Cyst nematode resistance and seed yield of soybean lines derived from SS97-6946

By

Gregory Lynn Doonan

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Program of Study Committee
Walter R. Fehr, Major Professor
William Beavis
Thomas Baum
Harish Gandhi

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ABSTRACT

New sources of resistance to the soybean cyst nematode (SCN) (*Heterodera glycines* Ichinohe) would be useful for soybean [*Glycine max* (L.) Merr.] cultivar development. The objective of this study was to determine the relationship between SCN resistance and seed yield for a new source of SCN resistance, SS97-6946, developed by the Univ. of Missouri-Columbia. F_5-derived lines were developed from the cross of SS97-6946 x S27-T7, a SCN-susceptible cultivar developed by Syngenta. Nine sets of 32 $F_{5:8}$ lines each were evaluated for yield in replicated tests at five Midwest locations during 2007. The lines were evaluated for resistance to four HG types of SCN populations in growth rooms by determining their female index, which was the number of cysts on the roots of a line relative to a SCN-susceptible cultivar. There were six out of the 36 combinations of sets and HG types that had significant negative phenotypic correlations between yields of the lines and their female indexes. This indicated that the lines with the highest yield tended to have lower female indexes and greater SCN resistance, and that SS97-6946 would be a useful source of SCN resistance for soybean cultivar development.

INTRODUCTION

Resistance to the soybean cyst nematode (SCN) (*Heterodera glycines* Ichinohe) is an important consideration in soybean [*Glycine max* (L.) Merr.] cultivar development. In the United States, it has been estimated that SCN resulted in a 41 million metric ton loss in yield during a 10-year period from 1996 to 2006 and 2.6 million metric ton loss in 2007 (Wrather and Koenning, 2007). The most common methods used to control SCN are to plant resistant cultivars and rotate with nonhost crops (Concibido et al., 2004).

Breeding for resistance to SCN has been successful; however, the sources of resistance have been limited. Noel (2007) estimated that the PI 88788 source of resistance was found in 99% of SCN-resistant cultivars grown in the United States in 2007. This poses a problem for soybean producers because SCN populations are genetically diverse and able to adapt to the resistance of the host plant (Colgrove et al., 2002; Guo et al., 2006). It is important for soybean breeders to incorporate new sources of SCN resistance in their programs to combat population shifts in the nematode.

There have been 118 plant introductions identified with some type of resistance to SCN (Arelli et al., 2000). Most of these are not included in breeding programs in the United States because of their inferior agronomic traits, especially seed yield. The association between SCN-resistance and seed yield has not been consistent among studies. SCN-resistant cultivars were estimated to yield 5 to10% less than SCN-susceptible cultivars when SCN pressure was low (Noel, 1992). Concibido et al. (1997) and Chen et al. (2000) reported that SCN resistance was associated with a 1 to 4% decrease in yield when SCN is absent. The lower yield is probably the result of unfavorable genes for yield that are linked to the genes for SCN resistance (Mudge et al., 1996; Kopisch-Obuch et al., 2005). Not all studies have shown a yield decrease associated with SCN resistance. Kabelka et al. (2006) reported that SCN resistance from PI 468916, an accession of *Glycines soja* Sieb. and Zucc., had no effect or a positive effect on seed yield.

A line developed by the Univ. of Missouri-Columbia, SS97-6946, has resistance to all of the major races of SCN against which it was evaluated and is considered a new source of resistance (D.A. Sleper, personal communication, 2007). The origin of the resistance in SS97-6946 is not known because neither of the lines assumed to be its parents have the same resistance. The line was obtained for breeding by Syngenta Seeds (Golden Valley, MN) in 2003. The objective of this study was to determine the relationship between seed yield and SCN resistance in progeny from the cross of SS97-6946 to an elite SCN-susceptible cultivar.

LITERATURE REVIEW

Importance of a new source of SCN resistance

Ross and Brim (1957) first identified soybean plant introductions resistant to SCN. Since then, many new plant introductions have been identified as resistant to SCN. To date, there have been 118 PIs identified with some type of resistance to SCN and only a few that have resistance to more than four SCN races (Arelli et al., 2000). However, very few of those are included in breeding programs in the United States. According to Diers and Arelli (1999), SCN-resistant cultivars acquired their resistance primarily from PI 88788, Peking, and PI 437654. Of the SCN-resistant sources, PI 88788 is the most commonly used. Noel (2007) estimated that the PI 88788 source of resistance was found in 99% of SCN-resistant cultivars grown in the United States in 2007. This lack of diversity in genes for resistance is of obvious concern. For some time, researchers have warned of possible population shifts in *H. glycines* when faced with the narrow base of resistant germplasm that is used commercially (Anand, 1991; Colgrove et al., 2002; Guo et al., 2006). PI 88788 has provided and continues to provide adequate resistance in many commercial fields, but there is increasing evidence that some populations of *H. glycines* have adapted to the PI 88788 resistance (Noel, 2007). According to Gregory Gebhart, who conducts the SCN-variety trials at Iowa State University, they have noticed significant race shifts related to PI 88788 resistance (Hoskins, 2007). On some trial sites where PI 88788 related-cultivars were grown, they observed up to a five-fold increase in nematodes per 100 cc of soil at the end of the growing season. Niblack et al. (2003), studied *H. glycines* populations in Missouri and found that 60% of the populations sampled were virulent on PI 88788. PI 88788 is used so often that more and more nematode populations have adapted and it appears that these virulent SCN populations are becoming more common.

Considering this new evidence, it is important for growers to rotate cultivars with different sources of resistance. Soybean breeders must continue their efforts to provide new sources of SCN resistance commercially. There is a clear benefit of using a new source of SCN resistance, such as SS97-6946, that is resistant to the five major races, races 1, 2, 3, 5, and 14.

Impact of SCN-resistance genes on seed yield

There has been concern among soybean growers and breeders that SCN-resistant cultivars often yield less than SCN-susceptible cultivars when grown under low SCN pressure. There have been several studies supporting this opinion. When first marketed, SCN-resistant cultivars were estimated to yield 5 to10% less than SCN-susceptible varieties when SCN pressure was low (Noel, 1992). Others have reported similar, but less significant effects. According to Concibido et al. (1997), SCN resistance has been associated with a 1 to 2% decrease in yield when SCN is absent. Chen et al. (2000) also reported similar results when they estimated the yield loss to be 67 to 135 kg ha^{-1}.

Studies have shown that the cause of this lower yield is probably unfavorable gene(s) linked to SCN-resistance loci (Mudge et al., 1996; Kopisch-Obuch et al., 2005). The yield suppression observed with SCN resistance when there is no SCN pressure has been attributed to a linked yield gene near *rhg1*, the major SCN-resistance gene (Mansur et al., 1996; Mudge et al. 1996; Concibido et al., 1997; Kopisch-Obuch et al., 2005). A study by Yuan et al. (2002) did not reveal a yield QTL at *rhg1*, but their data suggested that yield suppression related to SCN resistance was more likely caused by gene linkage than pleitropy. If yield depression was due to pleitropy, it would not be possible to obtain resistant lines that yielded as well as susceptible lines in the absence of SCN.

There have been studies that do not show a yield reduction associated with SCN resistance. Concibido et al. (1997) reported that many SCN-resistant cultivars display poor combining ability when used for crossing; that is, when SCN-resistant cultivars are used to develop breeding populations, the performance of their progeny is inferior to populations developed from SCN-susceptible cultivars. However, some plant introductions have better agronomic traits and combining ability than others; which is the reason PI 88788 has been used so extensively. According to Sleper (personal communication, 2007), SS97-6946 combines more favorably than some of the more common SCN-resistance sources. A recent study by Kabelka et al. (2006) showed that SCN-resistance alleles from PI 468916, an accession from *G. soja* Sieb. and Zucc., either had no effect on yield or significantly enhanced it when compared to the susceptible alleles. They observed as much as a 6 % increase in yield across environments that ranged from low to high SCN infestations.

