Reaction of Soybean Cyst Nematode Resistant Plant Introductions to Root-knot and Reniform Nematodes

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ABSTRACT Soybean cyst [SCN, *Heterodera glycines* Ichinohe], southern root-knot [RKN, *Meloidogyne incognita* (Kofoid and White) Chitwood] and reniform nematodes [RN, *Rotylenchulus reniformis* (Linford and Oliveria)] are common plant-parasitic nematode species in southern US fields. Each nematode individually or collectively causes significant economic losses to field grown soybean. A subset of 120 soybean plant introductions (PIs) selected from the USDA Soybean Germplasm Collection have been shown to be resistant to one or more SCN populations (HG Types); however, many of these PIs have not been screened for resistance to either RKN or RN. The objective of this research was to evaluate these germplasm accessions for resistance to RKN and RN. The evaluation for RKN resistance was conducted in RKN infested field plantings after potatoes near Charleston, MO in 2006 and 2007. The evaluation for RN resistance was performed in a greenhouse at Fayetteville, AR, in 2007. Out of these accessions, 64 PIs were identified with high or moderate resistance to RKN. Of these 64 lines, 24 accessions showed good resistance to both RKN and RN. These new sources of resistance to multiple nematodes will be valuable materials for soybean breeding programs to develop new resistant cultivars that can overcome yield losses caused by one or more of these nematode species.

Keywords Soybean, Cyst nematode, Root-knot nematode, Reniform nematode

INTRODUCTION

Soybean [*Glycine max* (L.) Merr.] cyst nematode (SCN, *Heterodera glycines* Ichinohe), southern root-knot nematode [RKN, *Meloidogyne incognita* (Kofoid and White) Chitwood], and reniform nematode (RN, *Rotylenchulus reniformis* Linford and Oliveria) are significant pathogens in southern U.S. soybean fields (Wrather and Koenning 2009). They cause approximately 157 billion U.S. dollars in damage worldwide (Klink et al. 2009).

SCN generally has caused more yield reduction than any other soybean disease. Estimated yield losses was 3.3 million tons in 2009 in 28 U.S. states (Wrather and Koenning 2009). RKN often occurs in soybean fields, but to a lesser extent than SCN (Wrather et al. 2003) with losses estimated at 1.9 million tons over 28 U.S. states in 2009 (Wrather and Koenning 2010). If RKN interacts with other disease pathogens, damage is greater than would occur with RKN alone (Goswami and Agrawal 1978). Another nematode species, RN causes root decay, poor growth, reduced pod set, and significant yield reduction in susceptible soybean cultivars (Niblack et al. 2004).

Nematicide applications were once a cost-effective manner and widely used as an option to manage nematode infestation (Niblack et al. 2004). However, growers were reluctant to use chemical control due to high costs, environmental toxicity and human health concerns. Thus, breeding for new soybean cultivars with resistance to one or more species is a cost effective and environmentally friendly measure to reduce soybean yield losses to nematodes.

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The use of SCN-resistant soybean cultivars, such as Forrest, prevented approximately $401 million in soybean yield losses at a cost of only about $1 million for the variety development (Bradley and Duffy 1982). However, continuous cultivation of SCN resistant soybean cultivars may accelerate selection pressure for other nematode species, particularly RKN and RN that also damage soybeans (Schmitt and Barker 1988). Stetina et al. (1997) reported that RKN resistant soybean likely results in an increase of RN over time. Therefore, cultivars with resistance to multiple nematode species are essential in preventing losses from these pests which can occur in the same field. Several sources of resistance to RKN have been identified in soybean, which were being used in soybean breeding programs to develop soybean germplasm lines resistant to both SCN and RKN (Boerma et al. 1991; Luzzi et al. 1997). SCN-resistant soybean genotypes derived from cultivars Custer, Hartwig, Peking, PI437654, and PI 90763 are potentially also resistant to RN (Robbins et al. 1994a; Robbins et al. 1994b; Davis et al. 1996).

