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Source: Weed Science, 60(4):634-640.
Published By: Weed Science Society of America
https://doi.org/10.1614/WS-D-11-00192.1
URL: http://www.bioone.org/doi/full/10.1614/WS-D-11-00192.1

Weed Science 2012 60:634–640

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

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

Certain winter annual weeds have been documented as alternative hosts to soybean cyst nematode (SCN), and infestations by such species are common in no-till production fields in the midwestern United States of Indiana, Ohio, and Illinois. The objective of this research was to determine the influence of crop rotation and winter annual weed management on winter weed growth, SCN population density, and crop yield. Two crop rotations (SS and soybean–corn rotation) and six winter annual weed-management systems (autumn-applied herbicide, spring-applied herbicide, autumn + spring applied herbicides, autumn-seeded Italian ryegrass, autumn-seeded wheat, and a nontreated check) were evaluated in long-term, no-tillage systems at West Lafayette, IN, and Vincennes, IN. In the fourth and fifth years of these experiments, the 2-yr corn–soybean rotation generally resulted in increased soybean yield, decreased winter annual weed growth, and reduced SCN population density compared with SS. Autumn or spring herbicide applications or both were a more effective option than cover crops at reducing winter annual weed density. Cover-crop systems generally did not differ from the nontreated check in winter weed density. Between years three and five, winter annual weed SCN hosts in nontreated check plots increased approximately threefold to levels as high as 102 and 245 plants m^{-2} at West Lafayette, IN, and Vincennes, IN, respectively, which are infestation levels at or above those commonly observed in production fields. However, controlling winter annual weeds did not influence crop yields or SCN population density. The results of these studies suggest that winter weed management, even at the high levels of weed infestation present in these studies, appears to have little value as a tool for SCN management in corn and soybean production systems in the midwestern United States.

Nomenclature: Soybean cyst nematode, *Heterodera glycines* Ichinohe; Italian ryegrass, *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot; corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.; wheat, *Triticum aestivum* L.

Key words: Cover crops, crop rotation, cropping systems, integrated pest management, integrated weed management.

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). 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) and reduced reliance on herbicides with soil residual activity (Barnes et al. 2003). Winter annual weeds can have a number of negative effects on a cropping system, particularly through delaying drying and warming of soil in the spring (Monnig and Bradley 2007) and interfering with mechanical operations, such as planting and tillage (Krausz et al. 2003).

Venkatesh et al. (2000) reported that certain winter annual weeds, including purple deadnettle (*Lamium purpureum* L.), henbit (*Lamium amplexicaule* L.), field pennycress (*Thlaspi arvense* L.), and shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik], can also serve as alternative hosts to SCN. These species are common in the midwestern United States and were recently documented to occur in 93% of fields of Indiana production fields (Creech and Johnson 2006). The widespread occurrence of winter annuals in soybean production areas of the 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 weed control. However, little is known about the effect of winter weed management on SCN density.

Creech et al. (2008) previously reported on the influence of crop rotation, cover crops, and herbicide application timing on winter annual weeds, SCN, and crop yield for the first 3 yr of this study. They reported no advantages to managing vs. not managing winter annual weeds to reduce SCN population density. This was a surprising result because after 3 yr, henbit and purple deadnettle, the dominant species in our research plots, had been reported in previous greenhouse studies to support SCN reproduction at levels comparable to SCN-susceptible soybean (Creech et al. 2007a; Venkatesh et al. 2000). Furthermore, the ability of SCN to reproduce on henbit and purple deadnettle under field conditions in Indiana, Illinois, and Ohio had previously been confirmed (Creech et al. 2005, 2007b).

Creech et al. (2008) attributed the lack of SCN response to winter annual weed management in the first 3 yr of this study to the relatively low density of winter annual weeds in the experimental plot area. At the end of the growing season in 2006, winter weed hosts of SCN occurred in nontreated check plots at densities as high as 36 and 75 plants m^{-2} at West Lafayette, IN, and Vincennes, IN, respectively (Creech et al.

