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RESEARCH

Corn and Soybean Yield Response to Tillage, Rotation, and Nematicide Seed Treatment

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ABSTRACT

Corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] rotations are common production systems across the midwestern United States. However, the interactive effect of crop rotation, tillage, and nematicide seed treatments on the yield of both crops in the rotation system is not well understood. Field trials were conducted in a long-term crop rotation experiment during 2013 to 2015 to measure yield response of both corn and soybean to three factors: (i) tillage system (no-till [NT] and conventional), (ii) crop rotation frequency (14 sequences involving corn and soybean), and (iii) three nematicide seed treatments (a control, abamectin/*Pasteuria nishizawae*, and *Bacillus firmus*). Rotations that involved consecutive years of soybean exhibited the greatest nematode populations in the soil, whereas, consecutive years of corn resulted in lower nematode populations. No significant differences in nematode populations were observed among the other examined management practices. Conventional tillage resulted in up to 18% greater corn and 10% greater soybean yield than NT. Yearly crop rotation increased corn yield by 20% and soybean yield by 22% compared with continuous cropping. Seed treatment nematicides had no effect on corn and soybean yield. The production system that involved yearly rotation of corn and soybean, regardless of tillage system and nematicide seed treatment, exhibited the greatest yield potential during the 3 yr of this study. Such rotation system using NT can be an attractive option for farmers in this region, since NT has reduced field operations and labor requirements.

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Abbreviations: 1C, first year of corn after 5 yr of soybean; 1S, first year of soybean after 5 yr of corn; 2C, second year of corn after 5 yr of soybean; 2S, second year of soybean after 5 yr of corn; 3C, third year of corn after 5 yr of soybean; 3S, third year of soybean after 5 yr of corn; 4C, fourth year of corn after 5 yr of soybean; 4S, fourth year of soybean after 5 yr of corn; 5C, fifth year of corn after 5 yr of soybean; 5S, fifth year of soybean after 5 yr of corn; AV, seed treatment containing abamectin; BF, seed treatment containing *Bacillus firmus*; CC, continuous corn; CS, corn–soybean rotation; NT, no-till; PN, seed treatment containing *Pasteuria nishizawae*; SCN, soybean cyst nematode; SS, continuous soybean.

Corn and soybean are the two major crops in the United States that, in 2015, had a combined planted area of ~66 million ha (USDA, 2016). It is common for these two crops to be grown in continuous monoculture or in a 2-yr rotation system because of the numerous beneficial attributes of the rotation cropping system. Crop rotation has been shown to improve soil structure (Raimbault and Vyn, 1991) and increase nutrient use efficiency (Karlen et al., 1994), water use efficiency (Roder et al., 1989; Copeland et al., 1993), and soil organic matter (Campbell and Zentner, 1993). The corn–soybean rotation system has been extensively examined, and several studies show that growing corn and soybean in rotation increased yield of both crops when compared with continuous cropping (Crookston and Kurle, 1989; Karlen et al., 1994; Wilhelm and Wortmann, 2004). In a multi-location study, Porter et al. (1997) reported that corn and soybean yielded 13 and 10% more when grown in a corn–soybean rotation system than when grown continuously. In Wisconsin and Nebraska, corn and soybean grown in rotation resulted in 18 and 38% greater corn yield

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and 13% greater soybean yield, respectively, than when grown continuously (Pedersen and Lauer, 2003; Peterson and Varvel, 1989a, 1989b). Similarly, another study in Wisconsin showed an 8% greater soybean yield when soybean was grown in yearly rotation with corn than when grown continuously (Marburger et al., 2015).

The negative impact of soybean cyst nematode (SCN, *Heterodera glycines* Ichinoche) on soybean yield is well documented (Chen, 2007; De Bruin and Pedersen, 2008; Grabau and Chen, 2016). Although crop rotation has been shown to increase corn and soybean yields, protection against SCN is crucial to maintain high soybean yield (Murillo-Williams and Pedersen 2008). In Wisconsin, it has been reported that >90% of the soybean production area was in counties where SCN had been detected (Barta et al., 2012). Using crop rotation with nonhost crops has been evaluated as a SCN management practice (Chen, 2007). Seed treatments that contain nematicides can also assist in SCN management. In a corn–soybean rotation study, SCN population decreased as a result of the use of nematicide; nevertheless, there was no rotation × nematicide effect (Grabau and Chen, 2016). Soybean cyst nematode is a primary nematode that affects soybean, and the root lesion nematode (*Pratylenchus penetrans*) affects corn. Since a corn–soybean rotation is common in the upper Midwest, reducing overall nematode levels in both crops can be beneficial. Additionally, since root lesion nematode is a pathogen of both crops, nematicides that control both nematodes can be beneficial. However, it has been shown that nematicide seed treatment efficacy on soybean yield can be inconsistent among a wide range of environments (Gaspar et al., 2014). The environment-specific effect of crop rotation and various seed treatments on the yield of all involved crops in rotation is not well understood.

