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Grafting to Manage Soilborne Diseases in Heirloom Tomato Production

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***Abstract*. Organic heirloom tomato production is limited in the southeastern United States by foliar and soilborne diseases, thermal stress, and weathered soil structure. Heirloom cultivars command a premium market, but tolerance to disease and abiotic stress is often poor. Organic growers need research that supports the advantages of market niches afforded by heirloom tomatoes through the development of integrated systems to manage pests and reduce risks of associated crop losses or low yields. Two major soilborne diseases common in the southeast, bacterial wilt (caused by *Ralstonia solanacearum*) and fusarium wilt (caused by *Fusarium oxysporum* f.sp. *lycopersici*), were effectively managed using susceptible heirloom scions grafted onto resistant rootstock. In naturally infested soil, bacterial wilt incidence for nongrafted 'German Johnson' was 79% and 75% in 2005 and 2006, respectively. 'German Johnson' showed no symptoms of bacterial wilt in either year when grafted onto the resistant genotypes CRA 66 or Hawaii 7996. Fusarium wilt incidence was 46% and 50%, respectively, in nongrafted and self-grafted 'German Johnson' controls. When 'Maxifort' rootstock was grafted with 'German Johnson', no symptoms of fusarium wilt were seen, and plants with 'Robusta' rootstock had an intermediate level of disease (29%). An evaluation of commercially available rootstock was carried out in three separate experiments in diverse organic production systems to determine yield impacts with low disease pressure. 'Maxifort' rootstock significantly increased yield in one location ($P = 0.05$), but 'Maxifort' and 'Robusta' rootstock did not consistently impact yield at the other two locations. Grafting is an effective management tool for organic growers in the southeast United States to reduce risk of crop loss resulting from soilborne diseases and will be a valuable component in an integrated pest management program.**

Profitable heirloom tomato production is a major challenge in the southeast as a result of weathered soil structure, abiotic stress, and diseases caused by foliar and soilborne plant pathogens. Diseases caused by pathogens such as *Fusarium oxysporum* f.sp. *lycopersici*, *Meloidogyne* spp., *Ralstonia solanacearum* (formerly *Pseudomonas solanacearum*), and *Verticillium dahliae* can lead to dramatic decreases in yield and are difficult to manage, especially in intensive organic production systems. These pathogens are particularly challenging for organic heirloom growers as a result of lack of major resistance genes within these cultivars and long rotation intervals required to reduce pathogen populations in the soil. Bacterial wilt (BW), caused by *R. solanacearum*, can be very problematic for all tomato growers as a result of lack of available resistance genes within cultivated tomato (Opena et al., 1990; Walter, 1967; Wang et al., 1998) and widespread distribution in the southeast United States.

Heirloom tomatoes are valued for their prolific coloration and exceptional flavor. U.S. markets for these varieties are consumer-driven, and revenue generated from heirloom production is typically higher than that of standard field-grown, fresh market fruit (Grassbaugh et al., 1999). Many organic heirloom growers have moved their tomato production into high tunnels. These unheated greenhouses, or hoophouses, can provide season extension, enhanced fruit quality, and reduced foliar disease (Lamont et al., 2003; Wittwer and Castilla, 1995), but make long-term rotation difficult. Resultant inoculum upsurge from soilborne pathogens can lead to increased disease pressure. Because of their economic importance and their susceptibility to diseases, heirloom growers need alternative pest management strategies that are effective and durable in an organic production setting.

The cultivation of grafted vegetable plants began in Korea and Japan in the early 20th century when watermelon scion was grafted onto squash rootstock (Rivero et al., 2003b). Currently, 81% and 54% of the vegetable acreage in Korea and Japan, respectively, use grafted plants (Lee, 2003). This cultural technique is most commonly used in intensively managed crops grown in greenhouses or tunnels (Lee et al., 1998). Grafting has become popular more recently in Mediterranean growing regions, where it has been adopted as a major component of an integrated program to manage soilborne pathogens (Besri, 2001; Bletsos, 2005; Giannakou and Karpouzas, 2003; Pavlou et al., 2002). Grafting with tolerant rootstock is also effective at overcoming abiotic stresses such as salinity (Cuartero et al., 2006; Estan et al., 2005; Rivero et al., 2003a), thermal stress (Abdelmageed et al., 2004), and excessive soil moisture (Black et al., 2003).

There are a variety of techniques to graft tomatoes (Lee, 2003). Tube grafting has been adopted as the commercial method for tomato grafting worldwide as a result of high-throughput production capability and typical success rates of 85% to 90% (Oda, 1995). This technique is carried out when the rootstock and scion seedlings are very small, and the two are attached with a small silicon tube or clip (Rivard and Louws, 2006).

Although the use of grafted vegetables is associated with disease reduction and/or abiotic stressors, yield can be increased without the presence of these identified stressors (Ruiz and Romero, 1999; Yetisir and Sari, 2003). Possible mechanisms for increased crop productivity could include increased water and nutrient uptake by vigorous rootstock genotypes. Stomatal conductance is improved in tomato with certain rootstock (Fernandez-Garcia et al., 2002). Similarly, macronutrient uptake such as phosphorus and calcium can be increased by using certain rootstock genotypes (Leonardi and Giuffrida, 2006; Ruiz et al., 1996).

