Grafting Tomato with Interspecific Rootstock to Manage Diseases Caused by *Sclerotium rolfsii* and Southern Root-Knot Nematode

C. L. Rivard, North Carolina State University, Department of Plant Pathology, Raleigh, NC 27695; S. O'Connell, North Carolina State University, Department of Horticultural Science, Raleigh, NC 27695; M. M. Peet, North Carolina State University, Department of Horticulture Science, Raleigh, NC 27695; and F. J. Louws, North Carolina State University, Department of Plant Pathology, Raleigh, NC 27695

ABSTRACT

Rivard, C. L., O'Connell, S., Peet, M. M., and Louws, F. J. 2010. Grafting tomato with interspecific rootstock to manage diseases caused by *Sclerotium rolfsii* and southern root-knot nematode. Plant Dis. 94:1015-1021.

Southern blight (*Sclerotium rolfsii*) and root-knot nematodes (*Meloidogyne* spp.) cause severe damage to fresh-market tomato (*Solanum lycopersicum*) throughout the southeastern United States. Grafting is an emerging technology in U.S. tomato production, and growers require information regarding the resistance characteristics conferred by rootstocks. In this study, southern blight (SB) and root-knot nematodes (RKN) were effectively managed using interspecific hybrid rootstocks. During 2007 and 2008, field trials were carried out at two locations that had soils naturally infested with *S. rolfsii*. At the end of the growing seasons, the mean SB incidence of nongrafted plants was 27 and 79% at the two sites. SB incidence among plants grafted onto rootstock cultivars Big Power (one location only), Beaufort, and Maxifort ranged from 0 to 5%, and area under the disease progress curve (AUDPC) values were lower than for nongrafted and self-grafted controls ($P < 0.01$). At one location, soils were naturally infested with RKN, and all three rootstocks reduced RKN AUDPC and RKN soil populations at first harvest ($P < 0.01$). Big Power was particularly effective at reducing RKN galling and RKN soil populations at final fruit harvest ($P < 0.01$). Fruit yield was higher when resistant rootstocks were utilized ($P < 0.05$), and in our study grafting was effective at maintaining crop productivity in soils infested with *S. rolfsii* and *M. incognita*.

Vegetable grafting is practiced worldwide (33) and gaining interest in the United States for open-field and high tunnel tomato (*Solanum lycopersicum*) production (17). This technology has been primarily used for intensively managed crops grown in greenhouses or tunnels. There are a variety of grafting techniques (18), but the most widely adopted method worldwide for grafted tomato production is tube grafting (26,31). Resistant rootstocks are available for tomato, and can be used to manage economically important soil-borne pathogens such as *Ralstonia solanacearum* (11,27,29,38) and root-knot nematodes (*Meloidogyne* spp.) (1,4).

Another serious disease on tomato in the southeastern United States where grafting offers a promising management alternative

is southern blight (SB) caused by *Sclerotium rolfsii*. SB affects fresh-market tomato throughout the southeastern United States (22). *S. rolfsii* has a broad host range (>600 species), and more than 270 susceptible host genera have been described (9). Diseases caused by *S. rolfsii* are most severe in the tropics and subtropics and in areas of the southern United States where temperatures are sufficiently high to promote the growth and survival of the fungus (30). SB of tomato results in rapid and permanent wilt of all above-ground parts (22). As disease develops, mycelial growth covers the host tissue, and tan to reddish brown sclerotia form on the mycelial mat (30). Sclerotia serve as survival structures and can remain viable for multiple years (22,30). Control of SB is difficult when inoculum levels are high and environmental conditions are suitable for disease development (22). Since *S. rolfsii* has a wide host range and can persist on many types of crop residue, rotation to nonhosts is difficult (30). A physical barrier to protect the stem at the soil line is recommended for gardeners (22), but is probably not practical for commercial growers. Numerous fungicides and soil fumigants inhibit the germination of sclerotia or the mycelial growth of *S. rolfsii* (25,30), but may be cost prohibitive in conventional systems

and are not allowed in organic production.

Host resistance could be a suitable management strategy for SB, but breeders have had little success at identifying and deploying host resistance against *S. rolfsii* into commercial cultivars. Resistance to SB was first identified in *Lycopersicon pimpinellifolium* (24). Six SB-resistant tomato breeding lines were reported in 1992 (19), but to date, no known resistance occurs in available cultivars for fresh-market tomato production (22,42).

Grafting has been utilized to manage root-knot nematodes (RKN) in tomato crops worldwide (1,4,6), but little work has been carried out in naturally infested soils in the United States (17,21). RKN are obligate endoparasites that infect more than 1,700 plant species and cause severe losses in crop yield (3,28,34,40). Although more than 50 species of *Meloidogyne* have been described, four species, *M. incognita*, *M. arenaria*, *M. javanica*, and *M. hapla*, are considered the most economically important worldwide (40). In the United States, *M. incognita* (southern root-knot nematode) is most prevalent on tomato, although *M. hapla* occurs in northern climates (28). Low populations of RKN may cause little economic damage on tomato, but severe infestations result in extensive root-galling, wilting, nutritional deficiencies, and stunting of the plant (28).

Nematicides can be cost-effective for managing diseases caused by *Meloidogyne* spp. in high-value vegetable crops (8). The soil fumigants methyl bromide, methyl iodide, and 1,3-dichloropropene have nematocidal properties (13), but methyl bromide is currently in the process of worldwide phaseout (8). Crop rotation with nonhosts is effective at reducing root-galling among susceptible vegetable crops (16,36). However, the wide host range of *M. incognita* makes development of profitable rotations difficult without the use of resistant crops.