In most agricultural production systems, tillage selection is a primary management decision that can affect productivity and profitability of a cropping system. No-till cropland has increased in the recent years, reaching 36% of total US cropland in 2009 (Horowitz et al., 2010). No-till is an appealing management practice because of the lower cost of the production system associated with machinery fuel, energy, and maintenance costs (Lal et al., 2007; Rathke et al., 2007) and because of the improvement of soil quality such as increased soil organic matter (Varvel and Wilhelm, 2010) and infiltration (Arshad et al., 1999), improved soil structure (Abid and Lal, 2008), erosion control (Blanco-Canqui et al., 2009), and C sequestration (Lal, 2004). Crop yield responses to NT can be location (Griffith and Wollenhaupt, 1994) and weather dependent (Norwood and Currie, 1996; Klocke et al., 2009). For example, in Wisconsin (Pedersen and Lauer, 2003; Marburger et al., 2015) and Minnesota (Vetsch et al., 2007), NT reduced corn and soybean yields when compared with intensive tillage systems. In Kansas, greater corn and soybean yields were observed with NT over a 4-yr period (Norwood, 1999). Similarly, in Nebraska, soybean yield with NT was either equal to or greater than with more intensive tillage systems over a 5-yr period (Dickey et al., 1994). Another study in Nebraska showed that NT often resulted in lower corn yield in the eastern part of the state, whereas NT corn yield was similar to or greater than conventional tillage in the south–central part of the state (Sims et al., 1998). Soil type and variable rainfall distribution could be the reason for these yield responses.

Across the southern United States, variable effects of tillage practices on SCN egg number have been reported among years, tillage, and rotation practices (Tyler et al., 1987; Koenning et al., 1995). A study that was conducted in Illinois showed that NT tended to support higher number of eggs than conventional tillage; however, long-term corn–soybean rotation mitigated nematode population increases in both NT and conventional tillage systems (Noel and Wax, 2003). Nonetheless, Conley et al. (2011) found fewer soybean cyst nematode eggs in NT plots vs. tilled plots in Wisconsin.

Because of the environment-dependent effects of tillage, crop rotation, and seed treatment on corn and soybean yield, environment-specific evaluation of such management practices is important to provide farmers with more robust recommendations. Therefore, the objective of this study was to examine the effect of tillage, rotation, and nematicide seed treatment on soybean and corn yields in Wisconsin.

MATERIALS AND METHODS

Field trials were conducted from 2013 through 2015 within a long-term corn–soybean rotation established in 1983 at the Arlington Agricultural Research Station at Arlington, WI (43°18′ N, 89°20′ W). The soil type was a Plano silt loam (fine-silty, mixed, mesic Typic Argiudolls). The experimental design was a randomized complete block in a split–split plot arrangement with four replications. Main plots were NT and conventional tillage systems that were established in 1987. Subplots consisted of 14 rotation sequences representing each phase of seven different corn and soybean crop rotations. For soybean, these crop rotations included (i) first-year soybean after five consecutive years of corn (1S); (ii) soybean alternated annually with corn (CS); (iii) two (2S), three (3S), four (4S), and 5 yr (5S) of continuous soybean after 5 yr of continuous corn; and (iv) continuous soybean (SS) since 1983. Similarly, the seven crop rotations for corn were (i) first-year corn after five consecutive years of soybean (1C); (ii) corn alternated annually with soybean (CS); (iii) two (2C), three (3C), four (4C), and 5 yr (5C) of continuous corn after 5 yr of soybean; and (iv) continuous corn (CC). Sub-subplots consisted of three nematicide seed treatments. For soybean, the three seed treatments were as follows: a control (no nematicide); *abamectin* (AV, used in 2013) and *Pasteuria nishizawae* (PN, used in 2014 and 2015); and *Bacillus firmus* (BF). The seed treatment change from Avicta (AV) to Clariva (PN) in 2014 was because AV was no longer labeled for soybean in Wisconsin after 2013. The AV label specifies "nematodes including SCN" for control, whereas PN

Table 1. Seed treatment products and rates used for soybean and corn from 2013 to 2015.