The HG type scheme and its relationship to SCN races

The term "races" has been used to describe different SCN populations based on the schemes of Golden et al. (1970) and Riggs and Schmitt (1988). They used four soybean lines, called differentials, to categorize SCN populations into 16 races. As additional information on SCN populations was reported, it became clear that this race system did not account for all of the variability present in SCN. For example, Rao-Arelli et al. (1992) reported a study where many isolates of *H. glycines* were classified as one race with the differentials but the isolates behaved differently when tested on different resistant cultivars. To better describe the diversity present in SCN, Niblack et al. (2002) devised a scheme that included seven resistant plant introductions, called indicator lines. The seven indicator lines selected represented the sources of resistance that have been used to develop SCN-resistant cultivars in the United States. *H. glycines* type (HG type) was used rather than race to describe SCN populations. The HG type of a SCN population is determined by how it reacts to the seven indicator lines. Much research had been done on SCN prior to the HG type scheme; therefore, many researchers still refer to SCN populations as races. For convenience, the SCN populations used in my study were categorized both by race and HG type. They will be referred to hereinafter by their HG type. The race determination for HG type is provided as a footnote in Table 1.

QTL identified as conferring resistance to SCN

SCN resistance is a quantitative trait, meaning there are multiple genes involved in complete resistance. Many studies over the years have focused on locating genes and/or QTL that confer resistance to SCN. Caldwell et al. (1960) first reported three recessive genes associated with SCN resistance from the cultivar Peking, designated *rhg1*, *rhg2*, and *rhg3*. An additional resistant gene found in Peking, *Rhg4*, was reported to be dominant (Matson and Williams, 1965). A dominant gene was found in PI 88788 and assigned the designation *Rhg5* (Rao-Arelli et al., 1992). By 2004, there had been 17 reports of 62 SCN-resistant-marker associations for resistance to the major SCN races (Concibido et al., 2004; Glover et al., 2004).

These 62 QTL-marker associations were found on the following linkage groups (LGs): A1, A2, B1, B2, C1, C2, D1a, D2, E, F, G, H, I, J, L, M, and N (Concibido et al., 2004; Glover et al., 2004). Linkage group G had five QTL associated with SCN resistance; B1, C2, and D2 had three; A1, B2, D1a, E, J, and M had two; and the rest had one (Concibido et al., 2004; Glover et al., 2004). In the Concibido et al. (2004) review of QTL-marker association studies, they found that the most important regions were *rhg1* found on LG G and *Rhg4* found on LG A2. These two regions have been the most often studied and markers have been identified within a few cM of each. Ruben et al. (2006) reported that the *rhg1* locus is a recessive or co-dominant locus and necessary for resistance to all HG types. They indicated that *rhg1* provides the major portion of resistance to HG type 0 (race 3) and HG type 1.3.5.6.7.8 (race 14), while *Rhg4* also can provide similar resistance as *rhg1* to HG type 0. Although these two loci play a significant role in SCN resistance, there are other genes involved as well. There is no single locus or gene that confers complete SCN resistance.

MATERIALS AND METHODS

Line Development

A single-cross population was developed by crossing S27-T7, a cultivar of maturity 2.7 developed by Syngenta to SS97-6946 of maturity 4.3. S27-T7 was chosen because of its favorable agronomic traits, susceptibility to SCN, resistance to glyphosate conferred by the CP4 EPSPS transgene developed by Monsanto Company (St. Louis, MO.), and unrelated background to SS97-6946. The cross was made in the field during July 2003 at St. Joseph, IL. The F_1 seeds were planted in November 2003 at the Syngenta Research Station located near Kekaha, HI. The F_1 plants were sprayed with glyphosate to confirm that the plants were hybrids. The F_2 seeds from the hybrid plants were harvested in bulk in February 2004. A random sample of 600 F_2 seeds was planted in Feb. 2004 at Kekaha. In this and all subsequent selfing generations, glyphosate was applied during early vegetative development and at the onset of flowering to reduce the frequency of viable gametes that lacked the CP4 EPSPS transgene resulting in an increased frequency of homozygous plants with glyphosate resistance (Walker et al., 2006). One pod from each F_2 plant was harvested and threshed in bulk.

A random sample of 600 F_3 seeds was planted in May 2004 at the Syngenta Research Station near St. Joseph, IL. A single pod was harvested from each plant and threshed in bulk. A random sample of 600 F_4 seeds was planted at Kehaha in Nov. 2004, and one pod from each plant was harvested and threshed in bulk. A random sample of 600 F_5 seeds was planted in Feb. at Kehaha, and 324 F_5 plants were harvested individually.

The 324 $F_{5:6}$ lines were planted in progeny rows in June 2005 at St. Joseph, IL. Each of 305 lines of maturity group III was harvested in bulk. The 305 $F_{5:7}$ lines were planted in May 2006 at St. Joseph for maturity classification and seed increase.

Yield Evaluation

The yield tests of the 288 $F_{5:8}$ lines in my study were planted in 2007 at five locations: Highland, IL; St. Joseph, IL; Mexico, MO; Shelbyville, MO; and Bendena, KS. The soil type at Highland is a Cowden silt loam (fine, smectitic, mesic Vertic Epiaqualfs), at St. Joseph is a Flanngan silty clay loam (fine, smectitic, mesic Aquic Argiudolls), at Mexico is a Mexico silt loam (fine, smectitic, mesic Veric Epiaqualfs), at Shelbyville is a Putnam silt loam (fine, smectitic mesic Vertic Albaqualfs), and at Bendena is a Monona silt loam (fine-silty mixed, superactive, mesic Typic Hapludolls). The lines were grouped by maturity into nine sets of 36 entries, which included 32 lines and four check cultivars. Each set was grown as a randomized complete-block design with two replications at each location. The plots were two rows 3.7 m long with a row spacing of 76.2 cm. There were 300 seeds planted in each plot.

Flower color, maturity, plant height, lodging, shattering, pod color, and pubescence notes were recorded for each entry in the nine sets as part of the cultivar development program of Syngenta. Flower color of purple or white was recorded in June for one replication at Highland and St. Joseph. Maturity notes were recorded at Highland and St. Joseph as the number of days after 31 August when 95% of pods had reached their mature color. Plant height was recorded as the length in centimeters of an average plant in each plot at Highland and St. Joseph. Lodging based on a visual score from 1 (all plants erect) to 9 (all plants prostrate) was taken at Bendena, Mexico, and St. Joseph. Shattering notes were taken based on a score of 1 (no shattering) to 9 (extensive shattering) at Bendena. Pod color was recorded as either brown or tan, and pubescence color was recorded as tawny, light tawny, or grey on one replication at Bendena, Highland, and St. Joseph. All notes were recorded on an Allegro data collector from Juniper Systems (Logan, UT). The plots were harvested using a two-row plot combine (Kincaid, Haven, KS) and yields of th**e** plots were adjusted to 13% moisture.

Soil samples were taken at the Bendena, KS, and St. Joseph, IL, sites to determine the egg densities of SCN. The soil samples were taken approximately 21 d after planting, according to the sampling protocol of Midwest Laboratories (Omaha, NE). Soil cores 10.2 cm in diameter were taken from the middle of rows at a depth of 15.2 cm. Samples were mixed thoroughly and stored at 4 ºC until processed. Cyst extraction and counting was performed by the proprietary protocol of Midwest Laboratories.