Grafting has been important in Asian tomato production to manage bacterial wilt incidence in solanaceous crops (Peregrine and Binahmad, 1982). CRA 66 is a breeding line that has been identified as a resistant rootstock genotype for grafted tomato production in Germany and India (Grimault et al., 1994; Tikoo et al., 1979). Hawaiian lines (Hawaii 7996 to 7998) have been identified as suitable candidates for resistance to bacterial wilt (Oda, 1999; Tresky and Walz, 1997). In Hawaii 7996, the movement of *R. solanacearum* is limited from the protoxylem into other xylem tissue, and this breeding line has been identified for future breeding programs in Japan (Nakaho et al., 2004). Hawaii 7996 has also been identified as a viable source of resistance for managing bacterial wilt caused by *R. solanacearum* (race 3, biovar 2) (Carmeille et al., 2006). Bacterial wilt caused by *Ralstonia solanacearum* is

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problematic in many southeastern U.S. crops, including tomato, potato, tobacco, and eggplant. Control of BW in tomato is very difficult. Crop rotation with a nonhost crop may provide some control, but this measure is difficult as a result of the wide host range of the pathogen (Adhikari and Basnyat, 1998; Lemaga et al., 2001; Melton and Powell, 1991) and long-term persistence in soils. Furthermore, this soil-inhabiting bacterium can easily move into and recolonize noninfested areas through infested water and soil and through infected plant material (Kelman, 1998). Even in conventional systems, chemical fumigants have had little success because methyl bromide, Telone-C35 (Dow Agrosciences, Indianapolis, IN), and chloropicrin showed no season-long efficacy in controlling this disease in several North Carolina field trials (Driver and Louws, 2002). Genetic resistance could be an effective management option for tomato, but small fruit size is closely linked with resistance to the disease (Opena et al., 1990; Walter, 1967; Wang et al., 1998). Furthermore, the complex diversity of pathogenic *Ralstonia* strains has led to the development of resistant lines that are not durable over diverse geographic regions (Scott, 1996). The world population of *R. solancearum* has been separated into four biovars (Hayward, 1964) and three races (Buddenhagen and Kelman, 1964). In the United States, biovar 1, race 1, is of greatest importance, because this race occurs endemically in the southeastern regions causing southern BW (McCarter, 1991). A worldwide study evaluated 31 tomato genotypes from at least 14 resistance sources in 11 countries (Wang et al., 1998). Of all the evaluated genotypes, Hawaii 7996 had the highest and most consistent survival percentages with a mean of 97% and a range of 85% to 100%.

