Cropping Sequence Effects on Soybean and *Heterodera glycines*

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ABSTRACT

Young, L. D., and Hartwig, E. E. 1992. Cropping sequence effects on soybean and *Heterodera glycines*. Plant Dis. 76:78-81.

Nine soybean (*Glycine max*) cropping sequences were compared for 11 yr in a field infested with the soybean cyst nematode (SCN), *Heterodera glycines*. Continuous cropping sequences included six soybean lines resistant to race 3 (Bedford, Forrest, Nathan, Peking, D72-8927, and D75-10710) with varying levels of resistance to race 4 and a 70:30 Bedford/Forrest (susceptible to this SCN population) blend. Two rotations, Bedford with corn (*Zea mays*) and Bedford with susceptible Forrest and Essex, were the other treatments. The most notable effect of continuous cropping of resistant soybean was the increased reproduction of the SCN population on resistant Bedford relative to reproduction on susceptible Essex. The increase in the ability to reproduce on Bedford was less in the continuously planted blend treatment and rotation of Bedford with Forrest and Essex than with continuously planted Bedford. Yield of continuously cropped resistant Bedford was significantly less than that of Bedford in rotation with corn in only one of two treatments with this rotation when compared over the 11-yr period. Yield of Bedford in rotation with Forrest and Essex was not greater than that of continuously cropped Bedford. In most years, continuously cropped Bedford had higher yield than continuously cropped Forrest. Cyst population density did not increase over time in plots of continuously grown Bedford, which may explain the lack of yield suppression.

The soybean cyst nematode (SCN), *Heterodera glycines* Ichinohe, is the major nematode pest of soybean (*Glycine max* (L.) Merr.) in the United States and has been identified in nearly all states in which the crop is grown. Nematode populations are usually heterogeneous and often differ in the ability to reproduce on cultivars carrying genes for resistance. Four races of the nematode were described in 1970 (5), and since then, a scheme that includes 12 additional races has been described (12). Planting resistant cultivars is the primary control measure for this pest, although there has been concern that frequent plantings of resistant cultivars will result in increased frequency of minority SCN phenotypes or the development of different SCN races.

Selection pressure exerted on SCN populations by continuous culture of resistant cultivars in greenhouse experiments resulted in a rapid increase in the ability of the nematode to reproduce on these cultivars (1,10,11,15,16). Recent field studies have verified a shift for increased SCN reproduction on resistant cultivars when they were planted frequently in fields infested with SCN (4,17,18,20), but suppressed yields of these cultivars have not been reported consistently. Cropping tactics to reduce selection pressure have been recommended (14) and evaluated (4,8,20) in fairly short-term experiments. Results of comparing the productivity of resistant soybeans grown continuously in the same soil and nematode reproduction on these cultivars with alternative cropping sequences, such as continuous susceptible cultivar, rotation of a resistant cultivar and corn (*Zea mays* L.), a blend of resistant and susceptible cultivars, and a rotation of resistant and susceptible cultivars for 6 yr at three locations, have been reported (20). This paper reports the results of continuing the 6-yr experiment at one of the locations for an additional 5 yr.

Land for this study was made available by the Tennessee Soybean Promotion Board. The authors express grateful appreciation for the efforts of A. L. "Bill" Fowler (deceased) for land preparation and tending the plots throughout this study.

Accepted for publication 24 July 1991 (submitted for electronic processing).

MATERIALS AND METHODS

A field of Centennial soybean (resistant to SCN race 3 and susceptible to race 4) in which plants showed severe SCN injury was identified in 1978. The field had a combination of Center and Routon-Bonn silt loam soils and had been planted to Forrest soybean in 1977 and to alfalfa in several previous years. No SCN-resistant cultivars had been grown before alfalfa. This study was initiated in 1979. Nine cropping treatments were established (Table 1), each with three replications, using a randomized complete block design. Six treatments included continuous culture of six soybean cultivars or breeding lines with varying levels of resistance to SCN race 4. Included were Forrest, susceptible; Bedford, resistant; Nathan, a sister line of Bedford but slightly less resistant (replaced by Epps in 1982); D75-10710, with parentage similar to Bedford but highly resistant; derivatives of Peking, moderately resistant (Peking has at least one gene for SCN resistance to race 4 that was not transmitted to Centennial and Forrest) (6); and D72-8927, moderately resistant. The six lines were resistant to SCN race 3.