SCN Phenotyping

The SCN resistance of each line was evaluated with four SCN populations of different HG types (Table 1). The HG type was determined with the seven indicator lines described by Niblack et al. (2002). Their protocol was based on the use of Lee 74 as the susceptible cultivar. That cultivar did not develop well in the four tests; therefore, the cultivar Essex was used as the susceptible standard for the three tests conducted by Syngenta at Bay, AR, for the HG 0, HG 2.5.7, and HG 1.3.6.7 types and the cultivar S19-R5 at Nevada, IA, for the HG 2.7 type. The female index of each line was calculated for the indicator lines and F_5-derived lines as the average number of cysts on a line divided by the number of cysts on the susceptible standard cultivar. The quotient was multiplied by 100 to express the female index as a percentage of the susceptible standard cultivar. Some lines did not have enough replications to have a female index calculated for all four HG types due to inadequate germination.

For the tests with the HG types 0 and 1.3.6.7 at Bay, $F_{5:7}$ lines were phenotyped with seed of the lines harvested in 2005. For the HG 2.5.7 test at Bay, $F_{5:9}$ lines were phenotyped with seed harvested in 2007. The tests were conducted in a growth room that averaged 28 ºC. Two replications were planted in sterile soil in 7.6 cm clay pots. Three seeds were planted in each pot and the pots were thinned to two plants. At 10 d after planting, each pot was inoculated with ~1000 eggs and juveniles. The amount of infection was determined 30 d after planting. The plants were tapped from the pots and the number of cysts were counted and recorded per plant. The average for the two plants in a pot was used to calculate the female index for that replication.

For the HG 2.7 test at Nevada, $F_{5:9}$ lines were phenotyped with seed harvested in 2007. Up to six seeds from each line were planted in four replications of 9.5 cm styrofoam cups that were placed in a temperature-controlled growth room at 27 ºC. The soil used for testing was obtained from a field at the Syngenta Research Station at Slater, IA. The soil from this location was known to have a SCN population that could overcome the resistance to PI 88788. PI 88788 was grown in the soil and cysts collected from its roots were added to the test soil. The soil was mixed thoroughly before planting. At 14 d after planting, the plants were cut off above the cotyledonary node to prevent excess overgrowth. At the same time, the cups were thinned to not more than five plants. The amount of infection was determined 30 d after planting. Plants were tapped from the cups and the average number of cysts on the plants was recorded. The average for the plants in a pot was used to calculate the female index for that replication.

Table 1. HG type populations of *Heterodera glycines* used to evaluate soybean lines for SCN resistance.

	HG type 0†		HG type 2.7‡		HG type 2.5.7§		HG type 1.3.6.7¶	
Indicator Lines	$\bar{x}$ ††	FI ‡‡	$\bar{x}$ ††	FI §§	$\bar{x}$ ††	FI ‡‡	$\bar{x}$ ††	FI ‡‡
	no. cysts	--%--	no. cysts	--%--	no. cysts	--%--	no. cysts	--%--
1. PI 548402	2	2	0	0	3	2	162	113
2. PI 88788	4	4	4	14	105	76	8	6
3. PI 90763	1	1	0	0	0	0	86	60
4. PI 437654	0	0	0	0	0	0	0	0
5. PI 209332	3	3	1	4	117	84	12	8
6. PI 89772	2	2	0	0	1	1	94	66
7. PI 548316	3	3	5	18	74	53	74	52
Essex	92		-		139		143	
S19-R5	-		28		-		-	

† Race 3.
‡ Race 1.
§ Race 5.
¶ Race 14.
†† Mean cyst counts plant^{-1} for four replications.
‡‡ Female index = ($\bar{x}$ cyst no. of a line ÷ $\bar{x}$ cyst no. of Essex) x 100.
§§ Female index = ($\bar{x}$ cyst no. of a line ÷ $\bar{x}$ cyst no. of S19-R5) x 100.

DATA ANALYSIS

Analyses of variance for yield were conducted for the 288 $F_{5:8}$ lines. The data were analyzed as a randomized complete-block design and check cultivars were not included in the analysis. Analysis was done by using the mixed model (type 3) procedure of SAS version 9.1 (SAS Institute, 2003).

The linear additive model for the analysis of variance for seed yield of lines across sets and environments was:

$$Y_{ijkl} = \mu + Set_i + E_j + SetE_{ij} + G_{k(i)} + GE_{k(i)j} + R_{l(ij)} + e_{ijkl}$$

Where;

Yijkl = observed value of k^{th} genotype within the i^{th} set at the j^{th} environment, within the l^{th} replication,

μ = overall mean,

Set_i = effect of the i^{th} set,

E_j = effect of the j^{th} environment,

$SetE_{ij}$ = effect of the interaction between the i^{th} set at the j^{th} environment,

$G_{k(i)}$ = effect of the k^{th} genotype within the i^{th} set,

$GE_{k(i)j}$ = effect of the interaction between the k^{th} genotype within the i^{th} set and the j^{th} environment,

$R_{l(ij)}$ = effect of the l^{th} replication within each i^{th} set and j^{th} environment, and

e_{ijkl} = error of the effect of the $ijkl^{th}$ observation, Sets, genotypes, environments, and replications were considered random effects. The genotypes x environments interaction mean squares was used to test the main effects of genotypes, while the sets x environments interaction mean squares was used to test main effects of environments. The sum of the sets x environments mean squares and the genotype mean squares, minus the genotypes x environments mean squares was used to test the main effects of sets. The error mean squares were used to test the main effect of replications within environments and genotypes x environments. The sum of replications mean squares and genotypes x environments mean squares, minus the error mean squares were used to test the effect of sets x environments.

Table 2. Analysis of variance and expected mean squares for a genotype within a set at an environment.

Sources of variation	Degrees of freedom	df	Expected mean squares
Sets (S)	s-1	8	$\sigma^2 + 2\sigma^2_{G(S)E} + 10\sigma^2_G + 32\sigma^2_R + 64\sigma^2_{SE} + 320\sigma^2_S$
Environments (E)	e-1	4	$\sigma^2 + 2\sigma^2_{G(S)E} + 32\sigma^2_R + 64\sigma^2_{SE} + 576\sigma^2_E$
Sets x Environments	(s-1)(e-1)	32	$\sigma^2 + 2\sigma^2_{G(S)E} + 32\sigma^2_R + 64\sigma^2_{SE}$
Replications (S/E)	(r-1)(s)(e)	45	$\sigma^2 + 32\sigma^2_R$
Genotype (Sets)	(g-1)(s)	279	$\sigma^2 + 2\sigma^2_{G(S)E} + 10\sigma^2_G$
Genotype (S) x E	(g-1)(s)(e-1)	1116	$\sigma^2 + 2\sigma^2_{G(S)E}$
Error		1395	σ^2
Total		2879	

The analysis of variance for seed yield across sets and environments was calculated (Table 3). The analysis revealed that there was significant genotypes x environments interaction and sets x environments interaction. In order to determine why that was occurring, the means for each set at each location was calculated (Table 4).

Table 3. Analysis of variance for seed yield expressed in kg ha^{-1} of the 288 $F_{5:8}$ soybean lines across sets and five environments in 2007.

		Mean Squares
Sources of variation†	df	Yield (kg ha^{-1})
G(S)	279	716879**
S	8	2291416
E	4	373859735**
R(S/E)	45	359254**
G(S) x E	1116	241299**
S x E	32	3063042**
Error	1395	99318
CV (%)		19.3

† G(S) = genotypes within sets, S = sets, E = environments, R(S/E) = replications within sets and environments.

Table 4. The mean yield of each of the nine sets at the five locations and across locations.

