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Tillage and Crop Sequence Effects on *Heterodera glycines* and Soybean Yields

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ABSTRACT

Conservation tillage has been increasingly used in the midwestern USA. Long-term effects of tillage practices on the soybean [*Glycine max* (L.) Merr.] cyst nematode (SCN), *Heterodera glycines*, and soybean yields in corn–soybean rotation were studied in two fields in Minnesota (USA). The experiments were arranged in a split-plot design with tillage treatments as main plots and crop sequences as subplots. Tillage treatments were no-tillage (NT) and conventional tillage (CT). The crop sequences were six (Waseca) or nine (New Richland) combinations of SCN-susceptible 'Sturdy', SCN-resistant 'Freeborn' ('PI 88788' resistance source) and 'Pioneer brand 9234' ('Peking' resistance source) soybean rotated annually with corn. Tillage did not affect SCN population density at New Richland and had only minimal and inconsistent effects on SCN at Waseca. However, CT resulted in up to 370 kg ha^{-1} greater soybean yield than NT at Waseca. Growing SCN-resistant cultivars was effective in the corn–soybean rotation for managing SCN and minimizing yield loss to SCN. Resistant soybean not only reduced SCN population density and increased soybean yield in the year when it was grown, but also resulted in a smaller inoculum population density and increased yield of susceptible and resistant soybean in the following soybean years. Pioneer brand 9234 was more effective than Freeborn in reducing SCN population density and increasing soybean yield in the following years. This study confirmed that use of resistant cultivars is an effective tactic for SCN management, but tillage is not an option solely for managing SCN population in the northern climate and soil conditions.

THE SOYBEAN CYST NEMATODE is one of the most serious threats to soybean production in most soybean-growing countries and regions in the world (Monson and Schmitt, 2004; Wrather et al., 2001). Rotation of SCN-susceptible soybean with nonhost and SCN-resistant cultivars is currently considered the best method to manage SCN (Chen et al., 2001a; MacGuidwin et al., 1995; Niblack, 2005; Niblack and Chen, 2004; Young, 1998). Some cultural measures such as tillage, water management, cover crops, planting date, selection of soybean maturity group, and soil fertility can play important roles in SCN management (Barker and Koenning, 1998; McSorley and Porazinska, 2001; Niblack and Chen, 2004), but much more research is needed for their effective use.

Since the late 1980s, conservation tillage has been used increasingly in the USA to limit soil erosion, preserve soil moisture during drought, improve water quality, increase organic matter, and reduce fuel costs (Fawcett and Towery, 2005; Noel and Wax, 2003). Tillage may affect nematode communities in soil, but no consistent benefit of using conservation tillage in managing plant-parasitic nematodes was observed in different studies (McSorley, 1998). A number of studies have been reported on the effects of tillage on SCN in the USA. In the southern USA, no-tillage reduced the SCN population density compared with conventional or minimum tillage (Edwards et al., 1988; Hershman and Bachi, 1995; Koenning et al., 1995; Lawrence et al., 1990; Tyler et al., 1983, 1987). Research in the north-central USA demonstrated inconsistent effects of tillage on SCN in the region. Workneh et al. (1999) reported that of all fields that were infested with SCN, the population densities were significantly smaller in no-tillage fields than in fields that received some type of tillage in the north-central USA. Niblack et al. (1999) reported no consistent effect of tillage on SCN population density in Missouri. Increased SCN reproduction in no-tillage as compared with conventional tillage has been reported in Illinois (Noel and Wax, 2003). However, no effect of tillage on SCN population density was observed in an experiment conducted from 1993 to1996 in Minnesota (Chen et al., 2001b). The inconsistent tillage effect on SCN was supported by an extensive study from 1997 to 2000 in nine states in the north-central region of the USA and in Ontario, Canada (Atibalentja et al., 2001).

Two field experiments were conducted in Minnesota to study the effects of tillage on *H. glycines.* One was initiated in 1993 and the results of the first 4 yr were reported in the previous paper (Chen et al., 2001b). The other field experiment was a part of the regional project initiated in 1997 (Atibalentja et al., 2001; Donald et al., 2000). This report documents the results of Years 5 through 10 from these two field experiments. The objective of this experiment was to determine any long-term effects of tillage practices and SCN-resistance in soybean cultivars on *H. glycines* population densities and soybean yields in the corn–soybean rotation in Minnesota.

MATERIALS AND METHODS

Experiment Establishment and Maintenance

This study was performed in two fields near New Richland and Waseca in Waseca County, MN. The New Richland experiment was established in 1993 initially to determine the effects of tillage and row spacing on the soybean cyst nematode and soybean yield (Chen et al., 2001b). The soil was a Webster clay loam (Typic Endoaquoll; fine-loamy, mixed, mesic) with 374 g kg^{-1} sand, 324 g kg^{-1} silt, 302 g kg^{-1} clay, 73 g kg^{-1} organic matter, and pH 7.8 measured in 1998. The SCN population in the field was classified as HG Type 0- (Race 3), which could not reproduce well on the four race differential soybean lines. The minus sign denotes that the HG Type test was not complete, and the reproduction potential of the popu-

Abbreviations: CT, conventional tillage; NT, no-tillage; SCN, soybean cyst nematode.

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lation on the other four HG Type lines was unknown (Niblack et al., 2002).

Two adjacent sites in the same field were used each year; Site A1 was planted to soybean and Site A2 was planted to corn in Year 1 so that in each year data could be obtained from both soybean and corn plots. The experiment at each site was a split-plot design with tillage treatments as main plots, crop sequences as subplots, and four randomized complete blocks (replicates). In the first 4 yr, five tillage treatments and four crop sequence/row spacing treatments were included (Chen et al., 2001b). In the four crop sequences, one SCN-resistant cultivar and one SCN-susceptible cultivar were used. Because there was no difference in SCN population among the five tillage treatments in the first 4 yr (Chen et al., 2001b), the experiment was modified in 1997 to emphasize the crop sequence in which another SCN-resistant cultivar was added. The modified experiment included two tillage treatments, NT and CT, and nine crop sequences: (i) R1–S–R1–R1–R1 (10-yr soybean–corn annual rotation), (ii) R1–S–R2–R2–R1, (iii) S–S–S–S–S, (iv) S–S–R2–R2–R2, (v) R1–S–R2–R1–R2, (vi) R1–S–R2–S–R1, (vii) R1–S–R1–S–R2, (viii) R1–S–R1–R1–R2, and (ix) R1–S–R1–R2–R1. The letters represent the 1st, 2nd, 3rd, 4th, 5th-years of soybean that was in annual rotation with corn. R1 was SCN-resistant soybean Freeborn (with resistance source from 'PI 88788', Maturity Group 1.6) (Hartwig and Epps, 1978), R2 was SCN-resistant cultivar Pioneer brand 9234 (with Peking resistance, Maturity Group 2.3) (Brim and Ross, 1966), and S was SCN-susceptible Sturdy (Maturity Group 2.1). The original NT plots continued to be NT, and the tillage treatments (annual fall moldboard plowing, fall moldboard plowing after harvesting corn, chisel plowing after soybean harvest, annual fall chisel plowing, and annual ridge tillage) (Chen et al., 2001b) were reassigned to either NT or CT. The CT treatment was fall moldboard plowing after corn harvest, chisel plowing after soybean harvest, and spring field cultivating before planting corn and soybean. Each experimental unit consisted of a plot 6 m long and 3 m wide with four rows of 76-cm row spacing. Since the original five tillage treatments and four crop sequence/row spacing treatments were changed to two tillage treatments and nine crop sequence treatments, 18 out of the original 20 plots in each of the four replicate blocks were used in the modified experiment.

