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Influence of Winter Annual Weed Management and Crop Rotation on Soybean Cyst Nematode (*Heterodera glycines*) and Winter Annual Weeds

J. Earl Creech, Andreas Westphal, Virginia R. Ferris, Jamal Faghihi, Tony J. Vyn, Judith B. Santini, and William G. Johnson*

Certain winter annual weeds have been documented as alternative hosts to soybean cyst nematode (SCN), and infestations of such species have become common in no-till production fields in the Midwest. This research was conducted to determine the influence of herbicide- and cover-crop-based winter annual weed management systems and crop rotation on winter annual weed growth and seed production, SCN population density, and crop yield. Two crop rotations (continuous soybean and soybean-corn) and six winter annual weed management systems (a nontreated control, fall and spring herbicide applications, spring-applied herbicide, fall-applied herbicide, fall-seeded annual ryegrass, and fall-seeded winter wheat) were evaluated in no-tillage systems from fall 2003 to 2006 at West Lafayette, IN and Vincennes, IN. Fall or spring herbicide treatments generally resulted in lower winter annual weed densities than cover crops. Densities of henbit and purple deadnettle increased over years in the cover crop systems but remained constant in the herbicide systems. Averaged over sites and years, winter annual weed densities were nearly 45% lower in the spring than the fall due to winter mortality. Corn yield was reduced by the cover crops at West Lafayette but not Vincennes. Winter annual weed management system had no influence on soybean yield. SCN population density was reduced by including corn in the crop sequence but was not influenced by winter annual weed management. The density of weedy host species of SCN in the experimental area was relatively low (less than 75 plants m^{-2}) compared to densities that can be observed in production fields. The results of these experiments suggest that inclusion of corn into a cropping sequence is a much more valuable SCN management tool than winter annual weed management. In addition, control of winter annual weeds, specifically for SCN management, may not be warranted in fields with low weed density.

Nomenclature: Soybean cyst nematode, *Heterodera glycines* Ichinohe; corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.; wheat, *Triticum aestivum* L.

Key words: Cover crop, integrated pest management, weed seedbank.

Soybean cyst nematode (SCN) consistently ranks as the most economically important soybean pathogen in the United States (Wrather et al. 2003; Wrather and Koenning 2006). SCN has been detected in most U.S. states where soybean is produced and is especially common in Indiana, where its presence has been confirmed in 82 of 92 counties (Faghihi and Ferris 2006). Current management recommendations for SCN include rotation to nonhost crops and use of SCN-resistant soybean cultivars (Faghihi and Ferris 2006; Niblack 2005).

Winter annual weeds have become more prevalent in crop production fields in recent years (Gibson et al. 2005; Nice and Johnson 2006). These species germinate anytime between late summer and early spring, but typically emerge in the fall, overwinter as small seedlings, and complete their life cycles in the spring. The proliferation of winter annual weeds has resulted from a number of factors, including the widespread adoption of conservation tillage practices (Wicks et al. 1994), reduced reliance on herbicides with soil residual activity (Barnes et al. 2003), and the relatively mild winters experienced in recent years (Krausz et al. 2003).

Winter annual weeds can have a number of negative impacts on cropping systems. Dense populations of winter annual weeds can slow drying and warming of soil in the spring (Bruce et al. 2000; Dahlke et al. 2001), the combination of which may lead to delayed planting dates and decreased yields (Güeli and Smeda 2001). In conventionally tilled fields, the presence of winter annuals can increase tillage, labor, and fuel costs required for spring seedbed preparation (Bruce et al. 2000; Dahlke et al. 2001). These weeds can also be difficult to control in no-till production systems with late spring herbicide applications because of their advanced growth stage. Similarly, winter annual weeds can interfere with crop seeding depth and crop establishment in high residue areas (Krausz et al. 2003).

Another potential problem associated with winter annual weeds is that a number of these species have been documented to serve as alternative hosts to SCN. In a greenhouse experiment, the abilities of purple deadnettle (*Lamium purpureum* L.), henbit (*L. amplexicaule* L.), field pennycress (*Thlaspi arvense* L.), and shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik] to support SCN reproduction were confirmed (Venkatesh et al. 2000). Earlier reports had identified common chickweed [*Stellaria media* (L.) Vill.] and smallflowered bittercress (*Cardamine parviflora* L.) as hosts to SCN (Riggs 1992).

In the field, soil temperature effects on SCN are of particular importance in the relationship between SCN and winter annual weed hosts. Alston and Schmitt (1988) found that SCN fails to develop at soil temperatures below 10 C. Weather station data from Indiana indicate that the period of overlap of high SCN activity and winter annual weed growth may be limited to a few weeks in early fall and late spring, when soil temperatures favor both nematode activity and winter annual weed growth. The ability of SCN to complete a reproductive cycle on purple deadnettle under field conditions in Indiana has recently been reported (Creech et al. 2005). Additionally, an increase in SCN egg density has been observed in purple-deadnettle-infested research plots (Venkatesh et al. 2004). A survey of Indiana fields with SCN

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revealed that winter annual weed hosts of SCN, as a composite, were present in 93% of the fields surveyed and occurred at an average density of approximately 150 plants m^{-2} (Creech and Johnson 2006). The widespread occurrence of winter annuals in the Midwestern United States coupled with the potential of these species to facilitate SCN reproduction and population increase may warrant expansion of SCN management practices to include winter annual weed control. However, the effect of winter annual weed management on SCN density is unknown.