Sets†	Bendena	Highland	Mexico	Shelbyville	St. Joseph	x̄
	----------------	----------------	----------------	(kg ha^{-1})	----------------	----------------
360	3621	1530	1546	2471	3327	2499
361	3668	1513	1542	2367	2828	2384
362	3638	1512	1567	2586	3085	2478
363	3890	1859	1728	2583	3232	2658
364	3569	1806	1586	2523	3127	2522
365	3796	2069	1706	2524	2641	2547
366	3806	1723	2008	2547	2830	2583
367	3598	1881	2186	2579	2689	2587
368	3582	2275	2160	2511	2645	2635

† Each set included 32 $F_{5:8}$ lines and excluded the checks. The standard errors of the mean and least significant differences were not calculated because the differences among sets were not significant based on an F test.

The significant genotypes x environments interaction was the result of genotypes performing differently in the five environments, which resulted in a change in rank among sets and in a change in the magnitude of the differences among sets across environments (Table 4). For those reasons, there also was a significant sets x environments interaction.

The linear additive model for seed yield within each set across environments was:

$$Y_{ijk} = \mu + E_i + R_{j(i)} + G_k + GE_{ki} + e_{ijk}$$

Where;

Y_{ijk} = observed value of k^{th} genotype within the j^{th} replication at the i^{th} environment,

μ = overall mean,

E_i = effect of the i^{th} environment,

$R_{j(i)}$ = effect of the j^th replication at the i^th environment,

G_k = effect of the k^th genotype,

GE_{ki} = effect of the interaction between the k^th genotype and the i^th environment, and

e_{ijk} = error of the effect of the ijk^th observation.

To test for the main effect of genotypes, the genotypes x environments mean squares was used. The error mean squares were used to test significance of replications within environments and genotype x environments interaction. The sum of the replications mean squares and the genotypes x environments mean squares, minus the error mean squares were used to test the effect of environments.

Table 5. Analysis of variance and expected mean squares for a genotype within each set across environments.

Sources of variation	Degrees of freedom	df	Expected mean squares
Genotype	g-1	31	$\sigma^2 + 2\sigma^2_{GE} + 10\sigma^2_G$
Environments	e-1	4	$\sigma^2 + 2\sigma^2_{GE} + 32\sigma^2_R + 64\sigma^2_E$
Replications (Env)	(r-1)(e)	5	$\sigma^2 + 32\sigma^2_R$
Genotype x Environments	(g-1)(e-1)	124	$\sigma^2 + 2\sigma^2_{GE}$
Error		155	σ^2
Total		319	

Analyses of variance for soybean cyst nematode resistance were conducted for the 288 F_5-derived lines. The SCN data were analyzed with the general linear model (GLM) procedure of SAS version 9.1. Genotypes and replications were considered random effects. The error mean squares were used to test the significance of the main effect of genotypes with an F-test.

The linear additive model for SCN resistance of genotypes within each set was:

$$Y_{ij} = \mu + R_i + G_j + e_{ij}$$

Y_{ij} = observed value of j^{th} genotype within the i^{th} replication,

μ = overall mean,

R_i = effect of the i^{th} replication,

G_j = effect of the j^{th} genotype,

e_{ij} = error of the effect of the ij^{th} observation.

The error mean squares were used to test significance of all main effects.

Table 6. Analysis of variance and expected mean squares for the female indexes of genotypes within each set.

Sources of variation	Degrees of freedom	df	Expected mean squares
Genotype	g-1	31	$\sigma^2 + 4\sigma^2_G$
Replications	(r-1)	3	$\sigma^2 + 32\sigma^2_R$
Error	(g-1)(r-1)	93	σ^2
Total		127	

Phenotypic correlations among SCN resistance and seed yield were based on entry mean yield across environments and the mean female index across four replications. The correlations were computed using the CORR procedure of the SAS statistical software, version 9.1.

The coefficient of variation (CV), standard error of the mean (SEM), and the least significant difference (LSD) at the 0.05 and 0.01 probability levels were calculated as:

CV (%) = $(\sqrt{MSE}) / \textit{Mean} \times 100$

$SEM = (\sqrt{MSE} / n)$

$LSD = t_{\alpha} (\sqrt{2MSE} / n)$

Where;

MSE = the genotypes x environments interaction for a set across environments or the error mean square for the female index of the genotypes,

Mean = mean of all entries for a trait,

n = number of observations in each entry mean, and

t = critical t value at either the 0.05 or 0.01 probability level.

RESULTS AND DISCUSSION

There was significant variation ($P < 0.01$) in the female indexes of the lines within each of the nine sets for the four HG types (Table 7). The ratings for resistance based on female indexes were resistant (0-9%), moderately resistant (10-30%), moderately susceptible (31-60%), and susceptible (>60%) (Schmitt and Shannon, 1992) (Table 8). The frequency of resistant lines was about four-fold greater for the HG 0 type of SCN population than for the other three HG types. This was not surprising because either *rhg1* or *Rhg4* can confer resistance to HG type 0 and it has been suggested that SS97-6946 has both resistant alleles (D.A. Sleper, personal communication, 2007).

The seed yields of the lines within each set were significantly different ($P < 0.01$) (Table 7). All of the significant phenotypic correlation coefficients between the seed yield of the lines and their female indexes were negative, which indicated that lines with the lowest female indexes and greatest SCN resistance tended to have the highest yields (Table 7). There were three of the nine sets with significant correlations for the HG 0 type, two for the HG 2.7, one with the HG 2.5.7, and none with the HG 1.3.6.7. The higher frequency of significant correlations with HG 0 likely was due in part to the four-fold greater frequency of resistant lines to HG 0 than to the other three types (Table 8).

Another assessment of the relationship between seed yield and SCN resistance was made by determining the female index of the five highest yielding lines in each set (Table 9). If female index was unrelated to seed yield, the percentage of the highest yielding lines across sets with resistance to a HG type should have been similar to the percentage of the 288 lines with resistance to that type. This was not the result observed for three of the HG types. There were 98 of the 288 lines (34.0%) with resistance to HG 0, but 24 out of the 45 highest yielding lines (53.3%) had resistance to that type; significantly different at the 0.05 probability level. For HG 2.7 and HG 2.5.7, 24 out of the 288 lines (8.3%) had resistance, which was significantly (at the 0.05 probability level) different than the 24.4% of the highest yielding lines with resistance to HG type 2.5.7 and the 20% to HG type 2.7. This indicated that lines with resistance to one or more of the three HG types tended to have higher yield than lines with less resistance. The same relationship was not observed for the HG 1.3.6.7 type. There were 22 out of 288 (7.6%) of the lines with resistance to that type and 8.9% of the highest yielding lines with resistance.

The positive relationships observed between seed yield and SCN resistance likely were due to SCN infestations at the five test sites and not due to favorable yield genes linked to the genes for SCN resistance in SS97-6946 or to positive pleiotropic effects of the genes for SCN resistance. Two of the five locations were evaluated for SCN egg densities. Bendena, KS, had an average of 2180 eggs 100 cm^{-3} and St. Joseph, IL, had 1248 eggs 100 cm^{-3}. Both SCN egg densities were considered moderate to high infestations according to Noel (1986). He reported that SCN damage can occur when the SCN density is greater than the threshold of 240 eggs 100 cm^{-3}.

Our results were similar to those of Kabelka et al. (2006) who found that SCN resistance from PI 468916, an accession of *G. soja* Sieb. and Zucc., had no effect on seed yield or was associated with as much as a 6% increase in yield when planted in environments with low to high SCN infestations. SS97-6946 should be useful for development of cultivars with resistance to one or more HG types of SCN populations.

Table 7. Range in mean yield and female index of soybean lines, and the phenotypic correlations between the mean yield and mean female index for each of the four HG types.

