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Population Dynamics of *Heterodera glycines* in Conventional Tillage and No-Tillage Soybean/Corn Cropping Systems

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Abstract: The effects of no-tillage (NT), conventional tillage (CT), and crop rotation on soybean yield and population dynamics of *Heterodera glycines* were compared during a 7-year study in a silty clay loam soil with 6% organic matter. Either *H. glycines*-resistant 'Linford' soybean or susceptible 'Williams 82' soybean was rotated with corn and grown on 76-cm-wide rows in both tillage systems. Soybean was planted in 1994, 1996, 1998, 1999, and 2000. Yield of Linford was significantly greater than Williams 82 in all years. Soybean yield was affected by tillage in 1999 and 2000. No-tillage production tended to support more reproduction (R = number of eggs at harvest/number of eggs at planting) on both cultivars. The largest R for Williams 82 were in 1998: 58.35 for NT plots and 11.78 for CT plots. For Linford, the largest R were 12.09 for NT plots in 1996, and 3.71 for CT in 1999. When corn was planted, R decreased more in NT. When soybean was planted in years subsequent to 1994, numbers of eggs at harvest (Pf) were greater for Williams 82 NT than for Williams 82 CT or Linford in both tillage systems; however, crop rotation with corn negated these population increases. The soil became suppressive to *H. glycines* in 1999 and was suppressive in 2000. After the 3 years of continuous soybean, Pf per 250 cm^3 soil were 2,870 for Williams 82 NT, 791 for Williams 82 CT, 544 for Linford NT, and 990 for Linford CT in 2000, compared with Pf of 13,100 for Williams 82 NT, 15,000 for Williams CT, 2,360 for Linford NT, and 2,050 for Linford CT in 1994. Describing population dynamics solely on the basis of R was not adequate, but also required independent examination of initial populations following overwintering and Pf after the growing season. Planting soybean either NT or CT in rotation with corn did not result in long-term increases in numbers of *H. glycines* eggs.

Key words: conservation tillage, crop loss, *Glycine max, Heterodera glycines,* nematode management, no-till, population dynamics, soybean, soybean cyst nematode.

Conservation tillage has been used increasingly in the United States since the late 1980s to reduce soil erosion, preserve soil moisture during drought, improve water quality, increase organic matter, and reduce fuel costs. Conservation tillage, which by definition leaves > 30% crop residue after planting, consists of no-tillage/strip-till, ridge-till, or mulch-till soil preparation (CTIC, 2001). Since 1989, conservation tillage has increased from approximately 27% of the hectares planted in the United States to 37% or nearly 44 million hectares in 2000. Although 55% of the 28 million hectares planted to full-season soybean (*Glycine max* (L.) Merr.) in the United States in 2000 received conservation tillage, scant information is available for cropping sequences and the effects of conservation tillage on population dynamics of *Heterodera glycines* Ichinohe and associated yield loss in soybean (Hershman and Bachi, 1995; Koenning et al., 1995; Schmitt and Nelson, 1987; Tyler et al., 1987). None of these reports concerned soybean production in the midwestern United States but pertained to the southeastern United States. Herein, we document results of an experiment in which we determined the effects of crop rotation of corn (*Zea mays* L.) with *H. glycines*-resistant or susceptible soybean on population dynamics of *H. glycines* and soybean yield in conventional and no-tillage production systems in soil typical of former prairies in the Midwest.

Materials and Methods

The experiment was established in 1994 in a field infested with a population of *H. glycines* classified as a race 3 and for which female indices were 3, 0, <1, and 0, respectively, for 'Pickett 71', 'Peking', Plant Introduction (PI) 88.788, and PI 90.763 (Riggs and Schmitt, 1988). The soil was a Drummer silty clay loam (Typic Haplaquolls; fine silty, mixed, mesic) with 61.1% silt, 28.8% clay, and 10.1% sand, pH 6.6, and 6.0% OM. Phosphorous and potassium levels were 118 and 345 kg/ha, respectively. The experimental design was a split-plot with no-tillage (NT) and conventional tillage (CT) (chisel plow in the fall and a field cultivator and finishing implement in the spring) as main plots and *H. glycines*-resistant 'Fayette' (1994) or 'Linford' (1996, 1998, 1999, and 2000), and susceptible 'Williams 82' soybean as subplots arranged in randomized complete blocks with six replications. Each experimental unit was a 3-m × 12-m plot with four rows on 76-cm centers. Each plot was divided equally lengthwise into two subsubplots to obtain subsamples for both yield and numbers of nematodes. Soybean was planted in 1994, 1996, 1998, 1999, and 2000, and corn was planted in 1995 and 1997. Plots that were planted to either the *H. glycines*-resistant or *H. glycines*-susceptible soybean in 1994 were planted in a resistant or susceptible monoculture when soybean was planted. When corn was planted, plots were labeled with the soybean cultivar planted the previous year to maintain continuity for comparisons among years. Instead of following the rotation with

