had close to normal total GDD, can be characterized as moderately wet with close to normal temperatures.

Tillage, rotation, and management systems affected corn densities, but year × tillage and year × management interactions were observed (Table 2). Corn densities averaged less under ridge compared with chisel tillage in all years except in 1994 (Table 4). Likewise, corn densities averaged less under chisel compared with moldboard plow tillage in all years except in 1996. West et al. (1996) reported no differences in corn densities between chisel and moldboard plow tillage, and greater

Table 3. Monthly precipitation and growing degree days (GDD) at Aurora, NY, during the 1993 to 1997 growing seasons.

Month	1993	1994	1995	1996	1997	Normal†
	Precipitation (mm)					
May	24	73	35	138	67	82
June	84	122	30	103	99	102
July	56	56	90	70	80	79
August	63	135	142	90	41	91
Total	227	386	297	401	287	354
	GDD (°C)					
May	172	132	161	137	99	165
June	268	321	334	303	296	275
July	377	390	390	320	316	350
August	256	303	366	343	300	324
September	244	301	192	299	205	215
Total	1384	1347	1443	1332	1216	1329

† 1961–1990 mean at the Robert B. Musgrave Research Farm.

Table 4. Corn densities under three tillage systems, five crop rotations, and high and low chemical management at Aurora, NY, from 1993 to 1997.

		1993		1994		1995		1996		1997		Mean	
Tillage	Rotation†	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
		plants ha^{-1}											
Chisel	Cont. Corn	57 900	56 700	63 500	67 700	69 100	68 000	70 500	68 600	59 100	57 700	63 630	64 110
	S–*C*	65 000	62 100	70 200	67 700	73 700	72 500	70 100	68 800	60 900	58 000	68 000	65 820
	S–*C*–C	64 100	62 700	71 600	69 300	69 100	72 700	67 400	67 700	62 400	57 600	66 920	66 000
	S–C–*C*	57 500	54 300	64 300	69 200	70 600	66 500	70 500	72 600	58 700	54 000	64 290	63 330
	S–W/RC–*C*	59 300	56 400	66 500	67 300	72 500	68 500	70 100	70 500	56 500	58 100	64 970	64 140
Plow	Cont. Corn	62 600	64 800	70 500	70 800	73 200	71 400	68 400	68 100	66 100	62 900	68 140	67 610
	S–*C*	65 200	62 200	73 000	72 800	74 200	70 900	66 500	64 100	67 500	62 600	69 270	66 540
	S–*C*–C	64 000	63 200	71 900	73 800	75 500	69 200	69 200	67 900	62 300	60 400	68 570	66 900
	S–C–*C*	64 400	66 800	70 700	73 300	72 100	66 200	69 400	67 700	66 600	63 600	68 640	67 520
	S–W/RC–*C*	64 000	59 500	73 400	71 500	69 700	70 200	67 200	65 400	65 400	61 500	67 930	65 600
Ridge	Cont. Corn	56 000	52 900	67 300	67 400	62 700	62 900	65 700	63 000	58 000	52 000	61 930	59 640
	S–*C*	54 900	49 800	71 100	70 800	71 400	64 500	68 800	65 900	59 000	58 600	65 030	61 920
	S–*C*–C	50 700	56 200	66 700	69 100	71 800	64 000	66 300	63 300	58 400	59 600	62 780	62 470
	S–C–*C*	53 400	57 400	67 200	66 600	67 300	60 700	67 500	64 500	53 600	57 200	65 030	61 920
	S–W/RC–*C*	51 100	59 600	70 400	68 800	68 300	66 900	69 200	66 700	46 600	43 300	61 120	59 070
	LSD (0.05)‡	8148		4808		4183		3467		6025		2430	

† Rotations are as follows: Cont. corn, continuous corn; S–C, soybean–corn; S–C–C, soybean–corn–corn; and S–W/RC–C, soybean–wheat/red clover–corn. Italics indicate the phase of the rotation.