Crop	Seed treatment code†	Seed treatment trade name	Pesticide components	Active ingredients	Product rate	Year 2013	2014	2015
					mg a.i. seed^{-1}			
Soybean	Control	CruiserMaxx Advanced	Fungicide + insecticide	Fludioxonil + mefenoxam + thiamethoxam	0.0907	+	+	–
		Vibrance	Fungicide	Sedaxane	0.0038	+	+	–
		CruiserMaxx Vibrance	Fungicide + insecticide	Fludioxonil + mefenoxam + thiamethoxam + sedaxane	0.0945	–	–	+
	AV	CruiserMaxx Advanced	Fungicide + insecticide	Fludioxonil + mefenoxam + thiamethoxam	0.0907	+	+	–
		Vibrance	Fungicide	Sedaxane	0.0038	+	+	–
		CruiserMaxx Vibrance	Fungicide + insecticide	Fludioxonil + mefenoxam + thiamethoxam + sedaxane	0.0945	–	–	+
		Avicta 500	Nematicide	Abamectin	0.1500	+	–	–
	PN	CruiserMaxx Advanced	Fungicide + insecticide	Fludioxonil + mefenoxam + thiamethoxam	0.0907	+	+	–
		Vibrance	Fungicide	Sedaxane	0.0038	+	+	–
		CruiserMaxx Vibrance	Fungicide + insecticide	Fludioxonil + mefenoxam + thiamethoxam + sedaxane	0.0945	–	–	+
		Clariva	Nematicide	*Pasteuria nishizawae*	‡	–	+	+
	BF‡	Maxim	Fungicide	Fludioxonil	0.0038	+	–	+
		Apron XL	Fungicide	Mefenoxam	0.0113	+	–	+
		Vibrance	Fungicide	Sedaxane	0.0038	+	+	+
		Poncho/VOTiVO	Insecticide + nematistat	Clothianidin + *Bacillus firmus*	0.1300	+	+	+
Corn	Control	Maxim Quattro	Fungicide	Fludioxonil + mefenoxam + azoxystrobin + thiabendazole	0.0640	+	+	+
		Cruiser 5FS	Insecticide	Thiamethoxam	0.5000	+	+	+
		Vibrance	Fungicide	Sedaxane	0.0125	–	–	+
	AV	Maxim Quattro	Fungicide	Fludioxonil + mefenoxam + azoxystrobin + thiabendazole	0.0640	+	+	–
		Avicta Duo 500	Insecticide + nematicide	Thiamethoxam + abamectin	0.7200	+	+	–
		Avicta Complete Corn 500	Fungicide + insecticide + nematicide	Fludioxonil + mefenoxam + azoxystrobin + thiabendazole + thiamethoxam + abamectin	0.7840	–	–	+
		Vibrance	Fungicide	Sedaxane	0.0125	–	–	+
	BF§	Maxim Quattro	Fungicide	Fludioxonil + mefenoxam + azoxystrobin + thiabendazole	0.0640	+	+	+
		Vibrance	Fungicide	Sedaxane	0.0125	–	–	+
		Poncho/VOTiVO	Insecticide + nematicide	Clothianidin + *Bacillus firmus*	0.6000	+	+	+

† AV, seed treatment containing abamectin; BF, seed treatment containing *Bacillus firmus*; PN, seed treatment containing *Pasteuria nishizawae*.

‡ Product rate for Clariva was 26.9 mL 100 kg seed^{-1}. Clariva contains at least 1.0×10^{10} spores mL^{-1} according to the label.

§ *Bacillus firmus* is classified as a nematode management product, not a true nematicide. It was classified as a nematicide for our analysis.

only specifies SCN for soybean. The BF label specifies control of SCN in soybean and root-lesion nematode in soybean and corn. The same base fungicide was used for each nematicide treatment each year to minimize confounding effects. For corn, the three seed treatments were (i) a control (no nematicide), (ii) AV, and (iii) BF. The same base fungicide package labeled for corn was also used for each seed treatment each year in an attempt to minimize any confounding effects. All seed treatment products and rates are listed in Table 1.