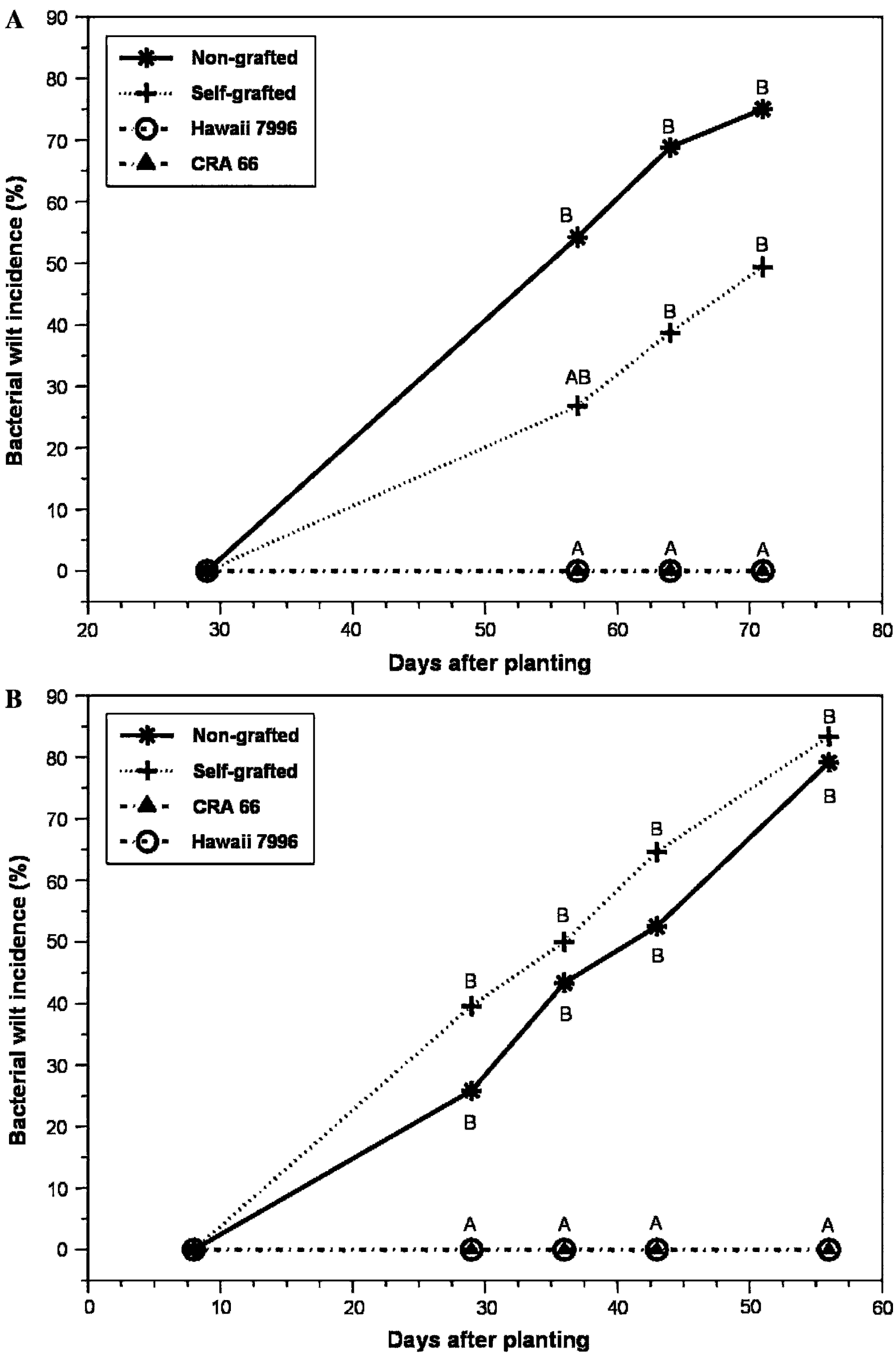

Fig. 1. Bacterial wilt disease incidence of grafted and nongrafted heirloom tomato cv. German Johnson in naturally infested fields during (**A**) 2005 and (**B**) 2006 (Pender County, NC). Disease incidence for both years was analyzed by mean separation with a protected least significant difference ($P = 0.05$) for each observation date.

In the southeastern United States, resistant rootstock genotypes must be evaluated under naturally infested conditions to determine their efficacy for heirloom tomato growers. We hypothesize that grafting heirloom tomato scion with resistant rootstock genotypes will reduce soilborne disease incidence in the field. Therefore, the primary purpose of this study was to evaluate CRA 66 and Hawaii 7996 as rootstock to manage BW in soils naturally infested with *R. solanacearum*. Furthermore, 'Maxifort' and 'Robusta' rootstocks were investigated to manage fusarium wilt. These rootstock-specific hybrids carry major resistance genes to many of the most common soilborne diseases in the United States. Finally, crop productivity effects of 'Robusta' and/or 'Maxifort' were evaluated in three experiments in organic production systems with little disease pressure to determine the usefulness of grafting as an economically sound integrated pest management tool for tomato production in the southeastern United States.

Materials and Methods

Grafting protocol. Grafted transplants were produced in greenhouse facilities on the North Carolina State University campus using the tube grafting technique (Rivard and Louws, 2006). In all experiments, the heirloom cultivar, German Johnson (Totally Tomatoes, Randolph, WI), was used as the nongrafted and self-grafted controls and were the scion for rootstock treatments. 'German Johnson' is a pink, indeterminate, open-pollinated cultivar used for fresh market production throughout central and eastern North Carolina. In the self-grafted treatments, 'German Johnson' scion was grafted onto its original root system and functions as a positive control for the effect of the grafting procedure. CRA 66 (*Solanum lycopersicum*) and Hawaii 7996 (*S. lycopersicum*) were used as rootstock for the BW trials. These are publicly available germplasm used in domestic breeding programs as sources of resistance to BW. 'Maxifort' (De Ruiter Seeds, Bergschenhoek, The Netherlands) and 'Robusta' (Bruinsma Seeds, Enkhuizen, The Netherlands) are rootstock-specific hybrids developed in Europe for the greenhouse tomato industry. Both are available to growers in the United States. Self-grafted and rootstock treatments were grafted 21 d after seeding, and field planting occurred 14 d after grafting.

Bacterial wilt trials. In 2005 and 2006, field trials were conducted in Pender County, NC (long. 37°25′8.18″ N, lat. 72°26′5.36″ W) on a nonorganic farm with a history of endemic populations of *R. solanacearum*. Soil type consisted of a Norfolk sandy loam (pH = 6.0). Cultural management was consistent with typical commercial production in North Carolina. Grafted and nongrafted 'German Johnson' plants were set into a 15-cm high, 75-cm wide raised bed plasticulture system with 1.5-m row spacing and 46-cm in-row spacing. Black plastic mulch and drip irrigation were used, and a stake-and-weave cultural management was used to train the plants vertically. Blended preplant fertilizer (8N–3P–20K) was applied at 672 kg·ha^{-1}, and two $Ca(NO_3)_2$ fertigation supplements were supplied at 67 kg·ha^{-1} on 20 May and 15 June. A randomized complete block design with four replications was used, and each plot contained seven plants.

In 2005, the plot was established on 10 May, and BW incidence was monitored on 8 June, 6 July, 13 July, and 20 July. For each plot, disease incidence was scored based on the number of plants per plot that displayed onset of total wilt. Diagnostic symptoms of BW included a total loss in turgor pressure and no signs of chlorosis or necrosis. Stem segments of wilted plants (2.5 cm) were excised, surface-sterilized, and examined for bacterial streaming from the xylem tissue. Bacteria were collected from the streaming assay and streaked for a single colony-forming unit on Kelman's TZC semiselective medium (Kelman, 1954). Change in pigmentation within bacterial colonies grown on the medium indicated the presence of virulent strains of *R. solanacearum*. Tomato fruit harvesting was carried out on 13, 20, and 27 July and 2 Aug. Fruit were graded as marketable or nonmarketable, and fruit number and weight were recorded. In 2006, grafted and nongrafted transplants were planted on 6 June. Bacterial wilt incidence was monitored as previously described on 20 June, 11 July, 18 July, 25 July, and 7 Aug. Although a severe epidemic of BW had moved throughout the field plot, the late planting time and excessive moisture from two hurricane events led to poor fruit set and yields were not recorded.