Soybean plant introductions (PIs) selected from the USDA Soybean Germplasm Collection were screened in several studies and it was reported that about 120 accessions have shown to be resistant to one or more SCN populations or HG types (Shannon et al. 2004). However, many of these PI lines have not been screened for resistance to either RKN or RN. The purpose of this study was to collectively evaluate this subset of SCN resistant accessions for resistance to RKN and RN to identify sources resistant to all three nematode species.

**MATERIALS AND METHODS**

**Soybean cyst nematode resistant genotypes**

A total of 120 soybean PIs in maturity groups (MGs) I to VII from the USDA Soybean Germplasm Collection (Shannon et al. 2004), previously identified as having SCN resistance to one or more SCN HG Types were evaluated to both RKN and RN to determine which of these SCN sources carried resistant to one or both of these species.

**Root-knot nematode evaluation**

One hundred twenty soybean PIs were evaluated for resistance to RKN in highly infested fields following potatoes near Charleston, MO on a Dundee sandy loam (Aeric Ochraqualfs). Levels of RKN at each site were not determined but, sandy soils following spring potatoes in Missouri often have high levels of RKN after harvest in late June and July. Ten seeds of each soybean accession were planted in hill plots spaced 61 cm apart in rows 76 cm wide at two sites in 2006 and one site in 2007. Planting dates were June 26, 2006 and June 30, 2007. The experimental design was a randomized complete block design (RCBD) with two replications. Six weeks after planting, soybean plants in each hill were dug with a shovel to expose root systems for determining reaction to RKN. Reaction to RKN damage was measured by root-knot galling and scored using a 1-5 scale (Luzzi et al. 1997) where 1=no galls and 5=very severe galling. A score of 3 or less was considered as resistance reaction. Cultivar 5601T (Pantalone et al. 2003) was used as the resistant check, and cultivar Anand (Anand et al. 2001) was used as the susceptible check.

**Reniform nematode evaluation**

After RKN evaluations, 64 PI lines that showed consistent resistance to RKN with galling scores ≤ 3 were phenotyped for resistance to RN in a greenhouse facility of the University of Arkansas, Fayetteville, AR, in 2007. Seeds were germinated in vermiculite. Seedlings at the cotyledon stage or VC growth stage (Fehr and Caviness 1977) were then transplanted into 10-cm-diameter clay pots (one seedling per pot) containing 500 cm³ of pasteurized fine sandy loam soil (ca. 91% sand, 5% silt, 4% clay, and < 1% organic matter). Each pot was inoculated into three, 2.5 cm-deep holes made in the soil with approximately 2,000 vermiform RN using an auto pipette. The experimental design was an RCBD with ten replications. For resistant checks, cultivars Anand (Robbins et al. 2006; Stetina et al. 2014) and Forrest (Stetina et al. 2014; Williams et al. 1981) and for susceptible checks, cultivars Braxton (Robbins and Rakes 1996) and Hutcheson (Buss et al. 1988) were included. A reproductive index (RI %) was estimated to evaluate the response of each pot of RN using the following
formula (Robbins et al. 1999), RI (%)=(Number of eggs+vermiform nematodes at test termination/Initial infestation level)×100.

**Statistical analysis**

All statistical analyses were conducted using PROC GLM scripts of SAS version 8 program (SAS Institute 2004). The differences among mean values were and tested by Duncan’s Multiple Range Test at $P \leq 0.05$. The statistical analysis and tests were performed for only the 64 selected accessions that showed resistance to RKN.

**RESULTS**

**Root-knot nematode resistance**

The RKN and RN reaction of SCN resistant germplasm accessions for resistance to RKN are presented in Table 1. Among the 120 SCN resistant PI lines studied, 64 accessions (Table 1) showed galling scores of 3.0 or less over two years of evaluation at three sites. Their means were not significantly different ($P=0.95$) and not different from the moderately resistant RKN check 5601T which had a score of 3.0. The root galling score of 64 accessions ranged from 1.3 to 3.0 with an average score of 2.3, indicating that these accessions were resistant or moderately resistant to RKN based on their performance relative to the resistant check, cv. 5601T. Among these, three accessions, PI404198B, PI438342, and PI532444A showed the lowest root galling scores with an average score of 1.3, indicating these three accessions possessed the highest level of resistance to RKN. According to a previous report (Shannon et al. 2004) PI404198B was reported to be highly resistant to SCN races 1, 3, and 5 (HG Types 2.5.7, 0, and 2.5.7, respectively) and moderately resistant to race 14 (HG Type 1.3.5.6.7), while PI438342 was resistant to SCN race 5 (HG Type 2.5.7) and PI532444A was moderately resistant to SCN races 2, 3, 5, and 14 (HG Types 1.2.5.7, 0, 2.5.7, and 1.3.5.6.7) as shown in Table 1.