Soybean was planted between 14 May and 1 June, and corn was planted between 16 April and 2 June. The corn planting dates after 15 May are considered late in southern Minnesota, and the delayed planting was due to busy planting schedule and/or wet weather conditions. Soybean seeding rate was 342 000 seeds ha^{-1} and corn ('Dekalb 493sr' in 1997–1999, and 'Dekalb 520rr' in 2000–2002) seeding rate was 79 000 seeds ha^{-1}. Phosphorus fertilizer (Triple Super Phosphate) at 36.7 kg P ha^{-1} and K fertilizer (KCl) at 47 kg K ha^{-1} were applied to both corn and soybean plots at planting in 1999 according to the University of Minnesota recommendations (Rehm et al., 1994, 2006). Each year, 168 kg N ha^{-1} as urea were applied to corn plots. No other fertilizer was applied to the soybean plots. A number of herbicides were used for pre-emergence and postemergence weed control according to weed species and pressure in different years, and the same herbicides were used across all treatments within a site in a year.

At Waseca, there were two adjacent sites (B1 and B2) in the same field in a corn–soybean rotation. This field experiment was established in 1997 for the study of tillage, row spacing and SCN-resistance effects on SCN in a north-central regional project (Atibalentja et al., 2001; Donald et al., 2000). The soil in the Waseca field was Webster clay loam with 385 g kg^{-1} sand, 310 g kg^{-1} silt, 305 g kg^{-1} clay, 53 g kg^{-1} organic matter (range 17–89 g kg^{-1} in individual plots), and pH 7.0 (range 5.4–7.8 in individual plots) measured in 1999. The SCN population in the field was classified as HG Type 0- (Race 3).

The B1 site was planted to soybean and the B2 site was planted to corn in Year 1 so that in each year data could be obtained from both soybean and corn plots. The experiment at each site was a split-plot design with six randomized complete blocks (replicates). The main plots were NT and CT in both corn and soybean years. The subplots were six crop sequences: (i) R1–R1–R1–R1 (8-yr soybean–corn annual rotation); (ii) R1–R1–R2–R1; (iii) R1–R1–S–R1; (iv) S–S–R1–S; (v) S–S–R2–S; and (vi) S–S–S–S, where R1, R2 and S were Freeborn, Pioneer brand 9234, and Sturdy, respectively. The letters represent the 1st, 2nd, 3rd, and 4th years of soybean that was in annual rotation with corn. Each experimental unit consisted of a plot 9.1 m long and 4.6 m wide with six rows of 76-cm row spacing.

Soybean was planted on 31 May 2001 and 15 May 2003 at B1 site, and on 15 May 2002 and 7 May 2004 at B2 site. Corn ('Dekalb 471rr' in 2000 and 2002, 'Pioneer 3730' in 2001 and 2003) was planted in May. No fertilizer was applied to soybean plots at Waseca. In corn plots, 151 to 168 kg N ha^{-1} as urea were applied each year, but no P and K fertilizers were applied during the experiment. A number of herbicides were used for pre-emergence and postemergence weed control according to weed species and pressure in different years, and the same herbicides were used across all treatments within a site in a year.

Data Collection

Nematode egg population densities were determined at planting and harvest each year. A composite soil sample consisting of 20 cores was taken with a 2.5-cm diam. soil probe to a 20-cm depth across the central area of approximately 1.5 m wide by 4 m (New Richland) or 6.1 m (Waseca) long from each plot. The soil samples were stored in a cool room (4°C) before being processed. Each soil sample was thoroughly mixed and cysts were initially extracted from a subsample of 100 cm^3 soil with a semiautomatic elutriator (Byrd et al., 1976). The cysts with some soil particles and debris caught on 250-μm aperture sieve were collected, suspended in 63% (w/v) sucrose solution in a 50-mL tube, and centrifuged at 1100 *g* for 5 min. The cysts in the supernatant were collected and crushed in a 40-mL glass tissue grinder (Fisher Scientific, Pittsburgh, PA) for New Richland samples or a motorized device (Faghihi and Ferris, 2000) for Waseca samples to release eggs. The eggs were collected into a 50-mL tube and counted. Nematode population density was expressed as number of eggs 100-cm^{-3} of soil.

Soybean and corn were harvested in October or November. Soybean seed yield was determined from 4 m (New Richland) or 6.1 m (Waseca) of the two central rows, and computed at 130 g kg^{-1} moisture.

Data Analysis

Nematode egg population densities were transformed to ln $(x + 1)$, and soybean yields were not transformed for the statistical analysis. The two sites in each field were considered two repeated experiments. Since only the nonhost corn crop was grown between two soybean-growing years and there was no nematode reproduction during that period, the four sampling occasions between the two soybean-growing years were considered four repeated measures. The data were initially analyzed with repeated measures of split-plot ANOVA with tillage as the main plots and crop sequence as subplots of the two sites (A1 and A2 in New Richland or B1 and B2 in Waseca) in each field. Since the interactions between soil sampling occasion and site and between soil sampling occasion

Table 1. Analysis of variance of tillage and crop sequence effects on population densities of *Heterodera glycines* in New Richland, MN.†

	Sampling occasion‡							
	1		2		3		4	
Treatment	df	*F* value	df	*F* value	df	*F* value	df	*F* value
				after 3rd-year soybean				
Site (S)	1	0.0NS	1	24.6***	1	2.9NS	1	0.4NS
Tillage (T)	1	0.1NS	1	0.1NS	1	0.6NS	1	1.1NS
S × T	1	0.0NS	1	0.0NS	1	0.0NS	1	0.0NS
Crop sequence (C)‡	5	49.2***	5	20.0***	5	17.3***	5	3.2***
T × C	5	0.2NS	5	0.5NS	5	0.4NS	5	0.4NS
S × C	5	0.9NS	5	1.5NS	5	1.0NS	5	0.3NS
T × C × S	5	1.3NS	5	0.8NS	5	2.3NS	5	1.2NS
Total	137		141		142		140	
				after 4th-year soybean				
S	1	1.3NS	1	14.7**	1	16.9**	1	4.7NS
T	1	0.0NS	1	0.3NS	1	1.0NS	1	0.8NS
S × T	1	0.0NS	1	0.0NS	1	0.6NS	1	0.4NS
C‡	8	41.0***	8	35.4***	8	31.3***	8	29.6***
T × C	8	0.4NS	8	1.1NS	8	0.9NS	8	0.4NS
S × C	8	1.5NS	8	2.1*	8	1.4NS	8	2.1*
T × C × S	8	0.4NS	8	0.4NS	8	1.5NS	8	1.6NS
Total	139		141		143		143	
				after 5th-year soybean				
S	1	8.9*	0					
T	1	1.2NS	1	7.5NS	1	3.2NS		
S × T	1	1.2NS						
C‡	8	30.9***	8	16.1***	8	18.3***		
T × C	8	1.2NS	8	0.7NS	8	1.7NS		
S × C	8	1.7NS						
T × C × S	8	1.4NS						
Total	142		71		70			