Organic crop productivity trials. Three experiments were carried out to investigate crop productivity dynamics associated with using commercially available rootstock in an organic production setting. An on-farm experiment was carried out to determine the efficacy of 'Maxifort' and 'Robusta' rootstock to affect crop productivity for organic heirloom tomato production in Alamance County, NC (long. 35°52′23.62″ N, lat. 79°15′29.31″ W). The same experiment was conducted on a second farm in Orange County, NC (long. 36°13′58.06″ N, lat. 79°11′3.36″ W). A similar and third experiment was repeated at the Center for Environmental Farming Systems (long. 35°24′0.5″ N, lat. 78°01′52.6″ W) except only 'Maxifort' rootstock was used and modified training systems were compared. In all three experiments, field sites were chosen based on their history of organic cropping systems. Furthermore, long-term crop rotations with nonsolanaceous vegetables and cut flowers had been carried out, and diseases caused by soilborne pathogens had not been previously observed as a major concern for tomato at each site.

In the on-farm field trials, the four grafting treatments were nongrafted, self-grafted, 'Maxifort' rootstock, and 'Robusta' rootstock. Each treatment consisted of seven plants per plot and tomato vines were trained to a vertical trellising system. Lower branches were suckered up to the first fruit hand. Disease incidence was monitored and tomato fruit were graded according to grower standards for marketability.

The Alamance County trial was planted on 22 May 2006. Soil type consisted of an Efland silt loam (pH = 6.0). Preplant nitrogen was supplied through a feathermeal application at 111 kg·ha^{-1} N. Plant spacing was set at 46 cm as per grower requirements, and straw mulch was used along with drip irrigation. A vertical trellis system was built using steel posts and