The seventh treatment included a rotation of corn and Bedford; two sets of plots were included to permit growing each entry each year. The eighth treatment was a blend of 70% Bedford and 30% Forrest. The ninth treatment was a 3-yr rotation of Bedford, Forrest, and Essex soybeans in three sets of plots to permit growing each cultivar each year. Essex, susceptible to all races of SCN, is equal to Bedford and Forrest in productivity when grown in the absence of SCN. Because D75-10710 was susceptible to stem canker caused by *Diaporthe* *phaseolorum* (Cooke & Ellis) Sacc. var. *caulivora* K. L. Athow & R. M. Caldwell, D83-3319 (Bedford × [Forrest × (Peking × Centennial)]) was substituted for D75-10710 in 1984. Also, J82-21 (Forrest × D72-8927) was substituted for D72-8927 in 1984 in an attempt to use a more productive soybean.

Individual plots were 16 rows 90 cm apart and 24 m long with 6-m alleys between ranges. The center four rows of plots were harvested each year, except in 1979 and 1980, when four 4.9-m row segments were harvested from the center rows. Seed yield was not determined for Peking in 1979. Twelve soil cores were collected and composited from the four center rows of each plot near harvest to determine cyst population densities. Cysts were extracted from 450-cm^3 soil samples by elutriation, collected on a 250-μm pore sieve, and counted (3). Soil was collected from about 15 places in the harvest rows of each plot in September or October of each year except 1979. Essex and Bedford were grown for 30 days in the soil in the greenhouse. White- and yellow-colored cysts washed from the roots and soil were counted to evaluate for changes in ability of the nematode to reproduce on resistant cultivars. An index of parasitism (IP) was calculated from the counts on Bedford and Essex: IP = (number of cysts on Bedford/number of cysts on Essex) × 100. The IP compensates for the variability of cysts developing on Bedford and Essex caused by differences in nematode population density among the plots.

Seed yield, number of cysts at harvest, and IP were subjected to analysis of variance for each year using the Statistical Analysis System software (13). Means were separated with Fisher's LSD ($P = 0.05$) only when the F test was significant. Only two replicates were included in the 1983 analysis for seed yield because of severe drought stress in one replicate. A combined analysis over years was also done for seed yield, number of cysts, and IP.

RESULTS

Seed yields of continuous Forrest (treatment A) and continuous Bedford (treatment B) were significantly different in 9 of the 11 yr (Table 2). Yield of continuous Bedford was not exceeded by other cultivar treatments, except in 1987, when yields of Bedford in rotation with corn (treatments G and H), the blend of Bedford and Forrest (treatment I), and Bedford in rotation with Forrest and Essex (treatments J–L) were significantly greater. Yields of the blend and Bedford in the two rotations were never statistically less than the yield of continuous Bedford. Treatment G of the corn-Bedford rotation (but not treatment H) had significantly greater yield than continuous Bedford when data were compared over the 11 yr of the experiment. Yield of Forrest when rotated with Bedford and Essex (treatments J–L) was not statistically less than Bedford until 1985, and then yield of Forrest in the rotation was always less than Bedford in the rotation. Yield of Essex following Forrest in the Bedford-Forrest-Essex rotation was less than Bedford in 7 yr, and yield of Essex was less than Forrest in the rotation in only 2 yr.

Cyst population density (Table 3) in

Table 1. Soybean cropping treatments grown in soil infested with soybean cyst nematodes at Woodland Mills, TN, 1979–1989