		HG type 0		HG type 2.7		HG type 2.5.7		HG type 1.3.6.7	
Set†	Yield Range	FI Range	*r*	FI Range	*r*	FI Range	*r*	FI Range	*r*
	----(kg ha^{-1})----	----%----		----%----		----%----		----%----	
360	2001-2941**	3-168**	-0.06	1-154**	-0.14	0-75**	0.07	3-83**	0.04
361	1717-2754**	0-165**	-0.22	1-117**	-0.39*	12-111**	0.10	0-136**	0.11
362	1946-3071**	0-156**	-0.38*	2-125**	-0.47**	0-90**	-0.39*	6-83**	0.05
363	2115-3125**	0-118**	-0.14	3-166**	0.06	4-114**	-0.06	7-93**	0.09
364	1907-3298**	1-113**	-0.04	2-147**	-0.34	0-119**	-0.15	0-84**	-0.15
365	2145-3087**	1-119**	-0.43*	3-123**	-0.18	1-95**	-0.32	4-91**	0.06
366	1876-3217**	1-183**	-0.36*	1-161**	-0.32	0-124**	-0.28	7-94**	-0.15
367	2205-3072**	1-131**	0.15	1-128**	-0.32	0-91**	-0.16	5-80**	-0.24
368	2122-3143**	0-68**	-0.35	3-130**	-0.21	0-93**	-0.15	6-135**	0.18

* Significant difference at the 0.05 probability level among the means of the lines in a set and significance of the phenotypic correlation coefficient.
** Significant difference at the 0.01 probability level among the means of the lines in a set and significance of the phenotypic correlation coefficient.
† Each set included 32 F_5-derived lines.

Table 8. Rating of the 288 F_5-derived lines for resistance to four HG types of SCN populations.

HG Type	R†	MR‡	MS§	S¶	NA#
	----------------------------------no. of lines-----------------------------------				
0	98	136	17	26	11
2.7	24	30	77	148	9
2.5.7	24	45	113	87	19
1.3.6.7	22	89	103	41	33

† Resistant, female index < 10%.

‡ Moderately resistant, female index of 10% to 30%.

§ Moderately susceptible, female index of 31% to 60%.

¶ Susceptible, female index > 61%.

Not available, no germination.

Table 9. Female indexes with four HG types for the five highest yielding soybean lines in each set.

Set	Rank	HG 0	HG 2.7	HG 2.5.7	HG 1.3.6.7
		---------------------------%†	---------------------------		
360	1	4	40	22	47
	2	18	58	17	23
	3	15	73	19	21
	4	10	59	29	49
	5	66	105	14	12
361	1	165	55	110	32
	2	0	2	16	27
	3	23	26	20	55
	4	19	32	16	64
	5	11	88	69	55
362	1	1	3	0	27
	2	1	41	40	21
	3	3	68	24	55
	4	0	17	0	41
	5	1	2	0	17
363	1	25	115	83	12
	2	13	88	82	73
	3	13	77	51	30
	4	86	100	28	48
	5	23	67	42	44
364	1	2	2	0	0
	2	10	71	58	16
	3	11	26	108	27
	4	1	20	39	12
	5	18	10	80	23
365	1	2	6	95	32
	2	3	84	28	14
	3	1	33	1	5
	4	6	33	34	49
	5	1	4	1	51

Table 9. Continued

Set	Rank	HG 0	HG 2.7	HG 2.5.7	HG 1.3.6.7
		-----------------------------%†	-----------------------------		
366	1	1	10	17	57
	2	3	42	76	32
	3	2	1	3	31
	4	4	42	1	11
	5	3	16	0	12
367	1	22	21	38	32
	2	13	72	74	5
	3	1	1	0	51
	4	8	82	38	20
	5	28	26	29	43
368	1	11	55	11	33
	2	0	3	1	38
	3	6	20	60	6
	4	1	10	73	113
	5	12	68	38	18

† < 10% = resistant; 10% to 30% = moderately resistant; 31% to 60% = moderately susceptible, and > 61% = susceptible.

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APPENDIX A

MEAN PERFORMANCE OF LINES ACROSS ALL ENVIRONMENTS

Table A1. Mean performance for yield across five environments and SCN resistance of 32 F_5-derived soybean lines in set 360.

		Mean FI‡			
Entry†	Mean Yield	HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	%			
05JR209487	2284	168	66	38	37
05JR209504	2092	11	72	10	55
05JR209507	2692	10	.	24	.
05JR209518	2603	4	1	.	.
05JR209526	2544	10	56	55	48
05JR209539	2590	14	43	19	38
05JR209550	2561	10	130	33	13
05JR209582	2589	16	65	36	28
05JR209586	2775	15	73	19	21
05JR209589	2591	15	90	18	36
05JR209604	2931	18	58	17	23
05JR209609	2399	6	65	32	.
05JR209620	2573	32	76	75	55
05JR209621	2465	44	62	50	24
05JR209628	2242	14	50	55	45
05JR209639	2941	4	40	22	47
05JR212269	2673	87	47	58	31
05JR212277	2293	5	60	63	.
05JR212287	2277	27	75	33	31
05JR212301	2415	9	55	29	40
05JR212304	2481	10	49	75	83
05JR212313	2376	7	63	15	24
05JR212316	2620	3	61	50	45
05JR212317	2622	8	78	59	25
05JR212324	2734	10	59	29	49
05JR212330	2464	21	154	10	38
05JR212337	2347	9	46	0	66
05JR212361	2346	13	97	6	9
05JR212362	2538	28	134	24	10

Table A1. Continued

		Mean FI‡			
Entry†	Mean Yield	HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	----------------------------------	%	----------------------------------	
05JR212369	2217	19	76	34	3
05JR212400	2701	66	105	14	12
05JR212428	2001	9	96	6	10
M061136	2888				
M09089	2942				
WW152201	3015				
WW169267	3339				
SEM	124	5.2	19.3	8.7	8.0
LSD 0.05	337	14.8	54.3	26.4	22.6
LSD 0.01	445	19.6	71.9	35.1	30.1

† Checks were not included in the calculations for the SEM and LSD's.
‡ Female index = ($\bar{x}$ cyst no. of a line ÷ $\bar{x}$ cyst no. of the susceptible check) x 100.

Table A2. Mean performance for yield across five environments and SCN resistance of 32 F_5-derived soybean lines in set 361.

		Mean FI‡			
Entry†	Mean Yield	HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	----------------------------------	----------------%	----------------	----------------------------------
05JR209489	2262	5	50	22	69
05JR209492	2329	14	114	50	88
05JR209519	2575	2	2	21	30
05JR209530	2656	0	2	16	27
05JR209542	2308	2	.	2	.
05JR209545	2288	31	91	62	14
05JR209556	2020	20	66	71	13
05JR209572	2511	12	77	.	51
05JR209590	2262	7	113	41	33
05JR209598	1719	19	117	.	45
05JR209616	2321	16	97	.	.
05JR209634	2754	6	35	77	.
05JR212267	2411	7	59	63	34
05JR212274	2308	10	69	47	74
05JR212290	2602	19	32	16	64
05JR212291	2518	9	82	60	69
05JR212292	2612	23	26	20	55
05JR212296	2587	11	88	69	55
05JR212297	2420	14	53	40	136
05JR212320	2319	0	1	76	21
05JR212346	2502	8	63	44	10
05JR212356	2567	11	77	51	10
05JR212372	2446	10	65	41	13
05JR212374	2433	.	121	.	0
05JR212378	2113	91	98	.	6
05JR212390	2354	.	67	41	33
05JR212391	2676	165	55	110	32
05JR212395	2738	46	51	.	14
05JR212406	2477	.	124	24	17

Table A2. Continued

Entry†	Mean Yield	Mean FI‡ HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	---%			---
05JR212408	2422	18	44	111	.
05JR212416	1717	132	39	12	7
05JR212436	2049	43	.	55	.
01JR123480	2621				
02JR111334	3147				
M09089	3064				
WW169267	2790				
SEM	162	5.9	14.8	11.7	10.5
LSD 0.05	454	16.7	41.8	33.3	29.8
LSD 0.01	601	22.2	55.5	44.4	39.8

† Checks were not included in the calculations for the SEM and LSD’s.
‡ Female index = ($\bar{x}$ cyst no. of a line ÷ $\bar{x}$ cyst no. of the susceptible check) x 100.