The winter annual weed management tools utilized in no-till corn/soybean production systems in Indiana are herbicides and winter cover crops (Creech and Johnson 2006). Winter annual weeds can be effectively controlled with herbicides in the fall (Flanigan et al. 2005; Krausz et al. 2003) or the spring (Martin and Call 2005; Monnig and Bradley 2005), but the effect of weed removal timing on SCN population density is unknown. Fall seeded cover crops also hold promise as a system to reduce winter annual weed growth. In corn/soybean production systems, research on weed suppression by fall-planted, spring-killed cover crops has generally focused on growth of summer annual weed species in the subsequent corn or soybean crop (Burgos and Talbert 1996; Curran et al. 1994; Gallagher et al. 2003; Teasdale et al. 1991; Yenish et al. 1996). Little is known about the ability of cover crops to suppress winter annual weed growth. In addition, an annual ryegrass (*Lolium multiflorum* Lam.) cover crop may offer an added benefit to an SCN management program, as it has been shown to cause a decrease in SCN population density in the greenhouse (Riga et al. 2001). However, this observation has not been confirmed in the field.

The objectives of this study were to determine the influence of herbicide and cover crop based winter annual weed management systems and crop rotation on (1) winter annual weed growth, (2) the weed seedbank, (3) SCN population density, and (4) corn and soybean yield.

Materials and Methods

Site Description and Experimental Design. Field trials were conducted at two SCN infested locations in Indiana from 2003 to 2006. Experimental sites were the Purdue University Agronomy Center for Research and Education near West Lafayette and the Southwest Purdue Agricultural Center near Vincennes. Soils were a Raub-Brenton complex (fine-silty, mixed, superactive, mesic, Aquic Argiudolls) with 3% organic matter and pH 6.3 at West Lafayette and a Patton silt loam (fine-silty, mixed, superactive, Typic Endoaquolls) with 1% organic matter and pH 6.9 at Vincennes. In the 5 yr prior to establishment of these experiments, plots were under conventional tillage in a 2-yr corn-soybean rotation at West Lafayette and continuous soybean at Vincennes. Continuous no-tillage production systems were initiated in spring 2003. In 2003, plot areas at each site were under soybean production with an SCN-susceptible soybean cultivar ('DKB31-51') to increase SCN population density. Two weeks prior to soybean harvest, seeds of purple deadnettle, henbit, shepherd's-purse, and common chickweed were scattered on the soil surface of the plot area to augment the natural weed populations.

The experiment was established in the fall of 2003 with various crop rotations and winter annual weed management systems in individual plots measuring 9.1 m wide by 9.9 m long. The experimental design was a randomized complete block split plot with six replications (blocks). The main plots were randomized and applied as strips across each block and consisted of two crop rotations: continuous soybean (SS) and a 2-yr rotation of soybean-corn (SC). The subplots were randomized within crop rotation and consisted of six winter annual weed management systems. Systems were (1) a non-treated control, (2) fall and spring herbicide applications, (3) spring herbicide application, (4) fall herbicide application, (5) fall-seeded annual ryegrass, and (6) fall-seeded winter wheat. After establishment, the plots to which the main- and subplot factors were applied remained fixed throughout the entire experiment to determine the cumulative treatment effects over time.

Cultural Practices. Winter annual weed management treatment regimes were initiated following crop harvest in early October of 2003, 2004, and 2005. Wheat was seeded at 67 kg ha^{-1} with the use of a no-till drill with a row spacing of 19 cm. Wheat varieties were 'Pioneer 25R42' in 2003 and 2004 and 'INW0302'[1] in 2005. Annual ryegrass was seeded by surface broadcasting at a rate of 34 kg ha^{-1}. Annual ryegrass varieties were 'Gulf' (2003 and 2004) and a commercial mixture[2] of 'Florlina', 'Bounty', and 'SBA Experimental' (1:1:1) (2005). The annual ryegrass mixture was adopted for improved winter hardiness in 2005 because of high levels of winterkill at the West Lafayette site in 2003 and 2004. In plots designated for winter annual weed removal, glyphosate[3] was applied at 1.2 kg ai ha^{-1} as needed through the fall and/or spring to maintain weed-free conditions (required one to three applications). Whenever necessary, glufosinate[4] was used to control volunteer glyphosate-resistant corn and soybean.

Seven to 10 d before planting, the entire plot area was treated with glyphosate at 2.4 kg ai ha^{-1}. On the 2004 planting date at Vincennes, a second glyphosate application at the same rate was required to kill the annual ryegrass. Corn and soybean were planted no till in 76-cm rows at seeding rates of 74,000 and 370,000 seeds ha^{-1}, respectively. A different planter was used at West Lafayette[5] than at Vincennes.[6] The corn hybrid was 'DKC61-45' (2005). Soybean varieties were 'DKB36-51' (2004) and 'AG3302' (2005 and 2006). The cultivar DKB36-51 was resistant to SCN, whereas AG3302 was SCN-susceptible. All crop varieties were glyphosate-resistant. The planting dates were May 10, 2004, May 11, 2005, and May 8, 2006 at West Lafayette and May 12, 2004, May 6, 2005, and May 8, 2006 at Vincennes.

Starter fertilizer was surface broadcast each year prior to planting at Vincennes at rates of 20 kg ha^{-1} of elemental N, 23 kg ha^{-1} of elemental P, and 112 kg ha^{-1} of elemental K. Fertilizer N was applied at 220 kg N ha^{-1} to corn plots immediately after planting in 2005. At West Lafayette, 28% urea ammonium nitrate was knifed 10 cm deep into the soil and at Vincennes, fertilizer N was surface broadcast in the form of ammonium nitrate. As needed, in-crop weed control consisted of glyphosate applied across the entire experimental area at the labeled rate appropriate for the weed species and weed growth stages present.