* $P \leq 0.05$.
** $P \leq 0.01$.
*** $P \leq 0.001$.
† Nematode population densities were eggs 100-cm^{-3} soil, which were transformed with ln $(x + 1)$ before being subject to split-plot ANOVA. NS stands for not significant at $P \geq 0.05$.
‡ Soybean was grown in annual rotation with corn (Fig. 3, 4, and 5). Sampling occasions 1, 2, 3, 4 were approximately at soybean harvest, at corn planting the following year, at corn harvest the following year, and at planting next soybean. The data of all sampling occasions "after 3rd-year soybean" and "after 4th-year soybean," and the sampling occasion 1 "after 5th-year soybean" were combination of two repeated (experiments) sites. The data of sampling occasions 2 and 3 "after 5th-year soybean" were from one site.

and crop sequence were significant in most cases, ANOVA was performed for each of individual sampling occasions, and the ANOVA tables are presented by sampling occasions. When an interaction between factors within a sampling occasion was significant, further ANOVA at individual tillage treatments and crop sequences were performed. Means were compared with the least significant difference (LSD) at $\alpha = 0.05$.

RESULTS

Nematode Population Density

As expected, different cultivars in different crop sequences affected nematode population density (Tables 1 and 2). At Waseca, susceptible soybean produced

Table 2. Analysis of variance of tillage and crop sequence effects on population densities of *Heterodera glycines* in Waseca, MN.†

	Sampling occasion‡											
	After 3rd-year soybean								After 4th-year soybean			
	1		2		3		4		1		2	
Treatment	df	*F* value	df	*F* value	df	*F* value	df	*F* value	df	*F* value	df	*F* value
Site (S)	1	1.4NS	1	7.5*	1	9.4**	1	9.0**	1	3.5NS	0	
Tillage (T)	1	0.5NS	1	0.2NS	1	0.1NS	1	0.0NS	1	0.3NS	1	9.2*
S × T	1	0.4NS	1	0.3NS	1	0.0NS	1	0.5NS	1	0.7NS		
Crop sequence (C)‡	5	61.6***	5	69.3***	5	75.3***	5	66.7***	5	109.5***	5	28.6***
T × C	5	0.9NS	5	0.9NS	5	2.9*	5	1.3NS	5	1.7NS	5	1.9NS
S × C	5	2.1NS	5	3.0*	5	2.0NS	5	1.5NS	5	2.6*		
T × C × S	5	0.5NS	5	1.9NS	5	1.0NS	5	2.1NS	5	2.0NS		
Total	142		143		142		143		143		71	

* $P \leq 0.05$.
** $P \leq 0.01$.
*** $P \leq 0.001$.
† Nematode population densities were eggs 100-cm^{-3} soil, which were transformed with ln $(x + 1)$ before being subject to split-plot ANOVA. NS stands for not significant at $P \geq 0.05$.
‡ Soybean was grown in annual rotation with corn (Fig. 1 and 2). Sampling occasions 1, 2, 3, 4 were approximately at soybean harvest, at corn planting the following year, at corn harvest the following year, and at planting next soybean, respectively. The data of all sampling occasions "after third-year soybean" and the sampling occasion 1 "after fourth-year soybean" were combination of two repeated experiments (sites). The data of sampling occasions 2 "after fourth-year soybean" were from one site.

similar high egg population densities regardless of the cultivars used in the preceding soybean years (Fig. 1 and 2). While the average egg population density across all treatments changed from 5107 at harvesting the 3rd-year soybean to 2083 eggs 100 cm^{-3} soil at planting 4th-year soybean, the effects of crop sequence on the egg population densities at these two sampling times were similar (Fig. 1A, 1E). Pioneer brand 9234 in the third soybean year resulted in smaller egg population density than Freeborn when Freeborn was used in the preceding soybean years (R1–R1–R2 vs. R1–R1–R1), but the egg population densities were similar in the two cultivars when the preceding soybean was susceptible (S–S–R2 vs. S–S–R1) (Fig. 1). Compared with a susceptible cultivar, a resistant cultivar in the second soybean year resulted in smaller egg population densities after the 3rd year of resistant soybean (S–S–R2 vs. R1–R1–R2 and S–S–R1 vs. R1–R1–R1) (Fig. 1). The cultivar in the third soybean year still affected the egg population density in Freeborn in the fourth soybean year; the egg population density after the 4th year of Freeborn was lowest in plots where Pioneer brand 9234 was grown in the 3rd year (R1–R1–R2–R1), intermediate in Freeborn (R1–R1–R1–R1), and highest in Sturdy (R1–R1–S–R1) in the third soybean year (Fig. 2A, 2B, 2C).

The trend of the crop sequence effect on *H. glycines* population density in New Richland was similar to that in Waseca, although the crop sequences were different in the two fields. At New Richland sites, average egg population density across all treatments changed from 2442 at harvesting 3rd-year soybean to 530 at planting 4th-year soybean, and from 2708 at harvesting 4th-year soybean to 1400 eggs 100-cm^{-3} soil at planting 5th-year soybean. The egg population density following the 3rd-year susceptible soybean (S-S-S) was greater than resistant cultivars at all sampling occasions (Fig. 3). The resistant Freeborn (R1) in the second soybean year resulted in smaller egg population density compared with the susceptible Sturdy after the 3rd-year soybean in plots where resistant soybean cultivars were grown (Fig. 3). In the plots where Freeborn was grown in the first two soybean years, the resistant Pioneer brand 9234 in the third soybean year (R1–R1–R2) supported smaller egg population densities compared with Freeborn (R1–R1–R1) at planting and harvesting corn in the following year (Fig. 3B, 3C). In the 4th-year soybean, susceptible soybean produced similar high egg population density regardless of whether a resistant or susceptible soybean was used in the third soybean year (Fig. 4). Two years (3rd and 4th soybean) of Pioneer brand 9234 resulted in smaller population densities than Freeborn in plots where either Sturdy (S–S–R2–R2 vs. R1–S–R1–R1) or Freeborn (R1–R1–R2–R2 vs. R1–R1–R1–R1) (Fig. 4A, 4C, 4D, 4F) was grown in the second soybean year. After the 5th year of soybean, the highest egg population densities were observed in the 5th-year susceptible soybean (S–S–S–S–S), followed by the plots where susceptible soybean was grown in the 4th year (R1–S–R1–S–R2 and R1–S–R2–S–R1) (Fig. 5). The lowest egg population density was observed