DOI: 10.1614/WS-D-11-00192.1

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2008). However, in a survey of Indiana production fields, the density of winter annual weed hosts of SCN was nearly 150 plants m^{-2} across all fields and, at times, exceeded 400 plants m^{-2} (Creech and Johnson 2006). In a greenhouse study, the authors reported that winter annual weed density can influence SCN reproduction and population increase (Creech et al. 2007a). Our results from the first part of this 5-yr study suggest that winter annual weed management to reduce SCN population density may not be warranted in fields with low weed density (Creech et al. 2008). However, value of winter weed management as an SCN management tool in fields with higher weed densities is unknown.

The objectives of this study were to further evaluate the influence of herbicide- and cover crop–based, winter weed-management systems and crop rotation on (1) winter annual weed growth, (2) SCN population density, and (3) corn and soybean yield in the fourth and fifth years of this long-term experiment.

Materials and Methods

Field Site History. Field trials were conducted at two SCN-infested locations in Indiana. Results of the first 3 yr (2003 to 2006) were reported by Creech et al. (2008). Results from 2006 to 2008 are reported in this manuscript. Experimental sites were the Purdue University Agronomy Center for Research and Education near West Lafayette, IN, and the Southwest Purdue Agricultural Center near Vincennes, IN. Soils were a Raub-Brenton complex (fine-silty, mixed, superactive, mesic, Aquic Argiudolls) with 3% organic matter and a pH of 6.3 at West Lafayette, IN, and a Patton silt loam (fine-silty, mixed, superactive, Typic Endoaquolls) with 1% organic matter and a pH of 6.9 at Vincennes, IN. Plots were established in fields in the autumn of 2003 following a soybean crop. In the 5 yr before establishment of these experiments, plots were under conventional tillage in a 2-yr corn–soybean rotation at West Lafayette, IN, and SS at Vincennes, IN. Continuous, no-tillage production systems were initiated in spring 2003.

Experimental Design and Cropping Practices. The experiment was established in the autumn of 2003 with various crop rotations and winter weed management systems in individual plots measuring 9.1 m wide by 9.9 m long (Creech et al. 2008). 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 weed-management systems. Systems were (1) autumn herbicide application, (2) spring herbicide application, (3) autumn + spring herbicide applications, (4) autumn-seeded winter wheat, (5) autumn-seeded Italian ryegrass, and (6) a nontreated control. 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.

Winter weed-management treatment regimes were initiated following crop harvest in early October, beginning in 2003, and continuing each year through 2007. Wheat was seeded at 67 kg ha^{-1} using a no-till drill with a row spacing of 19 cm (Creech et al. 2008). In 2006, the wheat varieties planted were 'Clark' (Crop Tech Seed Co. Inc., Vincennes, IN 47591) at Vincennes, IN, and 'INW0302'[2] (Agricultural Alumni Seed Improvement Association, Inc., Romney, IN 47981) at West Lafayette, IN. The wheat variety at both sites in 2007 was 'INW0302'. Italian ryegrass was seeded by surface broadcasting at a rate of 34 kg ha^{-1}. The Italian ryegrass variety used was a commercial mixture of 'Florlina', 'Bounty', and 'SBA Experimental' (1 : 1 : 1) (Saddle Pro Overseeding Blend, Saddle Pro PA, 10811 Richmond Road, Ft. Loudon, PA 17224). In plots designated for winter weed removal, glyphosate (Roundup WeatherMAX, Monsanto Company, 800 North Lindbergh Blvd, St. Louis, MO 63167) was applied at 1.2 kg ai ha^{-1} as needed through the autumn or spring or both to maintain weed-free conditions (required one to three applications). Whenever necessary, glufosinate (Liberty, Bayer CropScience, Research Triangle Park, NC 27709) 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}. In the spring of 2008, metribuzin (0.42 kg ai ha^{-1}) (Sencor 75DF, Bayer CropScience) was included with the preplant glyphosate application at both locations to manage the glyphosate-resistant horseweed [*Conyza canadensis* (L.) Cronq].

Corn and soybean were planted no-till in 76-cm rows at seeding rates of 76,000 and 370,000 seeds ha^{-1}, respectively. A different planter was used at West Lafayette, IN (John Deere 7300 MaxEmerge 2, Deere & Company, One John Deere Place, Moline, IL 61265) than at Vincennes, IN (John Deere 7000 conservation-till planter, Deere & Company). The corn hybrid in 2007 was 'DKC61-45' and the SCN-susceptible soybean variety used in 2007 and 2008 was 'DKB31-51'. All corn and soybean were glyphosate-resistant. The planting dates were May 14, 2007, and May 29, 2008 at West Lafayette, IN, and May 2, 2007, and May 6, 2008 at Vincennes, IN.