**Reniform nematode resistance**

There was a significant difference ($P < 0.01$) among the 64 RKN resistance PI accessions for reaction to RN as shown in Table 1. The average reproductive index (RI %) for RN was 13.1%. A minimum RI of 0.1% was estimated for PI507471 and a maximum RI of 45.8% was estimated for PI438496B. Among the four check genotypes, cv. Anand had the lowest RI of 0.8% and cv. Braxton had the highest index of 308.1%. Nine accessions, PI404198A, PI438498, PI467327, PI468915, PI494182, PI507470, PI507471, PI507476, and PI567516C showed similar or less RI (%) than a resistant check, cv. Anand. Thus, these nine accessions had high levels of resistance to RN. Among these accessions, PI404198A showed an RI of 0.5% for RN and a score of 2.8 for RKN. PI408198A had been reported to be resistant to SCN races 1, 2, 3, and 5 (HG Types 2.5.7, 1.2.5.7, 0, and 2.5.7, respectively). PI438489B with resistance to SCN races 1, 2, 3, 5, and 14 (HG Types 2.5.7, 1.2.5.7, 0, 2.5.7, and 1.3.5.6.7, respectively) showed RI of 0.9% for RN and a score of 2.2 for RKN. PI467327 was reported to be resistant to SCN races 1 and 3 (HG Types 2.5.7 and 0, respectively) with RI of 0.2% for RN and a RN score of 2.8. A wild soybean (G. soja) accession PI468915 with SCN resistance to races 1, 3 and 5 (HG Types 2.5.7, 0, and 2.5.7) showed 0.4% of RI for RN, and a score of 2.3 for RKN. PI494182 with resistance to races 1, 3, and 5 (HG Types 2.5.7, 0, 2.5.7, respectively) and moderately resistant to race 2 (HG Type 1.2.5.7) of SCN, had an RI of 0.4% for RN and a score of 2.8 for RKN. PI507470 with resistance to SCN race 1 (HG Type 2.5.7) and moderate resistant to race 5 (HG Type 2.5.7) had an RI of 0.7% for RN and a score of 2.7 for RKN. PI507471 with resistance to races 2 and 5 and moderately resistant to race 1 and 14 had a very low RI of 0.1% for RN and a score of 2.7 score for RKN. PI507476 with resistance to races 3 and 5 and moderate resistant to race 1 of SCN had an RI of 0.5% for RN, and a score of 2.2 score for RKN. PI567516C with SCN resistance to races 1 and 3 and moderate resistance to race 2 in addition to resistance to the Hartwig SCN HG type had an RI of 0.8% for RN, and a RKN score of 2.2. The resistant check cultivar, Forrest with resistance to races 1 (HG type 2.5.7) and 3 (HG type 0) and resistance to RKN (Hartwig and Epps 1973) showed an RI of 5.0% for RN. Among the 64 remaining RKN resistant accessions, 15 accessions, PI089772, PI303652, PI404198B, PI417091, PI424137B, PI437690, PI438342, PI438489B, PI468903,
Table 1. Response of SCN resistance sources (Shannon et al. 2004) to root-knot nematode (RKN) and reniform nematode (RN).