Measurements. Soil samples were collected from each plot at the onset of the experiment in early October 2003 and, thereafter, at crop planting in spring and at harvest in the fall in each growing season. Samples from each plot consisted of 40 soil cores that were randomly collected with a 3.1-cm stainless steel probe to a depth of 15 cm. Soil cores from each plot were passed through a 6-mm mesh screen and mixed thoroughly. SCN population density was determined by subjecting a 100-cc subsample of the soil from each plot to a sieving-and-decanting extraction procedure to collect SCN cysts (Faghihi et al. 1986). Cysts were then crushed and SCN eggs were enumerated and expressed as number of eggs (100 cc soil)$^{-1}$ (Faghihi and Ferris 2000).

A seedling emergence technique was used to monitor weed seedbank composition in the soil (Ball and Miller 1989; Forcella 1992). Soil from each plot (1,300 cc) was mixed with steam-sterilized sand (250 cc) and placed into 25 by 25-cm greenhouse flats. Flats were placed in a greenhouse at 18/15 $\pm$ 5 C day/night under natural sunlight and were watered as needed. Weed emergence was monitored weekly by counting and carefully removing the seedlings of each species that had emerged. After 1 mo, soils in each flat were thoroughly mixed, then subjected to an additional month of growth. Soils were then moved into a 5 C cooler for 1 mo to break dormancy of any remaining seeds, then returned to the greenhouse for a final month of growth (Cardina et al. 1996, 1997; Marino et al. 1997). This procedure was conducted between the months of November and March of each year to avoid high daytime air temperatures that would be unfavorable for winter annual weed germination and growth in the greenhouse. Seedbank determination occurred with fall soil samples only because this sample time provides an indication of the amount of winter annual weed seed in the soil entering the winter annual weed growth period.

Winter annual weeds were enumerated in each plot in both late November and mid-April. Five quadrats were placed on the ground in each plot and the identity and density of each species within the quadrat was documented. Quadrat placement was determined by stretching a measuring tape diagonally across each plot then positioning quadrats at preselected, equally spaced points along the tape. A larger quadrat was used at West Lafayette (0.5 m^2) than at Vincennes (0.25 m^2) because of the relatively low weed density at the West Lafayette site. The placement of each quadrat in each plot was identical between years and sampling timings.

Corn grain yields were determined at Vincennes by hand harvesting two adjacent 2.7-m rows at two separate locations in each plot for a total harvested area of 8.1 m^2. At West Lafayette, corn yield was determined by harvesting the entire 9.9-m length of the four center rows of each plot with a plot combine. Soybean grain yields were determined with the use of a plot combine by harvesting the entire 9.9-m length of the center four or eight rows at Vincennes and West Lafayette, respectively. Grain yields are presented at a moisture content of 155 and 130 g kg^{-1} for corn and soybean, respectively.

Statistical Analysis. The effects of winter annual weed management and crop rotation on weed density, the weed seedbank, SCN egg density, and crop yield were assessed with the use of analysis of variance (ANOVA). Data for individual species in the weed seedbank and in-field weed densities were combined into three groups for analysis and presentation: (1) *Lamium* spp. (henbit and purple deadnettle), (2) winter annual weed hosts of SCN (*Lamium* spp., common chickweed, shepherd's-purse, and small-flowered bittercress), and (3) total winter annual weeds (all winter annuals that appeared in quadrats). Weed density and seedbank data were square-root transformed prior to analysis. Weed-density data were analyzed with the use of an ANOVA appropriate for a randomized block split-block design with weed management system and year as whole-plot factors. A randomized block split-plot design was used to assess seedbank data; weed management system was treated as the whole plot factor whereas the subplot factor was year.

The rotational crop (corn) was not introduced into the experiment until the 2005 growing season, so SCN and soybean yield data were each analyzed with the use of two different statistical models—a continuous-soybean analysis and a crop-rotation analysis. The continuous-soybean analysis included data from only the SS plots that were collected from the inception of the experiment (2003) until 2006. The rotational analysis included data from both SS and SC plots in 2005 and 2006. SCN data were analyzed with the use of an ANOVA appropriate for a randomized block split-split plot design. In the continuous-soybean analysis, winter annual weed management was the whole-plot factor, year was the subplot factor, and season (fall or spring) was the sub-subplot factor. The crop-rotation analysis, on the other hand, included rotation as the whole-plot factor, winter annual weed control as the sub-plot factor, and season as the sub-subplot factor. SCN data were $\log_{10}(x + 1)$ transformed prior to analysis.

Soybean yield data were analyzed with the use of an ANOVA appropriate for a randomized block split-plot design. In the continuous-soybean analysis, weed management system and year were designated as the whole-plot and subplot factors, respectively. In the rotational analysis, crop rotation was the whole-plot factor and weed management system was the subplot factor. Corn yields were analyzed as a randomized complete block design.

ANOVA was performed with the use of the PROC MIXED procedure of SAS.[7] West Lafayette and Vincennes differed greatly with respect to initial weed and SCN infestation levels; therefore, locations were analyzed separately. All effects except replication were considered fixed. Although Type III *F* values are provided by PROC MIXED, mean-square values for the various model components are not given (SAS 1999). Therefore, mean separation was performed with the use of a series of pairwise contrasts among all treatments (Saxton 1998) at the 0.05 level of probability. Back-transformed means are presented for ease of discussion.