Many commercial tomato cultivars carry a major resistance gene, *Mi*, that confers effective resistance against *M. incognita*, *M. arenaria*, and *M. javanica* (10,40). This resistance was identified in an accession of *Lycopersicon peruvianum*, and the *Mi* gene has been introgressed into cultivated tomato (40). In *Mi*-mediated resistance, a hypersensitive response (HR) occurs re-

Corresponding author: Frank J. Louws
E-mail: frank_louws@ncsu.edu

Mention of a trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product and does not imply its approval to the exclusion of other products or vendors that also may be suitable.

Accepted for publication 7 April 2010.

doi:10.1094/PDIS-94-8-1015
© 2010 The American Phytopathological Society

sulting in programmed cell death and ultimately disruption of the nematode life cycle (40). This resistance mechanism is effective, but can be lost at soil temperatures above 28°C (7,40). Research in Spain showed variable infection and reproduction rates of *M. javanica* in tomato among 10 rootstocks, all of which carried the *Mi* gene (6). Among the rootstocks tested, cultivars Maxifort and Beaufort were susceptible to infection by *M. javanica*. Similar results were seen in greenhouse studies with *M. incognita* (21) on Beaufort rootstock, but fruit yield was not adversely affected by nematode damage, suggesting host tolerance. The results of these studies indicate that *Mi* is not functioning in a manner that is typical of HR-mediated resistance in some interspecific hybrid tomato rootstock cultivars, including Maxifort and Beaufort. These are the most accessible rootstocks to growers in the United States, and Maxifort was recommended for heirloom tomato production in a recent study (32). The ability of these rootstocks and others at reducing infection and crop losses by RKN in naturally infested soils in the United States is unknown.

This report determined the relevance of grafting as a viable tactic for disease control and yield benefits in organic and conventional tomato production systems in North Carolina. There were three primary objectives: (i) to evaluate the utility of three rootstock hybrid cultivars, Beaufort, Maxifort, and Big Power, to reduce the incidence of SB caused by *S. rolfssii* in naturally infested soils; (ii) to determine the efficacy of these rootstocks at reducing galling caused by native populations of RKN; and (iii) to ascertain how the deployment of resistant rootstock impacts fruit yield and whether it is a potentially useful integrated pest management (IPM) strategy against SB and RKN on tomato.

MATERIALS AND METHODS

Transplant production and grafting. All grafted and nongrafted tomato transplants were produced at the Southeastern Plant Environment Laboratory located at North Carolina State University (Raleigh, NC; <http://www.ncsu.edu/phytotron/>). Commercially available heirloom cultivars Cherokee Purple (Johnny's Selected Seeds, Winslow, ME) and German Johnson (Totally Tomatoes, Randolph, WI) were used as the scion cultivars for rootstock treatments and for nongrafted and self-grafted controls. These open-pollinated cultivars are used regionally for fresh-market production, and no known resistance to SB or RKN has been reported. Cherokee Purple and German Johnson were used at the Alamance and Sampson county locations, respectively.

Commercially available rootstock cultivars Big Power (Rijk Zwaan Seeds, De Lier, The Netherlands), Beaufort (De

Ruiter Seeds, Bergschenhoek, The Netherlands), and Maxifort (De Ruiter Seeds) were used as rootstock treatments. These interspecific rootstock hybrid cultivars are typically utilized for tunnel and greenhouse production throughout the United States, Canada, Northern Europe, and the Mediterranean. All three rootstocks are *S. lycopersicum* L. × *S. habrochaites* (S. Knapp & D.M. Spooner), and are *Mi/Mi* homozygous resistant at the *Mi* locus (6).

In all trials, a self-grafted treatment was included where the scion variety was grafted onto its original root system to account for any grafting/healing effects. The Japanese tube grafting technique was carried out for all grafted plants (31). Rootstock and scion seedling stems were severed and held together using a silicon clip. Once grafted, the plants were immediately moved into a "healing chamber" where humidity and light conditions were manipulated to promote graft union formation (31). Once grafting and subsequent healing had occurred, grafted and nongrafted tomato plants were transplanted to 10-cm pots and allowed to grow for 10 to 14 days in the greenhouse before being planted into field plots.

Alamance County trials. Field trials were conducted in 2007 and 2008 at a commercial organic farm located in Alamance County, NC (35.875959 N, 79.267759 W). Soil type consists of Efland silt loam (pH = 6.0). Organic practices have been employed for more than 20 years at this site. Heirloom tomatoes are rotated with cut flowers, non-solanaceous vegetables, and cover crops in 3-year intervals. Research trials were conducted within heirloom tomato production blocks in each year and located in multi-bay high tunnels. At this location, symptoms typical of RKN had not been seen in prior years, but SB was observed previously within pepper and tomato production blocks.

The grafting treatments included Cherokee Purple grafted onto Beaufort and Maxifort rootstocks in addition to nongrafted and self-grafted Cherokee Purple. In both years, a randomized complete block design was utilized with four replications, and planted within two 30-m rows (two blocks per row). The four grafting treatments were randomly assigned to 3.8-m plots within each of the four blocks; treatments were rerandomized in 2008. Seven plants were located within each plot, and cultural methods were consistent with on-farm heirloom tomato production. Plants were spaced at 46 cm within the row, and rows were 1.52 m apart. Preplant nitrogen was supplied through cover crop incorporation and supplemental feather-meal applications of 55 and 111 kg N/ha in 2007 and 2008, respectively, and water was provided by drip irrigation. Fabric mulch was used to suppress weeds, and a vertical trellis system was built using steel posts and 1.3-m-wide wire mesh with 10 ×

10 cm spacing. Vines were trained to the trellis with vinyl tape.

The Alamance County experiments were initiated on 5 May 2007 and 25 April 2008. In 2007, harvesting was carried out on 26 and 29 June; 3, 9, 12, 17, 19, 23, 26, and 30 July; 2, 6, 14, 16, 20, 23, 27, and 30 August; and 3, 6, 10, and 13 September. In 2008, harvesting was conducted on 23, 26, and 30 June; 3, 8, 11, 14, 18, 21, 25, and 29 July; 1, 7, 12, 15, 18, 21, 25, and 28 August; and 1 and 4 September. All tomato fruit were harvested and graded as marketable or nonmarketable based upon on-farm standards, and fruit weight and number were recorded for each grade.