Soil samples were taken prior to planting and analyzed for soil pH (Watson and Brown, 1998), organic matter (Schulte and Hopkins, 1996), P (Bray and Kurtz, 1945), and K (Munter, 1988) at the University of Wisconsin Soil and Plant Analysis Laboratory (Madison, WI). Soil fertility information is listed in Table 2. Soil samples were taken in the spring at planting time. Each sample was a composite of 10 soil cores (20 cm deep by 2.0 cm diam.) from each replication–rotation block (9.1 by 10.7 m). Soil samples were also collected in April 2016 and processed for SCN analysis by the SCN Diagnostic Laboratory at the University of Missouri. Samples were collected in similar fashion as described above but were collected from each subplot ($n = 336$). After collection, samples were stored in a cold room between 4 and 10°C until they were processed. Soil samples were air dried, thoroughly mixed, and a 100-cm^3 subsample was used to extract *H. glycines* eggs by elutriation and mechanical cyst crushing as described in Niblack et al. (1993). A custom-built

Table 2. Soil fertility, varieties used, and dates of field operations for corn and soybean during the 2013 to 2015 growing seasons at the Arlington Agricultural Research Station (43°18′ N, 89°20′ W; Plano silt loam; Fine-silty, mixed, mesic Typic Argiudolls).

	2013	2014	2015
Soil fertility			
P, mg kg^{-1}	16	14	12
K, mg kg^{-1}	102	103	142
pH	6.7	6.0	6.8
Organic matter, g kg^{-1}	32	36	36
Hybrid or variety used†			
Corn	N61P-3000GT	N61P-3000GT	N63R-3000GT
Soybean	S20Y2	S20Y2	S20-T6
Field operations			
Corn			
Planting date	2 May	21 May	12 May
Harvest date	29 October	5 November	27 October
Soybean			
Planting date	4 May	4 May	12 May
Harvest date	6 October	6 October	8 October

† Corn hybrid and soybean varieties were NK brand (Syngenta).

plot planter, with John Deere (Deere and Co.) row units equipped with a notched coulter positioned directly in front of each seed disc opener plus unit-mounted, spike-toothed-wheel residue managers, was used to plant both the corn and soybean plots. Planting dates are listed in Table 2. Plots were planted at 80,300 (corn) and 370,500 seeds ha^{-1} (soybean) in four rows each spaced 76 cm apart to a length of 9.4 m. Corn hybrids and soybean varieties used are listed in Table 2. The source of SCN resistance for both soybean varieties was PI88788. The change in corn hybrid and soybean cultivar in 2015 was due to seed availability. Fertilizers and pesticides were applied according to University of Wisconsin–Madison best management recommendations (Laboski and Peters, 2012; Jensen et al., 2016). At crop physiological maturity, the center two rows of the corn plots were harvested with a Kincaid plot combine (Kincaid Equipment Manufacturing), and the center two rows of the soybean plots were harvested with an Almaco plot combine (Almaco SPC-40). Grain weight and moisture content were recorded from each plot, and grain yield was adjusted to a moisture content of 155 (corn) and 130 g kg^{-1} (soybean). Harvest dates are listed in Table 2.

Yield data were subjected to mixed model analysis of variance using PROC GLIMMIX in SAS Version 9.3 (SAS Institute, 2011). Because of the heterogeneous yield variances among the 3 yr of the study (diagnostic plots and Levene's test $P \leq 0.05$) and because of changes in seed treatments among years, year-specific models were constructed for corn and soybean. Tillage system, crop rotation, seed treatment, and all two- and three-way interactions were considered to be fixed effects. Random effects included replication, replication × tillage, replication × tillage × crop rotation, and the overall error term. Degrees of freedom were calculated using the Kenward–Rogers method (Littell et al., 2006), which has been shown to perform well when small sample sizes, missing observations, and imbalanced data are present. For

Table 3. Effect of tillage, rotation, seed treatment, and their interactions on soil soybean cyst nematode (*Heterodera glycines* Ichinoche) egg count in soil sampled in April 2016.

Effect	Egg count $P > F$
Tillage (T)	0.477
Crop rotation (CR)	<0.001
T × CR	0.088
Seed treatment (ST)	0.628
T × ST	0.626
CR × ST	0.523
T × CR × ST	0.962

Table 4. Effect of crop rotation on soybean cyst nematode (*Heterodera glycines* Ichinoche) egg count.