Results and Discussion

Annual ryegrass and wheat cover crops were successfully established in the fall of each year at both sites. Plant populations of cover crops in the spring were similar to those in the fall, with the exception of annual ryegrass at West Lafayette, where, each year, the majority of the stand was lost to winterkill (data not shown). Average monthly temperatures throughout the experiment were higher at Vincennes than West Lafayette and were comparable to long-term averages (Tables 1 and 2). Generally, precipitation in each year was evenly distributed and was probably not limited to cover crop and winter annual weed growth or crop yield. One potential exception was at West Lafayette in 2005, where a relatively dry spring may have influenced crop response.

Table 1. Precipitation and average monthly air temperatures in 2003, 2004, 2005, and 2006 at the Agronomy Center for Research and Education located near West Lafayette, IN.

Month	Temperature 2003	2004	2005	2006	30-yr	Precipitation 2003	2004	2005	2006	30-yr
	C					mm				
January	−7.6	−4.9	−2.7	3.1	−4.8	27.2	55.9	150.6	62.2	45.5
February	−4.8	−2.2	0.3	−1.2	−2.3	29.2	11.7	67.3	25.4	39.9
March	4.8	6.5	2.2	4.0	3.8	17.3	102.4	29.7	102.6	72.1
April	11.4	11.6	12.4	12.6	10.1	69.6	33.8	51.8	87.6	90.7
May	15.6	18.5	15.5	15.6	16.3	172.7	151.4	45.7	131.1	110.5
June	19.7	20.3	22.9	21.2	21.4	97.3	251.2	51.1	61.0	107.7
July	22.7	21.6	23.3	24.3	23.2	200.7	77.7	116.8	156.0	101.6
August	23.1	19.4	23.3	22.4	22.0	90.2	97.8	51.1	135.9	93.5
September	17.3	18.8	20.6	16.7	18.3	181.4	13.0	122.2	72.1	75.7
October	11.2	11.6	12.6	10.3	11.8	33.0	72.6	36.1	103.1	69.3
November	7.1	6.8	6.3	6.7	5.1	103.4	110.2	56.9	94.6	78.2
December	0.3	−1.3	−4.7	—[a]	−1.6	70.1	66.8	36.3	—	61.7

[a] Weather station data missing.

Winter Annual Weed Growth. Weed management systems influenced fall and spring winter annual weed growth. The year by management system interactions were significant; therefore, weed count data were not averaged over years or treatments (Tables 3 and 4). Fall and spring weed densities generally exhibited similar trends over time and within weed management systems. At Vincennes, the fall (Table 3) and spring (Table 4) herbicide applications resulted in lower weed densities than the cover crop treatments. Compared to the nontreated control, *Lamium* spp. and winter annual weed hosts of SCN were not influenced by cover crops. However, total weed density of cover-crop-containing plots was lower than that of the nontreated check. At West Lafayette, winter annual weed growth in the nontreated control was generally similar to fall-seeded annual ryegrass. The high level of winter mortality of annual ryegrass at this site may have inhibited the ability of this cover crop to suppress weed growth. In fall weed growth, the winter wheat cover crop at West Lafayette was similar to the spring-applied herbicide and generally provided greater weed suppression than annual ryegrass (Table 3).

Henbit and purple deadnettle appear to be highly competitive weeds that can persist, and potentially thrive, in a number of management systems. Density of *Lamium* spp. increased in the cover-crop systems over time, whereas overall SCN host densities, comprised largely of *Lamium* spp., shepherd's-purse, and common chickweed, remained constant (Tables 3 and 4). *Lamium* spp., as a fraction of SCN host weeds, increased from 10 to 47% and 19 to 73% at West Lafayette and Vincennes, respectively, between the 2003 and 2005 fall sample times (Table 3). Similar increases were observed in the spring (Table 4). In the spring-applied herbicide treatment, *Lamium* spp. was the only weed group that maintained constant densities over time (Tables 3 and 4); suggesting that *Lamium* spp. may have more persistent seed in the soil seedbank and/or greater fall seed production than many other winter annual weed species present in these experiments.

Winter annual weed densities were generally lower in the spring than the fall (Table 5). At West Lafayette, total weed densities in the spring were 50, 85, and 31% lower in 2004, 2005, and 2006, respectively, than in the preceding fall. The reason for the higher level of winter annual weed mortality over the 2004 to 2005 winter annual weed growth period than in other years is unknown, because weather conditions were comparable (Tables 1 and 2). Total weed densities at Vincennes were not as variable between years, with spring densities of 28 to 41% lower than those in the fall across the 3 yr (Table 5). The actual percentage of weeds that experienced winterkill is probably higher than the spring densities would indicate, because spring counts included both winter-surviving and spring-emergent winter annual weeds. In a recent survey of Indiana production fields, winter annual weeds were found to be present in greater abundance in the southern than the northern regions of the state (Creech and

Table 2. Precipitation and average monthly air temperatures in 2003, 2004, 2005, and 2006 at the Southwest Purdue Agricultural Center located near Vincennes, IN.