Starter fertilizer was surface broadcast each year before planting at Vincennes, IN, 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 ha^{-1} to corn plots immediately after planting in 2005. At West Lafayette, IN, 28% urea ammonium nitrate was knifed 10 cm deep into the soil and at Vincennes, IN, 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.

Data Collection. Soil samples were collected at crop planting and harvest each year. 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-cm^3 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 per 100 cm^3 of soil)(Faghihi and Ferris 2000).

Winter annual weeds were enumerated in each plot in both late November and mid-April. Five 0.25-m^2 quadrats were placed on the ground in each plot, and the identity and

Table 1. Precipitation and average monthly air temperatures in 2006, 2007, and 2008 at the Agronomy Center for Research and Education located near West Lafayette, IN.

Month	Temperature				Precipitation			
	2006	2007	2008	30 yr	2006	2007	2008	30 yr
	C				mm			
January	3.1	−0.7	−2.7	−4.8	62.2	81.1	71.6	45.5
February	−1.2	−8.1	−3.8	−2.3	25.4	29.0	150.9	39.9
March	4.0	7.4	2.7	3.8	102.6	106.6	56.1	72.1
April	12.6	9.3	11.2	10.1	87.6	75.6	53.7	90.7
May	15.6	19.4	14.5	16.3	131.1	103.3	87.5	110.5
June	21.2	22.2	22.3	21.4	61.0	70.3	127.8	107.7
July	24.3	21.5	22.6	23.2	156.0	56.6	97.6	101.6
August	22.4	24.0	21.1	22.0	135.9	154.1	62.0	93.5
September	16.7	20.0	18.9	18.3	72.1	45.4	104.9	75.7
October	10.3	15.7	11.6	11.8	103.1	106.7	45.9	69.3
November	6.7	5.3	—[a]	5.1	94.6	123.5	—	78.2
December	2.5	−0.7	—	−1.6	63.7	92.5	—	61.7

[a] Weather station data missing.

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. The placement of each quadrat in each plot was identical between years and sampling timings.

Corn-grain yields were determined at Vincennes, IN, 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, IN, 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 using a plot combine by harvesting the entire 9.9 m length of the center four or eight rows at Vincennes, IN, and West Lafayette, IN, 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, SCN egg density, and crop yield were assessed using ANOVA. Data for in-field weed densities were combined into three groups for analysis and presentation: (1) henbit and purple deadnettle, (2) winter annual weed hosts of SCN (*Lamium* spp., common chickweed [*Stellaria media* (L.) Vill.], shepherd's-purse, and smallflowered bittercress (*Cardamine parviflora* L.), and (3) total winter weeds (all winter annuals that appeared in quadrats). Weed density data were $\log_{10}(x + 1)$–transformed before analysis. Weed density data were analyzed using an ANOVA appropriate for a split-plot, split-block design with crop rotation as the whole-plot factor and weed-management system as the subplot factor. Time was the split-block factor because the quadrats were placed in the same position in each plot over time.

SCN data were analyzed using an ANOVA appropriate for a randomized-block split–split-plot design. In this model, crop rotation was the whole-plot factor, winter annual weed management was the subplot factor, and time was the subplot factor. SCN data were $\log_{10}(x + 1)$ transformed before analysis. Soybean yield data were analyzed using an ANOVA appropriate for a randomized-block split–split-plot design. Crop rotation was the whole-plot factor, weed management system was the subplot factor, and year was the sub–subplot factor. Corn yields were analyzed as a randomized complete-block design.

ANOVA was performed using the PROC MIXED procedure of SAS (SAS 9.1 statistical software, SAS Institute, Inc., 100 SAS Campus Dr., Cary, NC 27513-2414). West Lafayette, IN, and Vincennes, IN, 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 using a series of pairwise contrasts

Table 2. Precipitation and average monthly air temperatures in 2006, 2007, and 2008 at the Southwest Purdue Agricultural Center located near Vincennes, IN.