‡ LSD compares means among different rotation–management systems within a tillage treatment.

corn densities in moldboard plow compared with ridge tillage only in continuous corn. Cool conditions in May, which had less than normal GDD in four of the five years, may have resulted in less emergence under ridge and chisel tillage because high residue accentuates cool soil conditions and subsequent corn emergence problems in northern latitudes (Swan et al., 1987; Cox et al., 1990). When averaged across years, tillage, and management systems, corn following soybean either in the soybean–corn (66 100 plants ha^{-1}) or soybean–corn–corn rotations (65 610 plants ha^{-1}) had greater corn densities compared with second-year corn in the soybean–corn–corn (64 480 plants ha^{-1}), continuous corn (64 180 plants ha^{-1}), and soybean–wheat/red clover–corn (63 800 plants ha^{-1}) rotations. Again, greater residue when corn followed corn or wheat/red clover in chisel and ridge tillage, coupled with the cool May conditions, probably contributed to lesser corn densities in those rotations.

Weed densities in corn had significant year × tillage × rotation and year × tillage × management interactions (Table 2). In 1993, the soybean–wheat/red clover–corn rotation in chisel and ridge tillage compared with other rotations resulted in greater weed densities (3.5 and 2.5 weeds m^{-2}, respectively, Table 5), predominantly volunteer red clover. In contrast, weed densities did not differ among the rotations in moldboard plow tillage. In 1993, we did not apply glyphosate or dicamba to clover in chisel tillage, and made the application in the spring to ridge tillage. In subsequent years, the glyphosate or dicamba application in the fall to clover in ridge and chisel tillage combined with the other weed control methods under high and low chemical management resulted in satisfactory corn weed control in the soybean–wheat/red clover–corn rotation. Iragavarapu et al. (1997) also reported regrowth of interseeded hairy vetch (*Vicia villosa* Roth) into wheat in the subsequent corn crop under ridge tillage.

The year × tillage × management interaction for weed densities existed because of differences among tillage systems between high and low chemical management in the dry 1993, 1995, and 1997 growing seasons. In all three growing seasons, low chemical management resulted in similar or lower weed densities compared with high chemical management in moldboard plow tillage (Table 5). In contrast, chisel tillage had greater weed densities in low vs. high chemical management in 1993, and ridge tillage had greater weed densities in low vs. high chemical management in all three dry years. Perennial weeds, including quackgrass, yellow nutsedge, field bindweed, Canadian thistle [*Cirsium arvense* (L.) Scop.], common milkweed (*Asclepias syriaca* L.), and clammy ground cherry (*Physalis heterophylla* Nees) were predominant in ridge tillage in most years.

Grain yield had significant year × tillage × management, year × rotation, tillage × rotation, and rotation × management interactions (Table 2). Corn in chisel and moldboard plow tillage responded similarly to the management systems, with yields averaging about 10% less under low vs. high chemical management in the dry years and about 25% less under low vs. high chemical management in the moderately wet years (Table 6). In contrast, corn yields under ridge tillage averaged about 25% less under low vs. high chemical management in all years of the study. Ridge tillage is generally recognized as the most sustainable tillage system (Reeder, 1990). The results from this study, however, indicate that corn under low chemical management yields less under ridge tillage than under moldboard plow and chisel tillage.

When averaged across years, corn in the soybean–wheat/red clover–corn rotation under ridge tillage yielded 7.5 Mg ha^{-1}, 16% greater than average yields in continuous corn (6.4 Mg ha^{-1}) and 4% greater than average yields in the soybean–corn rotation (7.2 Mg ha^{-1}, Table 6). In contrast, corn yields in the soybean–wheat/red clover–corn rotation under moldboard plow tillage averaged 9.4 Mg ha^{-1}, 36% greater than average yields of continuous corn (6.9 Mg ha^{-1}) and 6% greater

Table 5. Weed densities under three tillage systems, five crop rotations, and high and low chemical management at Aurora, NY, from 1993 to 1997.