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corn in 1999, soybean was planted in 1999 and 2000 in an attempt to exert selection pressure on the *H. glycines* population to overcome the resistance of Linford.

Soil samples collected at planting (for estimation of initial nematode population density [Pi]) and at harvest final nematode population density [Pf]; consisted of 12 cores taken in a zig-zag pattern 5 to 10 cm from the center two rows of each sub-subplot. Cysts were extracted by gravity sieving with nested screens of 850- and 250-µm-pore openings (Cobb, 1918). Cysts were selected, crushed individually, and the number of eggs per 250 cm^3 soil was determined. Even though soybean and corn yields were obtained from the center two rows of each sub-subplot, only soybean yield is reported.

Weed control in soybean consisted of preplant applications of glyphosate and 2,4-D and postemergence applications of acifluorfen + bentazon and sethoxydim. Weed control in corn consisted of preplant applications of glyphosate and 2,4-D and a preemergence application of metolachlor + atrazine.

Analysis of data (PROC UNIVARIATE and PROC MIXED; SAS Institute Inc., Cary, NC) was conducted on yield and egg numbers transformed to $\log_{10}(X + 1)$ values. Crop rotation was considered as a random variable. Values for reproduction (Pf/Pi [number of eggs at harvest/number of eggs at planting] are the antilogs derived from means provided by SAS. Means and standard errors for figures were calculated using Sigma Plot (SPSS, Inc., Chicago, IL).

Results

1994 growing season: The mean and standard deviation for the numbers of eggs per 250 cm^3 soil at the initiation of the experiment were 1,456 ± 2,404 for Fayette planted following CT, 1,528 ± 2,650 for Fayette planted NT, 3,049 ± 6,663 for Williams 82 planted CT, and 626 ± 471 for Williams 82 planted NT (Fig. 1).

In both tillage systems the number of eggs during the 1994 growing season increased on both the susceptible cultivar Williams 82 and the resistant cultivar Fayette. Under CT, Pf/Pi for Fayette and Williams 82 were 1.90 and 11.14, respectively (Table 1). Under NT, the ratios were 2.78 and 22.30 for Fayette and Williams 82, respectively. In spite of a 2-fold increase in population increase under NT, these differences were significant only at $P = 0.1613$ (Table 2). Planting Fayette affected Pf/Pi ($P = 0.0001$), but there was no tillage × cultivar interaction.

Tillage did not affect yield of soybean (Tables 3, 4). However, yield of resistant Fayette was greater ($P = 0.0001$) than the susceptible Williams 82.

1995 growing season: Corn reduced the numbers of eggs for all combinations of tillage and cultivar. The main effect of tillage on Pf/Pi was significant at $P = 0.0538$, and level of significance for the tillage × cultivar