Month	Temperature				Precipitation			
	2006	2007	2008	30 yr	2006	2007	2008	30 yr
	C				mm			
January	5.2	1.3	−0.5	−2.6	74.2	105.4	107.2	66.0
February	0.2	−3.3	−0.1	0.0	44.5	75.9	152.2	63.8
March	6.8	11.1	6.0	5.9	246.4	72.1	433.0	91.4
April	15.0	11.4	12.9	11.9	185.2	93.2	100.4	108.7
May	17.7	21.2	16.4	17.7	162.1	54.5	177.2	130.3
June	23.1	23.7	24.3	22.5	79.2	145.1	140.7	102.9
July	26.2	23.8	24.4	24.6	61.0	68.9	78.9	118.6
August	25.6	27.2	23.5	23.5	162.8	139.6	62.2	94.5
September	18.7	22.5	21.2	19.4	110.0	50.7	15.2	80.3
October	12.5	16.9	14.2	13.0	116.7	115.3	27.8	81.5
November	7.8	—[a]	6.0	6.5	135.1	—	70.9	108.2
December	3.8	—	0.7	0.2	133.4	—	155.9	82.3

[a] Weather station data missing.

Table 3. Autumn density of winter annual weeds in response to weed-management systems and crop rotation in permanently established quadrats in 2006 and 2007 at West Lafayette, IN, and Vincennes, IN.

Weed management system[a]	West Lafayette, IN Continuous soybean	West Lafayette, IN Soybean–corn	Vincennes, IN
	Lamium spp.[b] m^{-2}		
Nontreated check	94 aA[c]	21 aB	195 a
Spring-applied herbicide	1 cA	1 bA	28 b
Autumn-seeded Italian ryegrass	79 abA	20 aB	233 a
Autumn-seeded wheat	48 bA	33 aA	227 a
	Winter weed hosts of SCN[d,e] m^{-2}		
Nontreated check	102 aA	25 bB	245 a
Spring-applied herbicide	1 bA	1 cA	34 b
Autumn-seeded Italian ryegrass	100 aA	37 abB	295 a
Autumn-seeded wheat	59 aA	49 aA	271 a
	Total winter weeds[f] m^{-2}		
Nontreated check	138 aA	27 bB	482 a
Spring-applied herbicide	3 cA	2 cA	69 b
Autumn-seeded Italian ryegrass	165 aA	53 aB	416 a
Autumn-seeded wheat	81 bA	53 aA	443 a

[a] Autumn-applied herbicide and autumn-applied + spring-applied herbicide treatments were weed free in the autumn and were not included in the analysis.
[b] *Lamium* spp. included henbit and purple deadnettle.
[c] Treatment means within a column and within weed group followed by the same lowercase letter are not statistically different at the 0.05 level. Differences within rows and within location are designated with uppercase letters.
[d] Abbreviation: SCN, soybean cyst nematode.
[e] Winter weed hosts of SCN included *Lamium* spp., common chickweed, shepherd's-purse, and smallflowered bittercress.
[f] Total winter weeds included all winter annuals that appeared in quadrats.

Table 4. Spring density of winter annual weeds in response to year and weed-management systems in permanently established quadrats in 2007 and 2008 at West Lafayette, IN, and Vincennes, IN.

Weed management system[a]	West Lafayette, IN	Vincennes, IN 2007	Vincennes, IN 2008
	Lamium spp.[b] m^{-2}		
Nontreated check	22 a[c]	14 bB	108 aA
Autumn-applied herbicide	0 b	0 cA	0 bA
Autumn-seeded Italian ryegrass	21 a	26 aB	129 aA
Autumn-seeded wheat	19 a	29 aB	110 aA
	Winter weed hosts of SCN[d,e] m^{-2}		
Nontreated check	26 a	40 bB	129 aA
Autumn-applied herbicide	0 b	4 cA	0 bB
Autumn-seeded Italian ryegrass	32 a	74 aB	162 aA
Autumn-seeded wheat	24 a	49 bB	144 aA
	Total winter weeds[f] m^{-2}		
Nontreated check	33 b	231 aA	262 aA
Autumn-applied herbicide	0 c	26 cA	10 bB
Autumn-seeded Italian ryegrass	60 a	179 abA	235 aA
Autumn-seeded wheat	33 b	141 bB	297 aA