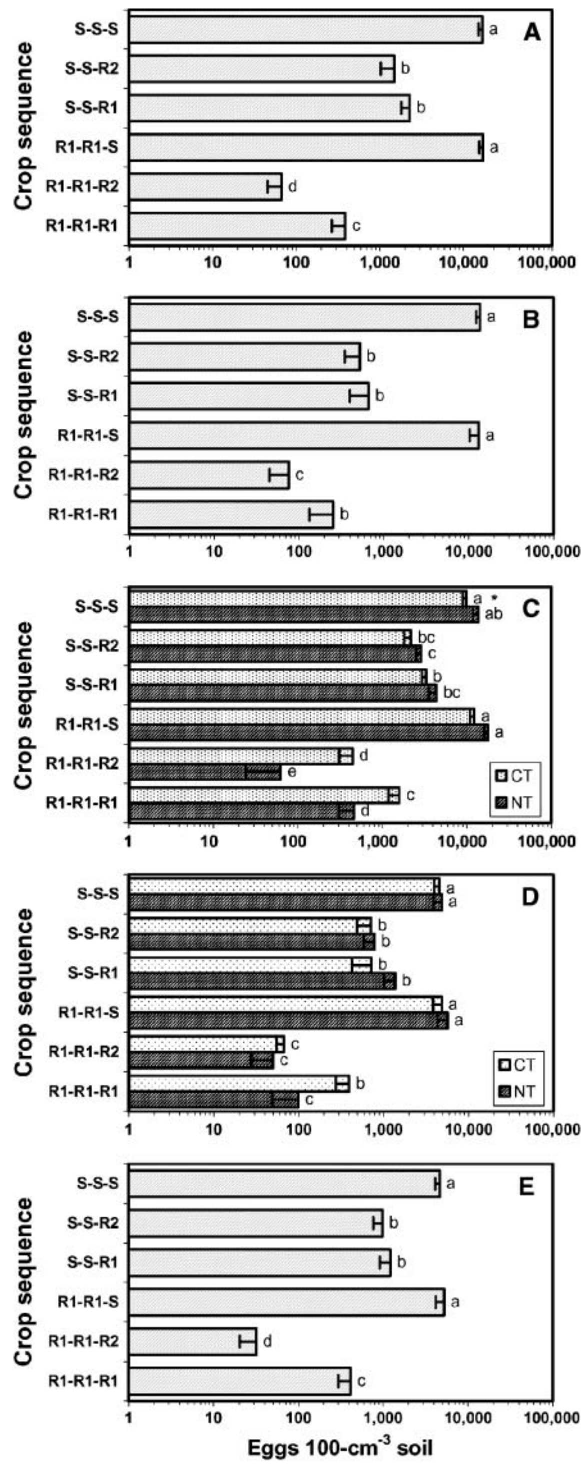

Fig. 1. ***Heterodera glycines*** **egg population densities after 3rd-year soybean in a soybean–corn annual rotation at Waseca. (A) Data are means of two sites and two tillage treatments at soybean harvest. (B) Means of two tillage treatments at corn planting at B1 site. (C) Individual tillage treatments at corn planting at B2 site. (D) Means of two sites of individual tillage treatments at corn harvest. (E) Means of two sites and two tillage treatments at next soybean planting. Six replicates were included. The lines within the bars indicate the standard error. The data were transformed with ln (x +1) before being subjected to split-plot ANOVA. Bars annotated by the same letters within the same graph are not different at $P \geq 0.05$ according to LSD test. The * in B and D indicates difference at $P < 0.05$ between the two tillage treatments within the same crop sequence.**

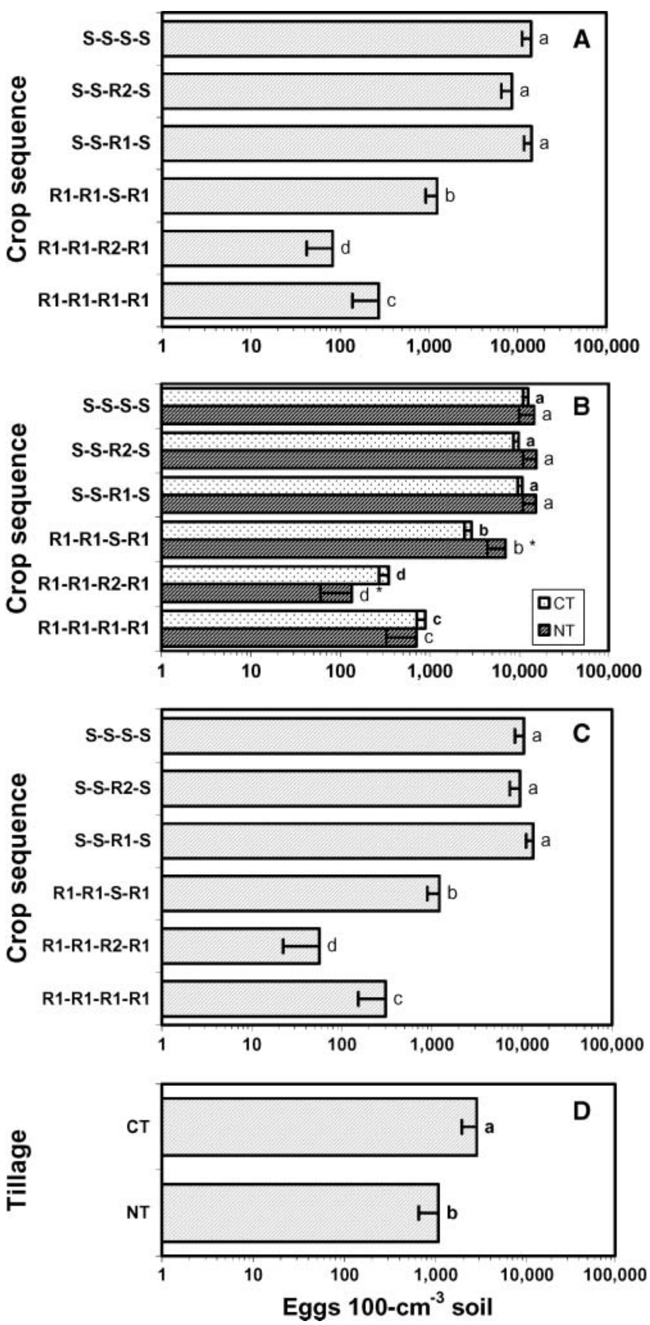

Fig. 2. ***Heterodera glycines*** **egg population densities after 4th-year soybean in soybean–corn annual rotation at Waseca. (A) Data are means of two tillage treatments at soybean harvest at B1 site. (B) Individual tillage treatments at soybean harvest at B2 site. (C) Means of two tillage treatments in the spring following the soybean at B1 site. (D) Means of six crop sequences in the spring following the soybean at B1 site. Six replicates were included. The lines within the bars indicate the standard error. The data were transformed with ln (x +1) before being subjected to split-plot ANOVA. Bars annotated by the same letters within the same graph are not different at $P \geq 0.05$ according to LSD test. The * in B indicates difference at $P < 0.05$ between the two tillage treatments within the same crop sequence.**