	Soybean lines grown[z]										
Treatment	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**
A	Forrest	Forrest	Forrest	Forrest	Forrest	Forrest	Forrest	Forrest	Forrest	Forrest	Forrest
B	Bedford	Bedford	Bedford	Bedford	Bedford	Bedford	Bedford	Bedford	Bedford	Bedford	Bedford
C	Nathan	Nathan	Nathan	Epps	Epps	Epps	Epps	Epps	Epps	Epps	Epps
D	D75-10710	D75-10710	D75-10710	D75-10710	D75-10710	D83-3319	D83-3319	D83-3319	D83-3319	D83-3319	D83-3319
E	Peking	PC	PC	PC	PC	PC	PC	PC	PC	PC	PC
F	D72-8927	D72-8927	D72-8927	D72-8927	D72-8927	J82-21	J82-21	J82-21	J82-21	J82-21	J82-21
G	Corn	Bedford	Corn	Bedford	Corn	Bedford	Corn	Bedford	Corn	Bedford	Corn
H	Bedford	Corn	Bedford	Corn	Bedford	Corn	Bedford	Corn	Bedford	Corn	Bedford
I	Blend	Blend	Blend	Blend	Blend	Blend	Blend	Blend	Blend	Blend	Blend
J	Bedford	Forrest	Essex	Bedford	Forrest	Essex	Bedford	Forrest	Essex	Bedford	Forrest
K	Forrest	Essex	Bedford	Forrest	Essex	Bedford	Forrest	Essex	Bedford	Forrest	Essex
L	Essex	Bedford	Forrest	Essex	Bedford	Forrest	Essex	Bedford	Forrest	Essex	Bedford

[z]PC = Peking × Centennial breeding line. Blend was composed of 70% Bedford and 30% Forrest. Forrest, Peking, PC, D72-8927, J82-21, and Essex were susceptible to this nematode population; Bedford, Nathan, Epps, D75-10710, and D83-3319 were resistant.

Table 2. Mean seed yield for soybean cropping treatments at Woodland Mills, TN, 1979–1989

	Yield (kg/ha)											
Treatment[x]	**1979**	**1980**	**1981**	**1982**	**1983[y]**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**Mean**
A	1,662	1,718	2,424	2,379	1,398	2,209	2,034	1,630	1,869	2,086	1,508	1,918
B	2,779	2,256	2,566	2,862	1,866	2,554	2,843	2,494	2,389	2,559	2,087	2,498
C	2,389	2,045	2,856	2,773	2,084	2,179	2,600	2,843	2,569	2,708	1,859	2,458
D	2,423	2,136	2,251	1,097	1,492	2,388	2,472	2,234	2,530	2,436	2,109	2,164
E	···	1,680	1,565	1,956	1,761	1,834	2,055	1,787	1,934	2,092	1,465	1,813
F	1,936	1,995	2,094	2,375	1,583	2,255	2,553	2,264	2,318	2,592	2,112	2,207
G	···	2,439	···	3,171	···	2,787	···	2,792	···	2,930	···	2,824
H	2,612	···	2,704	···	2,203	···	2,579	···	2,924	···	2,242	2,566
I	2,663	2,530	2,729	2,947	1,885	2,613	2,813	2,460	2,784	2,562	2,117	2,577
J	2,635*[z]	2,069	2,582**	2,912*	1,921	1,902**	2,770*	1,655	2,314**	2,849*	1,678	2,312
K	1,698	1,625**	2,704*	2,798	1,794**	2,583*	2,417	1,889**	2,707*	2,208	1,845**	2,220
L	1,427**	2,509*	2,556	2,350**	2,188*	2,383	2,570**	2,689*	2,209	1,782**	2,317*	2,274
LSD (0.05)	452	476	366	398	NS	255	339	524	305	451	346	196
C.V. (%)	12	13	9	9	13	6	8	14	7	4	10	9

[x]Treatment A = Forrest; B = Bedford; C = Nathan (Epps during 1982–1989); D = D75-10710 (D83-3319 during 1985–1989); E = selection of Peking × Centennial (Peking in 1979, yield not determined); F = D72-8927 (J82-21 during 1984–1988); G and H = rotation of corn and Bedford (yield of corn not determined); I = blend of 70% Bedford and 30% Forrest; and J, K, and L = Bedford, Forrest, and Essex grown in sequence.

[y]Only two replicates were included in the analysis because of drought effects in one replicate.

[z]* = Value for Bedford; ** = value for Essex.

the continuous Bedford plots (treatment B) averaged 45% of the cysts in the continuous Forrest plots (treatment A), although the difference between these two treatments was generally much less in the latter years. In the last 3 yr, there were no differences in cyst densities among the treatments. The lowest cyst population density over time occurred in plots of corn in the corn-Bedford rotation (treatments G and H) and plots of Bedford in the rotation with Forrest and Essex (treatments J–L). Cyst density in the corn plots never exceeded 26% of that in the continuous Forrest plots (treatment A), although cyst density in the corn plots was significantly less than in continuous Bedford plots (treatment B) in only 3 yr.