Crop rotation†	Eggs 100 cm^{-3}
5S	12,720a‡
3S	9030a
SS	8000a
2S	7760a
4S	7640a
1C	3120b
CS	2820b
1S	2320b
2C	1430bc
3C	470dc
4C	200d
CC	120d
5C	120d

† 1C, first-year corn after 5 yr of continuous soybean; 2C, 3C, 4C, and 5C, second, third, fourth, and fifth year of continuous corn after 5 yr of continuous soybean, respectively; CC, continuous corn since the experiment was initiated in 1983; CS, corn rotated annually with soybean. 1S, first-year soybean after 5 yr of continuous corn; 2S, 3S, 4S, and 5S, second, third, fourth, and fifth year of continuous soybean after 5 yr of continuous corn, respectively; SS, continuous soybean since the experiment was initiated in 1983.

‡ Values followed by the same letter are not significantly different at $P < 0.05$.

all analyses, the level of significance was set to 5%, and the Tukey adjustment was used for pairwise means comparisons.

RESULTS AND DISCUSSION

Soybean Cyst Nematode Population

Soybean cyst nematode egg counts showed minimal differences among the levels of the examined management practices (Table 3). Soil samples from this study in 2013 averaged 3700 SCN eggs 100 cm^{-3} across all rotations. Populations varied significantly among the crop rotation levels. Rotations that involved consecutive years of soybean exhibited the greatest nematode population in the soil, whereas, the more the consecutive years of corn, the lower the nematode population (Table 4). These results agree with other studies (Chen et al., 2001; Conley et al., 2011). No other significant effects were observed. These results differ from Conley et al. (2011), who found fewer soybean cyst nematode eggs in NT plots vs. tilled plots in Wisconsin. Though this was the same experimental area

Table 5. Effect of tillage, rotation, seed treatment, and their interactions on corn and soybean grain yields in 2013 to 2015.

	2013		2014		2015	
	Corn	Soybean	Corn	Soybean	Corn	Soybean
Effect	$P > F$					
Tillage (T)	0.073	0.603	<0.001	0.001	<0.001	<0.001
Crop rotation (CR)	0.001	<0.001	<0.001	0.001	<0.001	<0.001
T × CR	0.057	0.784	0.002	0.184	<0.001	0.012
Seed treatment (ST)	0.081	0.003	0.290	<0.001	0.236	0.002
T × ST	0.090	0.814	0.273	0.071	0.184	0.227
CR × ST	0.337	0.515	0.401	0.039	0.307	0.002
T × CR × ST	0.529	0.790	0.076	0.467	0.408	0.520

where the previous experiment was conducted in 2006 to 2008, the number of soybean cyst nematode eggs in NT and tilled plots was low (<300 eggs 100 cm^{-3}), and individual plots may have equilibrated as a result of planter or water movement of soil. A similar lack of significance was observed in central Iowa in the same study (Conley et al., 2011). The ineffectiveness of tillage as a management tactic for SCN was also reported by Chen (2007) in a study conducted in Minnesota. The differences of tillage impact on SCN populations among the locations of these studies may be explained by year of *H. glycines* infestation, previous cropping history, fungal parasitism, soil conditions, weather, and date of trial initiation (1983 for Wisconsin, 1993 for Minnesota, and 2004 for Iowa).

Corn Yield Response

The effect of tillage on corn yield was significant in 2 out of 3 yr of the study (Table 5). In 2014, yield in conventional tillage plots was 16% greater than NT, whereas the difference in 2015 was 18% (Table 6). This result is in agreement with previous studies in Wisconsin (Pedersen and Lauer, 2003; Marburger et al., 2015). It has been reported that low soil temperature reduces root growth, nutrient and water uptake, and suppresses transpiration and photosynthesis rates (Repo et al., 2005; Ambebe et al., 2009). As a result of cold weather conditions during winter and spring in Wisconsin, it is hypothesized that soil warming under NT was delayed in spring compared with conventional tillage, and that this contributed to suppressed yields.

Crop rotation frequency had a significant effect on corn yield in every year of the study (Table 5). In all 3 yr, greater yields were observed when corn was in yearly rotation with soybean (CS) or when corn was planted after 5 yr of soybean (1C) (Table 7). The yield difference between CS and CC was 12, 21, and 20% in 2013, 2014, and 2015, respectively. This result is in agreement with numerous previous studies that reported a greater corn yield potential of a corn–soybean rotation system when compared with corn monoculture (Pedersen and Lauer, 2003; Peterson and Varvel, 1989a,b).