[a] Spring applied herbicide and autumn + spring applied herbicide treatments were weed free in the autumn and were not included in the analysis.
[b] *Lamium* spp. included henbit and purple deadnettle.
[c] Treatment means within a column and within weed group followed by the same lowercase letter are not statistically different at the 0.05 level. Differences within rows and within location are designated with uppercase letters.
[d] Abbreviation: SCN, soybean cyst nematode.
[e] Winter weed hosts of SCN included *Lamium* spp., common chickweed, shepherd's-purse, and smallflowered bittercress.
[f] Total winter weeds included all winter annuals that appeared in quadrats.

among all treatments (Saxton 1998) at the 0.05 level of probability. Back-transformed means are presented for ease of discussion.

Results and Discussion

Autumn-seeded winter wheat and Italian ryegrass were successfully established each year. Plant populations of cover crops in the spring were similar to those in the autumn, with the exception of Italian ryegrass at West Lafayette, IN, where, each year, most of the stand was lost to winterkill (data not shown). Average monthly temperatures throughout the experiment were higher at Vincennes, IN, than they were at West Lafayette, IN, and were comparable to long-term averages (Tables 1 and 2). Generally, precipitation in each year was evenly distributed and was probably not limiting to cover crop and winter annual weed growth or crop yield. One exception was at Vincennes, IN, in 2008, where intense rain in autumn and low temperatures in the spring caused cool soil temperatures and flooding, which resulted in a loss of several plots and poor soybean stands overall.

Winter Annual Weed Growth. Weed management systems influenced autumn and spring winter annual weed growth at both sites. The crop rotation by management system interaction was significant at West Lafayette, IN, in the autumn analysis and the year by weed management system interaction was significant at Vincennes, IN, in the spring analysis; therefore, weed density data were not pooled where significant interactions existed (Tables 3 and 4). Autumn and spring weed densities generally exhibited similar trends over time and within weed-management systems. At each site, the autumn (Table 3) and spring (Table 4) herbicide applications resulted in lower weed densities than were seen in the wheat or Italian ryegrass cover crop treatments. However, winter annual weed densities in the cover crop–treated plots were generally not different from that of the nontreated check. Furthermore, some of the cover crop–treated plots, particularly those in the SC rotation at West Lafayette, IN (Table 3) and in the yr 2007 at Vincennes, IN (Table 4), had greater weed density than the nontreated check had. These results agree with those previously reported in the first 3 yr of this experiment (Creech et al. 2008). Winter annual weeds are highly competitive with cover crops and, of the treatments included in this study, herbicides appear to be the best option for managing winter annual weeds.

Crop rotation and sampling time also influenced winter annual weed growth (Tables 5–7). Winter annual weed densities were consistently lower in the spring than they were in the autumn. Furthermore, plots in the SC rotation generally had less winter annual weed growth than plots had under SS production (Tables 6 and 7). Crop-rotation effects were not observed during the first 3 yr of these experiments (Creech et al. 2008). Corn was planted in years two and four in the rotational plots, with soybean in years one, three, and five. Two complete rotation cycles were required to detect differences in winter annual weed growth. Similar findings were reported in a long-term experiment by Davis et al (2009). Rotation to corn has long been considered an

Table 5. Autumn (2006 and 2007) and spring (2007 and 2008) density of winter annual weeds in response to crop rotation in permanently established quadrats at West Lafayette and Vincennes, IN.[a]

Crop rotation	West Lafayette, IN Autumn	West Lafayette, IN Spring	Vincennes, IN Autumn	Vincennes, IN Spring
	Lamium spp.[b] m^{-2}			
Continuous soybean	28 aA[c]	13 aB	111 aX	20 aY
Soybean–corn	11 bA	6 bA	155 aX	18 aY
	Winter weed hosts of SCN[d] m^{-2}			
Continuous soybean	34 aA	16 aB	131 aX	30 aY
Soybean–corn	17 bA	9 aB	198 aX	42 aY
	Total winter weeds[e] m^{-2}			
Continuous soybean	51 aA	26 aB	419 aX	178 aY
Soybean–corn	21 bA	11 bB	184 bX	75 bY