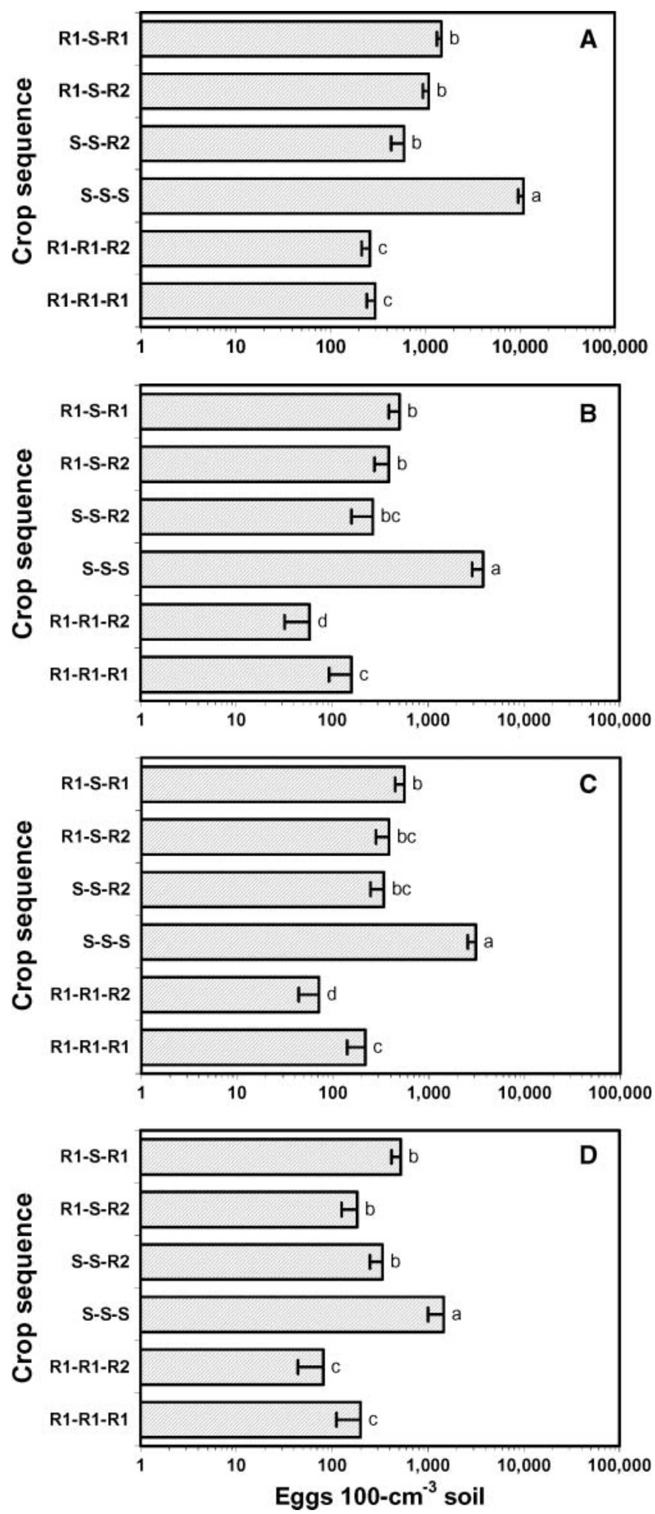

Fig. 3. ***Heterodera glycines*** **egg population densities after 3rd-year soybean in soybean–corn annual rotation at New Richland. A, B, C, and D represent sampling occasions at soybean harvest, corn planting following soybean, corn harvest, and next soybean planting, respectively. The lines within the bars indicate the standard error. The data were transformed with ln (x +1) before being subjected to split-plot ANOVA. The data are means of two sites (A1 and A2) and two tillage practices (no-tillage and conventional tillage) with four, eight (R1-R1-R2) or 12 (R1-R1-R1) replicates. Bars annotated by the same letters within the same graph are not different at $P \geq 0.05$ according to LSD test.**

in the plots where Pioneer brand 9234 was grown in the 3rd, 4th and 5th soybean years (S–S–R2–R2–R2) (Fig. 5B, 5C). In the last 3 yr of soybean, 2 yr of Pioneer brand 9234 (R1–S–R2–R1–R2 and R1–R1–R2–R2–R1)

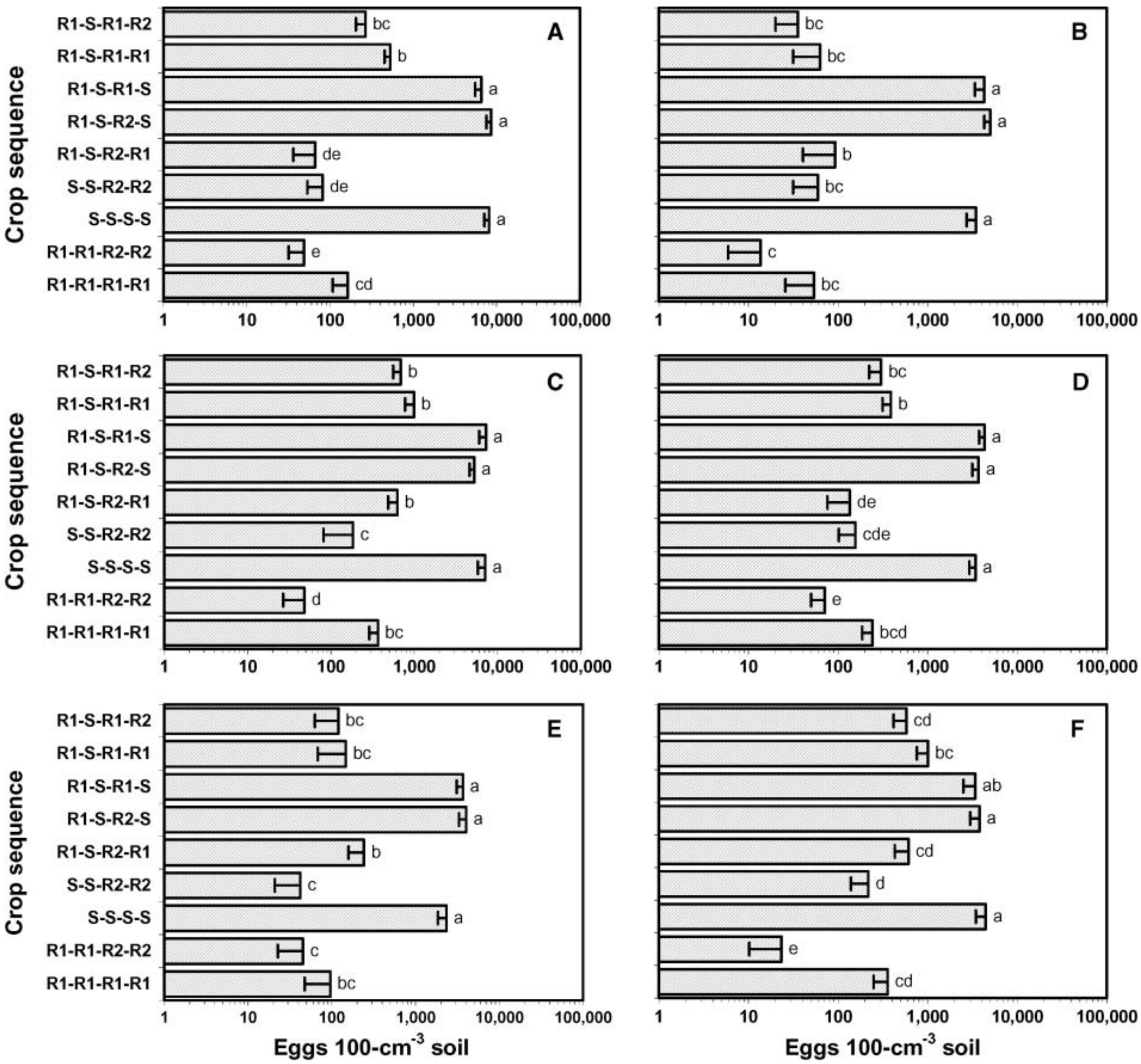

Fig. 4. ***Heterodera glycines*** **egg population densities after 4th-year soybean in soybean–corn annual rotation at New Richland. (A) Data are means of two sites at soybean harvest. (B) A1 site at corn planting. (C) A2 site at corn planting. (D) Two sites at corn harvest. (E) A1 site at next soybean planting. (F) A2 site at next soybean planting. All data are means of two tillage treatments with four replicates. The lines within the bars indicate the standard error. The data were transformed with ln (x +1) before being subjected to split-plot ANOVA. Bars annotated by the same letters within the same graph are not different at $P \geq 0.05$ according to LSD test.**

resulted in smaller egg population density at soybean harvest than 1 yr of Pioneer (R1–S–R1–R2–R1 and R1–S–R1–R1–R2) (Fig. 5A).