The IP (Table 4) measured on Bedford was always significantly higher in the continuous Bedford plots (treatment B) than in the continuous Forrest plots (treatment A) after 1983. The IP on Bedford was also higher for the other two race 4-resistant cultivars/breeding lines, Epps and D83-3319, than in continuous Forrest plots after 1983, except for Epps in 1985. In treatment H of the corn-Bedford rotation, the IP on Bedford was significantly higher than in the continuous Forrest treatment in the years after 1983, but in treatment G of this rotation, the IP was not greater than the IP in the Forrest plots when corn was grown in 1985 and 1989. In the other treatments, IP on Bedford was similar to that in the continuous Forrest plots, except in 1989 when the IP in plots of the blend was higher.

DISCUSSION

The most notable effect of planting resistant cultivars each year was the increased ability of the nematode to reproduce, as measured by the IP, on resistant Bedford soybean. Rotating Bedford with corn may have slowed the increase in IP, although not significantly. Either blending or rotating resistant Bedford with susceptible cultivars slowed the increase in IP. However, the data indicated that eventually, the IP could increase in these treatments to the levels obtained with continuous planting of resistant cultivars. The increase in IP with the alternative options to planting a resistant cultivar each year is supported by data obtained in other experiments. Young and Hartwig (18) reported that after 10 yr, the IP on resistant cultivar Pickett 71 grown in soil from plots in which resistant Centennial was planted each year was not different from that in which a 80:20 blend of Centennial and susceptible Tracy-M was planted each year. Also, the IP was not less in plots of a rotation of 2 yr of Centennial with 1 yr of Tracy-M. All of these treatments had significantly greater IP than Tracy-M planted each year. Francl and Wrather (4) reported increased IP on resistant

Table 3. Mean cyst densities for soybean cropping treatments at Woodland Mills, TN, 1979–1989

Treatment[y]	Cysts per 450 cm^3 of soil											
	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	Mean
A	364	330	190	383	132	395	202	83	127	233	33	228
B	94	84	103	130	98	192	113	62	100	117	37	103
C	172	24	32	153	85	263	122	52	65	143	27	104
D	26	16	12	107	25	242	130	85	132	132	23	86
E	330	328	100	255	155	357	178	68	133	220	23	197
F	284	122	120	170	90	292	108	102	108	130	48	145
G	20*[z]	28	2*	43	12*	157	33*	80	7*	183	8*	53
H	48	10*	45	23*	8	2*	97	22*	147	25*	45	44
I	152	54	118	137	73	125	85	60	72	85	27	90
J	48**	276	138***	100**	80	443***	53**	73	103***	20**	45	127
K	454	102***	12**	437	178***	23**	212	28***	33**	260	28***	160
L	636***	20**	302	402***	25**	595	163***	28**	118	192***	27**	234
LSD (0.05)	312	147	102	204	74	128	NS	44	NS	NS	NS	62
C.V. (%)	84	75	62	62	42	29	69	42	55	69	82	67

[y]Treatment A = Forrest; B = Bedford; C = Nathan (Epps during 1982–1989); D = D75-10710 (D83-3319 during 1985–1989); E = selection of Peking × Centennial (Peking in 1979); F = D72-8927 (J82-21 during 1984–1988); G and H = rotation of corn and Bedford; I = blend of 70% Bedford and 30% Forrest; and J, K, and L = Bedford, Forrest, and Essex grown in sequence.

[z]* = Value for corn, ** = value for Bedford, and *** = value for Essex.