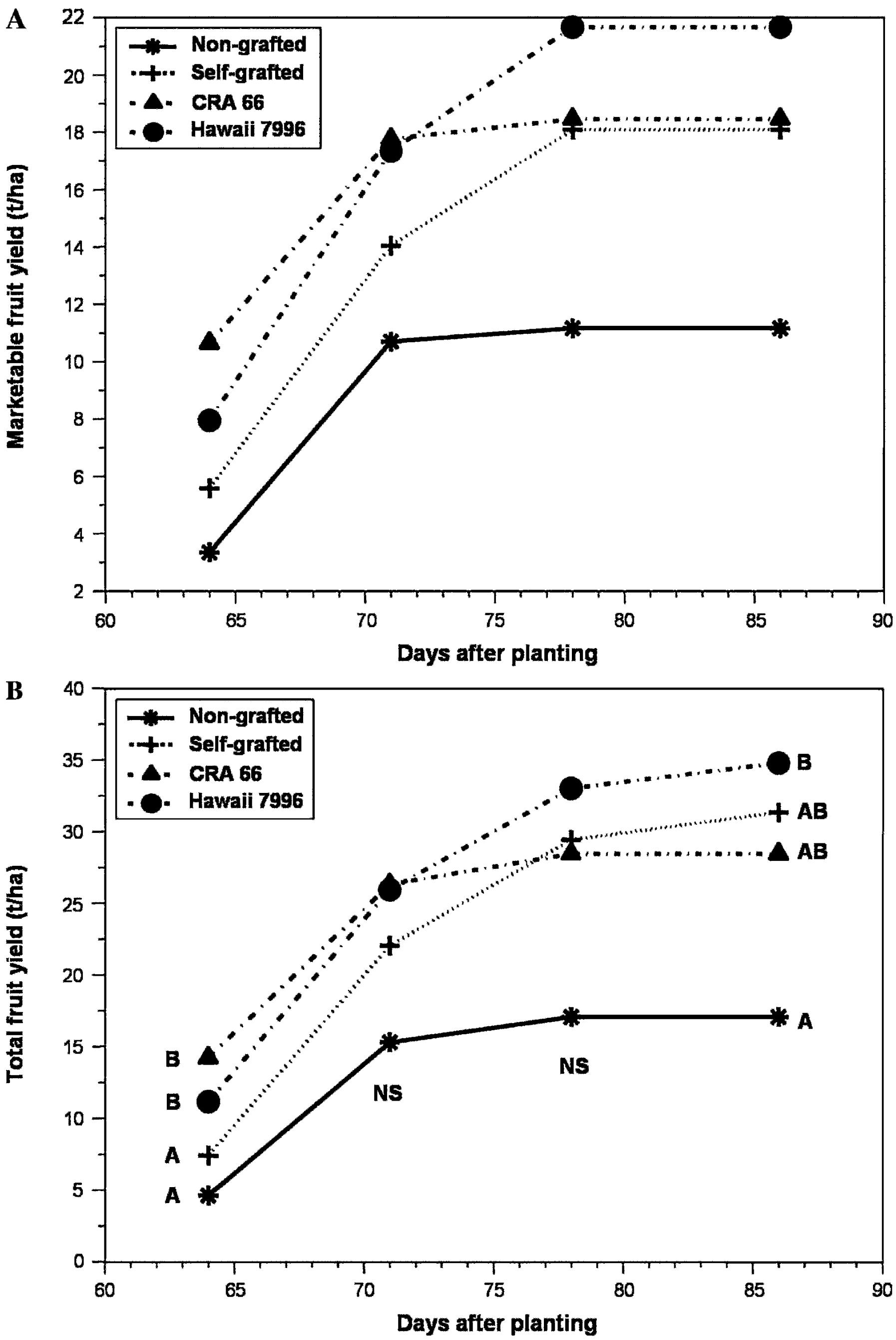

Fig. 2. Cumulative marketable (**A**) and total (**B**) fruit yield of grafted and nongrafted heirloom tomato cv. German Johnson in bacterial wilt-infested fields (Pender County, NC). Results for marketable yield were not significant. First and last cumulative total yield was analyzed by separation of the mean with a protected least significant difference value ($P = 0.05$); other observation dates were nonsignificant (NS).

1.3-m wide wire mesh with 10 cm × 10-cm spacing. Vines were attached to the trellis system with a "fast tapener", which bound the vines onto the metal wire mesh with vinyl tape. Harvesting was carried out on 25 July, 1, 9, 14, 21, 24, and 30 Aug., and 4 and 15 Sept. Fusarium wilt, caused by *F. oxysporum* f.sp. *lycopersici*, occurred unexpectedly throughout the field. Disease incidence was scored as number of symptomatic plants per plot on 29 June, 12 and 21 July, 9 and 21 Aug., and 5 Sept. Symptomatic plants were identified by unilateral foliar chlorosis and wilting and diagnostic discoloration of the xylem tissue. *Fusarium oxysporum* f.sp. *lycopersici* was isolated from symptomatic plants. Stem segments from symptomatic plants were excised (1 cm), surface-sterilized in 10% bleach solution, rinsed with distilled water, and placed on acidified potato dextrose agar.

The Orange County trial was planted on 23 May 2006. Soil type consisted of an Appling sandy loam (pH = 6.8) Preplant fertilizer applications included feathermeal at 111 kg·ha^{-1} N and sulfate of potash at 140 kg·ha^{-1} K. Transplants were set into a raised-bed plasticulture system with drip irrigation. The beds were 15 cm high and 75 cm wide. Plants were spaced 56 cm within the row and 1.5 m between rows. Vines were trained to a single 2-m stake throughout the season with nylon twine. Harvesting was carried out on 21, 28, and 31 July, 4, 7, 10, 13, 17, 22, 25, 28, 30 Aug., and 15 Sept.