Month	Temperature 2003	2004	2005	2006	30-yr	Precipitation 2003	2004	2005	2006	30-yr
	C					mm				
January	−4.3	−2.2	2.6	5.2	−2.6	8.9	123.7	183.9	74.2	66.0
February	−2.2	−0.2	3.9	0.2	0.0	136.9	25.7	68.3	44.5	63.8
March	6.7	8.8	4.9	6.8	5.9	109.2	78.7	69.3	246.4	91.4
April	13.2	13.3	14.1	15.0	11.9	89.2	21.8	91.7	185.2	108.7
May	17.8	21.1	17.2	17.7	17.7	171.5	58.2	90.4	162.1	130.3
June	21.1	22.8	24.2	23.1	22.5	138.1	167.4	107.7	79.2	102.9
July	24.7	23.9	25.3	26.2	24.6	101.1	58.4	109.5	61.0	118.6
August	24.8	21.0	25.9	25.6	23.5	104.9	25.9	283.2	162.8	94.5
September	19.0	21.0	22.7	18.7	19.4	150.6	115.1	84.1	110.0	80.3
October	14.6	13.8	14.6	12.5	13.0	45.2	202.8	22.4	116.7	81.5
November	9.0	9.5	8.5	—[a]	6.5	131.3	124.2	126.7	—	108.2
December	2.7	0.3	−0.3	—	0.2	71.6	—	76.2	—	82.3

[a] Weather station data missing.

Table 3. Fall density of winter annual weeds in response to weed management systems in permanently established quadrats in no-till continuous soybean at West Lafayette, IN and Vincennes, IN.

	West Lafayette			Vincennes		
Weed management system[a]	2003	2004	2005	2003	2004	2005
	Lamium spp.[b] m^{-2}					
Nontreated check	2 aB[c]	17 aA	18 aA	15 aY	30 aXY	49 aX
Spring-applied herbicide	2 abB	3 cAB	4 bA	9 aX	7 bX	6 bX
Fall-seeded annual ryegrass	1 bC	10 abB	17 aA	15 aY	21 aY	57 aX
Fall-seeded wheat	1 bB	8 bA	6 bA	11 aY	39 aX	75 aX
	Winter annual weed hosts of SCN[d] m^{-2}					
Nontreated check	23 aB	53 aA	36 aB	65 aX	45 aX	75 aX
Spring-applied herbicide	24 aA	8 bB	5 bB	64 aX	25 aY	9 bZ
Fall-seeded annual ryegrass	6 bC	26 aB	44 aA	80 aX	34 aY	83 aX
Fall-seeded wheat	6 bB	14 bA	11 bAB	60 aX	53 aX	89 aX
	Total winter annual weeds[e] m^{-2}					
Nontreated check	25 aB	58 aA	40 aB	171 aY	127 aY	295 aX
Spring-applied herbicide	25 aA	10 cAB	7 bB	188 aX	59 bY	96 cY
Fall-seeded annual ryegrass	6 bC	28 bB	51 aA	166 aY	82 abZ	216 bX
Fall-seeded wheat	6 bA	15 cA	14 bA	161 aX	86 abY	207 bX

[a] Fall-applied herbicide and fall + spring–applied herbicide treatments were weed free in the fall and were not included in the analysis.
[b] *Lamium* spp. included henbit and purple deadnettle.
[c] Treatment means within a column followed by the same lower-case letter are not statistically different at the 0.05 level. Differences within rows and within location are designated with upper-case letters.
[d] Winter annual weed hosts of SCN included *Lamium* spp., common chickweed, shepherd's-purse, and small-flowered bittercress.
[e] Total winter annual weeds included all winter annuals that appeared in quadrats.

Johnson 2006). The lower levels of winter mortality documented at Vincennes than West Lafayette in this study may partially explain why winter annual weeds tend to thrive in the southern Indiana fields.

Winter Annual Weeds in the Soil Seedbank. The composition of the weed seedbank was influenced by winter annual weed management system (Table 6). At West Lafayette, the nontreated check generally exhibited the highest amount of weed seedling emergence across all winter annual weed groups. Soil samples from plots in the annual ryegrass system produced a greater number of individuals of each weed group than the sequential fall + spring–applied herbicide program. At Vincennes, weed seedling emergence was more pronounced in the annual ryegrass system than in any herbicide treatment. Fall-seeded wheat was similar to all other treatments in each of the weed groups. Of the treatments included in this study, herbicide systems and fall-seeded wheat appear to possess the greatest ability to reduce the weed seedbank.

Soybean Cyst Nematode Density. Year by sample-time interactions were significant in the continuous-soybean analysis; therefore, mean SCN eggs (HG type 2.5.7) were not pooled over year or sample time (Table 7). Due to field history, SCN population density was nearly 25-fold greater at Vincennes than at West Lafayette in spring 2004. However, both sites responded similarly to the use of an SCN-resistant soybean cultivar, as SCN population levels at both sites decreased by fall 2004. Planting SCN-resistant soybean

Table 4. Spring density of winter annual weeds in response to weed management systems in permanently established quadrats in no-till continuous soybean at West Lafayette, IN and Vincennes, IN.