A significant tillage × crop rotation interaction was observed in 2014 and 2015 (Table 5). In 2014, CS and 1C

Table 6. Effect of tillage and tillage × crop rotation on corn yield in 2014 and 2015.

	2014	2015
	Mg ha^{-1}	
Tillage†		
CT	12.0a‡	13.3a
NT	10.1b	11.0b
Tillage × crop rotation§		
CT-1C	13.9a	15.1ab
CT-2C	11.8bd	13.1abc
CT-3C	11.1d	12.2dc
CT-4C	10.9d	12.9abc
CT-5C	11.0d	12.7bc
CT-CC	11.6d	12.9abc
CT-CS	13.5a	14.5abc
NT-1C	13.3ab	15.2a
NT-2C	10.7d	10.0ed
NT-3C	8.9e	9.5e
NT-4C	8.0e	8.6e
NT-5C	8.3e	9.0e
NT-CC	9.0e	10.3ed
NT-CS	12.4ab	14.5abc

† CT, conventional tillage; NT, no-till.

‡ Yields followed by the same letter within a given year and effect are not significantly different at $P \leq 0.05$.

§ 1C, first-year corn after 5 yr of continuous soybean; 2C, 3C, 4C, and 5C, second, third, fourth, and fifth year of continuous corn after 5 yr of continuous soybean, respectively; CC, continuous corn since the experiment was initiated in 1983; CS, corn rotated annually with soybean.

resulted in the greatest yields regardless of the tillage system (Table 6). However, 3C, 4C, and 5C rotation frequencies in conventional tillage resulted in significantly greater yield, up to 27% than those under NT. A similar response was also detected in 2015; however, CC under conventional tillage was among the highest yielding systems. Additionally, minimal differences were observed among rotation sequences under conventional tillage. The beneficial effect of conventional tillage on corn yield in this study diminished the yield differences among rotation sequences. An important finding was that 1C and CS rotations with NT and with conventional tillage resulted in similar yield, suggesting that the NT cropping system can have higher profitability potential from the reduced tillage-associated costs.

Table 7. Effect of rotation frequency on corn yield in 2013 to 2015.

Crop rotation†	2013	2014	2015
		Mg ha^{-1}	
1C	13.0ab‡	14.6a	16.2a
2C	13.1ab	12.1b	12.4b
3C	12.3c	10.7c	11.7b
4C	11.8abc	10.1c	11.5b
5C	11.4c	10.3c	11.6b
CC	11.7bc	11.0bc	12.5b
CS	13.2a	13.9a	15.5a

† 1C, first-year corn after 5 yr of continuous soybean; 2C, 3C, 4C, and 5C, second, third, fourth, and fifth year of continuous corn after 5 yr of continuous soybean, respectively; CC, continuous corn since the experiment was initiated in 1983; CS, corn rotated annually with soybean.

‡ Yields followed by the same letter within a given year are not significantly different at $P \leq 0.05$.

Table 8. Effect of tillage, crop rotation, and nematicide seed treatment on soybean yield in 2013 to 2015.

	2013	2014	2015
		Mg ha^{-1}	
Tillage†			
CT	4.0a‡	3.9a	4.1a
NT	4.0a	3.5b	3.7b
Crop rotation§			
1S	4.6a	3.8ab	4.7a
2S	4.3abc	3.9ab	4.0b
3S	3.6d	3.7abc	3.9bc
4S	3.9bcd	3.5bc	3.9b
5S	3.7dc	3.9ab	3.4dc
CS	4.3ab	4.0a	4.3ab
SS	3.5d	3.2c	3.3d
Seed treatment¶			
Control	4.1a	3.8a	4.0a
AV/PN	4.0a	3.8a	4.0a
BF	3.9b	3.6b	3.8b

† CT, conventional tillage; NT, no-till.

‡ 1S, first-year soybean after 5 yr of continuous corn; 2S, 3S, 4S, and 5S, second, third, fourth, and fifth year of continuous soybean after 5 yr of continuous corn, respectively; SC, soybean rotated annually with corn; SS, continuous soybean since the experiment was initiated in 1983.

§ Yields followed by the same letter within a given year and effect are not significantly different at $P \leq 0.05$.