No effect of tillage was observed in any sampling occasion at New Richland and in most cases at Waseca (Tables 1 and 2). In Waseca, the egg population density in NT was greater than CT at the second sampling time (at corn planting) after the 3rd-year soybean in the crop sequence S–S–S at B2 site (Fig. 1C) and at harvesting the 4th-year soybean in the crop sequence R1–R1–S–R1 at Site B2 (Fig. 2B). In contrast, the egg population density was greater in CT than NT at harvesting the 4th-year soybean in the crop sequence R1–R1–R2–R1 at Site B2 (Fig. 2B) and the second sampling time (at corn planting) after the 4th-year soybean at Site B1 in Waseca (Fig. 2D).

Soybean Yield

Crop sequence affected soybean yield every year in all sites (Table 3). At both the B1 and B2 sites in Waseca, the 3rd-year susceptible soybean treatment (S–S–S) had less yield than all other crop sequence treatments (Fig. 6A, 6C). Yield of the 3rd-year susceptible soybean Sturdy was increased 586 (Site B1) or 617 (Site B2) kg ha^{-1} in plots where the resistant Freeborn was grown in the first and second soybean years (R1–R1–S) compared with a susceptible soybean in the first two soybean years (S–S–S) (Fig. 6A, 6C). In the fourth soybean year, Sturdy (S) produced less yield than Freeborn (R1) in both B1 and B2 sites (Fig. 7A, 7C). The yield of 4th-year susceptible soybean was greater in plots where resistant soybean was used in the preceding soybean year (S–S–R1–S and S–S–R2–S) than in the plots where susceptible

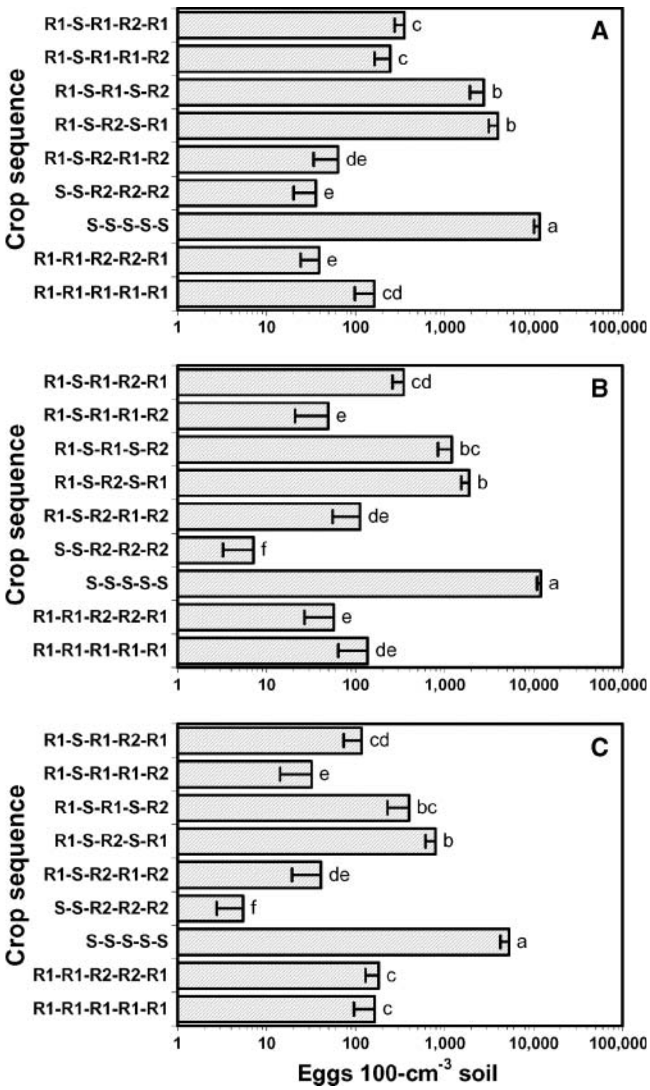

Fig. 5. ***Heterodera glycines*** **egg population densities after 5th-year soybean in soybean–corn rotation at New Richland. (A) Data are means of two sites at soybean harvest. (B) A1 site at corn planting. (C) A1 site at corn harvest. All data are means of two tillage treatments with four replicates. The lines within the bars indicate the standard error. The data were transformed with ln (x + 1) before being subjected to split-plot ANOVA. Bars annotated by the same letters within the same graph are not different at $P \geq 0.05$ according to LSD test.**

soybean was used (S–S–S–S) at both sites. There was no difference in yield of 4th-year susceptible soybean between the two resistant cultivars used in the preceding year (S–S–R1–S vs. S–S–R2–S) at the B1 site (Fig. 7A), but the difference was significant at the B2 site (Fig. 7C). The yield of Freeborn in the fourth soybean year was numerically less (Fig. 7A, B1 site, 150–190 kg h^{-1}, $P = 0.09$) or significantly less (Fig. 7B, B2 site, 310–360 kg ha^{-1}, $P = 0.02$) in the plots where susceptible soybean was grown in the third soybean year (R1–R1–S–R1) than the plots where resistant soybean was grown in the third soybean year (R1–R1–R1–R1 and R1–R1–R2–R1).

In New Richland, Sturdy in the third soybean year (S–S–S) produced less yield than Pioneer brand 9234 (R1–S–R2, S–S–R2) but not significantly different than

Table 3. Analysis of variance of tillage and crop sequence effects on soybean yield in field infested with *Heterodera glycines* in New Richland and Waseca, MN.

	New Richland						Waseca			
	3rd-yr soybean		4th-yr soybean		5th-yr soybean		3rd-yr soybean		4th-yr soybean	
Treatment	df	*F* value	df	*F* value	df	*F* value	df	*F* value	df	*F* value
Site (S)	1	0.06NS†	1	6.99*	1	0.29NS	1	22.7***	1	12.4**
Tillage (T)	1	0.06NS	1	0.92NS	1	0.1NS	1	8.5**	1	12.3**
S × T	1	0.22NS	1	1.05NS	1	0.06NS	1	0.6NS	1	5.7*
Crop sequence (C)‡	5	5.05***	8	9.76***	8	7.45***	5	32.1***	5	14.9***
T × C	5	1.83NS	8	1.44NS	8	2.49*	5	0.5NS	5	1.0NS
S × C	5	1.24NS	8	0.38NS	8	1.51NS	5	3.5**	5	1.7NS
T × C × S	5	1.35NS	8	1.51NS	8	1.19NS	5	0.3NS	5	1.3NS
Total	141		143		143		142		143	

* $P \leq 0.05$.
** $P \leq 0.01$.
*** $P \leq 0.001$.
† NS stands for not significant at $P \geq 0.05$.
‡ Soybean was grown in annual rotation with corn (Fig. 6, 7, and 8).