	West Lafayette			Vincennes		
Weed management system[a]	2004	2005	2006	2004	2005	2006
	Lamium spp.[b] m^{-2}					
Non-treated check	1 Ab[c]	1 aB	10 aA	7 aY	8 aY	27 aX
Fall-applied herbicide	0 aA	0 bA	0 cA	1 bX	3 bX	1 bX
Fall-seeded annual ryegrass	1 aC	2 aB	11aA	11 aY	5 abZ	32 aX
Fall-seeded wheat	0 aC	1 aB	5 bA	7 aY	12 aY	36 aX
	Winter annual weed hosts of SCN[d] m^{-2}					
Nontreated check	9 aB	5 aC	21 aA	38 aX	20aY	44 aX
Fall-applied herbicide	2 bA	1 bA	0 cB	17 bX	12 abX	2 bY
Fall-seeded annual ryegrass	3 bB	7 aB	31 aA	48 aX	15 bY	50 aX
Fall-seeded wheat	2 bB	2 abB	8 bA	42 aX	18 abY	45 aX
	Total winter annual weeds[e] m^{-2}					
Nontreated check	12 aB	5 aC	24 bA	127 aY	118 aY	199 aX
Fall-applied herbicide	3 bA	1 aA	0 dA	78 bX	42 bY	60 cX
Fall-seeded annual ryegrass	4 bB	9 aB	37 aA	122 aX	38 bY	118 bX
Fall-seeded wheat	2 bB	3 aB	11 cA	111 abX	98 aX	106 bX

[a] Spring-applied herbicide and fall + spring–applied herbicide treatments were weed free in the spring and were not included in the analysis.
[b] *Lamium* spp. included henbit and purple deadnettle.
[c] Treatment means within a column followed by the same lower-case letter are not statistically different at the 0.05 level. Differences within row (within location) are designated with upper-case letters.
[d] Winter annual weed hosts of SCN included *Lamium* spp., common chickweed, shepherd's-purse, and small-flowered bittercress.
[e] Total winter annual weeds included all winter annuals that appeared in quadrats.

Table 5. Year and sampling time effects (fall or spring) on winter annual weeds in response to weed management systems in permanently established quadrats in no-till continuous soybean at West Lafayette, IN and Vincennes, IN.[a]

	West Lafayette				Vincennes		
Species	Years	Fall	Spring	P value[b]	Fall	Spring	P value
		Number m^{-2}			Number m^{-2}		
Lamium spp.[c]	2003–2004	1	0	< 0.0001	13	8	0.0099
	2004–2005	11	1	< 0.0001	29	8	< 0.0001
	2005–2006	13	8	0.0002	59	31	< 0.0001
Winter annual weed hosts of SCN[d]	2003–2004	10	4	< 0.0001	68	43	0.0004
	2004–2005	29	4	< 0.0001	44	15	< 0.0001
	2005–2006	28	19	< 0.0001	82	46	< 0.0001
Total winter annual weeds[e]	2003–2004	12	6	< 0.0001	166	120	< 0.0001
	2004–2005	34	5	< 0.0001	173	120	0.1788
	2005–2006	35	24	0.0009	239	141	< 0.0001

[a] Fall-applied herbicide, spring-applied herbicide, and fall + spring–applied herbicide treatments were weed free in the fall and/or the spring and were not included in the analysis.
[b] Within location, the P value compares treatment means within a row (year).
[c] *Lamium* spp. included henbit and purple deadnettle.
[d] Winter annual weed hosts of SCN included *Lamium* spp., common chickweed, shepherd's-purse, and small-flowered bittercress.
[e] Total winter annual weeds included all winter annuals that appeared in quadrats.

cultivars is well established as a critical component of SCN management programs (Faghihi and Ferris 2006; Niblack 2005).

In order to isolate the effects of winter annual weeds on SCN population density, the experiment was originally designed to use only SCN-resistant soybean varieties. However, low SCN egg densities in the experimental areas following the 2004 growing season necessitated a switch to SCN-susceptible soybean in 2005 and 2006. The susceptible variety had variable effects on overall SCN population density. At West Lafayette, SCN egg levels in 2005 increased over 200-fold, but in 2006, a significant decrease in SCN was observed when the same variety was planted. SCN population density at Vincennes failed to change in response to the susceptible cultivar in either the 2005 or 2006 growing seasons. The reason for the variable response in SCN egg density at these sites to the presence of a susceptible soybean variety is unknown. One possible explanation is that these soils may have become suppressive to the nematode. Suppression of SCN has been documented in a number of soils and results from the presence or development of a population of microorganisms that feed on the nematode (Chen 2004). Noel and Wax (2003) observed a decrease in SCN egg density over time when an SCN-susceptible soybean variety was used and attributed this trend to the development of a suppressive soil. Xing and Westphal (2006) documented the development of suppressive soil in a soybean monoculture in Indiana. A similar effect may have occurred at the West Lafayette and Vincennes experiment sites, although the soil has not been specifically tested for the presence of microorganisms antagonistic to SCN.

In the crop-rotation analysis, rotation by sample-time interactions were not significant; therefore, SCN densities are reported separately for sample time and rotation (Tables 8 and 9). At both sites, the use of a soybean-corn crop sequence resulted in lower SCN egg density than planting continuous soybean. The value of rotating corn with soybean in reducing SCN population density has been shown in other studies (Koenning et al. 1993, 1995; Noel and Edwards 1996; Porter et al. 2001; Sasser and Uzzell 1991; Schmitt 1991; Young 1998). Sample time was significant at West Lafayette but not Vincennes. Lower SCN counts at West Lafayette were recorded in the spring than the fall, and were probably attributable to egg hatch, as soil temperatures increased in the spring (SCN proceeded from the egg to the larval stage and were no longer detectable as eggs). Similar results have been reported in other studies (Bonner and Schmitt 1985; Hill and Schmitt 1989).