[a] Autumn-applied herbicide and autumn-applied + spring-applied herbicide treatments were weed free in the autumn and were not included in the autumn analysis. Similarly, the spring-applied herbicide and autumn-applied + spring-applied herbicide treatments were weed free in the spring and were not included in the spring analysis.
[b] *Lamium* spp. included henbit and purple deadnettle.
[c] Treatment means within a column and within weed group followed by the same lowercase letter are not statistically different at the 0.05 level. Differences within rows and within location are designated with uppercase letters.
[d] Winter weed hosts of soybean cyst nematode included *Lamium* spp., common chickweed, shepherd's-purse, and smallflowered bittercress.
[e] Total winter weeds included all winter annuals that appeared in quadrats.

important SCN management practice (Faghihi and Ferris 2006; Niblack 2005). The results of this study suggest that including corn in rotation with soybean may serve a second SCN management purpose: suppressing growth of winter annual weed hosts of SCN.

Weed Density after 5 Yr. As the experiment concluded in autumn 2008, winter annual weed-density data were collected without winter weed-management treatments in place to allow for comparison of the cumulative treatment effect over 5 yr (Table 8). At West Lafayette, IN, all herbicide treatments resulted in lower weed densities than DID all other treatments. Timing of herbicide application, however, did not make a difference. Cover crops were generally similar to the nontreated check. One exception was total winter annual weeds where the Italian ryegrass cover crop had higher weed density than did the wheat cover crop or the nontreated check. The high level of winter mortality of Italian ryegrass at this site may have inhibited the ability of this cover crop to suppress weed growth. In addition, the soil disturbance from the drill may have promoted additional weed density, resulting in higher weed density than the nontreated check had. At Vincennes, IN, weed response to herbicides was similar to that seen at West Lafayette, IN, with the exception that some weed species were suppressed by herbicide treatments that included a spring-application component. The winter annual weeds at the study sites primarily produced seed in the spring (data not shown), and the spring herbicide application likely interfered with flowering and subsequently reduced the seed contribution of those weeds into the soil seedbank.

Table 6. Autumn density of winter annual weeds in response to crop rotation and year in permanently established quadrats in 2006 and 2007 at West Lafayette, IN, and Vincennes, IN.

Crop rotation	West Lafayette, IN 2006	West Lafayette, IN 2007	Vincennes, IN
	Lamium spp.[a] m^{-2}		
Continuous soybean	17 aB[b]	45 aA	111 a
Soybean–corn	11 aA	12 bA	155 a
	Winter weed hosts of SCN[c,d] m^{-2}		
Continuous soybean	18 aB	62 aA	131 a
Soybean–corn	14 aA	19 bA	198 a
	Total winter weeds[e] m^{-2}		
Continuous soybean	22 aB	121 aA	419 a
Soybean–corn	15 aB	30 bA	184 b

[a] *Lamium* spp. included henbit and purple deadnettle.
[b] Treatment means within a column and within weed group followed by the same lowercase letter are not statistically different at the 0.05 level. Differences within rows and within location are designated with uppercase letters.
[c] Abbreviation: SCN, soybean cyst nematode.
[d] Winter weed hosts of SCN included *Lamium* spp., common chickweed, shepherd's-purse, and smallflowered bittercress.
[e] Total winter weeds included all winter annuals that appeared in quadrats.

Table 7. Spring density of winter annual weeds in response to crop rotation and year in permanently established quadrats in 2007 and 2008 at West Lafayette, IN, and Vincennes, IN.

Crop rotation	West Lafayette, IN	Vincennes, IN 2007	Vincennes, IN 2008
	Lamium spp.[a] m^{-2}		
Continuous soybean	13 a[b]	8 aB	45 aA
Soybean–corn	6 a	13 aB	26 bA
	Winter weed hosts of SCN[c,d] m^{-2}		
Continuous soybean	16 a	31 aB	57 aA
Soybean–corn	9 a	26 aA	34 bA
	Total winter weeds[e] m^{-2}		
Continuous soybean	26 a	140 aB	225 aA
Soybean–corn	11 b	89 bA	63 bA

[a] *Lamium* spp. included henbit and purple deadnettle.
[b] Treatment means within a column and within weed group followed by the same lowercase letter are not statistically different at the 0.05 level. Differences within rows and within location are designated with uppercase letters.
[c] Abbreviation: SCN, soybean cyst nematode.
[d] Winter weed hosts of SCN included *Lamium* spp., common chickweed, shepherd's-purse, and smallflowered bittercress.
[e] Total winter weeds included all winter annuals that appeared in quadrats.