Sampson County trials. Field trials were conducted in 2007 and 2008 at the Horticultural Crops Research Station, located in Sampson County, NC (35.023244 N, 78.278146 W). The research trials were carried out in a field that is naturally infested with a native population of southern RKN (*M. incognita*). Soil type consisted of Norfolk loamy sand (pH = 5.7). This trial was treated in a conventional manner, and typical herbicide and insecticide applications were administered.

The grafting treatments included German Johnson grafted onto Big Power, Beaufort, and Maxifort rootstocks, as well as non- and self-grafted controls. In addition, a fumigant treatment was included whereby nongrafted plants were grown in plots that had been fumigated with 1,3-dichloropropene, a broad-spectrum nematocide (8). In both years, a randomized complete block design with four replications was utilized, and treatments were rerandomized in 2008. The six treatments were randomly assigned to 7.6-m plots within each of the four 56.1-m rows that served as blocks. An unplanted 1.5-m buffer was included between all plots to reduce interplot interference between fumigated and nonfumigated treatments. Cultural methods were consistent with open-field tomato production in the region. A raised-bed plasticulture system was employed using white plastic mulch and drip irrigation. Raised beds were 15 cm high and 75 cm wide. In-row spacing was 46 cm in 2007 and 61 cm in 2008. Stake-and-weave cultural management was used to train the plants vertically to 2-m metal posts located between every other plant.

Raised beds were formed and 1,3-dichloropropene was applied to fumigated treatments on 24 May and 16 April in 2007 and 2008, respectively. Telone II (Dow AgroSciences, LLC, Indianapolis, IN) was applied at 136 kg/ha (broadcast) through two 20-cm shank injectors, spread 30 cm apart, as the beds were formed and covered with white plastic mulch. Grafted and nongrafted transplants were set in the field on 22 June 2007 and 15 May 2008. In 2007 and 2008, 14 and 12 plants of each treatment were centrally located within the 7.6-m plot, respectively. Fruit was har-

vested on 29 August and 5, 12, and 19 September in 2007; and on 6, 12, 20, and 26 August in 2008. Final fruit harvest included all fruit larger than 5 cm. All fruit were harvested and graded as marketable or nonmarketable based upon the appearance of fruit shriveling, sunscald, blossom-end rot, insect damage, or severe fruit cracking.

Disease assessment. SB disease ratings were performed nondestructively at weekly intervals. Disease incidence was recorded based on the presence of typical signs and symptoms of SB. Tomato plants that have been infected and killed by *S. rolf sii* undergo rapid and permanent wilt, and mycelium and sclerotia are visible on the stem. During the course of the season, stems of plants that had been killed by *S. rolf sii* were removed and incubated to verify the presence of viable sclerotia, and any remaining fruit was harvested and recorded.

Because the Sampson County location had a history of RKN infestation, root-knot nematode severity was assessed through biweekly destructive sampling and examination of the roots for galling and other damage caused by *Meloidogyne* spp. Destructive sampling was carried out on 25 July; 8 and 22 August; 5 and 19 September; and 1 October in 2007 and on 17 June; 1, 15, and 29 July; and 12 and 25 September in 2008. After the upper 30 cm of roots were removed from the soil, the galling index was rated using the system outlined by Zeck (41) on a 0 to 10 scale (0 = no observable galls, 1 = very few small galls, 2 = numerous small galls, 3 = numerous small galls of which some are grown together, 4 = numerous small and some big galls, 5 = 25% of roots severely galled, 6 = 50% of roots severely galled, 7 = 75% of roots severely galled, 8 = no healthy roots but plant is still green, 9 = roots rotting and plant dying, 10 = plant and roots dead). In Alamance County, three root samples from all plots were visually examined for RKN damage at the end of the growing season in both years.

In Sampson County, soil samples were taken at first harvest and final harvest in both years to observe root-knot nematode soil populations. Soil was gathered using a nematode-specific sampling soil core that allows for 8 to 16 soil cores to be stored in the upper column of the sampler. Approximately 1 liter of soil per plot was systematically sampled from the root zone by removing cores from the upper 10 cm of soil that were within 15 cm of the main stem. Bulk 1-liter soil samples from each plot were thoroughly mixed, and 500 cm³ of soil was analyzed by the Nematode Assay Section of the North Carolina Department of Agriculture and Consumer and Agronomic Services (Raleigh, NC; <http://www.ncagr.gov/agronomi/nemhome.htm>) for the presence of RKN juveniles. Plant parasitic nematodes were extracted from

samples by a combination of elutriation (5) and centrifugation (15), and nematodes were identified by morphology (12). Soil was sampled from the field on 29 August and 19 September in 2007; and on 6 and 26 August in 2008. A 1-liter soil sample was also systematically taken from the entire field 6 August 2008 and submitted for identification of the dominant species within the field. Species identification was carried out through perineal patterns and host-differentiation (12). Sequence of the ITS1 region of DNA extracted from RKN recovered was also included in RKN species analysis.

Statistical analysis. All data were analyzed using analysis of variance (PlotIt, Scientific Programming Enterprises, Haslett, MI), and where significant treatment effects were identified, a mean separation test was carried out using an *F* protected least significant difference (LSD) test. Data from the two locations were treated in a similar manner, but were analyzed independently. Data collected in 2007 and 2008 were combined and analyzed using split-plot factorial ANOVA whereby main plots included grafting treatments and subplots represent the 2 years at a given location. The occurrence of statistical interaction between grafting and year determined the presentation of pooled data. LSD tests were carried out at *P* = 0.05 and *P* = 0.01. Total (both marketable and culled fruit) and marketable yield were analyzed in a similar manner and were calculated to represent tonnes/hectare (t/ha) in the tables. In the Sampson County trial, fumigation was utilized to compare grafting with a registered nematicidal fu-

migant and not included as a factorial element. Therefore, it was analyzed as a grafting effect treatment in the full grafting*year split-plot design. Disease progress curves for SB incidence and RKN galling index over time were plotted. An area under the disease progress curve (AUDPC) value was calculated (35) and analyzed using split-plot factorial ANOVA. Root knot nematode populations were log transformed ($\log_{10}(1 + x)$) for analysis, and separated means were back-transformed for presentation of the data.