| Genotype  | Maturity group | SCN (Race 1 HG Type 2.5.7) | Race 2 (HG Type 1.2.5.7) | Race 3 (HG Type 0) | Race 5 (HG Type 2.5.7) | Race 14 (HG Type 1.3.5.6.7) | RKN (1-5) | RN (RI %) |
|-----------|----------------|-----------------------------|--------------------------|-------------------|------------------------|-----------------------------|-----------|-----------|
| Peking    | IV             | R                           | R                        | R                 | MR                     | MR                          | 1.5 a     | 5.3 p-z   |
| PI079693  | III            | MR                          | MR                       | MR                | MR                     | 2.0 a                       | 23.8 e-m  |
| PI083788  | III            | R                           | R                        | R                 | MR                     | 2.0 a                       | 17.8 f-p  |
| PI089008  | II             | MR                          | MR                       | MR                | MR                     | 2.3 a                       | 19.1 f-p  |
| PI089014  | II             | MS                          | MS                       | MS                | MS                     | 3.0 a                       | 15.0 h-t  |
| PI089772  | IV             | R                           | R                        | R                 | R                      | 2.0 a                       | 3.4 r-z   |
| PI090763  | IV             | R                           | R                        | R                 | R                      | 1.5 a                       | 6.3 p-z   |
| PI209332  | IV             | R                           | R                        | R                 | MR                     | 2.0 a                       | 31.5 b-g  |
| PI303652  | V              | R                           | R                        | R                 | MR                     | 2.2 a                       | 1.8 s-z   |
| PI398680  | IV             | MR                          | MR                       | MR                | MR                     | 2.7 a                       | 38.4 b-e  |
| PI398682  | IV             | MR                          | MR                       | MR                | MR                     | 2.2 a                       | 27.6 d-i  |
| PI404198A | IV             | R                           | R                        | R                 | R                      | 2.8 a                       | 0.5 xyz   |
| PI404198B | IV             | R                           | R                        | MR                | MR                     | 1.3 a                       | 1.1 u-z   |
| PI407729  | IV             | MR                          | MR                       | MR                | MR                     | 2.2 a                       | 8.7 n-z   |
| PI416762  | II             | MR                          | R                        | R                 | R                      | 1.7 a                       | 13.6 h-y  |
| PI417091  | II             | MR                          | R                        | R                 | R                      | 2.0 a                       | 4.4 q-z   |
| PI417094  | III            | MR                          | MR                       | MR                | MR                     | 2.5 a                       | 14.5 h-u  |
| PI424137B | IV             | MR                          | MR                       | MR                | MR                     | 3.0 a                       | 1.3 t-z   |
| PI437090  | I              | MS                          | MS                       | MS                | MS                     | 2.5 a                       | 12.1 j-z  |
| PI437655  | III            | R                           | R                        | R                 | MR                     | 3.0 a                       | 12.3 j-z  |
| PI437690  | III            | R                           | R                        | R                 | MR                     | 2.8 a                       | 2.4 r-z   |
| PI437725  | IV             | R                           | R                        | R                 | MR                     | 2.7 a                       | 17.8 f-p  |
| PI437770  | III            | R                           | MR                       | MR                | MR                     | 2.8 a                       | 25.3 d-k  |
| PI437908  | II             | MR                          | MR                       | MR                | MR                     | 2.5 a                       | 16.3 g-r  |
| PI438183  | II             | MR                          | MR                       | MR                | MR                     | 2.8 a                       | 9.6 m-z   |
| PI438342  | VI             | R                           | R                        | R                 | MR                     | 1.3 a                       | 1.1 u-z   |
| PI43849B  | IV             | R                           | R                        | R                 | R                      | 2.2 a                       | 0.9 u-z   |
| PI438496B| III            | MR                          | R                        | R                 | MR                     | 2.7 a                       | 45.8 b    |
| PI438498  | IV             | R                           | MR                       | R                 | R                      | 2.3 a                       | 0.5 xyz   |
| PI438503A | II             | R                           | MR                       | R                 | MR                     | 2.0 a                       | 14.5 h-u  |
| PI458175B| IV             | MR                          | MR                       | MR                | MR                     | 2.0 a                       | 6.6 o-z   |
| PI458199  | IV             | MR                          | MR                       | MR                | MR                     | 2.0 a                       | 14.4 h-w  |
| PI458519A | IV             | MR                          | MR                       | MR                | MR                     | 2.3 a                       | 19.0 f-p  |
| PI458520  | II             | R                           | R                        | MR                | MR                     | 1.5 a                       | 20.9 f-o  |
| PI461509  | I              | MR                          | MR                       | MR                | MR                     | 1.8 a                       | 7.4 n-z   |