Soybean Cyst Nematode Egg Density. The crop rotation by sample-time interaction was significant in the analysis for the West Lafayette, IN, site; therefore, mean SCN eggs (*Heterodera glycines* [HG] test type 2.5.7) were not pooled over crop rotation or season (Table 9). At West Lafayette, IN, SCN population density was reduced by nearly 50% from the spring to the autumn sampling time through rotating corn with soybean. During the same period, plots under SS had increased SCN population densities from an average of 58 to 170 eggs per 100 cm^3 of soil because of the use of an SCN-susceptible soybean cultivar. Crop rotation and use of SCN-resistant soybean cultivars have long been known to be critical components of SCN management programs (Faghihi and Ferris 2006; Niblack 2005). The nearly eightfold difference in autumn egg counts at West Lafayette, IN, in plots rotated to corn (22 eggs per 100 cm^3 of soil) vs. SCN-susceptible soybean (170 eggs per 100 cm^3 of soil) reaffirms the importance of these long-standing SCN management tactics.

At Vincennes, IN, the crop rotation by sample-time interaction was not significant; therefore, data were pooled over crop rotation (Table 9). SCN egg density decreased between the spring and autumn sample timings, regardless of crop rotation. The reason for the lack of response at the

Table 8. Weed density after 5 yr of winter weed management and crop rotation at West Lafayette, IN, and Vincennes, IN, in the autumn of 2008.[a]

	West Lafayette, IN			Vincennes, IN			
				SS	SC		
Weed management system	*Lamium* spp.[b] m^{-2}	SCN hosts[c] m^{-2}	Total[d] m^{-2}	*Lamium* spp. m^{-2}		SCN hosts m^{-2}	Total m^{-2}
Nontreated check	35 a[e]	44 a	158 b	405 a	327 a	383 a	429 a
Autumn-applied herbicide	1 b	2 b	9 c	23 b	55 b	54 b	165 b
Spring-applied herbicide	1 b	2 b	9 c	38 b	42 b	43 b	77 c
Autumn- + spring-applied herbicide	1 b	1 b	6 c	32 b	20 c	30 c	58 c
Autumn-seeded wheat	26 a	41 a	149 b	420 a	297 a	365 a	377 a
Autumn-seeded Italian ryegrass	39 a	67 a	332 a	393 a	302 a	360 a	393 a

[a] Abbreviations: SC, soybean–corn rotation; SS, continuous soybeans; SCN, soybean cyst nematode.
[b] *Lamium* spp. included henbit and purple deadnettle.
[c] Winter weed hosts of SCN included *Lamium* spp., common chickweed, shepherd's-purse, and smallflowered bittercress.
[d] Total winter weeds included all winter annuals that appeared in quadrats.
[e] Treatment means within a column and within weed group followed by the same lowercase letter are not statistically different at the 0.05 level.

Vincennes, IN, site to the presence of corn vs. an SCN-susceptible soybean variety is unknown. In the first 3 yr of the study at this experimental site, crop-rotation effects at Vincennes, IN, were significant (Creech et al. 2008). One possible explanation for the change in SCN response over time is that the soil may have become suppressive to the nematode, particularly in plots under soybean monoculture. This phenomena has been documented in a number of soils and results from the presence or development of a population of microorganisms that feed on SCN (Chen 2004; Noel and Wax 2003; Xing and Westphal 2006). Although the soil has not been specifically tested for the presence of microorganisms antagonistic to SCN, a similar effect may have occurred in this study.

Winter annual, weed-management main effects and interactions were not significant in the analysis of SCN population density at either site in years four and five (data not shown). Creech et al. (2008) previously reported a lack of SCN response to winter annual weed management in the first 3 yr of this experiment (Creech et al. 2008). We were surprised by this result and suggested that the relatively low weed density (up to 36 and 75 plants m^{-2} at West Lafayette, IN, and Vincennes, IN, respectively) in the experimental plot area was not sufficient to support an increase in SCN egg density (Creech et al. 2008). In a greenhouse study, we reported that winter annual weed density can influence SCN reproduction and population increase (Creech et al. 2007a). By year five, densities of winter annual weed SCN hosts had increased to levels as high as 102 and 245 plants m^{-2} at West Lafayette, IN, and Vincennes, IN, respectively (Table 3), which are at or above average infestation levels reported in a recent survey of Indiana production fields (Creech and Johnson 2006). The lack of SCN response to winter annual weed management, even at the high levels of weed infestation present in these studies, suggests that winter annual weed management may have little value as a tool for SCN management in corn and soybean production systems in Indiana.