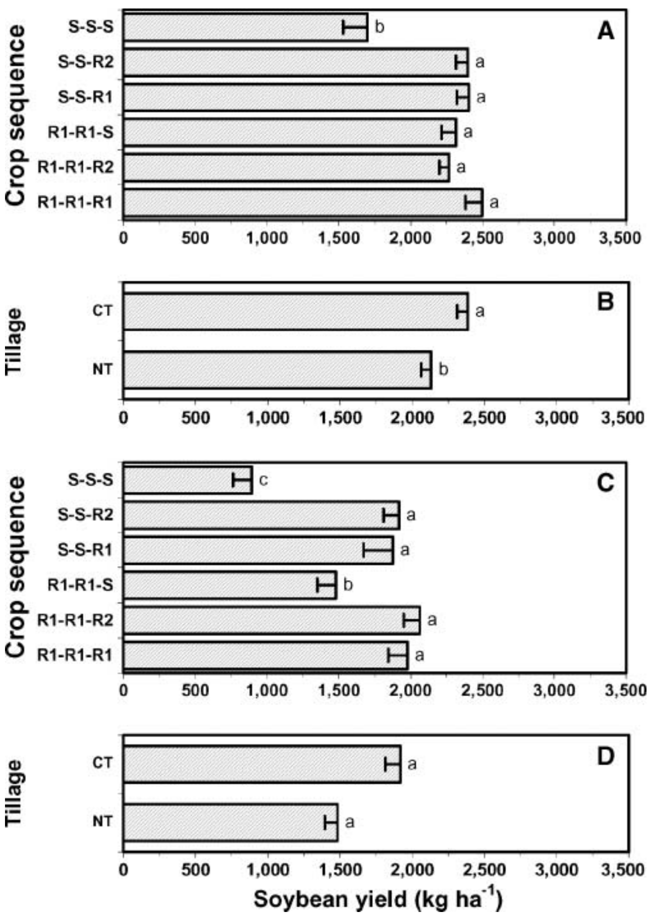

Fig. 6. Yield of 3rd-year resistant and susceptible soybean cultivars in annual rotation with corn in a field at Waseca infested with *Heterodera glycines*. (A, B) B1 site. (C, D) B2 site. The data are means of two tillage treatments (A, C) or six crop sequences (B, D) with six replicates. Bars annotated by the same letters within the same graph are not different at $P \geq 0.05$ according to LSD test.

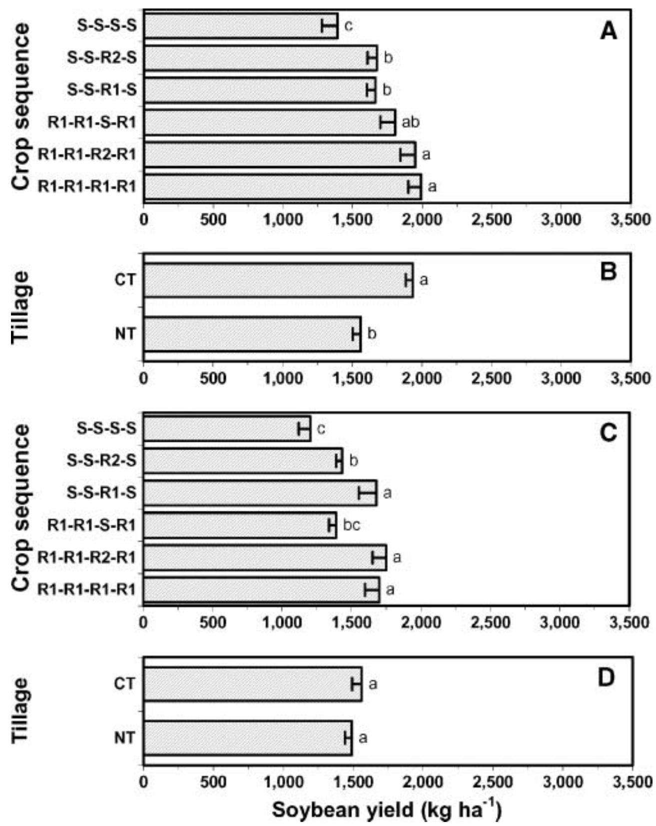

Fig. 7. Yields of 4th-year resistant and susceptible soybean cultivars in annual rotation with corn in a field at Waseca infested with *Heterodera glycines*. (A, B) B1 site. (C, D) B2 site. The data are means of two tillage treatments (A, C) or six crop sequences (B, D) with six replicates. Bars annotated by the same letters within the same graph are not different at $P \geq 0.05$ according to LSD test.

Freeborn (R1–S–R1) when susceptible soybean was used in the second soybean year (Fig. 8A). Cultivar in the second soybean year did not affect the yield of the resistant soybean (R1 or R2) in the third soybean year. In the fourth soybean year, susceptible soybean (S–S–S–S) produced less yield than any other sequences except R1–S–R2–S (Fig. 8B). No yield differences were observed between the two resistant cultivars in the third and fourth soybean year except yield of Pioneer brand 9234 in S–S–R2 was greater than Freeborn in R1–S–R1 (Fig. 8A, 8B). In the fifth soybean year, it appeared there were greater differences in yield among the crop sequences in the NT than CT (Fig. 8C). The yield of Freeborn in the fifth soybean year was greater (433–440 kg ha^{-1}) in plots where 2 yr of Pioneer brand 9234 (R1–R1–R2–R2–R1) were grown in the preceding soybean years than in plots where a susceptible cultivar was grown in the fourth soybean year (R1–S–R2–S–R1) for both tillage treatments (Fig. 8C).

Tillage affected soybean yield, although the effect varied among sites, years, and crop sequences (Table 3). In Waseca, CT increased yield compared with NT at the B1 site in both the third (252 kg ha^{-1} greater) and fourth (372 kg ha^{-1} greater) soybean years (Fig. 6B, 7B). At the B2 site, the yield of 3rd-year soybean was 437 kg ha^{-1} greater with CT than NT, but the difference was not statistically significant (Fig. 6D). No difference in the yield of 4th-year soybean was observed between the two tillage treatments at the B2 site (Fig. 7D). In New Richland, no tillage effect on soybean yield was observed in the third and fourth soybean years. In the fifth soybean year in New Richland, the interaction between tillage and crop sequence was significant. No-tillage produced 550 kg ha^{-1} more seed yield of Pioneer brand 9234 than CT, but only in the sequence R1–S–R2–R1–R2 (Fig. 8C). This was probably due to other factors that resulted in an unexpected low yield of Pioneer brand 9234 in the CT plots.

DISCUSSION

In a previous report, tillage did not affect SCN population density in the first 4 yr of the experiment in the New Richland field (Chen et al., 2001b). The results of the present study demonstrated that longer-term (5–10 yr) effect of tillage on SCN population density was also minimal, confirming that tillage is not an option for managing SCN population in the northern climate and soil conditions (Chen et al., 2001b; Niblack et al., 1999).