Table A3. Mean performance for yield across five environments and SCN resistance of 32 F_5-derived soybean lines in set 362.

		Mean FI‡			
Entry†	Mean Yield	HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	---------------------------------%---------------------------------			
05JR209483	2574	2	16	36	66
05JR209497	2468	8	44	30	73
05JR209501	2166	10	76	48	.
05JR209502	2760	18	44	47	80
05JR209508	2334	17	61	70	56
05JR209512	2756	19	99	18	11
05JR209517	2219	10	101	11	.
05JR209534	2768	2	11	33	6
05JR209543	2113	9	36	51	.
05JR209552	1963	14	86	47	26
05JR209553	2866	1	2	0	17
05JR209558	2991	1	41	40	21
05JR209583	2585	23	58	24	20
05JR209594	2407	17	35	33	31
05JR209597	1946	16	81	78	41
05JR209599	2411	8	3	26	.
05JR209611	3071	1	3	0	27
05JR209614	2759	21	84	77	66
05JR209615	2220	15	87	.	55
05JR209617	2829	3	4	1	43
05JR209622	2215	12	104	71	36
05JR209627	2191	15	43	65	51
05JR209629	2888	0	17	0	41
05JR209630	2446	16	67	37	68
05JR209637	2414	1	31	1	45
05JR209645	2108	13	88	20	.
05JR209647	2549	8	70	60	37
05JR209648	2623	17	125	45	43
05JR212315	2598	1	3	90	83

Table A3. Continued

Entry†	Mean Yield	Mean FI‡ HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	---%			---
05JR212340	2893	3	68	24	55
05JR212394	2087	156	87	34	9
05JR212407	2071	68	65	44	7
02JR111334	3082				
M09089	3088				
SJ919784	3020				
WW169267	2700				
SEM	188	5.7	17.3	9.4	10.2
LSD 0.05	527	15.9	48.6	26.6	29
LSD 0.01	696	21.1	64.4	35.4	38.6

† Checks were not included in the calculations for the SEM and LSD's.
‡ Female index = ($\bar{x}$ cyst no. of a line ÷ $\bar{x}$ cyst no. of the susceptible check) x 100.

Table A4. Mean performance for yield across five environments and SCN resistance of 32 F_5-derived soybean lines in set 363.

		Mean FI‡			
Entry†	Mean Yield	HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	---------------------------------	------%	------	---------------------------------
05JR209482	2650	66	25	71	47
05JR209510	2759	21	92	88	31
05JR209554	2487	29	74	98	27
05JR209560	2340	34	72	76	14
05JR209567	2956	6	36	.	.
05JR209576	2850	12	116	112	59
05JR209578	2623	3	69	42	27
05JR209624	3004	13	77	51	30
05JR209625	2881	23	67	42	44
05JR209650	2745	26	90	53	20
05JR212270	2173	10	94	45	34
05JR212273	2608	9	78	55	63
05JR212279	2556	19	76	37	24
05JR212305	2440	6	55	4	23
05JR212312	2808	1	6	52	30
05JR212319	2874	12	155	79	13
05JR212321	2115	13	96	63	41
05JR212323	2669	2	10	57	65
05JR212331	2647	34	85	89	93
05JR212332	2643	7	120	59	.
05JR212342	2551	9	108	.	26
05JR212345	2744	28	166	70	40
05JR212347	2415	6	71	114	8
05JR212353	3009	13	88	82	73
05JR212354	2210	11	102	93	68
05JR212360	2703	12	114	70	7
05JR212383	2133	118	44	65	9
05JR212384	2876	.	83	73	16
05JR212420	2690	0	14	69	52

Table A4. Continued

		Mean FI‡			
Entry†	Mean Yield	HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	----------------------------------	----------------%	----------------	----------------------------------
05JR212430	2988	86	100	28	48
05JR212439	3125	25	115	83	12
05JR212443	2803	0	3	.	37
02JR111334	3134				
05ALL90318	3053				
M07437	3137				
WW169267	3290				
SEM	153	8.6	15	12.3	8.1
LSD 0.05	427	24.1	42.3	37.5	23
LSD 0.01	565	31.9	56	49.9	30.5

† Checks were not included in the calculations for the SEM and LSD's.
‡ Female index = ($\bar{x}$ cyst no. of a line ÷ $\bar{x}$ cyst no. of the susceptible check) x 100.

Table A5. Mean performance for yield across five environments and SCN resistance of 32 F_5-derived soybean lines in set 364.

		Mean FI‡			
Entry†	Mean Yield	HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	----------%			----------
05JR209475	2831	64	20	36	84
05JR209486	2301	18	10	41	22
05JR209505	2018	10	109	38	29
05JR209514	3083	10	71	58	16
05JR209515	2481	20	90	60	17
05JR209520	2507	18	53	77	82
05JR209541	2174	16	13	.	.
05JR209544	2240	22	61	77	21
05JR209561	2848	18	10	80	23
05JR209580	2291	24	70	74	22
05JR209595	2602	14	48	65	41
05JR209596	2561	10	103	38	51
05JR209608	2921	2	4	.	46
05JR209623	2856	11	26	108	27
05JR209633	2558	6	43	61	79
05JR209651	2747	26	64	56	56
05JR212275	1907	15	51	.	44
05JR212278	3298	2	2	0	0
05JR212284	2281	17	23	75	57
05JR212286	2432	8	85	98	.
05JR212294	2099	18	86	79	62
05JR212295	2784	36	54	119	51
05JR212308	2407	37	147	57	15
05JR212318	1968	6	101	51	63
05JR212351	2764	11	74	52	50
05JR212355	2198	12	51	60	.
05JR212359	2425	19	58	49	23
05JR212371	2370	8	57	74	9
05JR212373	2851	1	20	39	4

Table A5. Continued

Entry†	Mean Yield	Mean FI‡			
		HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	---------------------------------%---------------------------------			
05JR212412	2253	113	46	80	6
05JR212417	2893	.	81	83	18
05JR212432	2765	28	56	48	33
02JR111334	2930				
05ALL90318	3031				
M07437	3167				
WW169267	3096				
SEM	156	4.7	12.2	12.7	9.9
LSD 0.05	436	13.1	34.3	39	27.9
LSD 0.01	577	17.4	45.5	51.9	37.2

† Checks were not included in the calculations for the SEM and LSD’s.
‡ Female index = ($\bar{x}$ cyst no. of a line ÷ $\bar{x}$ cyst no. of the susceptible check) x 100.

Table A6. Mean performance for yield across five environments and SCN resistance of 32 F_5-derived soybean lines in set 365.

		Mean FI‡			
Entry†	Mean Yield	HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	---%			
05JR209480	2607	55	66	58	58
05JR209481	2696	1	3	30	46
05JR209495	3032	1	33	1	5
05JR209496	2610	16	9	67	91
05JR209499	2855	1	4	1	51
05JR209506	2452	21	26	79	55
05JR209509	2799	17	64	43	14
05JR209524	2145	34	55	36	65
05JR209551	2260	24	15	55	13
05JR209559	2467	6	65	47	58
05JR209563	2524	26	123	40	19
05JR209579	2451	11	26	45	20
05JR209581	3065	3	84	28	14
05JR209631	2628	5	18	59	70
05JR209640	2557	4	38	39	73
05JR212268	2497	9	27	88	30
05JR212300	2791	6	42	70	26
05JR212302	2615	1	4	72	44
05JR212341	2555	18	90	76	62
05JR212349	2329	9	41	71	16
05JR212366	2920	6	33	34	49
05JR212368	2381	2	19	92	19
05JR212370	2217	12	66	.	6
05JR212375	2270	63	32	61	10
05JR212376	2442	4	5	71	31
05JR212379	2333	80	69	68	.
05JR212382	3087	2	6	95	32
05JR212396	2484	119	38	50	21
05JR212401	2475	18	38	59	4

Table A6. Continued

Entry†	Mean Yield	Mean FI‡ HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	---%			---
05JR212404	2285	84	29	61	.
05JR212433	2301	61	87	50	20
05JR212435	2380	80	45	49	.
02JR111334	2989				
02JR423005	3749				
02JR423016	3720				
M07437	3114				
SEM	159	10.3	12.2	9.1	10.1
LSD 0.05	445	28.8	34.2	25.5	31.5
LSD 0.01	588	38.2	45.4	33.9	44.1

† Checks were not included in the calculations for the SEM and LSD’s.
‡ Female index = ($\bar{x}$ cyst no. of a line ÷ $\bar{x}$ cyst no. of the susceptible check) x 100.