Tillage	Rotation†	1993 High	1993 Low	1994 High	1994 Low	1995 High	1995 Low	1996 High	1996 Low	1997 High	1997 Low	Mean High	Mean Low
		weeds m^{-2}											
Chisel	Cont. Corn	0.6	1.6	0.8	1.2	1.7	1.8	1.3	1.9	0.8	1.0	1.1	1.4
	S–*C*	1.1	2.6	0.3	1.6	2.2	1.8	1.8	2.7	1.7	1.6	1.4	2.0
	S–*C*–C	1.2	2.6	0.7	0.9	2.9	3.2	1.5	1.9	1.1	1.7	1.5	2.0
	S–C–*C*	1.0	1.6	0.6	1.6	2.3	1.4	1.9	2.6	0.7	0.3	1.3	1.5
	S–W/RC–*C*	3.6	3.3	0.5	2.0	1.6	1.7	1.8	2.1	0.7	0.9	1.6	2.0
Plow	Cont. Corn	1.5	1.6	0.5	1.5	1.4	1.0	1.1	1.7	1.9	0.9	1.3	1.3
	S–*C*	2.0	1.5	0.6	1.7	1.1	0.9	1.5	2.2	1.7	1.0	1.4	1.5
	S–*C*–C	1.1	1.6	0.7	1.7	3.6	1.7	1.3	1.6	1.8	1.6	1.7	1.6
	S–C–*C*	2.0	1.2	0.4	2.0	1.8	1.8	1.4	2.0	0.7	0.8	1.3	1.6
	S–W/RC–*C*	1.7	1.9	0.7	3.0	2.3	1.1	1.6	2.0	2.1	1.7	1.7	1.9
Ridge	Cont. Corn	0.3	0.5	0.3	0.6	2.1	1.9	0.7	1.2	0.1	1.4	0.7	1.1
	S–*C*	0.6	1.4	1.1	1.5	0.5	1.8	1.2	1.7	0.3	2.8	0.7	1.9
	S–*C*–C	0.3	0.9	1.1	1.3	1.4	2.0	0.9	1.5	0.6	2.1	0.9	1.6
	S–C–*C*	0.3	0.6	0.3	0.6	0.7	2.2	1.1	1.8	0.6	1.6	0.6	1.4
	S–W/RC–*C*	1.9	3.2	0.3	0.9	0.9	1.4	0.6	0.8	0.9	2.5	0.9	1.7
	LSD (0.05)‡	0.9		0.7		1.2		0.5		1.2		0.4	

† Rotations are as follows: Cont. corn, continuous corn; S–C, soybean–corn; S–C–C, soybean–corn–corn; and S–W/RC–C, soybean–wheat/red clover–corn. Italics indicate the phase of the rotation.
‡ LSD compares means among different rotation–management systems within a tillage treatment.

than average yields in the soybean–corn rotation (8.9 Mg ha^{-1}). Volunteer clover regrowth resulted in low corn yields in the soybean–wheat/red clover–corn rotation in ridge tillage in 1993, especially under low chemical management, which contributed to year × rotation and tillage × rotation interactions for grain yield. Nevertheless, excluding the 1993 data, corn yields in the soybean–wheat/red clover–corn rotation compared with continuous corn averaged 42% greater in moldboard plow but only 29% greater in ridge tillage. In Minnesota, corn also yielded greater under moldboard compared with ridge tillage when following wheat in the rotation (Iragavarapu et al., 1997).

The rotation × management interaction was associated with the much lower yield of continuous and second-year corn compared with rotated corn under low (5.9 Mg ha^{-1}) vs. high (7.7 Mg ha^{-1}) chemical management, mostly because of inadequate N fertility (Singer and Cox, 1998a). In contrast, corn in the soybean–wheat/red clover–corn rotation in chisel and moldboard plow tillage yielded the same under low and high chemical management (Table 6). Stute and Posner (1995) reported that red clover interseeded into small grains and incorporated the following spring can provide 75 to 115 kg N ha^{-1} to the subsequent corn crop under Wisconsin conditions. In fact, Vyn et al. (1999) suggested that red clover interseeded into wheat and incorporated the following spring may eliminate the need to apply N fertilizer to the subsequent corn crop under growing conditions in Ontario, Canada. Corn received 67 kg ha^{-1} less N fertilizer under low vs. high chemical management, so corn probably had adequate N in the soybean–wheat/red clover–corn rotation, regardless of management systems, in most years under moldboard plow and chisel tillage. Iragavarapu et al. (1997) reported that interseeded legumes into wheat were an inconsistent N

Table 6. Corn yield under three tillage systems, five crop rotations, and high and low chemical management at Aurora, NY, from 1993 to 1997.