RESULTS

SB (caused by *S. rolf sii*) was observed at both locations and during both years of the research trials. The mean incidence of SB among non- and self-grafted treatments ranged from 27 to 79% at the end of the growing season. Symptoms typical of RKN were seen in both years of the study in Sampson County, and the final RKN galling index of the non- and self-grafted plants was 9.9 and 9.3, respectively. The results of the differential host test and perineal pattern analysis indicated that the dominant species in the field was *M. incognita* (race 1). ITS1 DNA sequence from the nematodes in the field showed 100% similarity to *M. incognita* (AY438556.1), but also had high similarity to other *Meloidogyne* spp. (AY438554.1, AY438555.1, AY858795.1) (BLASTN Suite, National Center for Biotechnology Information, Bethesda, MD). No damage from RKN was observed at the Alamance County location in either year. A summary of the resulting *P* values for each split-plot ANOVA are shown in Table 1. In all cases,

Table 1. Effects of year and grafting for Alamance and Sampson county tomato trials

County	Parameter	<i>P</i> values ^w		
		Year	Grafting	Year*grafting
Alamance	Southern blight AUDPC ^x	0.015	<0.001	0.095
	Total yield (t/ha)	0.016	<0.001	0.250
	Total fruit number	0.026	<0.001	0.406
	Total fruit size	0.012	<0.001	
	Marketable yield (t/ha)	0.008	<0.001	0.117
	Marketable fruit number	0.017	<0.001	0.150
	Marketable fruit size	0.004	<0.001	
	Percent marketable (by weight)	0.020		
	Percent marketable (by number)	0.116		
Sampson	Southern blight AUDPC	0.247	<0.001	0.101
	Root-knot AUDPC		<0.001	
	Root-knot pop. (first harvest) ^y	0.080	<0.001	0.402
	Root-knot pop. (final harvest) ^z	0.010	<0.001	
	Total yield (t/ha)	0.075	<0.001	
	Total fruit number	0.170	0.013	
	Total fruit size	0.019	<0.001	0.346
	Marketable yield (t/ha)	0.208	<0.001	
	Marketable fruit number		<0.001	
	Marketable fruit size	0.003	0.018	
	Percent marketable (by weight)	0.170	<0.001	
	Percent marketable (by number)	0.161	<0.001	

^w Data from 2007 and 2008 were pooled and analyzed using split-plot ANOVA. Blank spaces denote *F* < 1.

^x Calculated area under the disease progress curve (AUDPC) values.

^y Root-knot nematode soil populations sampled on first day of fruit harvest.

^z Root-knot nematode soil populations sampled on last day of fruit harvest.

grafting*year interactions were not significant at $P = 0.05$. Therefore, data from 2007 and 2008 for each of the locations were combined and used for presentation.

Alamance County. The SB epidemic began among non- and self-grafted treatments 70 days after planting (DAP), and final disease incidence for nongrafted and self-grafted plants was 27 and 39%, respectively (Fig. 1). Total and marketable fruit yields (t/ha) were significantly greater among treatments with Beaufort and Maxifort rootstocks compared to nongrafted and self-grafted treatments ($P = 0.01$, Table 2), and no significant differences in fruit yield were observed between the rootstocks. Total yield increased with the use of rootstock by 36 to 75%, and marketable yield increased by 34 to 79%. Average total and marketable fruit size was significantly larger with Beaufort and Maxifort rootstock ($P = 0.01$, Table 2), and total fruit number was increased by rootstock treatments ($P = 0.01$, Table 2).

Sampson County. SB incidence rapidly increased throughout the non- and self-grafted treatments, and final SB incidence was 79 and 72%, respectively (Fig. 2A). Plants grafted onto Big Power, Beaufort, and Maxifort showed low levels of SB (1 to 5%), and fumigated plots had 51% final disease incidence. The impact of the epidemic over time was significantly lower

Fig. 1. Mean southern blight incidence on non-grafted and self-grafted tomato cultivar Cherokee Purple as well as Cherokee Purple grafted onto rootstock cultivars Beaufort and Maxifort at the Alamance County location in 2007 and 2008.

among rootstock treatments, as indicated by the AUDPC values ($P = 0.01$, Fig. 2B). Fumigation with Telone II reduced SB as compared to nongrafted plants, but had significantly higher AUDPC values than the rootstock treatments ($P = 0.01$, Fig. 2B).

Damage from RKN was observed in both years (Fig. 3), and non- and self-grafted treatments had severe galling (RKN index >5) 61 DAP (Fig. 3A). Fumigated treatments had no galling at 61 DAP and the RKN index was 7.1 by final fruit harvest. Beaufort and Maxifort rootstocks showed moderate galling throughout the season, and the final RKN index was 2.8 and 2.9, respectively. The RKN index of Big Power remained at zero until 90 DAP, and the final mean galling index was 0.25 (Fig. 3A). The RKN index AUDPC values showed highly significant separation of the means ($P = 0.01$, Fig. 3B). Fumigation reduced the AUDPC values as compared to non- and self-grafted controls. However, Maxifort and Beaufort rootstock treatments showed lower AUDPC values compared to nongrafted, self-grafted, and fumigated treatments, and Big Power AUDPC values were even less than Maxifort ($P = 0.01$, Fig. 3B).