¶ AV, abamectin (used in 2013); BF, *Bacillus firmus*; Control, seed treatment containing no nematicide; PN, *Pasteuria nishizawae* (used in 2014 and 2015). The seed treatment change from AV to PN in 2014 was because AV was no longer labeled for soybean after 2013. The same base fungicides and insecticides labeled for soybean were used for each seed treatment each year to minimize confounding effects. All seed treatment products and rates are listed in Table 1.

Nevertheless, 2C, 3C, 4C, and 5C rotation sequences in conventional tillage resulted in significantly greater yield—up to 34%—than those under NT. These results suggest that the beneficial effect of rotation on corn yield diminishes as corn is planted more consecutively.

Corn could be benefited by a nematicide treatment that controls root lesions nematodes such as the AV treatment. However, the effect of seed treatment on corn yield was not significant in any year of the experiment (Table 5). It is speculated that root lesion nematode levels were not large enough to significantly reduce corn yield. No other corn yield differences were observed during the 3 yr of the study.

Soybean Yield Response

During the 3 yr of the experiment, significant main effects on soybean yield were observed (Table 5). Specifically, the tillage effect was significant in 2014 and 2015; whereas, crop rotation and seed treatment effects were significant in all 3 yr. Soybean grown under conventional tillage resulted in 8 and 10% greater yield than soybean under NT in 2014 and 2015, respectively (Table 8). This response was similar to corn and was attributed to the delayed warming in spring of NT soil compared with soil under conventional tillage and is in agreement with previous studies conducted in Wisconsin (Pedersen and Lauer, 2003; Marburger et al., 2015).

Frequent crop rotations resulted in the greatest soybean yield in all 3 yr of the study (Table 8). In 2013 and 2015, the CS and 1S crop rotations exhibited greatest yield. Specifically, the CS rotation during the first 2 yr of the experiment resulted in 20 to 22% greater yield than SS, whereas 1S resulted in 15 to 30% greater yield than SS. Similar soybean yield responses have been reported in previous studies in the Midwest (Pedersen and Lauer, 2003; Peterson and Varvel, 1989a).

A consistent nematicide seed treatment effect was observed in all 3 yr of the study. The control and AV treatment in 2013 and PN treatment in 2014 and 2015 resulted in significantly greater seed yield than BF (Table 8). The yield differences reached 4, 5, and 4% in 2013, 2014, and 2015, respectively. However, there was no variation (Table 3) in SCN population among the control and nematicide treated plots, which could explain the lack of a statistically significant yield benefit from nematicide seed treatment use. It appears that prophylactic use of multiple-input seed treatments including a nematicide failed to increase soybean yield compared with the nematicide-untreated control. This result suggests that the additional cost of applying multiple active ingredients seed treatments is not justified. Similar results have been reported from a study that examined multiple seed treatment components across diverse environments (Gaspar et al., 2014). Another recent study reported that prophylactic use of multiple inputs on a soybean production system failed to significantly and consistently increase soybean yield (Mourtzinis et al., 2016).

A significant tillage × crop rotation interaction was detected in the last year of the study (Table 5). Soybean after 5 yr of corn (1S) and CS resulted in the highest yield regardless the tillage system (Table 9). Additionally, continuous soybean under conventional tillage resulted in 28% greater yield than continuous soybean under NT. However,

Table 9. Effect of tillage × crop rotation on soybean yield in 2015.

Tillage† × crop rotation	2015
	Mg ha^{-1}
CT-1S	4.8a‡
CT-2S	4.3abcd
CT-3S	4.0bcde
CT-4S	3.9bcde
CT-5S	3.5e
CT-SC	4.5abc
CT-SS	3.9cde
NT-1S	4.6ab
NT-2S	3.6de
NT-3S	3.7de
NT-4S	3.9bcde
NT-5S	3.3ef
NT-SC	4.0bcde
NT-SS	2.8f

† 1S, first-year soybean after 5 yr of continuous corn; 2S, 3S, 4S, and 5S, second, third, fourth, and fifth year of continuous soybean after 5 yr of continuous corn, respectively; CT, conventional tillage; NT, no-till; SC, soybean rotated annually with corn; SS, continuous soybean since the experiment was initiated in 1983.

‡ Yields followed by the same letter are not significantly different at $P \leq 0.05$.

similarly to the tillage × crop rotation interaction on corn yield, the beneficial effect of a soybean–corn rotation system diminished the yield suppressing effects of NT.