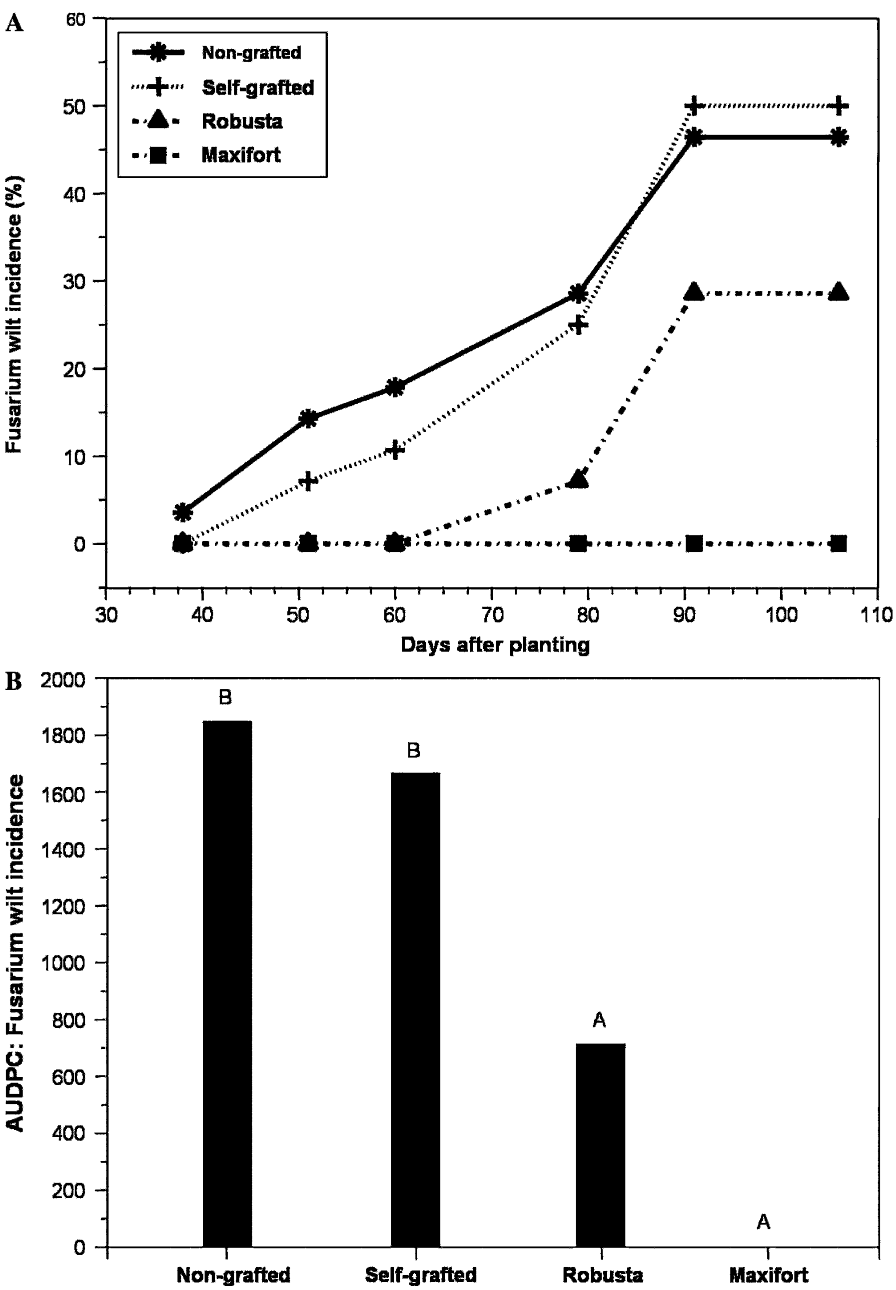

Fig. 3. Disease incidence (**A**) and area under the disease progress curve (AUDPC) (**B**) for fusarium wilt of grafted and nongrafted heirloom tomato cv. German Johnson in naturally infested soils (Alamance County, NC). Results of AUDPC were analyzed by mean separation with a protected least significant difference (P = 0.05).

A split-plot trial was planted within the small farm unit at the Center for Environmental Farming Systems (CEFS) to evaluate grafting with 'Maxifort' rootstock and alternative cultural methods. The small farm unit at CEFS educates local sustainable and organic practices through internship and apprentice programs, farm tours, and extension workshops and has been managed organically since 1996. Soil type consisted of a sandy loam (pH = 6.5). Preplant nitrogen was supplied through the application of soybean meal at 111 Kg·ha^{-1} N. Ten centimeter high, 120-cm wide raised bed plasticulture with 1.8-m row spacing was used. Reflective plastic mulch was used to minimize tomato spotted wilt incidence. Plant training methods included standard field culture, commonly referred to as the California/Florida stake-and-weave method, as well as a twin row culture, whereby a parallel twin row of stakes ran down the length of the bed in a similar fashion to the stake-and-weave system. Main plots consisted of plant training systems and the subplots comprised of the three grafting treatments (nongrafted, self-grafted, and 'Maxifort' rootstock). The four replications were planted into four 60-m rows, and main plots were randomized within each replication and subplots randomized within the main plots. Each plot consisted of six plants with 46-cm spacing between plants. The trial was established on 5 July 2006, and fruit was harvested 12, 21, and 29 Sept. and 9, 13, 20, and 25 Oct.

Statistical analysis. All data were analyzed using analysis of variance (PlotIt; Scientific Programming Enterprises, Haslett, MI), and a mean separation test was carried out by using an F-protected least significant difference (LSD) test. A separate analysis was carried out for each individual observation date, and the results of the LSD test are shown where statistically significant treatment effects occurred. Regression analysis was performed on the disease progress curves to compare the anatomy of the epidemics. Regression analysis was done on linear and Logit-X transformed data to determine the best fit based on residuals and R^2 values. In the Alamance County trial, a disease progress curve was plotted for the fusarium wilt epidemic, and an area under the disease progress curve (AUDPC) value was calculated for each treatment (Shaner and Finney, 1977).

Results

Bacterial wilt trials. In the Pender County trial, high levels of BW incidence occurred in 'German Johnson' for the nongrafted and self-grafted treatments in 2005 and 2006 (Fig. 1). Disease incidence at the end of the season had reached 75% in the nongrafted plots in 2005 and 79% in 2006. The self-grafted plants had an intermediate level of wilt incidence in 2005 of 49% and a high incidence of 83% in 2006. No symptomatic plants were identified when 'German Johnson' was grafted onto the CRA 66 or Hawaii

7996 rootstock in 2005 or 2006 (Fig. 1). Linear regression provided the best fit for the disease progress data with R^2 values of 0.982 to 0.993 (data not shown). Further analysis of the epidemic in grafted and self-grafted plants demonstrated that the slope and intercept of the regression lines were not significantly different within each year. In 2005, marketable yield was unaffected by grafting treatment (Fig. 2A), but cumulative total yield was 104% higher in treatments with Hawaii 7996 rootstock as compared with the nongrafted controls (P = 0.05, Fig. 2B). Furthermore, total yield of treatments with CRA 66 and Hawaii 7996 rootstock were significantly higher than nongrafted treatments (P = 0.05) at first harvest. In 2005, tomato spotted wilt virus (TSWV) occurred. Cumulative TSWV incidence ranged between 20% and 75% across all treatments (data not shown). TSWV incidence was higher in nongrafted treatments as compared with CRA 66 (P = 0.05), but no other treatment effects were seen.