At first harvest, extremely high populations of RKN (>8,000 nematodes/500 cm³ soil) were found among nongrafted and self-grafted treatments (Table 3). Fumigation with 1,3-dichloropropene significantly reduced populations at first harvest, but populations were not significantly lower than the controls at the final harvest at $P = 0.01$ (Table 3) or $P = 0.05$ (data not shown). Beaufort and Maxifort rootstock treatments significantly reduced populations as compared to non- and self-grafted treatments at first harvest, but were statistically similar to nongrafted, self-grafted, and fumigated treatments at final harvest. Big Power had the lowest population at first harvest, and was the only treatment that had significantly reduced populations at final fruit harvest ($P = 0.01$, Table 3).

Total and marketable yields were greater in Big Power, Beaufort, and Maxifort rootstock treatments than in nongrafted, self-grafted, and fumigated treatments ($P = 0.05$, Table 4). Fumigation increased total and marketable yields by 55 and 75% compared to nongrafted treatments, but

this difference was not statistically significant ($P = 0.05$, Table 4). Beaufort showed the highest yield of all treatments but was not significantly different compared to the other two rootstock treatments ($P = 0.05$, Table 4). Total and marketable fruit yields were increased among rootstock treatments by 70 to 173% and 132 to 248%, respectively, compared to non- and self-grafted treatments.

Average total fruit size was highest among the three rootstock treatments ($P = 0.05$, Table 4), and Maxifort had the largest total fruit size. Big Power had the smallest total fruit size of the rootstock treatments, but was statistically similar to Beaufort and Maxifort, and was larger than the nongrafted, self-grafted, and fumigated treatments ($P = 0.05$, Table 4). Fruit number was also impacted by rootstock, and Beaufort had the highest fruit number but was statistically similar to Big Power and Maxifort ($P = 0.05$, Table 4).

DISCUSSION

Grafting with resistant rootstocks could play an important role in management of *S. rolfii* and *M. incognita* in U.S. high tunnel and field tomato production. This technology can be quickly deployed without causing significant changes in farming operations and can aid in the development of successful crop rotation systems. Our results demonstrated that SB can be effectively managed through the use of the interspecific rootstocks. In the Alamance County trials, these rootstocks provided complete resistance to SB in both years. In Sampson County, SB was particularly severe, and Big Power, Beaufort, and Maxifort showed exceptionally high levels of disease resistance to SB. At this location, final disease incidence of the rootstocks ranged from 1 to 5%, suggesting that host resistance among these rootstocks is quantitative in nature.

S. rolfii produces large amounts of oxalic acid and other cell-wall-degrading enzymes as it infects its host, and plant tissues tolerant of these enzymes may be resistant to hyphal invasion (30). Resistance to SB in tomato breeding lines was attributed to precocious development of secondary tissue on the basal mainstem (19). In other crops, resistance to infection by *S. rolfii* is related to calcium concen-

Table 2. Combined^x yield and marketability of grafted and nongrafted tomato fruit harvested from the cultivar Cherokee Purple at Alamance County^y

	Marketable fruit yield			Total fruit yield			Marketability (%)	
	(t/ha)	Size (g)	No. (10 ³ /ha)	(t/ha)	Size (g)	No. (10 ³ /ha)	Weight	Number
Nongrafted	56.1 a	253 a	221.3 ab	75.6 a	244 a	309.9 a	72.8 a	70.1 a
Self-grafted	45.5 a	248 a	183.1 a	64.7 a	238 a	272.4 a	69.6 a	66.8 a
Beaufort ^z	75.0 b	306 b	245.4 bc	102.7 b	289 b	355.3 b	72.4 a	68.8 a
Maxifort ^z	81.4 b	300 b	271.6 c	112.9 b	291 b	388.0 b	71.3 a	69.4 a

^x Pooled yield data from 2007 and 2008. Values followed by the same letter are not significantly different according to a protected least significant difference test ($P = 0.01$).

^y Under moderate disease pressure from southern blight.

^z Interspecific tomato rootstocks grafted with Cherokee Purple scion.

tration within host tissue (30), and this relationship has been suggested in tomato (24,39). Interspecific rootstocks play an important role in macro- and micronutrient uptake and metabolism (33). However, many studies that address this area utilize leaf tissue analysis, distal from the infection court of *S. rolfssii*. One report showed that the rootstock Beaufort elevated calcium in the epigeous biomass (stem, leaf, and fruit tissues) of grafted tomato plants (20). A productive area for future research would be to identify the genetic and mechanistic sources of resistance to SB seen in this study.

In the Sampson County trials, the severity of SB among the non- and self-grafted plants could have been increased by RKN damage. 1,3-Dichloropropene showed no efficacy against *S. rolfssii* when applied through drip application (23). In contrast, the shank application utilized in our study reduced SB AUDPC values compared to nongrafted controls. The difference seen between our study and others (23) may have been the result of decreased RKN damage, and therefore reduced susceptibil-

ity to SB. There is conflicting evidence in the literature on whether RKN damage can predispose tomato to increased SB susceptibility (23,28,30). However, regardless of whether predisposition is occurring, Beaufort and Maxifort sustained moderately high levels of damage from RKN and these rootstock cultivars maintained effective resistance to SB. To our knowledge, this report represents the first evidence of effective use of host resistance against SB in tomato among commercially available cultivars, and grafting technology provides a unique opportunity to quickly deploy this resistance into established production systems.

At the Sampson County location, grafting with resistant rootstocks reduced galling and reproduction by RKN in naturally infested soils. Big Power had higher levels of resistance to RKN than Beaufort and Maxifort throughout the growing season, and the results of this study suggest that this rootstock is more effective at reducing RKN populations in infested soils than fumigation. Maxifort and Beaufort dis-

played partial resistance to RKN compared to the non- and self-grafted controls as indicated by the AUDPC. Big Power had high resistance in soils naturally infested with *M. javanica* (6), and our study showed similar results with *M. incognita*. The low RKN index and corresponding AUDPC values displayed by plants grafted with Big Power rootstock indicate that resistance in this rootstock is effective at reducing infection and establishment of feeding sites. There was slight galling seen on Big Power at the end of the season, but this loss-of-function and its relation to heat stability is not clear.