Tillage	Rotation†	1993 High	1993 Low	1994 High	1994 Low	1995 High	1995 Low	1996 High	1996 Low	1997 High	1997 Low	Mean High	Mean Low
		Mg ha^{-1}											
Chisel	Cont. Corn	7.9	6.6	9.8	7.8	7.3	6.7	7.8	5.6	5.3	4.1	7.6	6.2
	S–*C*	8.1	7.7	11.8	9.5	8.5	8.6	8.8	7.2	7.2	6.7	8.9	7.9
	S–*C*–C	7.6	6.5	11.4	9.4	8.9	7.5	9.2	7.7	7.5	5.9	8.9	7.4
	S–C–*C*	7.2	6.1	10.9	8.0	7.2	6.4	7.9	6.3	4.7	3.7	7.6	5.9
	S–W/RC–*C*	5.6	6.1	12.2	9.9	9.3	9.1	8.9	8.4	7.6	8.1	8.7	8.3
Plow	Cont. Corn	7.7	6.2	10.8	6.7	8.4	7.2	7.9	5.7	5.0	3.1	7.9	5.8
	S–*C*	8.8	8.6	11.7	10.0	9.2	9.4	9.4	7.6	7.2	6.8	9.3	8.5
	S–*C*–C	8.5	8.6	12.0	9.7	9.3	9.3	8.5	7.5	7.4	6.5	9.1	8.3
	S–C–*C*	8.1	6.7	10.8	8.2	8.7	7.6	7.8	5.8	5.7	3.8	8.2	6.4
	S–W/RC–*C*	7.9	8.4	12.6	11.1	9.8	10.0	8.7	8.4	9.1	8.1	9.6	9.2
Ridge	Cont. Corn	7.1	6.0	9.8	6.6	7.5	5.7	7.8	5.0	5.2	3.6	7.5	5.4
	S–*C*	7.1	5.4	10.2	8.2	7.8	7.2	8.0	5.1	7.3	5.7	8.1	6.3
	S–*C*–C	7.7	6.2	10.7	9.0	7.8	7.5	8.4	6.5	6.0	4.7	8.1	6.8
	S–C–*C*	7.3	5.6	10.2	7.7	7.8	4.6	8.0	5.4	4.8	3.7	7.6	5.4
	S–W/RC–*C*	6.0	2.6	11.2	11.2	8.1	7.7	8.1	7.1	6.4	6.1	8.0	6.9
	LSD (0.05)‡	1.2		1.0		1.5		1.0		1.1		0.5	

† Rotations are as follows: Cont. corn, continuous corn; S–C, soybean–corn; S–C–C, soybean–corn–corn; and S–W/RC–C, soybean–wheat/red clover–corn. Italics indicate the phase of the rotation.
‡ LSD compares means among different rotation–management systems within a tillage treatment.

Table 7. Grain moisture under three tillage systems, five crop rotations, and high and low chemical management at Aurora, NY, from 1993 to 1997.

		1993		1994		1995		1996		1997		Mean	
Tillage	Rotation†	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
		g hg^{-1}											
Chisel	Cont. Corn	273	287	281	296	220	222	214	222	360	361	270	278
	S–*C*	267	273	274	283	227	220	209	224	352	352	266	271
	S–*C*–C	257	273	281	289	218	219	210	218	340	358	261	271
	S–C–*C*	262	285	276	299	225	226	217	222	375	366	271	280
	S–W/RC–*C*	285	294	289	293	226	223	209	219	346	346	271	275
Plow	Cont. Corn	278	274	277	294	227	226	214	232	356	371	270	279
	S–*C*	262	249	277	279	231	219	208	221	350	360	266	266
	S–*C*–C	249	245	277	288	229	221	216	219	334	352	261	265
	S–C–*C*	261	263	291	291	226	224	219	227	349	365	269	274
	S–W/RC–*C*	271	265	286	285	226	223	222	222	342	347	271	269
Ridge	Cont. Corn	279	286	296	301	226	224	229	234	359	371	278	283
	S–*C*	279	303	319	320	229	226	231	251	363	374	284	295
	S–*C*–C	271	277	320	316	225	224	227	230	371	373	283	284
	S–C–*C*	276	276	307	308	228	229	236	244	375	377	284	287
	S–W/RC–*C*	319	376	301	316	223	219	228	227	374	374	289	302
	LSD (0.05)‡	17		12		7		11		15		6	