Organic crop productivity trials. In the Alamance County trial, symptoms of fusarium wilt (caused by *F. oxysporum* f.sp. *lycopersici*) were observed 50 d after planting for nongrafted and the self-grafted controls (Fig. 3A). Disease incidence in the nongrafted and self-grafted controls had final incidences of 46% and 50%, respectively (Fig. 3A). No symptoms of fusarium wilt were seen when 'German Johnson' was grafted onto 'Maxifort' rootstock and plants on 'Robusta' rootstock had an intermediate terminal incidence of 29% (Fig. 3A). Over the course of the season, the AUDPC for fusarium wilt showed a significant benefit of grafting with 'Maxifort' and 'Robusta' rootstock compared with nongrafted and self-grafted controls (P = 0.05, Fig. 3B). 'Maxifort' treatments had the lowest AUDPC values, and 'Robusta' had an intermediate value, but there was no significant effect between the two (Fig. 3B). Regression of Logit-X [$\ln(x_0/(1 - x_0))$] transformed data provided the best fit for the disease progress data with R^2 values of 0.940 for nongrafted, 0.904 for self-grafted, and 0.806 for 'Robusta' treatments (data not shown). The slope of the regression line for the controls compared with 'Robusta' was not impacted by grafting treatment. In contrast, the calculated intercept for 'Robusta' was significantly different from the nongrafted and self-grafted controls (P = 0.05). No evidence of disease pressure from soilborne pathogens was seen at the Orange County trial or at the CEFS location.

In the Alamance County trial, crop productivity on 'Robusta' rootstock was greater than all other treatments during early harvests (Fig. 4, P = 0.05). Plants on 'Maxifort' rootstock showed reduced yield as compared with 'Robusta' during this time, but cumulative marketable and total yields were equivalent 91 and 84 d after planting, respectively (P = 0.05, Fig. 4). In the Orange County trial, marketable yield was not impacted (Fig. 5A). No treatment effects were seen for cumulative total yield up to 85 d after planting, but by 90 d after planting, the 'Robusta' rootstock treatment had reduced total fruit weight as compared with the self-grafted and 'Maxifort' treatments (P = 0.05, Fig. 5B).

At the CEFS location, no interactions were observed between training system and grafting treatment. Therefore, only main effects are reported here. No difference in yield was found between the two plant training systems. However, the main effect of grafting with 'Maxifort' rootstock showed significantly increased cumulative fruit yield in comparison with nongrafted or self-grafted controls (P = 0.05, Fig. 6). Cumulative total yield was higher in the 'Maxifort' treatment as compared with the nongrafted control at the fourth harvest and remained significantly elevated through the last three harvests. By the end of the season, plants grafted onto 'Maxifort' rootstock had produced 43% higher total yield than the nongrafted control (P = 0.05, Fig. 6).