In the rootstocks utilized for this study, the *Mi* gene was previously verified by REX-1 and Mi23 molecular markers (6). Recent studies indicate that host resistance in interspecific rootstocks containing *Mi* have variable efficacy at reducing infection and reproduction by *M. javanica* (6) and *M. incognita* (21). Our results found that *M. incognita* can infect and reproduce on Beaufort and Maxifort rootstocks. Similarly to the non- and self-grafted plants, galling was first observed on Maxifort and Beaufort rootstocks 47 DAP, suggesting that heat stability did not play a significant role in the efficacy of *Mi*. Other studies (6) also indicate that susceptibility of these rootstocks to RKN is not related to soil temperature. However, due to the unexpected results in regards to RKN shown by Beaufort and Maxifort in this study and others, it appears that further field evaluations of interspecific rootstocks in naturally infested soils are needed to provide rootstock recommendations in the southeastern United States. In this study, the heirloom cultivar German Johnson was utilized as a susceptible control. Future studies that evaluate the efficacy of *Mi* in rootstocks would benefit from a nongrafted or rootstock treatment that utilizes a com-

Fig. 2. A, Mean southern blight incidence and B, area under the disease progress curve (AUDPC) of nongrafted and self-grafted tomato cultivar German Johnson as well as German Johnson grafted onto rootstock cultivars Big Power, Beaufort, and Maxifort and nongrafted plants grown in soil fumigated with Telone II (1,3-dichloropropene). Data were collected from the Sampson County trials in 2007 and 2008, and AUDPC data were analyzed by separation of the means with a protected least significant difference test ($P = 0.01$).

Fig. 3. A, Mean root-knot nematode (RKN) galling index and B, area under the disease progress curve (AUDPC) values of nongrafted and self-grafted tomato cultivar German Johnson as well as German Johnson grafted onto rootstock cultivars Big Power, Beaufort, and Maxifort and nongrafted plants grown in soil fumigated with Telone II (1,3-dichloropropene). Data were collected from the Sampson County trials in 2007 and 2008, and AUDPC data were analyzed by separation of the means with a protected least significant difference test ($P = 0.01$).

Table 3. Root-knot nematode soil population^u at Sampson County^v

	First harvest ^w	Final harvest ^x
Nongrafted	8,357 d	1,964 b
Self-grafted	8,751 d	1,228 b
Telone II ^y	379 b	1,260 b
Big Power ^z	77 a	40 a
Beaufort ^z	2,680 c	2,542 b
Maxifort ^z	3,091 c	1,251 b

^u Values represent numbers of root-knot nematode juveniles per 500 cm³ soil.

^v Pooled data from 2007 and 2008. Values followed by the same letter are not significantly different according to a protected least significant difference test ($P = 0.01$).

^w Root-knot nematode soil populations sampled on the first day of fruit harvest.

^x Root-knot nematode soil populations sampled on the last day of fruit harvest.

^y Nongrafted tomato cultivar German Johnson grown in plots fumigated with Telone II (1,3-dichloropropene).

^z Interspecific tomato rootstocks grafted with German Johnson scion.

mercial hybrid cultivar containing the functional *Mi* gene.

At the Sampson County location, all three rootstocks maintained fruit production under exceptionally high levels of disease pressure from RKN and SB. Beaufort and Maxifort had the highest yields, even though RKN populations were moderately high at first harvest. In previous greenhouse studies with Beaufort (21), the authors suggested that this rootstock confers tolerance to RKN, and our results were similar. However, because SB and RKN were both present at this location, it is difficult to determine if RKN tolerance is being conferred by Beaufort and Maxifort rootstocks. Similarly, the lack of statistical separation for fruit yield between fumigated and nonfumigated plots could be the result of the combined impact of SB and the rapid increase in RKN damage seen late in the season.

Fruit marketability was higher among the three rootstocks in the Sampson County trials. Fruit marketability can be affected by SB as severe wilting leads to fruit shriveling and sunscald. Although the specific parameters of nonmarketable fruit were not recorded, resistance to SB among rootstock treatments may have increased the likelihood of marketable fruit in the Sampson County trials. Although disease pressure was less severe, fruit yield of grafted plants was higher at the Alamance County location as well. Rootstocks may also provide elevated yield through added vigor and plant growth (17,33), but recent trials in North Carolina with German Johnson did not show consistent yield effects of grafting with Maxifort rootstock under little or no disease pressure (32).

Host resistance is a preventative IPM strategy that is used to avoid disease outbreaks in the field (14). In this study, Big Power was more effective than fumigation at reducing RKN populations at the end of the growing season. This finding may be important for growers who double-crop or follow tomatoes with susceptible cash crops. Resistant pepper cultivars have been used to manage root-knot nematode damage in susceptible cucurbit crops grown in double-cropping production systems (37). Our data suggest that grafting with Big

Power offers flexibility as growers develop profitable rotation programs. Similarly, sclerotia formation by *S. rolfii* positively correlates with SB disease incidence and severity in following years (30).