† Rotations are as follows: Cont. corn, continuous corn; S–C, soybean–corn; S–C–C, soybean–corn–corn; and S–W/RC–C, soybean–wheat/red clover–corn. Italics indicate the phase of the rotation.
‡ LSD compares means among different rotation–management systems within a tillage treatment.

source to the subsequent corn crop in ridge tillage. Excluding 1993, however, when volunteer clover regrowth reduced corn yields, corn yielded only 6% less (8.0 Mg ha^{-1}) in the soybean–wheat/red clover–corn rotation in ridge tillage under low vs. high chemical management (8.5 Mg ha^{-1}).

Corn following soybean in the soybean–corn and soybean–corn–corn rotations yielded 14% less under low (7.5 Mg ha^{-1}) vs. high chemical management (8.7 Mg ha^{-1}, Table 6). Corn under moldboard plow tillage in the soybean–corn rotation yielded only 9% less in low vs. high chemical management compared with 14% less in chisel and 19% less in ridge tillage. Weed densities did not differ under high and low management in the soybean–corn rotation in moldboard plow and chisel tillage, so weed interference did not contribute to yield differences in those tillage systems. Corn apparently requires greater N rates when following soybean compared with wheat/red clover in moldboard plow and chisel tillage. Corn yielded 7% greater in the soybean–corn rotation under high chemical management compared with continuous corn under high chemical management in ridge tillage, whereas corn yielded 17% greater in chisel and moldboard plow tillage. West et al. (1996) reported that corn responded more positively when following soybean in the rotation in ridge compared with moldboard plow tillage. It is not clear why corn responded less when following soybean or wheat/red clover in the rotation under ridge compared with moldboard plow and chisel tillage in this study.

Grain moisture at harvest had numerous interactions, including year × tillage × rotation, year × tillage × management, year × rotation × management, and tillage × rotation × management interactions (Table 2). Many of the interactions involving years can be attributed to the high grain moisture in corn in the soybean–wheat/red clover–corn rotation under ridge tillage in low chemical management in 1993 (Table 7). Consequently, when averaged across years, corn had 13 g kg^{-1} more moisture in the grain at harvest in the soybean–wheat/red clover–corn rotation in ridge tillage under low vs. high chemical management (302 vs. 289 g kg^{-1}, respectively), compared with no differences in moisture under moldboard plow and chisel tillage. Corn also had 11 g kg^{-1} more moisture in the grain at harvest in the soybean–corn rotation in ridge tillage under low vs. high chemical management (295 vs. 284 g kg^{-1}, respectively), compared with no difference in moldboard plow (265 g kg^{-1}) and chisel tillage (269 g kg^{-1}). Other researchers (Al-Darby and Lowery, 1986; Griffith et al., 1988; Cox et al., 1992) reported similar grain moisture between ridge and moldboard plow tillage in continuous corn. In this study, average grain moisture in continuous corn differed the least between ridge (281 g kg^{-1}) and moldboard plow tillage (274 g kg^{-1}). It is not clear why corn grain moisture differed by 25 g kg^{-1} between ridge and moldboard plow tillage in the soybean–corn rotation.

Crop rotation, tillage, and management systems did not affect soil pH (Table 8). Other researchers (Edwards et al., 1992; Lal et al., 1994; Riedell et al., 1998) reported a decrease in soil pH as frequency of corn in the rotation increased because of greater N fertilizer applications to corn. Although continuous corn compared with the soybean–corn rotation received twice the fertilizer N rate over the six years of this study, soil pH did not differ between rotations, presumably because of the high buffering capacity of the soils. A tillage × management interaction for soil pH existed (Table 2) because of the lower soil pH in chisel tillage under high chemical management (7.5) compared with all other tillage and management systems (7.7). It is not clear why chisel tillage under high chemical management, which received the same N fertilizer rate as the high chemical management treatments in moldboard plow and ridge tillage systems, had a lower soil pH.