Means followed by the same letter are not significantly different at P=0.05 by Duncan’s Multiple Range Test.

aSCN reaction based on Niblack et al. 2004 and Shannon et al. 2004 and given as R, resistant or MR, moderately resistant to races 1 (HG Type 2.5.7), 2 (HG Type 1.2.5.7), 3 (HG Type 0), 5 (HG Type 2.5.7), and 14 (HG Type 1.3.5.6.7).

bRKN data: mean value averaged data from three locations with two reps across 2006 and 2007. Scored from 1=no root galls and 5=severe root galling, a score of 3.0 or less is considered showing some resistance.

cRN reaction is reproductive index (RI), calculated by dividing the average number of eggs + vermiform nematodes on each PI at test termination by the number of eggs and vermiform nematodes on cultivars Anand and Forrest (resistant checks).
Table 1. Continued.

| Genotype   | Maturity group | Race 1 (HG Type 2.5.7) | Race 2 (HG Type 1.2.5.7) | Race 3 (HG Type 0) | Race 5 (HG Type 2.5.7) | Race 14 (HG Type 1.3.5.6.7) | SCN(2) | RKN(3) | RN(3) | RI (%) |
|------------|----------------|------------------------|--------------------------|--------------------|------------------------|-----------------------------|--------|--------|--------|--------|
| PI467312   | II             | MR                     | R                        | R                  | R                      | 2.7 a                        | 7.7 n-z |
| PI467327   | II             | R                      | R                        | R                  | R                      | 2.8 a                        | 0.2 z   |
| PI468903   | II             | MR                     | R                        | R                  | R                      | 3.0 a                        | 1.5 t-z |
| PI468915   | II             | R                      | MR                       | R                  | R                      | 2.3 a                        | 0.4 yz  |
| PI475810   | II             |                        | MR                       | MR                 | MR                    | 2.0 a                        | 45.4 bc |
| PI490769   | III            | MR                     | MR                       | MR                 | MR                    | 2.7 a                        | 24.7 d-l|
| PI494182   | 0              | R                      | MR                       | R                  | R                      | 2.8 a                        | 0.4 yz  |
| PI495017C  | IV             | MR                     | R                        | MR                 |                        | 2.2 a                        | 3.2 r-z  |
| PI506862   | IV             | MR                     | R                        | R                  |                        | 2.0 a                        | 4.0 q-z  |
| PI507354   | I              | MR                     | MR                       | R                  | R                      | 1.5 a                        | 1.0 u-z  |
| PI507422   | VI             | R                      | R                        | R                  |                        | 2.0 a                        | 2.3 s-z  |
| PI507423   | VI             | MR                     | R                        | R                  |                        | 1.8 a                        | 3.9 q-z  |
| PI507470   | VI             | R                      | MR                       | R                  | MR                    | 2.7 a                        | 0.7 xyz  |
| PI507471   | III            | MR                     | R                        | R                  | MR                    | 2.7 a                        | 0.1 z    |
| PI507476   | VI             | MR                     | R                        | R                  |                        | 2.2 a                        | 0.5 xyz  |
| PI509095   | VII            | MR                     | R                        | R                  | MR                    | 2.7 a                        | 1.4 t-z  |
| PI532434   | II             | MR                     | MR                       | MR                 | MR                    | 3.0 a                        | 40.6 bcd |
| PI532444A  | I              | MR                     | MR                       | MR                 | MR                    | 1.3 a                        | 21.3 f-n |
| PI548316   | III            | MR                     |                        |                    |                       | 2.2 a                        | 13.9 h-x |
| PI567285   | IV             | R                      |                        |                    |                       | 2.0 a                        | 16.2 g-r |
| PI567415A  | IV             | MR                     | MR                       | R                  |                        | 2.7 a                        | 11.1 k-z |
| PI567421   | IV             |                        | R                        | R                  |                       | 3.0 a                        | 15.8 h-s |
| PI567492   | IV             |                        | R                        | R                  |                       | 3.0 a                        | 15.9 g-s |
| PI567510A  | III            | R                      |                        |                    |                       | 2.8 a                        | 33.6 b-f |
| PI567512B  | II             | R                      | MR                       | R                  |                       | 1.5 a                        | 13.3 i-z |
| PI567516C  | IV             | R                      | MR                       | R                  |                       | 2.2 a                        | 0.8 w-z  |
| PI567535A  | IV             |                        | R                        | R                  |                       | 1.7 a                        | 40.1 b-e |
| PI567581   | IV             |                        | R                        | R                  |                       | 2.5 a                        | 27.7 c-i |
| PI567636   | IV             |                        | R                        | R                  |                       | 2.3 a                        | 28.1 b-h |
| 5601T      | Check          |                        |                          |                    |                       |                              |         |
| Anand      | Check          |                        |                          |                    |                       |                              |         |
| Forrest    | Check          |                        |                          |                    |                       |                              |         |
| Hutcheson  | Check          |                        |                          |                    |                       |                              |         |
| Braxton    | Check          |                        |                          |                    |                       |                              |         |
| P          |                |                        |                          |                    |                       | 0.95                         | < 0.01  |