Grafting will be an important component for U.S. tomato growers that are seeking nonchemical strategies to manage soil-borne diseases. The resistance to SB seen here is an example of how grafting with interspecific rootstocks provides a platform for host resistance deployment where major resistance genes are not available for commercial cultivars. Quantitative resistance traits are often widely known among wild species, but their deployment into commercial cultivars can be problematic. Resistance to SB was first identified in 1959 (24), and successful incorporation of resistance into commercial cultivars for fresh-market production has not been accomplished to date (22,42). Similarly, alternative sources of resistance to *Meloidogyne* spp. have been identified in wild accessions of tomato (i.e., heat tolerance and resistance to *M. hapla*) even though their contribution to cultivated tomato production has been insignificant thus far (2,40). The benefit of grafting with interspecific rootstock is that breeding programs can readily utilize host resistance from wild plant species without penalizing fruit production, and this technology may be a vital component in an IPM program that seeks to reduce damage caused by soilborne pathogens without the use of chemical fumigants.

ACKNOWLEDGMENTS

We sincerely thank the NCSU Phytotron staff as well as Jim Driver, Mike Carnes, Amanda McWhirt, Ryan Faulk, and Seth Avis for technical assistance, and H. D. Shew and E. L. Davis for their excellent comments. Special thanks to Weimin Ye and the NCDA Nematode Assay Section as well as our on-farm collaborators: Alex and Betsy Hitt, and the NCDA staff at the Horticultural Crops Research Station. Rootstock seed donated by De Ruiter Seeds and Rijk Zwaan Seeds. Funding provided by Southern Region SARE LS06-193 and USDA-NIFA 2007-51106-03794.

LITERATURE CITED

1. Abdelhaq, H. 2004. Integrated Production and Protection in Greenhouse Crops. Pages 95-106 in: Institut Agronomique et Veterinaire Hassan II.

2. Ammati, M., Thomason, I. J., and McKinney, H. E. 1986. Retention of resistance to *Meloidogyne incognita* in *Lycopersicon* genotypes at high soil temperature. *J. Nematol.* 18:491-495.
3. Barker, K. R. 2003. Perspectives on plant and soil nematology. *Annu. Rev. Phytopathol.* 41:1-25.
4. Besri, M. 2001. New developments of alternatives to methyl bromide for the control of tomato soilborne pathogens in covered cultivation in a developing country, Morocco. Pages 9.1-9.3 in: 2001 Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions San Diego, CA.
5. Byrd, D. W. J., Barker, K. R., Ferris, H., Nusbbaum, C. J., Griffin, W. E., and Small, R. H. 1976. Two semi-automatic elutriators for extracting nematodes and certain fungi from soil. *J. Nematol.* 8:206-212.
6. Cortada, L., Sorribas, F. J., Omat, C., Kaloshian, I., and Verdejo-Lucas, S. 2008. Variability in infection and reproduction of *Meloidogyne javanica* on tomato rootstocks with the *Mi* resistance gene. *Plant Pathol.* 57:1125-1135.
7. Dropkin, V. H. 1969. Necrotic reaction of tomatoes and other hosts resistant to *Meloidogyne* - reversal by temperature. *Phytopathology* 59:1632-1637.
8. Duniway, J. M. 2002. Status of chemical alternatives to methyl bromide for pre-plant fumigation of soil. *Phytopathology* 92:1337-1343.
9. Farr, D. F., Rossman, A. Y., Palm, M. E., and McCray, E. B. 2006. Fungal Databases. Systematic Botany & Mycology Laboratory, U.S. Dep. Agric. Agric. Res. Serv.
10. Gilbert, J. C., and McGuire, D. C. 1956. Inheritance of resistance to several root-knot from *Meloidogyne incognita* in commercial type tomatoes. *Proc. Am. Soc. Hortic. Sci.* 38:573-575.
11. Grimault, V., and Prior, P. 1994. Grafting tomato cultivars resistant or susceptible to bacterial wilt - analysis of resistance mechanisms. *J. Phytopathol.-Phytopathol. Z.* 141:330-334.
12. Hartman, K. M., and Sasser, J. N. 1985. Identification of *Meloidogyne* species on the basis of differential host test and perineal pattern morphology. In: An Advanced Treatise on Meloidogyne. K. R. Barker, C. C. Carter, and J. N. Sasser, eds. North Carolina State University Graphics, Raleigh, NC.
13. Hutchinson, C. M., McGiffen, M. E., Jr., Ohr, H. D., Sims, J. J., and Becker, J. O. 1999. Evaluation of methyl iodide as a soil fumigant for root-knot nematode control in carrot production. *Plant Dis.* 83:33-36.
14. Jacobsen, B. J. 1997. Role of plant pathology in integrated pest management. *Annu. Rev. Phytopathol.* 35:373-391.
15. Jenkins, W. R. 1964. A rapid centrifugal-floatation technique for separating nematodes from soil. *Plant Dis. Rep.* 48:692.
16. Johnson, A. W., Burton, G. W., Wilson, J. P., and Golden, A. M. 1995. Rotations with

Table 4. Combined^w yield and marketability of grafted and nongrafted tomato fruit harvested from the cultivar German Johnson at Sampson County^x

	Marketable fruit yield			Total fruit yield			Marketability (%)	
	(t/ha)	Size (g)	No. (10 ³ /ha)	(t/ha)	Size (g)	No. (10 ³ /ha)	Weight	Number
Nongrafted	10.5 a	250 a	41.8 a	16.8 a	169 a	99.5 a	60.6 ab	42.3 ab
Self-grafted	12.9 a	256 a	50.3 a	23.0 a	191 a	120.3 ab	53.0 a	40.2 a
Telone II ^y	18.4 a	279 ab	65.9 ab	26.1 a	208 a	125.3 b	65.8 bc	51.7 b
Big Power ^z	30.1 b	283 abc	106.4 c	38.9 b	245 b	159.0 c	78.0 c	67.9 c
Beaufort ^z	36.3 b	295 bc	123.1 c	45.9 b	254 b	180.7 c	79.4 c	68.4 c
Maxifort ^z	29.8 b	318 c	93.8 bc	40.8 b	263 b	155.3 bc	73.2 c	61.6 c

^w Pooled yield data from 2007 and 2008. Values followed by the same letter are not significantly different according to a protected least significant difference test ($P = 0.05$).