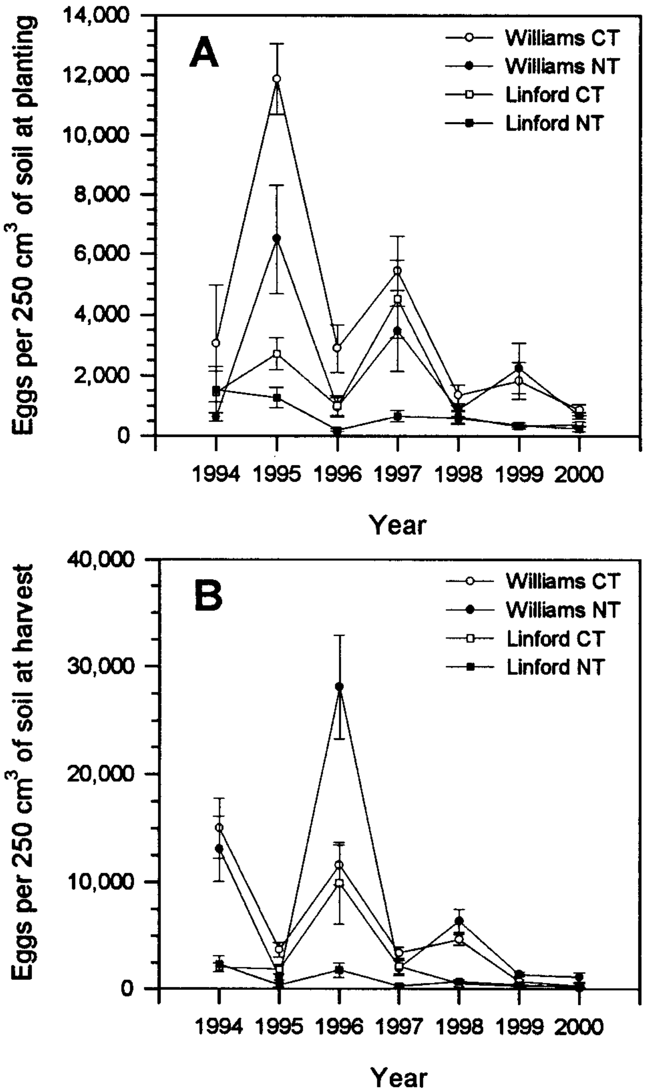

Fig. 1. Population dynamics of *Heterodera glycines* in a soybean-corn rotation planted either with conventional tillage (CT) or no-tillage (NT). A) Numbers of eggs at planting. B) Numbers of eggs at harvest. Soybean cvs. Williams 82, susceptible to *H. glycines,* and Fayette or Linford, resistant to *H. glycines,* were planted in 1994 (Fayette) 1996, 1998, 1999, and 2000. Corn was planted in 1995 and 1997. Each datum is the treatment mean, and bars represent the standard error of the mean.

interaction was $P = 0.1412$ (Tables 1, 2). There was no residual cultivar effect from either the resistant or the susceptible soybean in 1994. However, comparisons of Pf/Pi between the treatments of Linford CT and Linford NT planted in 1994 were different ($P = 0.0179$). There was no difference in Pf/Pi ($P = 0.7342$) in corn plots where Williams 82 CT and Williams 82 NT were planted in 1994.

1996 growing season: Tillage and cultivar affected Pf/Pi, $P = 0.0142$ and $P = 0.0004$, respectively (Tables 1, 2). Numbers of eggs recovered from plots of Williams 82 NT increased 7-fold when compared with plots planted following conventional tillage. However, the tillage × cultivar interaction was not significant. One sample from Williams 82 NT contained 73,000 eggs/250 cm^3

TABLE 1. Reproduction (Pf/Pi)[a] of *Heterodera glycines* as affected by conventional tillage or no-tillage, crop rotation, and planting susceptible Williams 82 or resistant cultivars.[b]

Cultivar and tillage[c]	Year and crop 1994 Soybean	1995 Corn	1996 Soybean	1997 Corn	1998 Soybean	1999 Soybean	2000 Soybean
William 82 CT	11.14	0.26	8.79	0.70	11.78	1.02	0.55
Williams 82 NT	22.30	0.21	58.35	0.52	24.0	2.70	1.88
Linford CT	1.90	0.56	2.54	0.38	2.07	3.70	1.36
Linford NT	2.78	0.11	12.09	0.09	5.44	1.74	8.05

[a] Pi = number of eggs at planting; Pf = number of eggs at harvest.
[b] Fayette planted in 1994 and Linford in 1996, 1998, 1999, and 2000.
[c] CT = conventional tillage; NT = no-tillage.

soil. Two other samples contained nearly 40,000 eggs/250 cm^3 and two others approximately 30,000 eggs/250 cm^3. Only two samples from Williams 82 CT contained more than 20,000 eggs/250 cm^3 (20,600 and 21,700). The largest number of eggs recovered from a plot planted to Linford was 8,800 eggs/250 cm^3 in an NT planting.

Yield of Linford was greater than Williams 82 (P = 0.0004). Tillage did not affect yield of either cultivar, and there was no tillage × cultivar interaction for yield (Tables 3, 4).