Means followed by the same letter are not significantly different at P = 0.05 by Duncan’s Multiple Range Test.

(2)SCN reaction based on Niblack et al. 2004 and Shannon et al. 2004 and given as R, resistant or MR, moderately resistant to races 1 (HG Type 2.5.7), 2 (HG Type 1.2.5.7), 3 (HG Type 0), 5 (HG Type 2.5.7), and 14 (HG Type 1.3.5.6.7).

(3)RKN data: mean value averaged data from three locations with two reps across 2006 and 2007. Scored from 1 = no root galls and 5 = severe root galling, a score of 3.0 or less is considered showing some resistance.

(4)RN reaction is reproductive index (RI), calculated by dividing the average number of eggs + vermiform nematodes on each PI at test termination by the number of eggs and vermiform nematodes on cultivars Anand and Forrest (resistant checks).
PI495017C, PI506862, PI507354, PI507422, PI507423, and PI50909 showed an RI for RN equal to or less than the Forrest but higher than the Anand indicating that these 15 accessions are resistant to RN.

**DISCUSSION**

Among 120 cultivated soybean germplasm accessions from the USDA Soybean Germplasm Collection, previously reported to be resistant to single or multiple SCN HG Types, 64 accessions showed resistant to RKN (Table 1). Greg et al. (2008) reported that cultivars JGL934014XRJ and JGL937014XRJ were resistant to SCN, but were highly susceptible to RKN. About half of the SCN resistant accessions evaluated showed susceptibility to RKN. Out of 64 accessions showing different levels of resistance to both SCN and RKN, 24 accessions showed high resistant to RN. Therefore, these 24 accessions have resistance to SCN, RKN, and RN.

Efforts have been made to develop new soybean varieties resistant to SCN, RKN, and RN. For SCN resistance, the cultivar Hartwig was utilized as a resistance source in different soybean breeding programs to develop superior soybean cultivar with broad resistance to SCN (Anand 1992; Faghihi et al. 1995). Vierling et al. (1996) identified and mapped a QTL region on Chromosome (Chr. 11) for resistance to SCN race 3 (HG Type 0) in a mapping population derived from cv. Hartwig that explained 91% of the total phenotypic variation for resistance to SCN. This QTL region showed the highest effect ever reported for a single SCN resistance QTL. Genetic studies reported five major genes, Rhg1 to Rhg5, underlying resistance to different SCN races (Rao-Arelli 1994). The QTL conferring a high level of resistance to SCN in many sources was mapped to the regions containing rhg1 and Rhg4 on Chrs. 8 and 18, respectively (Concibido et al. 2004; Vuong et al. 2011; Wu et al. 2009). Multiple resistance to SCN races 1, 2, 3, 5, 14, and LY1 QTL were identified and mapped on Chrs. 10 and 18 from PI567516C (Vuong et al. 2010). Recently, Jiao et al. (2015) reported that three significant QTLs associated with resistance to RKN were mapped on Chrs. 10, 13, and 17, and also two QTLs associated with resistance to RN were detected on Chrs. 11 and 18 form PI 567516C. For RKN resistance, Luzzi et al. (1987) identified partial resistance in cultivar Forest (Luzzi et al. 1994). Recently, Pham et al. (2013) identified four candidate genes on Chr. 10 that carry a high level of resistance to RKN from PI96354 previously identified as having a high level of resistance to RKN. Three QTLs underlying RKN resistance in PI438489B, were identified on Chrs. 8, 10, and 13 (Xu et al. 2013).