Winter annual weed management main effects and interactions were not significant in either the continuous-

Table 6. Winter annual weed seedling emergence from the weed seedbank in response to weed management systems in no-till continuous soybean at West Lafayette, IN and Vincennes, IN.[a]

	West Lafayette					Vincennes		
	Lamium spp.[b]		SCN hosts[c]					
Weed management system	2004	2005	2004	2005	Total[d]	*Lamium* spp.	SCN hosts	Total
	Number of seedlings (1,300 cc soil)$^{-1}$							
Nontreated check	0.3 a[e]	3.3 a	19.2 a	8.9 a	15.3 a	7.8 ab	10.9 ab	54.6 a
Fall-applied herbicide	0.0 a	0.0 c	0.1 c	0.5 bd	2.9 bc	1.1 bc	2.9 bc	17.7 b
Spring-applied herbicide	0.0 a	0.1 c	0.0 c	0.7 bcd	1.9 bc	0.8 c	2.0 bc	18.6 b
Fall + spring-applied herbicide	0.1 a	0.0 c	0.4 c	0.0 d	1.0 c	0.7 c	1.6 c	21.8 b
Fall-seeded annual ryegrass	0.0 a	1.3 b	2.7 b	2.8 b	3.2 b	11.7 a	12.1 a	53.7 a
Fall-seeded wheat	0.0 a	0.1 c	0.2 c	1.1 bc	1.9 bc	4.3 abc	6.8 abc	33.9 ab

[a] Fall-applied herbicide and fall + spring–applied herbicide treatments were weed free in the fall and were not included in the analysis.
[b] *Lamium* spp. included henbit and purple deadnettle.
[c] Winter annual weed hosts of SCN included *Lamium* spp., common chickweed, shepherd's-purse, and small-flowered bittercress.
[d] Total winter annual weeds included all winter annuals that appeared in quadrats.
[e] Treatment means within a column followed by the same lower-case letter are not statistically different ($P \leq 0.05$).

Table 7. SCN egg density (HG type 2.5.7) in continuous-soybean plots in 2004, 2005, and 2006 at West Lafayette, IN and Vincennes, IN.

Year	West Lafayette			Vincennes		
	Spring	Fall	P value[a]	Spring	Fall	P value
	SCN eggs (100 cc soil)$^{-1}$			SCN eggs (100 cc soil)$^{-1}$		
2004	174 b[b]	24 b	0.0003	4,222 b	158 a	<0.0001
2005	13 c	3,066 a	<0.0001	54 a	117 a	0.1574
2006	655 a	67 b	<0.0001	81 a	144 a	0.2895

[a] Within location, the P value compares treatment means within a row (year).
[b] Treatment means within a column followed by the same letter are not statistically different at the 0.05 level of significance.

soybean or crop-rotation analyses of SCN population density. In adjoining studies at both experiment sites, however, SCN reproduction (cyst and egg production) on winter annual weeds was documented throughout the course of the experiment (Creech et al. 2005). The failure of winter annual weed removal to impact overall SCN egg densities in the soil may indicate that these weeds contribute little, if any, to SCN population levels on the field scale.

Winter annual weeds such as henbit and purple deadnettle are excellent hosts for SCN in the greenhouse (Creech et al. 2007a, 2007b; Venkatesh et al. 2000) but environmental factors in the field may limit the ability of SCN to reproduce at appreciable levels on these weeds. The majority of the fall winter annual weed emergence in these experiments occurred near crop harvest (data not shown). In September, average monthly temperatures were below 20 C at both sites, then declined to less than 15 C and 10 C in October and November, respectively (Tables 1 and 2). SCN hatch, root penetration, and development occur over a fairly wide range of temperatures, but the rate of SCN growth and development is strongly temperature dependent. The rate of SCN development increases linearly with temperature between 15 and 30 C, and the optimum temperature for SCN development is 25 C (Alston and Schmitt 1988). Alston and Schmitt (1988) also found that SCN fails to develop at soil temperatures below 10 C. Therefore, SCN development and reproduction probably occurs at a much slower rate on winter annual weeds under field conditions than in the greenhouse or on soybean during the growing season.

In addition, the rate of SCN egg hatch and juvenile emergence declines in the fall as soil temperatures drop, then increases in the spring as soil temperatures rise and dormancy is broken (Bonner and Schmitt 1985; Hill and Schmitt 1989; Ross 1963). Thus, another factor that may limit SCN reproduction on winter annual weeds is that the emergence of winter annuals in the field corresponds to the time period in which SCN typically enters into diapause.

The lack of SCN response to winter annual weed management may have also been a reflection of the density of winter annual weed hosts of SCN in the experimental plot area. Over the course of the experiment, winter annual weed hosts of SCN occurred in nontreated check plots at densities as high as 36 and 75 plants m^{-2} at West Lafayette and Vincennes, respectively (Tables 4 and 5). However, in a recent survey of Indiana production fields, winter annual weed hosts of SCN occurred at an average, statewide density of approximately 150 plants m^{-2} (Creech and Johnson 2006). In some fields, average field-wide densities of henbit and purple deadnettle alone exceeded 400 plants m^{-2} (Creech and Johnson 2006). Because the distance an SCN juvenile can migrate through the soil is usually limited (Koenning 2004), host root density can impact SCN reproduction (Creech et al. 2007b). The low weed densities present at the West Lafayette and Vincennes sites may have limited the ability of SCN juveniles to locate a root for feeding-site establishment and reproduction. The results of these experiments suggest that winter annual weed management, specifically for SCN control, may not be warranted in fields with low weed density. However, the effect of winter annual weed management on SCN population density in fields with high weed densities was not addressed in these studies.

Crop Yield. With the exception of annual ryegrass in at Vincennes in 2004, which required a second glyphosate application at planting, all cover crops and weeds were successfully controlled prior to planting. Corn yield in 2005 was influenced by winter annual weed management at West Lafayette but not Vincennes (Table 10). At West Lafayette, corn yield in plots that had contained fall-seeded annual ryegrass and wheat were similar to the nontreated check but were lower than all herbicide-treated plots.