1997 growing season: Planting of corn reduced the number of eggs in both tillage systems. There was a cultivar effect ($P = 0.0176$) on Pf/Pi in plots that were planted to soybean in 1996 due to greater decreases in number of eggs recovered from plots planted to Linford the previous season in 1996 (Tables 1, 2). The level for significance for tillage on Pf/Pi was $P = 0.1353$ (Tables 1, 2). Plots planted to Linford NT in 1996 differed from plots planted to Linford CT in 1996 (P = 0.0679). However, there were no differences in Pf/Pi between Williams 82 CT and Williams 82 NT. There was no tillage × cultivar interaction.

1998 growing season: The level of significance for tillage on Pf/Pi was $P = 0.1462$. The Pf/Pi for both cultivars planted NT was 2-fold greater when compared to planting following conventional tillage (Tables 1, 2). There was a cultivar effect for Pf/Pi ($P = 0.0089$). Yield of Linford was greater than Williams 82 ($P = 0.0001$). Yield was not affected by tillage, nor was there a tillage × cultivar interaction (Tables 1, 2).

1999 growing season: There was no effect of tillage on Pf/Pi, and there was no cultivar effect on Pf/Pi (Tables 1, 2). The Pf/Pi for susceptible Williams 82 planted NT was numerically greater than that of Williams 82 planted in conventionally prepared soil, whereas the opposite was observed for Linford. The probability level for significance for the tillage × cultivar interaction on Pf/Pi was $P = 0.0994$ (Table 2). Reproduction on Williams 82 was lower than observed in previous plantings of soybean (Table 1).

Yield of Linford was greater than Williams 82 (P = 0.0001; Tables 3, 4). The effect of tillage was significant at $P = 0.0624$, but there was no tillage × cultivar interaction.

2000 growing season: Both tillage and cultivar effects were observed for Pf/Pi ($P = 0.0184$ and $P = 0.0598$, respectively; Tables 1, 2), but there was no tillage × cultivar interaction. Reproduction on Linford NT was 8.05, the highest Pf/Pi observed for this treatment. This was due to six subsamples for which no eggs were recovered at planting, but eggs were recovered from those plots in samples taken at harvest.

Yield was affected by tillage ($P = 0.0033$) and resistant soybean ($P = 0.0140$). There was no tillage × cultivar interaction (Tables 3, 4).

Population dynamics during the 7-year-long experiment were examined by plotting Pi (Fig. 1A) and Pf (Fig. 1B). Rotation with corn in 1995 and 1997 was effective in reducing numbers of eggs recovered at planting of soybean in 1996 and 1998 (Fig. 1). However, in 1995 and 1997 when corn was planted NT following Williams 82 NT, the Williams 82 NT had lower numbers of eggs recovered at planting in 1996 and 1998 compared with Williams 82 CT. In 1999 and 2000 there were no differences in numbers of eggs at plant-

TABLE 2. Summary analysis of variance table for effects on reproduction (Pf/Pi) of *Heterodera glycines* of conventional tillage or no-tillage, crop rotation, and planting susceptible Williams 82 or resistant soybean cultivars.[a]

Source	df	$P > F$ 1994 Soybean	1995 Corn	1996 Soybean	1997 Corn	1998 Soybean	1999 Soybean	2000 Soybean
Tillage (T)	1	0.1613	0.0538	0.0142	0.1353	0.1462	0.8315	0.0184
Cultivar (C)	1	0.0001	0.9242	0.0004	0.0176	0.0089	0.4024	0.0598
T × C	1	0.5259	0.1412	0.6461	0.2938	0.8224	0.0994	0.6560

[a] Fayette planted in 1994 and Linford in 1996, 1998, 1999, and 2000.