Tillage × management and rotation × management interactions existed for soil P concentrations (Table 2). Soil P concentrations in chisel tillage averaged 5.7 mg kg^{-1} under high and 6.9 mg kg^{-1} under low chemical management systems at the conclusion of the experiment (Table 8). In contrast, soil P concentrations averaged 6.5 mg kg^{-1} under high and 5.8 mg kg^{-1} under low

Table 8. Soil pH and soil P and K concentrations in the fall of 1997 under three tillage systems, five crop rotations, and high and low chemical management at Aurora, NY.

Tillage	Rotation†	pH		P		K	
		High	Low	High	Low	High	Low
				mg kg⁻¹			
Chisel	Cont. Corn	7.5	7.5	5.7	6.5	54	58
	S–*C*	7.5	7.8	6.1	8.4	54	58
	S–*C*–C	7.6	7.7	5.8	6.3	49	53
	S–C–*C*	7.4	7.7	5.3	7.0	52	55
	S–W/RC–*C*	7.5	7.8	5.4	6.1	57	59
Plow	Cont. Corn	7.7	7.8	6.8	6.9	47	54
	S–*C*	7.8	7.6	5.9	5.6	52	52
	S–*C*–C	7.7	7.6	6.3	4.6	44	49
	S–C–*C*	7.8	7.7	5.8	6.3	47	54
	S–W/RC–*C*	7.7	7.6	7.9	5.7	48	52
Ridge	Cont. Corn	7.7	7.8	5.3	5.8	50	51
	S–*C*	7.7	7.7	6.0	6.0	47	50
	S–*C*–C	7.7	7.8	6.6	5.1	47	46
	S–C–*C*	7.8	7.8	5.5	5.8	45	56
	S–W/RC–*C*	7.7	7.7	6.3	5.0	54	51
	LSD (0.05)‡	NS		0.4		NS	

† Rotations are as follows: Cont. corn, continuous corn; S–C, soybean–corn; S–C–C, soybean–corn–corn; and S–W/RC–C, soybean–wheat/red clover–corn. Italics indicate the phase of the rotation.
‡ LSD compares means among different rotation–management systems within a tillage treatment. NS, not significant.

chemical management in moldboard plow tillage and 5.9 mg kg^{-1} under high and 5.5 mg kg^{-1} under low chemical management in ridge tillage. Greater P solubility at a soil pH value of 7.5 vs. 7.7 probably did not contribute to greater soil P concentrations under high vs. low chemical management in chisel tillage, so it is not clear why this interaction existed.

The soybean–wheat/red clover–corn rotation and first-year corn in the soybean–corn–corn rotation had greater soil P concentrations under high (6.5 and 6.2 mg kg^{-1}, respectively) compared with low chemical management (5.6 and 5.3 mg kg^{-1}, respectively). In contrast, the other rotations had greater soil P concentrations under low compared with high chemical management (Table 8). Both management systems received either the same starter or no starter P fertilizer annually across rotations, so differential fertilizer rates did not contribute to the rotation × management interaction. Also, corn, soybean, and wheat do not take up a great amount of P, so differential crop removal of P probably did not contribute to the interaction. Soil P concentrations, however, were in the high soil test range for all tillage–rotation–management systems. Consequently, crop rotation had no practical effect on soil P concentrations, despite applying starter P fertilizer only every other year to the soybean–corn rotation.