Ibrahim et al. (2011) identified that silencing of tyrosine phosphatase (TP) and mitochondrial stress-70 protein precursor (MSP) genes can decrease gall formation of RKN. Charlton et al. (2010) mentioned that suppression of dual oxidase and a subunit of a signal peptidase reduced RKN numbers in roots. For RN resistance, six soybean lines, PI656647, PI659348, PI567516C, DS97-84-1, 02011-126-1-1-2-1, and 02011-126-1-1-5-1 were identified as having resistance to RN (Stetina et al. 2014). Melo et al. (2013) evaluated 199 genotypes for RN resistance. Among them Custer, PI437654, Fayette, BRSGO Ipameri, BRSMT Pintado, and BRSS262 showed high levels of resistance to RN. Asmus (2008) evaluated 31 soybean genotypes for resistance to RN. Among them BRSMG250, TMG115RR, TMG121RR, MGR015849, TMG113RR, BRS Jiripoca, and M-SOY833RR were not significantly different from the resistant cultivar ‘Custer’ (Rebois et al. 1970). Cardoso et al. (2014) reported that soybean resistance to RN is inherited quantitatively based on lines evaluated from two populations of Forrest (resistant) x BR96-25619 (susceptible) and Custer (resistance) x BR96-25619 (susceptible) normal distribution from highly resistant to highly susceptible. Ha et al. (2007) identified three QTLs conditioning RN resistant on Chrs. 11, 18, and 19 that explained 16, 8, and 21% of phenotypic variation, respectively from accession PI437654. This PI was also reported to be resistant to all known SCN HG Types and several resistance QTLs have been mapped from this source (Concibido et al. 2004). Iatsenko et al. (2014) reported that Bacillus thuringiensis DB27 produces two protoxins, Cry21Fa1 and Cry21Ha1, which act synergistically against nematodes.

Studham et al. (2009) conducted a study to identify whether Rag1, a single dominant gene for aphid resistance
also confers resistance to both SCN and RKN similar to Mi-1.2, a tomato gene that confers resistance to both aphid and RKN. They reported that the gene Rag1 does not confer resistance to SCN and RKN. Davis et al. (1998) identified N87539 and N91245 from the breeding program in North Carolina and G801515, G83559, G939106, and G939223 from the University of Georgia with resistance to both SCN and RKN. Kruger et al. (2008) reported that LS94-3207 and LNX97164-35-5 were resistant to SCN and RKN. Youssef et al. (2013) identified expression of cloned AtPAD4 (Phytoalexin-deficient4) gene in soybean roots, showing broadened resistance to SCN and RKN. Two soybean genotypes, Jake (PI643912) and S99-2281 developed by the University of Missouri Agricultural Experiment Station showed broad resistance to three nematode species, SCN, RKN, and RN (Shannon et al. 2007; 2009).

Kim et al. (2011) reported that stacking SCN resistance alleles of two QTL regions, cqSCN-006 and cqSCN-007, significantly increased resistance level compared to each allele separately. Thus, stacking resistance genes or QTL could result in high levels of resistance to SCN. Meksem et al. (2001) identified and mapped two genomic regions of rhgl and Rhg4 that together explained over 98% of the phenotypic variation associated with resistance to SCN race 3 (HG Type 0).

The identification of new genetic sources with broad spectrum resistance to multiple SCN HG types, RKN and RN would be beneficial for the development of germplasm and varieties to reduce losses from these nematode species. In this study, 24 accessions were identified as sources of resistance to three nematode species in soybeans. Some of the resistance accessions to the three nematode species or were studied to understand genetics of nematode resistance. However, many of these sources have not been studied for inheritance of resistance to these different nematode species. These sources may possess unique and previously unidentified resistance genes that could be incorporated into new varieties with higher levels of resistance. This information will be useful to soybean breeders and other researchers who want to study genotypes or develop soybean cultivars with cross resistance to multiple nematodes species.

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