TABLE 3. Soybean yield in a field infested with *Heterodera glycines* as affected by tillage, crop rotation (1995 and 1997), and planting either susceptible Williams 82 or resistant soybean cultivars.[a]

	Year (kg/ha)				
Cultivar and tillage[b]	1994	1996	1998	1999	2000
Williams 82 CT	2,185	2,309	2,130	2,578	1,936
Williams 82 NT	2,124	2,320	2,108	2,476	1,754
Linford CT	3,299	3,098	2,852	3,045	2,271
Linford NT	3,120	3,240	2,839	2,951	1,877

[a] Fayette planted in 1994 and Linford in 1996, 1998, 1999, and 2000.
[b] CT = conventional tillage; NT = no-tillage.

ing between Williams 82 CT and Williams 82 NT. Numbers of eggs at planting for Linford CT and Linford NT differed in 1995 through 1997 but were not different in 1998 through 2000. In 1995 and 1997, Pi resulting from planting soybean the year before corn was planted were greater for Williams 82 CT, Williams 82 NT, and Linford CT when compared to Linford NT (Fig. 1A). In all years that soybean was planted subsequent to establishing the experiment in 1994, Williams 82 NT had larger numbers of eggs at harvest than Williams 82 CT, Linford NT, and Linford CT (Fig. 1B). In 1994, 1996, and 1998 Pf for Williams 82 CT differed from Linford planted with both tillage systems, but in 1999 and 2000 there were no differences among the three treatments.

DISCUSSION

Studies on the effects of NT production of soybean on population dynamics of *H. glycines* in the United States have been restricted to southern production areas, and results have been variable. In a study in Tennessee, numbers of second-stage juveniles (J2) of *H. glycines* in July were higher in soil that received CT without wheat in the cropping sequence when compared with NT and CT with wheat in the cropping sequence (Baird and Bernard, 1984). In that study, numbers of cysts were not affected, and numbers of eggs were not determined. Long-term NT was associated with lower numbers of cysts when compared with several CT treatments, but short-term (1 and 2-year) NT did not affect numbers of cysts (Tyler et al., 1987). In the first year of a 3-year study in North Carolina, numbers of eggs were lower following in-row subsoiling followed by NT when compared with NT and CT (Schmitt and Nelson, 1987). No differences were observed in the second year. In the third year, lower numbers of eggs were observed in the NT treatment when compared with the subsoiled/NT and the CT treatment. Numbers of J2 were affected by NT only in the first year. In the second and third years there was no effect of tillage on numbers of J2. In a study conducted in Georgia, CT also resulted in higher numbers of J2 in soil in August when compared with strip tillage and, in particular, NT (Edwards et al., 1988). In the continuous soybean cropping system of that research, numbers of J2 were nearly identical when CT was compared with NT. A subsequent study in Kentucky that evaluated NT and minimum tillage found no effect of tillage on numbers of cysts or eggs at planting or at harvest, but there was a tillage × wheat residue interaction (Hershman and Bachi, 1995). In a study done in North Carolina, numbers of eggs plus J2 at harvest were lower in NT plots in 4 of 6 years (Koenning et al. 1995).

TABLE 4. Summary analysis of variance for effects on soybean yield of conventional tillage or planting no-tillage and planting susceptible Williams 82 or resistant[a] cultivars in a field infested with *Heterodera glycines*.

		$P > F$				
Source	df	1994	1996	1998	1999	2000
Tillage (T)	1	0.4237	0.9374	0.7902	0.0624	0.0033
Cultivar (C)	1	0.0001	0.0004	0.0001	0.0001	0.0140
T × C	1	0.6201	0.7155	0.9275	0.9356	0.2162

[a] Fayette planted in 1994 and Linford in 1996, 1998, 1999, and 2000.

In our study, the trend was for larger Pf/Pi ratios in NT than in tilled plots in the years that soybean was planted except for 1999. That was the only year that Pf/Pi was not numerically greater for NT for either the resistant or the susceptible cultivar. In 1999 the soil became suppressive and continued to be suppressive in 2000. Numbers of eggs averaged among all treatments were lower at planting in 2000 than any of the previous years. Other than attempting to identify *Pasteuria* sp. in plots (Atibalentja et al., 1998), no effort was made to isolate potential pathogens of *H. glycines*. In 2000 the high Pf/Pi ratio for Linford NT was due to six subsamples from which no eggs were recovered at planting, but for which final egg numbers ranged from 77 to 732/250 cm^3 soil. Thus, Pf/Pi values for those subsamples were exaggerated. Linford CT also had two subsamples for which Pi was 0. If the samples with Pi = 0 were eliminated, Pf/Pi was 1.27 for Linford NT and 0.76 for Linford CT.