Table 9. Crop rotation and season effects on SCN egg density (HG Type 2.5.7) at West Lafayette and Vincennes, IN.[a]

	West Lafayette, IN			
Season	Soybean–corn	Continuous soybean	P value[b]	Vincennes, IN
Spring	40 a[c]	58 b	0.4619	86 a
Autumn	22 b	170 a	< 0.0001	14 b

[a] Abbreviation: SCN, soybean cyst nematode; HG, *Heterodera glycines* test.
[b] P values compare crop rotation treatment means within a season.
[c] Treatment means within a column followed by the same letter are not statistically different at the 0.05 level of significance.

SCN hatching, 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 egg development increases linearly with temperature between 15 and 30 C but ceases all together at temperatures below 10 C (Alston and Schmitt 1988). Previous studies have shown that henbit and purple deadnettle can support SCN reproduction at levels comparable to SCN-susceptible soybean in the greenhouse (Creech et al. 2007a; Venkatesh et al. 2000). In the field, however, soil temperatures are not optimal for SCN development at the time that winter annual weeds are actively growing. Soil temperature data collected in these plots over the course of the study suggest that the period of overlap between high SCN activity and winter annual weed growth is likely limited to a few weeks in early autumn and late spring (data not shown).

Although the ability of SCN to reproduce on henbit and purple deadnettle under field conditions in Indiana, Illinois, and Ohio has also been confirmed (Creech et al. 2005, 2007b), the results of this 5-yr study suggest that SCN reproduction on winter annual weeds appears to contribute little, if any, to the overall SCN population levels in the field. Nelson et al. (2006) reported an inconsistent response of SCN to winter annual weed management in Missouri where the few treatment differences that were observed in a single year were not significant in another year.

Crop Yield. Soybean yield varied by year at both sites (Table 10). Soybean yield was higher in 2008 than 2007 at West Lafayette, IN, whereas the opposite occurred at Vincennes, IN. The lower yields at Vincennes, IN, in 2008 were probably the result of cool soil temperatures and

Table 10. Soybean yield in continuous-soybean plots in 2007 and 2008 at West Lafayette, IN, and Vincennes, IN.

	Soybean yield[a]	
Year	Vincennes, IN	West Lafayette, IN
	kg ha^{-1}	
2007	3,802 a	4,200 b
2008	3,020 b	4,466 a

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

flooding in the spring because of intense rain in autumn and low temperatures in the spring (Table 2), which resulted in a loss of several plots and poor soybean stands overall. Crop rotation effects were significant at Vincennes, IN, with soybean yields under SC (3,468 kg ha^{-1}) higher than were those in SS (3,018 kg ha^{-1}) ($P = 0.0149$). Crop rotation effects on soybean yield were not significant at West Lafayette, IN (data not shown). In addition, soybean yield was not influenced by winter annual weed management at either site (data not shown). The lack of soybean yield response to the various winter weed-management tactics was also reported in the first 3 yr of this experiment (Creech et al. 2008). Corn yield was not affected by any treatment at either site (data not shown).

In conclusion, the 2-yr corn–soybean rotation generally resulted in increased soybean yield, decreased winter annual weed growth, and reduced SCN population density compared with SS. Herbicides were a more-effective option than were cover crops for winter annual weed management. However, controlling winter annual weeds did not influence crop yields or SCN population density. The lack of SCN response to winter annual weed management, even at the high levels of weed infestation present in these studies, suggests that winter annual weed management may have little value as a tool for SCN management in corn and soybean production systems in the eastern Corn Belt.

Acknowledgments

The authors would like to thank Josh Hunnicutt for technical assistance. This research was funded by the Indiana Soybean Board, North Central Region IPM Competitive Grants Program, and Purdue University Agricultural Research Programs.

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Received July 18, 2011, and approved June 30, 2012.