Reduction in corn grain yield following annual ryegrass or winter wheat cover crops has been documented in other studies (Dapaah and Vyn 1998; Decker et al. 1994; Torbert et al. 1996; Vyn et al. 1999). Although not actively competing with the corn, terminated annual ryegrass and wheat can reduce N availability to the subsequent crop (Decker et al. 1994; Torbert et al. 1996; Vyn et al. 1999). Moreover, studies indicate that decomposing wheat residues release phenolic compounds that can inhibit corn growth (Janovicek et al. 1997; Opoku et al. 1997). Cover crops can also limit moisture availability to the succeeding crop (Clark et al. 1995, 1997; Munawar et al. 1990), which may have influenced corn

Table 8. Crop-rotation effects on SCN egg density (HG type 2.5.7) at the fall 2005 and 2006 sample timings at West Lafayette, IN and Vincennes, IN.

Crop rotation	West Lafayette	Vincennes
	SCN eggs (100 cc soil)$^{-1}$	
Soybean–corn	22 b[a]	21 b
Continuous soybean	206 a	93 a

[a] Treatment means within a column followed by the same letter are not statistically different at the 0.05 level of significance.

Table 9. Season effects on SCN egg density (HG type 2.5.7) in fall 2005 and fall 2006 at West Lafayette, IN and Vincennes, IN.

Season	West Lafayette	Vincennes
	SCN eggs (100 cc soil)$^{-1}$	
Fall	234 a[a]	21 a
Spring	64 b	20 a

[a] Treatment means within a column followed by the same letter are not statistically different at the 0.05 level of significance.

Table 10. Effect of winter annual weed management systems on corn yield in 2005 at West Lafayette, IN and Vincennes, IN.

Treatment	Corn yield	
	West Lafayette	Vincennes
	kg ha^{-1}	
Nontreated check	12,580 ab[a]	12,850 a
Spring-applied herbicide	13,830 a	11,830 a
Fall-applied herbicide	13,350 a	10,440 a
Fall + spring–applied herbicide	13,630 a	12,570 a
Fall-seeded annual ryegrass	11,860 b	10,700 a
Fall-seeded wheat	11,360 b	10,900 a

[a] Treatment means within a column followed by the same letter are not statistically different at the 0.05 level of significance.

response in a relatively dry spring at West Lafayette in 2005 (Table 1).

In the continuous-soybean analysis, year by weed management system interactions were not significant (Table 11). At West Lafayette, soybean yield varied by year, with highest yields being recorded in 2006 and lowest in 2005. No soybean yield differences were detected at Vincennes. Rotation by weed management system interactions in the rotation analysis were not significant. Soybean grown after corn had higher yields than soybean after soybean at West Lafayette, but soybean yields were not different at Vincennes, regardless of rotation (Table 12). The difference in SCN population density between plots in the SS and SC rotations was greater at West Lafayette than Vincennes (Table 8). At West Lafayette, high SCN levels in the SS plots may have caused lower soybean yields than plots in the SC rotation. Winter annual weed management system had no influence on soybean yield at either location (Table 12).

In conclusion, fall and/or spring herbicide applications appear to be a more effective option than cover crops both in terms of reducing winter annual weed growth/seed production and minimizing the potential for crop yield loss. Crop rotation and use of an SCN-resistant soybean cultivar resulted in a decrease in SCN population density, but winter annual weed management had no effect. The density of weedy SCN host species in the experimental area was relatively low compared to densities that can be observed in production fields. The results of these experiments suggest that winter annual weed management, specifically for SCN control, may not be warranted in fields with low weed density. Future research should be directed toward assessing the effect of winter annual weed management on SCN population density in fields with high weed densities.

Table 11. Soybean yield in continuous-soybean plots in 2004, 2005, and 2006 at West Lafayette, IN and Vincennes, IN.

Year	Soybean yield	
	West Lafayette	Vincennes
	kg ha^{-1}	
2004	3,930 b[a]	3,360 a
2005	3,700 c	3,240 a
2006	4,320 a	3,260 a

[a] Treatment means within a column followed by the same letter are not statistically different at the 0.05 level of significance.

Table 12. Crop-rotation effects on soybean yield in 2006 at West Lafayette, IN and Vincennes, IN.

Crop rotation	Soybean yield	
	West Lafayette	Vincennes
	kg ha^{-1}	
Soybean–soybean	4,320 b[a]	3,250 a
Soybean–corn	4,460 a	3,260 a

[a] Treatment means within a column followed by the same letter are not statistically different at the 0.05 level of significance.

Sources of Materials

[1] INW0302 wheat seed, Agricultural Alumni Seed Improvement Association, Inc., P.O. Box 158, Romney, Indiana 47981.

[2] Saddle Pro Overseeding Blend, Saddle Pro PA, 10811 Richmond Road, Ft. Loudon, PA 17224.

[3] Roundup WeatherMAX®, Monsanto Company, 800 North Lindbergh Blvd, St. Louis, MO 63167.

[4] Liberty®, Bayer CropScience, Research Triangle Park, NC 27709.

[5] John Deere 7300 MaxEmerge 2, John Deere Co., One John Deere Place, Moline, IL 61265.

[6] John Deere 7000 conservation-till planter, John Deere Co., One John Deere Place, Moline, IL 61265.

[7] SAS Institute, Inc., SAS Campus Drive, Cary, NC 27513-2414.

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