Table A7. Mean performance for yield across five environments and SCN resistance of 32 F_5-derived soybean lines in set 366.

		Mean FI‡			
Entry†	Mean Yield	HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	---------------------------------%			---------------------------------
05JR209511	2606	19	30	124	24
05JR209523	2538	16	93	33	60
05JR209527	2687	28	117	67	52
05JR209533	2613	12	83	35	.
05JR209535	2499	6	52	63	21
05JR209548	2430	11	57	28	.
05JR209573	2562	23	48	46	34
05JR209592	2363	32	65	90	89
05JR209600	2735	6	112	93	38
05JR209610	2100	14	69	45	28
05JR209612	2463	11	88	50	67
05JR209626	1876	16	59	74	40
05JR209632	2649	2	20	44	46
05JR209638	3035	2	1	3	31
05JR209642	3217	1	10	17	57
05JR209644	3053	3	42	76	32
05JR209646	2725	9	48	84	36
05JR212280	2619	6	63	24	7
05JR212283	2622	12	101	51	12
05JR212293	2685	11	66	58	59
05JR212303	2639	1	43	1	24
05JR212310	2884	4	42	1	11
05JR212334	2710	11	52	68	29
05JR212377	2278	18	37	48	94
05JR212380	2364	79	107	54	15
05JR212385	2797	.	45	49	.
05JR212387	2769	3	.	0	12
05JR212397	2532	162	116	13	19
05JR212402	2172	183	33	59	8

Table A7. Continued

Entry†	Mean Yield	Mean FI‡ HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	----------------------------------%----------------------------------			
05JR212409	2448	144	161	43	78
05JR212413	2454	151	118	80	94
05JR212422	2527	121	64	.	46
02JR111334	2617				
02JR423005	3540				
02JR423016	3678				
M07437	3011				
SEM	157	8.6	15	11.7	8.2
LSD 0.05	439	24.3	42.1	35.8	23.3
LSD 0.01	580	32.2	55.8	47.5	31.1

† Checks were not included in the calculations for the SEM and LSD’s.
‡ Female index = ($\bar{x}$ cyst no. of a line ÷ $\bar{x}$ cyst no. of the susceptible check) x 100.

Table A8. Mean performance for yield across five environments and SCN resistance of 32 F_5-derived soybean lines in set 367.

		Mean FI‡			
Entry†	Mean Yield	HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	---%			
05JR209476	2655	.	48	0	36
05JR209478	2766	57	60	63	46
05JR209488	2655	6	12	0	65
05JR209494	2417	10	48	40	80
05JR209500	2414	27	48	51	.
05JR209513	2592	11	42	.	40
05JR209516	2540	9	78	26	14
05JR209525	2530	45	115	63	25
05JR209529	2649	16	45	4	31
05JR209568	2822	16	75	35	.
05JR209571	2295	24	60	32	38
05JR209575	2729	9	40	41	40
05JR209577	2564	19	31	75	24
05JR209591	2869	1	1	0	51
05JR209601	2868	8	82	38	20
05JR209602	2205	13	115	50	31
05JR209613	2565	9	72	39	40
05JR209649	2521	.	98	75	.
05JR212281	2214	17	128	91	36
05JR212288	3072	22	21	38	32
05JR212306	2747	17	104	51	37
05JR212307	2342	22	62	19	.
05JR212311	2362	2	99	21	58
05JR212325	2337	8	42	45	56
05JR212363	2977	13	72	74	5
05JR212367	2577	1	9	55	.
05JR212389	2779	131	88	45	.
05JR212393	2587	.	68	37	5
05JR212421	2460	23	62	36	28

Table A8. Continued

		Mean FI‡			
Entry†	Mean Yield	HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	----------------------------------	%		----------------------------------
05JR212434	2788	28	26	29	43
05JR212441	2500	41	72	77	67
05JR212442	2375	12	21	45	28
02JR423003	3567				
02JR423016	3413				
M07437	2944				
SJ143606	3276				
SEM	140	6.8	15.9	10.8	7.7
LSD 0.05	393	19.1	44.5	30.3	21.9
LSD 0.01	520	25.3	59	40.3	29.2

† Checks were not included in the calculations for the SEM and LSD's.
‡ Female index = ($\bar{x}$ cyst no. of a line ÷ $\bar{x}$ cyst no. of the susceptible check) x 100.

Table A9. Mean performance for yield across five environments and SCN resistance of 32 F_5-derived soybean lines in set 368.

		Mean FI‡			
Entry†	Mean Yield	HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	%			
05JR209490	2856	1	10	73	113
05JR209493	2688	2	111	12	79
05JR209521	2524	27	159	31	63
05JR209531	3118	11	55	11	33
05JR209537	2696	19	108	93	36
05JR209562	2722	10	90	1	.
05JR209564	2751	23	86	74	44
05JR209569	2286	21	105	66	.
05JR209584	2524	8	103	70	41
05JR209585	2867	20	.	82	13
05JR209587	2706	12	86	54	19
05JR209606	3032	0	4	1	38
05JR209607	2459	22	84	.	50
05JR209636	2639	16	73	30	54
05JR212282	2854	12	69	38	18
05JR212285	2703	6	100	51	38
05JR212309	2635	9	110	63	43
05JR212326	2575	13	53	21	34
05JR212335	2122	12	57	39	53
05JR212336	2792	4	115	.	47
05JR212338	2797	12	121	41	135
05JR212343	2295	19	99	.	30
05JR212348	2394	14	68	40	7
05JR212350	2542	6	105	35	16
05JR212352	2338	19	84	2	11
05JR212364	2323	12	16	59	17
05JR212365	2985	6	20	60	6
05JR212399	3143	2	6	8	.
05JR212410	2605	68	67	.	56

Table A9. Continued

Entry†	Mean Yield	Mean FI‡			
		HG Type 0	HG Type 2.7	HG Type 2.5.7	HG Type 1.3.6.7
	kg ha^{-1}	--------------------------------%	--------------------------------		
05JR212411	2523	4	38	0	16
05JR212424	2477	120	.	26	24
05JR212440	2341	52	.	87	21
02JR423003	3617				
02JR423016	3499				
SJ143606	3353				
X140R	2980				
SEM	154	3.4	16.6	9.1	12.1
LSD 0.05	432	9.6	46.7	28.1	34.3
LSD 0.01	571	12.7	61.9	34.5	45.7

† Checks were not included in the calculations for the SEM and LSD’s.
‡ Female index = ($\bar{x}$ cyst no. of a line ÷ $\bar{x}$ cyst no. of the susceptible check) x 100.

APPENDIX B

ANALYSIS OF VARIANCE FOR YIELD WITHIN A SET ACROSS ENVIRONMENTS

Table B1. Analysis of variance for yield expressed in kg ha^{-1} across five environments in 2007 within each of the nine sets.