^x Under severe disease pressure from southern blight and root-knot nematodes.

^y Nongrafted German Johnson grown in plots fumigated with Telone II (1,3-dichloropropene).

^z Interspecific tomato rootstocks grafted with German Johnson scion.

- coastal bermudagrass and fallow for management of *Meloidogyne incognita* and soilborne fungi on vegetable crops. *J. Nematol.* 27:457-464.
17. Kubota, C., McClure, M. A., Kokalis-Burelle, N., Bausher, M. G., and Roskopf, E. N. 2008. Vegetable grafting: History, use, and current technology status in North America. *HortScience*. 43:1664-1669.
18. Lee, J. M. 2003. Advances in Vegetable Grafting. *Chronica Hortic.* 43:13-19.
19. Leeper, P. W., Phatak, S. C., Bell, D. K., George, B. F., Cox, E. L., Oerther, G. E., and Scully, B. T. 1992. Southern blight-resistant tomato breeding lines - 5635m, 5707m, 5719m, 5737m, 5876m, and 5913m. *HortScience* 27:475-478.
20. Leonardi, C., and Giuffrida, F. 2006. Variation of plant growth and macronutrient uptake in grafted tomatoes and eggplants on three different rootstocks. *Eur. J. Hortic. Sci.* 71:97-101.
21. Lopez-Perez, J. A., Le Strange, M., Kaloshian, I., and Ploeg, A. T. 2006. Differential response of *Mi* gene-resistant tomato rootstocks to root-knot nematodes (*Meloidogyne incognita*). *Crop Prot.* 25:382-388.
22. McCarter, S. 1991. Southern Blight. Pages 22-23 in: *Compendium of Tomato Diseases*. J. B. Jones, J. P. Jones, R. E. Stall, and T. Zitter, eds. American Phytopathological Society, St. Paul, MN.
23. Minuto, A., Gullino, M. L., Lamberti, F., D'Addabbo, T., Tescari, E., Ajwa, H., and Garibaldi, A. 2006. Application of an emulsifiable mixture of 1,3-dichloropropene and chloropicrin against root knot nematodes and soilborne fungi for greenhouse tomatoes in Italy. *Crop Prot.* 25:1244-1252.
24. Mohr, H., and Watkins, G. 1959. The nature of resistance to southern blight in tomato and the influence of nutrition on its expression. *Proc. Am. Soc. Hortic. Sci.* 74:484-493.
25. Munnecke, D. E., Kolbezen, M. J., and Bricker, J. L. 1982. Effects of moisture, chloropicrin, and methyl-bromide singly and in mixtures on sclerotia of *Sclerotium rolfsii* and *Verticillium albo-atrum*. *Phytopathology* 72:1235-1238.
26. Oda, M. 1995. New grafting methods for fruit-bearing vegetables in Japan. *Jpn. Agric. Res. Quart.* 29:187-194.
27. Oda, M. 1999. Grafting of vegetable to improve greenhouse production. Pages 1-11 in: *College of Agriculture*, ed. Osaka Prefecture University, Japan.
28. Overman, A. 1991. Root-knot nematodes. Pages 49-50 in: *Compendium of Tomato Diseases*. J. B. Jones, J. P. Jones, R. E. Stall, and T. Zitter, eds. American Phytopathological Society, St. Paul, MN.
29. Peregrine, W. T. H., and Binahmad, K. 1982. Grafting - A simple technique for overcoming bacterial wilt in tomato. *Trop. Pest Manage.* 28:71-76.
30. Punja, Z. K. 1985. The biology, ecology, and control of *Sclerotium rolfsii*. *Annu. Rev. Phytopathol.* 23:97-127.
31. Rivard, C. L., and Louws, F. J. 2006. Grafting for disease resistance in heirloom tomatoes. *College of Agriculture and Life Sciences*, ed. North Carolina Cooperative Extension Service.
32. Rivard, C. L., and Louws, F. J. 2008. Grafting to manage soilborne diseases in heirloom tomato production. *HortScience* 43:2104-2111.
33. Rivero, R. M., Ruiz, J. M., and Romero, L. 2003. Role of grafting in horticultural plants under stress conditions. *Food. Agric. Environ.* 1:70-74.
34. Sasser, J. N. 1980. Root-knot nematodes - A global menace to crop production. *Plant Dis.* 64:36-41.
35. Shaner, G., and Finney, R. E. 1977. The effect of nitrogen fertilization on the expression of slow mildewing resistance in Knox wheat. *Phytopathology* 67:1051-1056.
36. Sumner, D. R., Minton, N. A., Breneman, T. B., Burton, G. W., and Johnson, A. W. 1999. Root diseases and nematodes in bahiagrass-vegetable rotations. *Plant Dis.* 83:55-59.
37. Thies, J. A., Davis, R. F., Mueller, J. D., Fery, R. L., Langston, D. B., and Miller, G. 2004. Double-cropping cucumbers and squash after resistant bell pepper for root-knot nematode management. *Plant Dis.* 88:589-593.
38. Tikoo, S. K., Mathai, P. J., and Kishan, R. 1979. Successful graft culture of tomato in bacterial wilt sick soils. *Curr. Sci.* 48:259-260.
39. Watkins, G., Mohr, H., and Young, P. 1958. Control of southern blight in tomatoes in northeast Texas. *Phytopathology* 48:346.
40. Williamson, V. M. 1998. Root-knot nematode resistance genes in tomato and their potential for future use. *Annu. Rev. Phytopathol.* 36:277-293.
41. Zeck, W. 1971. A rating scheme for field evaluation of root-knot nematode infestations. *Pflanzenschutz-Nachrichten Bayer* 24:141-144.
42. Zitter, T. A., and McGrath, M. T. 2006. Tomato: Disease resistance table. In: *Vegetable MD Online* Cornell University, Department of Plant Pathology.