In contrast to the results from northern states, NT suppressed SCN population densities in southern USA

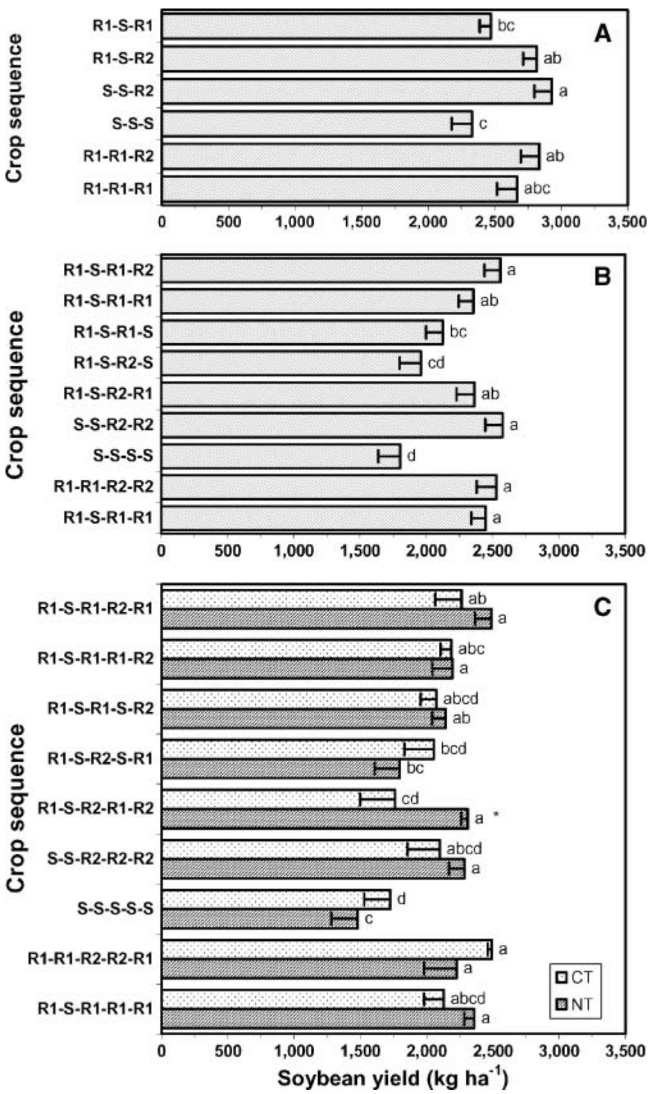

Fig. 8. Yields of resistant and susceptible soybean cultivars in annual rotation with corn in a field at New Richland infested with *Heterodera glycines*. (A) 3rd-year soybean. The data are means of two sites (A1 and A2) and two tillage practices (NT = no-tillage, and CT = conventional tillage) with four, eight (R1-R1-R2) or 12 (R1-R1-R1) replicates. (B) 4th-year soybean. The data are two site and two tillage treatments with four replicates. (C) 5th-year soybean. The data are individual tillage treatments of two sites with four replicates. The lines within the bars indicate the standard error. Bars annotated by the same letters within the same graph are not different at $P \geq 0.05$ according to LSD test. The * in C indicates difference at $P < 0.05$ between the two tillage treatments within the same crop sequence.

(Hershman and Bachi, 1995; Koenning et al., 1995; Lawrence et al., 1990; Tyler et al., 1983, 1987). The reasons for the different tillage effects between the southern and northern climates are not fully understood. It is possible that different soil biological activities including the activities of parasites and predators of nematodes are responsible for the different tillage effects on SCN. The lower temperature and longer period of frozen soil in the northern states may result in less difference in the biological activities between NT and CT. Tyler et al. (1987) speculated that reduction of SCN population density in NT could be partially attributed to the higher level of nematode parasites present in the long-term NT plots. However, a subsequent study demonstrated that fungal parasitism of SCN eggs did not differ between NT and CT (Bernard et al., 1997). Parasitism of SCN second-stage juveniles by the nematophagous fungi *Hirsutella* spp. in the two fields in the present study did not differ between CT and NT (Liu and Chen, 2007, unpublished data). It appeared that the difference in tillage effect on SCN between the southern and northern climates cannot be explained by any differences in fungal parasites of SCN.

Inconsistent tillage effects on SCN population in different sites and years were also observed in the same states (Niblack et al., 1999). In the present study, there was also little difference in response of SCN populations to the tillage treatments between the two fields; while a small difference in SCN population densities between NT and CT was observed in a few occasions in Waseca, there was no any difference in SCN population densities between the NT and CT in the New Richland field. The difference between the two fields was probably due to different soil environments. Compared with the first 4 yr of data in the Waseca sites (1997–2000, unpublished data), it seemed there was increase of the difference between the two tillage treatments in the last 4 yr, although the difference was still small. In the New Richland sites, although the data was obtained during the 5th to 10th years of the study, NT and CT treatments were reassigned in the 5th year, and thus the period of tillage treatments should be considered only 1 to 6 yr. The smaller size of plots and fewer replicates in the New Richland sites might have less power to detect any tillage effect as compared with the Waseca sites.

Conventional tillage increased yields compared with NT in Waseca, although the effect of tillage on soybean yields may depend on the number of years of tillage treatments and environments such as soil fertility. Tillage did not affect soybean yield in the first 4 yr of the experiment at New Richland (Chen et al., 2001b) and at Waseca (Chen, 1997–2000, unpublished data). Another study in Minnesota showed that tillage did not consistently affect soybean yield and yield differences were small in most years of a 4-yr experiment (Lueschen et al., 1992). Randall et al. (2001) reported that there was no significant difference among various tillage practices on a low P testing site, but soybean yield was greater with CT than NT on a high P testing site. Soil test P (Olsen) at Waseca B1 (mean 4.9 ± SD 2.5 mg kg^{-1}) and B2 (mean 4.0 ± SD 1.4 mg kg^{-1}) were low. More studies are needed to determine why and how the tillage effect on soybean yield differs in different environments.

The results of this study confirmed that planting resistant cultivars is the best option in the corn–soybean rotation for managing SCN and minimizing yield losses to the nematode. Resistant soybean not only suppressed SCN population and increased soybean yield in the year when it was grown, but also resulted in a smaller inoculum population density and increased yield of the susceptible soybean Sturdy and the resistant soybean Freeborn in the following soybean year. Pioneer brand 9234 with the resistance source from Peking had a greater degree of resistance to SCN than Freeborn with the resistance source from PI 88788. Consequently, Pioneer brand 9234 was more effective in suppressing SCN population density and increasing soybean yield in the following year than Freeborn. Rotation of resistant cultivars was assumed to slow the change of parasitic ability of SCN populations and maintain resistance of the cultivars used, but this benefit was not detected in this study due to limited time period of the experiments.

It appeared there was a greater difference in yield among the crop sequences in the NT plots than in CT plots, suggesting more yield loss for Sturdy was caused by the SCN in the NT plots than in the CT plots. More studies are needed to determine if there is any difference in yield loss to SCN between NT and CT.

In conclusion, tillage had little to no effect on the soybean cyst nematode population density in Minnesota fields and selection of tillage practices is not an effective means for managing SCN population. However, tillage significantly affected soybean yield in some years in Waseca where CT generally resulted in greater yield than NT, agreeing with the studies reported previously. Use of resistant cultivars in a corn–soybean rotation was the most effective means for reducing SCN population density and increasing soybean yield not only in the year when they were grown but also in the following year when either resistant or susceptible soybean was grown. Pioneer brand 9234 with Peking resistance source was more resistant to the SCN populations in the two fields than Freeborn with PI 88788 resistance. It suppressed SCN population density to a greater extent and increased soybean yield more than Freeborn.

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