		Mean Squares				
Sources of variation†	df	360	361	362	363	364
G	31	405037**	633925**	1020490**	703686**	1159378**
R(E)	5	836493**	185077	75578	984146**	164604
E	4	63134368**	53025636**	55849699**	53731305**	45607882**
G x E	124	152904**	263450**	353959**	232938**	243170**
Error	155	74802	100555	115893	103462	106673
CV (%)		15.6	21.5	24.0	18.2	19.6

		Mean Squares			
Sources of variation†	df	365	366	367	368
G	31	628915**	732509**	467942**	628206**
R(E)	5	291788*	85138	156209	38497
E	4	40071264**	42061125**	27073118**	20263852**
G x E	124	252321**	245604**	197232**	238182**
Error	155	94644	87076	104007	85027
CV (%)		19.7	19.2	17.2	18.5

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† G = genotype, R(E) = replications nested in environments, E = environments, G x E = genotypes by environments interaction.

APPENDIX C

ANALYSIS OF VARIANCE FOR SCN RESISTANCE WITHIN A SET

Table C1. Analyses of variance for female indexes of lines for SCN resistance within a set.

	Mean Squares							
	360							
Sources of variation†	df	HG type 0	df	HG type 2.7	df	HG type 2.5.7	df	HG type 1.3.6.7
G	30	3927.5**	31	3569.2**	30	1521.1**	27	1129.0**
R	3	73.2	3	3755.9	3	520.0	3	294.0
G x R	86	110.0	80	1492.3	74	300.8	54	254.6
CV (%)		45.6		54.4		51.0		48.4

	361							
Sources of variation†	df	HG type 0	df	HG type 2.7	df	HG type 2.5.7	df	HG type 1.3.6.7
G	29	5948.8**	28	4295.0**	25	2332.1**	26	2361.7**
R	3	124.2	3	145.2	3	1404.5	3	424.2
G x R	72	141.4	75	881.1	49	549.5	50	440.9
CV (%)		44.0		45.0		49.9		58.3

	362							
Sources of variation†	df	HG type 0	df	HG type 2.7	df	HG type 2.5.7	df	HG type 1.3.6.7
G	31	1710.6**	31	4724.5**	30	1980.3**	26	1527.2**
R	3	80.2	3	1176.6	3	519.3	3	722.7
G x R	88	128.2	78	1194.8	63	354.5	53	416.7
CV (%)		80.9		62.8		48.3		48.6

Table C1. Continued

	Mean Squares							
	363							
Sources of variation†	df	HG type 0	df	HG type 2.7	df	HG type 2.5.7	df	HG type 1.3.6.7
G	31	2481.5**	30	6089.9**	28	1760.4**	29	1497.7**
R	3	161.3	3	1583.0	3	191.2	3	49.9
G x R	88	292.5	77	905.6	54	603.2	65	264.2
CV (%)		81.4		38.1		37.2		47.8

	364							
Sources of variation†	df	HG type 0	df	HG type 2.7	df	HG type 2.5.7	df	HG type 1.3.6.7
G	31	1416.1**	30	4590.6**	28	1610.8**	28	1571.0**
R	3	20.0	3	969.3	3	681.3	3	303.0
G x R	91	87.0	78	597.5	54	646.9	56	388.9
CV (%)		49.1		43.6		41.0		54.8

	365							
Sources of variation†	df	HG type 0	df	HG type 2.7	df	HG type 2.5.7	df	HG type 1.3.6.7
G	31	3576.3**	31	3378.7**	30	1757.4**	28	1607.5**
R	3	393.1	3	1061.6	3	2274.0**	3	43.8
G x R	89	420.4	83	593.8	72	328.2	59	412.0
CV (%)		82.0		59.4		32.4		61.5

Table C1. Continued

Mean Squares

	366							
Sources of variation†	df	HG type 0	df	HG type 2.7	df	HG type 2.5.7	df	HG type 1.3.6.7
G	31	9401.2**	30	5014.6**	30	2825.8**	28	2019.6**
R	3	161.7	3	418.1	3	980.5	3	173.3
G x R	91	296.9	72	898.4	66	548.6	56	271.6
CV (%)		50.7		47.6		46.8		42.3
	367							
Sources of variation†	df	HG type 0	df	HG type 2.7	df	HG type 2.5.7	df	HG type 1.3.6.7
G	31	1923.8**	28	4267.7**	30	1750.7**	25	953.5**
R	3	240.1	3	1268.2	3	251.3	3	5.2
G x R	93	183.0	72	1005.3	70	462.4	53	238.8
CV (%)		64.4		52.0		50.0		42.9
	368							
Sources of variation†	df	HG type 0	df	HG type 2.7	df	HG type 2.5.7	df	HG type 1.3.6.7
G	27	1341.9**	31	5589.1**	27	2443.5**	28	2522.2
R	3	118.4	3	1583.1	3	693.2	3	208.3
G x R	76	46.8	87	1097.3	55	334.4	53	584.0
CV (%)		42.8		43.0		43.5		60.4

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† G = genotype, R = replications, G x R = genotype by replication interaction.

APPENDIX D

ORIGINAL RELEASE NOTICE FROM MISSOURI SOYBEAN MERCHANDISING COUNCIL REGARDING SS97-6946

Soybean Germplasm Line SS97-6946

Missouri Agricultural Experiment Station in Cooperation with the Missouri Soybean Merchandising Council

March 2004

An experimental line has been developed that is resistant to all major races (races 1, 2, 3, 5, and 14) of the soybean cyst nematode (SCN). The experimental designation is SS97-6946. The relative maturity is 4.3 with purple flower color and tawny pubescence. SS97-6946 measured 50 inches and is susceptible to lodging. The line was developed from a cross of Essex x PI 438503A made in 1994 at the Agronomy Research Center located near Columbia, MO. Essex is susceptible to the SCN while PI 438503A is resistant to all major races of the SCN and is black seeded. SS97-6946 was selected for yellow seeds.

Yield of SS97-6946 is less than checks (Table 1). However, based on our experience with maturity groups III and IV, SS97-6946 combines more favorably than ‘Hartwig’ types in developing higher yielding SCN resistant strains.

Table 1. Yield of SS97-6946 which has resistance to all major SCN races evaluated at three Missouri locations. There were a total of 16 entries in the test.

	Seed yield in bushels per acre			
Selection	Dairy Farm	Grand Pass	Novelty	Mean
Macon	79	45	67	64
Mustang	70	44	67	61
SS97-6946	**70**	**47**	**55**	**57**
Test Mean	64	43	56	
CV (%)	5.9	9.6	5.0	
LSD (0.05)	5	6	4	

We have evaluated the reaction of SS97-6946 to SCN numerous times and have always found that this selection is resistant to all five major races. Data in Table 2 is very typical of the studies conducted.

Table 2. Average number of cysts per plant and female index (FI) values for differentials as compared to SS97-6946.

Entry	Race I		Race II		Race III		Race V		Race XIV	
	Ave/Plant	FI	Ave/Plant	FI	Ave/Plant	FI	Ave/Plant	FI	Ave/Plant	FI
Peking	1.8	0.7	36.2	29.0	1.7	1.3	2.2	1.2	263.5	39.8
Pickett	3.5	1.5	68.4	54.8	0.1	0.1	135.0	72.9	541.8	81.9
PI 88788	100.8	41.8	80.8	64.7	5.1	3.8	127.8	69.0	26.7	4.0
PI 90763	0.5	0.2	4.0	3.2	0.3	0.2	1.8	1.0	149.8	22.6
Hutcheson	240.9	100.0	124.8	100.0	132.7	100.0	185.1	100.0	661.6	100.0
SN97-6946	**1.8**	**0.7**	**10.0**	**8.0**	**3.9**	**3.0**	**2.8**	**1.5**	**8.5**	**2.8**

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