Table 4. Mean indices of parasitism (IP) for soybean cropping treatments at Woodland Mills, TN, 1979–1989

Treatment[x]	Index of parasitism[y]									
	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	Mean
A	8	7	12	4	3	4	11	8	23	20	10
B	29	50	86	65	42	87	57	87	116	100	72
C	23	29	39	40	29	43	67	65	69	107	52
D	39	21	71	56	23	69	59	84	110	137	67
E	7	6	6	8	7	9	4	8	11	10	8
F	10	7	6	6	6	7	7	6	13	12	8
G	12	21*[z]	54	88*	29	31*	81	82*	67	53*	51
H	12*	35	52*	30	20*	48	50*	49	59*	88	45
I	10	6	16	8	11	24	32	34	38	77	26
J	6	6***	28**	6	7***	14**	14	23***	32**	46	19
K	12***	11**	8	6***	7**	15	8***	37**	22	31***	16
L	36**	4	31***	12**	4	11***	20**	8	30***	44**	20
LSD (0.05)	22	NS	39	NS	13	40	34	30	28	54	13
C.V. (%)	75	132	68	130	48	79	59	44	34	52	65

[x]Treatment A = Forrest; B = Bedford; C = Nathan (Epps during 1982–1989); D = D75-10710 (D83-3319 during 1985–1989); E = selection of Peking × Centennial; F = D72-8927 (J82-21 during 1984–1988); G and H = rotation of corn and Bedford; I = blend of 70% Bedford and 30% Forrest; and J, K, and L = Bedford, Forrest, and Essex grown in sequence.

[y]Index of parasitism equals the number of soybean cyst females (cysts) developing on Bedford expressed as percentage of the number of females developing on Essex in a greenhouse test. Means of three replicates.

[z]* = Value for corn, ** = value for Bedford, and *** = value for Essex.

Bedford when it was planted in rotation with susceptible Forrest, compared with Forrest planted each year.

Yield was statistically lower in the continuous Bedford plots only when compared with rotating corn with Bedford. Cyst population density did not increase greatly in the continuous Bedford plots in conjunction with the increased IP. This situation may be the reason there was little yield advantage to the alternative use of Bedford where the IP was lower. However, yield was significantly higher in only one of the two sets of the corn-Bedford rotation for the 11-yr period. When data from both treatments were combined, yield of Bedford in this rotation remained significantly greater than yield of continuous Bedford. Because the treatments were grown in the same plots throughout the study, yield advantage of Bedford in the rotation may have been inherent in the chance assignment of plots to each treatment, although a real effect from the rotation was likely.

Three treatments included resistant soybeans Bedford, Epps, and D83-3319 planted each year, and another three treatments included susceptible soybeans Forrest, J82-21, and Peking × Centennial planted each year. The IP was similar for the three soybeans of like reaction to the nematode, and resistant and susceptible soybeans had significantly different IP. This duplication of responses for similar treatments gives greater credibility to the observed responses for resistant and susceptible cultivars.

Although there was no distinct yield advantage to alternatives of planting resistant soybean cultivars in a monocropping system, the potential for yield suppression after a shift in SCN populations exists. SCN race 5 was identified in a 200-ha field after 10 yr of continuous production of Bedford. Cordell (7), resistant to race 5, had a 2-yr mean seed yield advantage of 640 kg/ha over Bedford (19). The early recognition of race 5 as a potential problem alerted research workers to search for a source of resistance and transfer this resistance to a productive cultivar. In another field initially heavily infested with either race 4 or 14, Bedford continues to yield well after 12 yr of monocropping with race 5 now present (L. D. Young and E. E. Hartwig, *unpublished*). As productive cultivars having different combinations of SCN race resistance become available, it may be prudent for the growers not to grow one combination of resistance more than 5 yr before rotating to another combination. Recently, soybean germ plasm S88-2036 was released for research purposes. Its resistance to SCN is derived from PI 437654, which has resistance to all SCN races (2). S88-2036 is expected to be released as a cultivar, and because it has a broad range of resistance to SCN races, it is likely to be widely adopted by producers. Effects on SCN populations from monocropping this cultivar are unknown because attempts to select SCN populations that could reproduce on PI 437654 were unsuccessful (9).

The differences in yield suppression experienced in the two Tennessee fields with monocropping of resistant cultivars illustrate the difficulty growers have in selecting the best nematode management practices to obtain the greatest profit for their operations. A promising alternative to growing Bedford in a monocropping system is the blend of 30% Forrest and 70% Bedford. It is assumed that SCN reproduction on Forrest had an inhibitory effect upon SCN reproduction on Bedford. Planting such a blend in rotation with a nonhost crop such as corn, cotton (*Gossypium hirsutum* L.), or grain sorghum (*Sorghum bicolor* (L.) Moench) is also a promising alternative to monocropping resistant cultivars.

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