The crop rotation × seed treatment interaction had a significant effect on soybean yield in 2014 and 2015 (Table 5). Specifically, in 2014, the lowest yields were observed in continuous soybean (SS) regardless of the seed treatment (Table 10). These yields were significantly different from the control seed treatment within the 2S, 5S, and CS crop rotations, which were among the highest yielding treatment combinations. It is presumed that these effects were driven from the effect of rotation (up to a 22% yield difference; Table 8) rather than the effect of the nematicide seed treatment (up to a 5% yield difference; Table 8). In 2015, the lowest yields were also observed in continuous soybean regardless of the seed treatment. These yields were different than all the nematicide seed treatments within the 1S and SC rotations. Similar to 2014, the strongest effect of rotation was presumed to drive the interaction. This suggests that the rotation effect during the 3 yr of the study was stronger than the effect of seed treatment on soybean yield. Additionally, the greater SCN population in rotations that involve consecutive years of soybean (Table 4) likely contributed to the observed yield differences.

This study was performed on a long-term rotation study field. We would expect SCN numbers to be high and increasing in the rotations where soybean is most common. Control of SCN is best accomplished using rotation with nonhost crops and resistant varieties in combination with effective nematicides. Since SCN has a long life in the soil and rotations and crop species were fixed in this study, nematicides were tested to determine their effectiveness. In this study, use of nematicide seed treatments was not justified, as they did not result in a yield benefit.

Table 10. Effect of crop rotation × nematicide seed treatment on soybean yield in 2014 and 2015.

Crop rotation† × seed treatment‡	2014	2015
	Mg ha^{-1}	
1S-PN	3.9abc§	4.7ab
1S-BF	3.6abcd	4.6abc
1S-Control	3.7abc	4.8a
2S-PN	4.0abc	4.1bcde
2S-BF	3.8abcd	3.9defgh
2S-Control	4.0ab	3.9cdef
3S-PN	3.8abcd	4.0cde
3S-BF	3.7abcd	3.5fgh
3S-Control	3.5abcd	4.1cde
4S-PN	3.6abcd	3.8defgh
4S-BF	3.4bcd	3.9defg
4S-Control	3.6abcd	4.1cdef
5S-PN	4.0abc	3.5efgh
5S-BF	3.6bcd	3.5efgh
5S-Control	4.1ab	3.2h
SC-PN	4.1a	4.3abcd
SC-BF	3.9abc	4.2abcd
SC-Control	4.0ab	4.2abcd
SS-PN	3.2d	3.2gh
SS-BF	3.2d	3.2h
SS-Control	3.3cd	3.5fgh

† 1S, first-year soybean after 5 yr of continuous corn; 2S, 3S, 4S, and 5S, second, third, fourth, and fifth year of continuous soybean after 5 yr of continuous corn, respectively; SC, soybean rotated annually with corn; SS, continuous soybean since the experiment was initiated in 1983.

‡ BF, seed treatment containing *Bacillus firmus*; Control, seed treatment containing no nematicide; PN, seed treatment containing *Pasteuria nishizawae*. The same base fungicides and insecticides labeled for soybean were used for each nematicide seed treatment each year to minimize confounding effects. All seed treatment products and rates are listed in Table 1.

§ Yields followed by the same letter within a given year are not significantly different at $P \leq 0.05$.

CONCLUSIONS

Results from this study show that yearly rotation of corn and soybean produced greater grain yields than continuous planting of either crop. Although conventional tillage resulted in greater yield than NT, yearly crop rotation under NT was among the highest yielding production systems in the study. Additionally, the nematicide seed treatment effect was significant, but treatments with nematicide resulted in similar or lower yield than the control. These results suggest that yearly rotation of corn and soybean with NT has high yield potential in Wisconsin, and nematicide seed treatment input is not always justified. A cropping system that involves yearly rotation of corn and soybean with NT is associated with lower production cost than conventional tillage because of reduced fuel and labor hour cost, and therefore potentially increased profitability.

The results from this study imply that decision between crop rotation vs. continuous cropping is more important than decision of nematicide seed treatment use. This was also justified by the lower SCN population in frequent corn–soybean rotations than rotations that involve consecutive years of soybean.

Conflict of Interest Disclosure

The authors declare there to be no conflict of interest.

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