Rotation and management systems affected soil K concentrations (Table 8). The first-year corn phase in the soybean–corn–corn rotation had the same soil K concentration (48 mg kg^{-1}) as the soybean–corn rotation (50 mg kg^{-1}) but less when compared with the other rotations (52 to 53 mg kg^{-1}). Edwards et al. (1992) reported lower soil K concentrations in soybean–corn compared with continuous corn, despite the same annual K applications in both rotations. Over the six years of our study, the soybean–corn rotation compared with continuous corn received only half the K fertilizer rate, but both rotations had the same soil K concentrations. Soil K concentrations averaged more under low chemical management (53 mg kg^{-1}) compared with high chemical management (49 mg kg^{-1}), despite less crop removal of K associated with lower yields under low chemical management. Soil K concentrations were in the medium-high to high soil test range for all tillage–rotation–management systems. Consequently, crop rotation and management systems had limited practical effects on soil K concentrations.

CONCLUSIONS

Numerous interactions involving years, tillage, rotation, and management systems existed for corn densities, weed densities, corn yields, grain moisture, soil pH, and soil P concentrations. The results from this study corroborate the statement by Riedell et al. (1998) that the level of inputs (tillage, fertilizer rate, and pesticide use) affect the response of corn to crop rotation. Unlike the study by Riedell et al. (1998), who investigated crop rotation and management inputs at the cropping systems level, thus confounding some of the management inputs, the results from this study allow for recommendations on specific tillage–rotation–management systems.

In moldboard plow tillage, corn in the soybean–wheat/red clover–corn rotation under low chemical management yielded as well as corn in the soybean–wheat/red clover–corn, soybean–corn, and soybean–corn–corn rotations under high chemical management. Of equal importance, corn yielded 17% greater in the soybean–wheat/red clover–corn rotation under low chemical management compared with continuous corn under high chemical management. Likewise, corn yielded 7% greater in the soybean–corn rotation under low chemical management compared with continuous corn under high chemical management. The soybean–corn and soybean–wheat/red clover–corn rotations under low chemical management had the same soil P and K concentrations as continuous corn under high chemical management after 6 yr, despite receiving 33 to 50% less P and K fertilizer. Growers who use moldboard plow tillage under environmental conditions similar to those in this study have the opportunity to significantly increase corn yields while greatly reducing inputs by substituting soybean–wheat/red clover–corn or soybean–corn rotations for continuous corn. In fact, Singer and Cox (1998b) reported that corn under low chemical management yielded 10% greater in soybean–corn and soybean–wheat/red clover–corn rotations compared with continuous corn under high chemical management in field-scale demonstrations where four participating farmers performed all field operations. The use of such rotations would ensure greater yield stability of corn, as evidenced by much greater corn yields in the soybean–wheat/red clover–corn rotation under low chemical management compared with continuous corn under high chemical management in dry years (9, 19, and 62% greater) vs. wet years (3 and 6% greater).

In chisel tillage, corn yielded 8% greater in the soybean–wheat/red clover–corn rotation under low chemical management compared with continuous corn under high chemical management. The soybean–wheat/red clover–corn rotation under low chemical management, however, received a glyphosate and dicamba application in the fall for clover control, which increased inputs in this system. Corn in the soybean–corn rotation yielded 4% greater under low chemical management and 17% greater under high chemical management compared with continuous corn under high chemical management. Growers who use chisel tillage under environmental conditions similar to those in this study have the opportunity to increase corn yields while reducing inputs by substituting a soybean–corn rotation under low chemical management for continuous corn under high chemical management. Growers who use chisel tillage, however, should adopt the soybean–corn rotation with close to high chemical inputs to achieve maximum yields. Singer and Cox (1998b) reported about a 10% yield increase for corn in a soybean–corn rotation, which received 40 g kg^{-1} less N compared with continuous corn under high chemical management, in a farmer-participatory study in which farmers used chisel tillage.

In ridge tillage, corn yielded 8% less in the soybean–wheat/red clover–corn rotation under low chemical management compared with continuous corn under high chemical management. Likewise, corn in the soybean–corn rotation under low chemical management yielded 16% less when compared with continuous corn under high chemical management. Corn in soybean–corn or first-year corn in soybean–corn–corn rotations under high chemical management, however, yielded 18% greater than continuous corn under high chemical management. Growers who use ridge tillage and wish to rotate corn can adopt soybean–corn or soybean–corn–corn rotations, which would increase corn yields but not reduce chemical inputs.

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