Trends in population dynamics were not adequately expressed by Pf/Pi ratios. For example, Pf/Pi ratios for Linford NT were consistently higher than Linford CT, except for 1999. However, the Pf/Pi ratios did not translate to larger populations of *H. glycines* during the 7 years the experiment was conducted. Populations on Linford were similar in year 7 to those when the experiment was initiated. Although Pf/Pi ratios for Linford were as high as 12.0 in 1996, that Pf/Pi resulted in a final population of 1,800 in 1996 compared with a Pf of 2,360 in 1994 when Pf/Pi was 2.8. The PI88.788 source of resistance in Linford (Bernard and Noel, 1991) was durable during the course of the experiment. The full level of PI88.788 resistance found in public cultivars such as Linford, and others developed in the cooperative USDA/University of Illinois program and that share a similar pedigree, seems to express a general resistance to most populations of *H. glycines* encountered in the Midwest. This resistance allows for some population increases. If crop rotation is practiced optimally, these increases might not reach damaging levels in the high-organic matter and high-moisture retention capacity of former prairie soils found in the Midwest.

Although NT resulted in higher Pf for the susceptible cultivar, this result is in contrast to a survey conducted in the Midwest in 1995 and 1996 (Workneh et al., 1999b). In that study, prevalence and numbers of eggs were greater in CT than minimum tillage and increasing percentage clay in NT fields was associated with lower detection and numbers of eggs (Workneh, et al., 1999b). The texture classification of the soil in the field used in this experiment was a silty clay loam, the second-highest percentage clay categorized in the survey. Effects of NT and conservation tillage on populations of *H. glycines* may be site-specific and be influenced by other edaphic factors such as pH, micro-, or macronutrients.

Although the susceptible cultivar grown NT had higher numbers of eggs at harvest, those numbers were not maintained during the year that corn was planted. Planting NT did not result in a long-term increase in numbers of eggs. However, long-term results may have been confounded by the soil becoming suppressive. Of interest is the greater reduction in numbers of eggs under NT during the corn rotation when compared to CT. At planting, rows in NT were within 10 cm of the previous year's rows. It is possible that corn influenced rhizosphere bacteria or fungi that parasitized eggs in cysts. No-tillage exerts many influences on soil. The myriad of organisms that are influenced have not been studied completely, especially potential nematode pathogens. Both bacterial and fungal biomass increased in NT (Aon et al., 2001). In the top 7.5 cm of NT soil, numbers of aerobic microorganisms, facultative anaerobes, and denitrifying organisms were higher than in CT (Doran, 1980). Phosphatase and dehydrogenase enzymatic activity were greater, as were water content, organic C, and N. From 7.5 to 30 cm, these trends were reversed in CT. In NT soil between 7.5 to 15 cm deep, facultative anaerobes and denitrifiers were higher than in CT. Plants can alter the spatial patterns of physical properties of soil and affect microbial activity. Carbon input is affected differently in the rhizosphere by different plants as are C, N, and P cycles, resulting in a soil microbiology and biochemistry that is plant-driven (Aon et al. 2001). The mechanism by which NT affected numbers of eggs during rotation is not known. It is more likely that parasitism of eggs was increased and less likely that hatch increased in the presence of a non-host (Sikora and Noel, 1996).

Because there was no long-term effect of NT on *H. glycines,* soybean producers should be more concerned with other diseases that may be affected by NT. Gray leaf spot of corn, the crop most commonly grown in rotation with soybean in the Midwest, has long been known to be more severe in NT than in CT (Roane et al., 1974). Populations in soil of the phytopathogenic fungi *Fusarium avenaceum, F. oxysporum,* and *Rhizoctonia solani* remained constant during a 3-year period of NT (Sturz and Carter, 1995). However, there was a decrease in root colonization of soybean roots by *R. solani* in NT. Stem canker of soybean (caused by *Diaporthe phaseolorum* var. *caulivora*) increased in incidence and severity in NT (Rothrock et al., 1985). A subsequent report indicated that in the Midwest the incidence of *Phialophora gregata* (causal organism of brown stem rot) and *Phytophthora sojae* (causal organism of Phytopthora root rot) were greater in conservation tillage fields than CT fields (Workneh et al., 1999a). Additional studies are needed to elucidate the various effects of conservation tillage and other production practices on pests and diseases in the soybean/corn production systems in the midwestern United States.

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