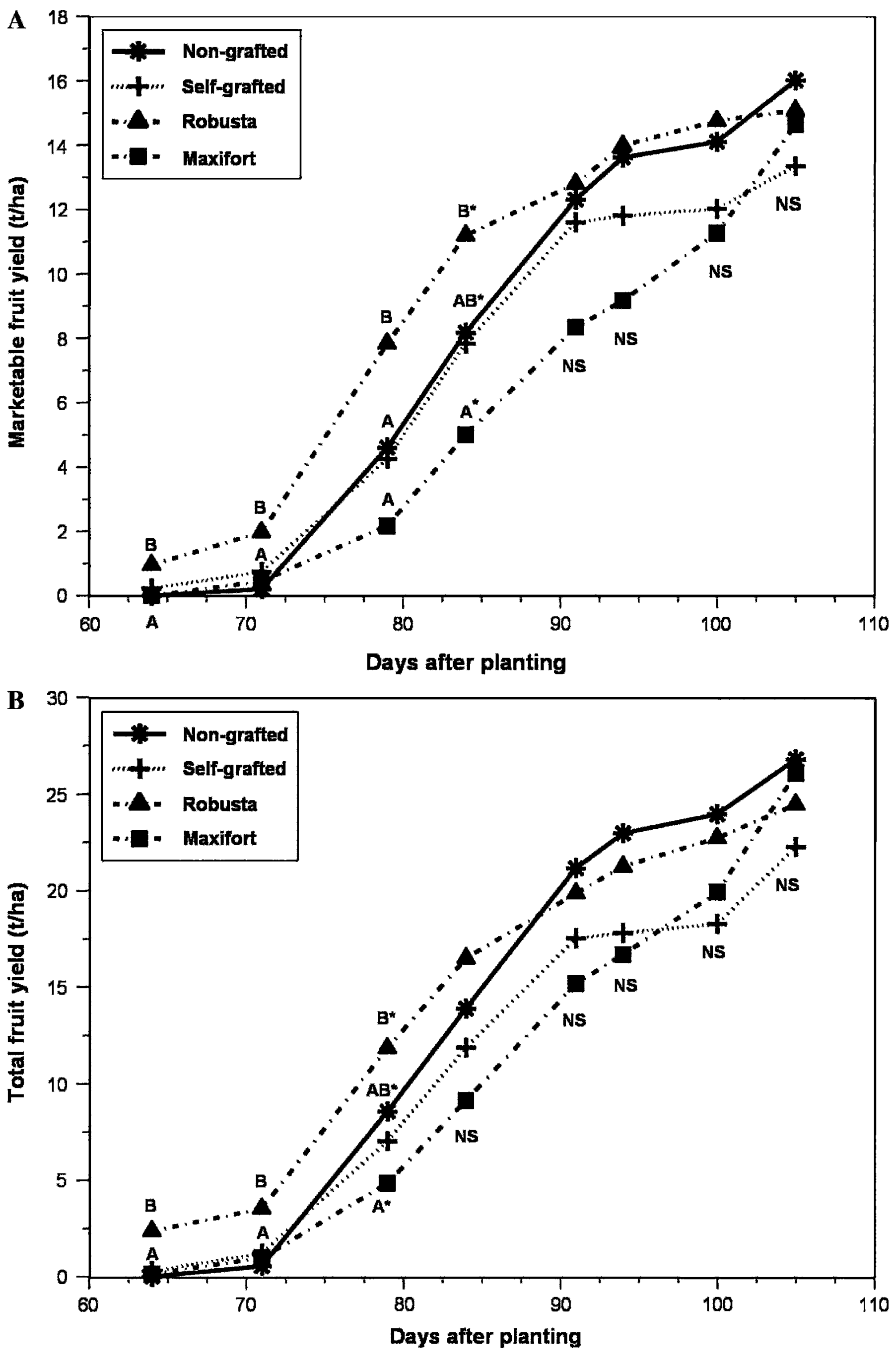

Fig. 4. Cumulative marketable (**A**) and total (**B**) fruit yield of grafted and nongrafted heirloom tomato cv. German Johnson (Alamance County, NC). Cumulative yield was analyzed for each harvest date, and the results of a mean separation test with a protected least significant difference (*P = 0.09, all others P = 0.05) are shown.

Discussion

Grafting has at least two distinct functions. First, resistant rootstock can be deployed to limit risk of crop losses from soilborne pathogens. Second, rootstock hybrid lines could be identified for increased plant vigor and crop yield, even in the absence of disease pressure. In this study, we evaluated both functions. In fields with endemic populations of *R. solanacearum*, CRA 66 and Hawaii 7996 completely controlled BW when used as rootstock for the susceptible heirloom cultivar German Johnson (Fig. 1). To our knowledge, this is the first report of grafting to manage BW of tomato in the United States. Tomato growers in the southeast United States do not have effective tools to manage this serious soilborne pathogen. Even in conventional systems, fumigation is not effective (Driver and Louws, 2002), and lines with BW resistance tend toward small fruit size or incomplete control (Scott et al., 2005). This disease can be especially acute for organic heirloom tomato growers. In North Carolina, organic farmers will often abandon land from tomato production that has a history of BW pressure. The resilient BW resistance shown in this study by CRA 66 and Hawaii 7996 rootstocks indicates the importance of grafting with resistant rootstock to manage BW in severely infested soils. In 2005 and 2006, no symptoms of wilt were seen among treatments with CRA 66 and Hawaii 7996 rootstock. In 2005, the self-grafted treatments had an intermediate effect, resulting in slightly reduced BW incidence. However, this trend was not seen in 2006, and linear regression showed that the self-grafted and nongrafted controls behaved in a similar manner in both years.

This data highlights the potential of CRA 66 and Hawaii 7996 for future breeding programs. CRA 66 has been previously identified as a resistant rootstock genotype for grafted tomato production in Germany (Grimault et al., 1994; Tikoo et al., 1979). In one study, yield of the tomatoes with CRA 66 rootstock was four times that of the susceptible lines (Tikoo et al., 1979). Hawaii 7996 is effective against many of the various strains of *R. solanacearum* worldwide (Wang et al., 1998). In the conditions of our study, it was evident that both CRA 66 and Hawaii 7996 genotypes displayed extremely high resistance to endemic populations of *R. solanacearum* in eastern North Carolina. However, resistance to BW in tomato is complex, being controlled quantitatively and strongly influenced by environmental conditions such as soil temperature, pH, and moisture (Scott et al., 2005), and future work with these lines may be important to further identify the efficacy of these rootstocks throughout North Carolina and the southeastern United States.

The Pender County trials demonstrated the efficacy of the resistance, but crop yield data are not reliable. In 2005, cumulative total yield was higher in treatments with Hawaii 7996 rootstock. However, high levels of TSWV occurred, creating concerns about the relevance of crop yield and marketability in regard to BW specifically. A surprising discovery in the 2005 trial was the impact CRA 66 had on TSWV incidence. Tolerance to viruses, moderated by rootstock with increased vigor, has been observed for Tomato Yellow Leaf Curl Virus (Rivero et al., 2003b), but never suggested for TSWV to date. TSWV incidence did not occur in 2006, so the robustness of this rootstock to limit TSWV is not clear but is worth evaluating in the future.

The unexpected incidence of fusarium wilt on the Alamance County organic farm reiterates the value of resistant rootstock to reduce risk in heirloom production. 'Maxifort' carries F1 and F2 resistance, and 'Robusta' has F2 resistance, leading us to predict the fusarium race present in the field was race 1. Regression of Logit-X [$\ln(x_0/(1-x_0))$] transformed data provided a platform for analysis of the anatomy of the epidemic. The slopes of the regression lines were similar and the x-intercept was significantly different for 'Robusta' compared with the two control treatments. These data suggest that 'Robusta' was effective in delaying the onset of disease development but did not slow down the rate of plant wilting compared with the controls. Although 'Robusta' was not able to reduce the rate of symptom expression, 'Maxifort' offered complete control of fusarium wilt. To

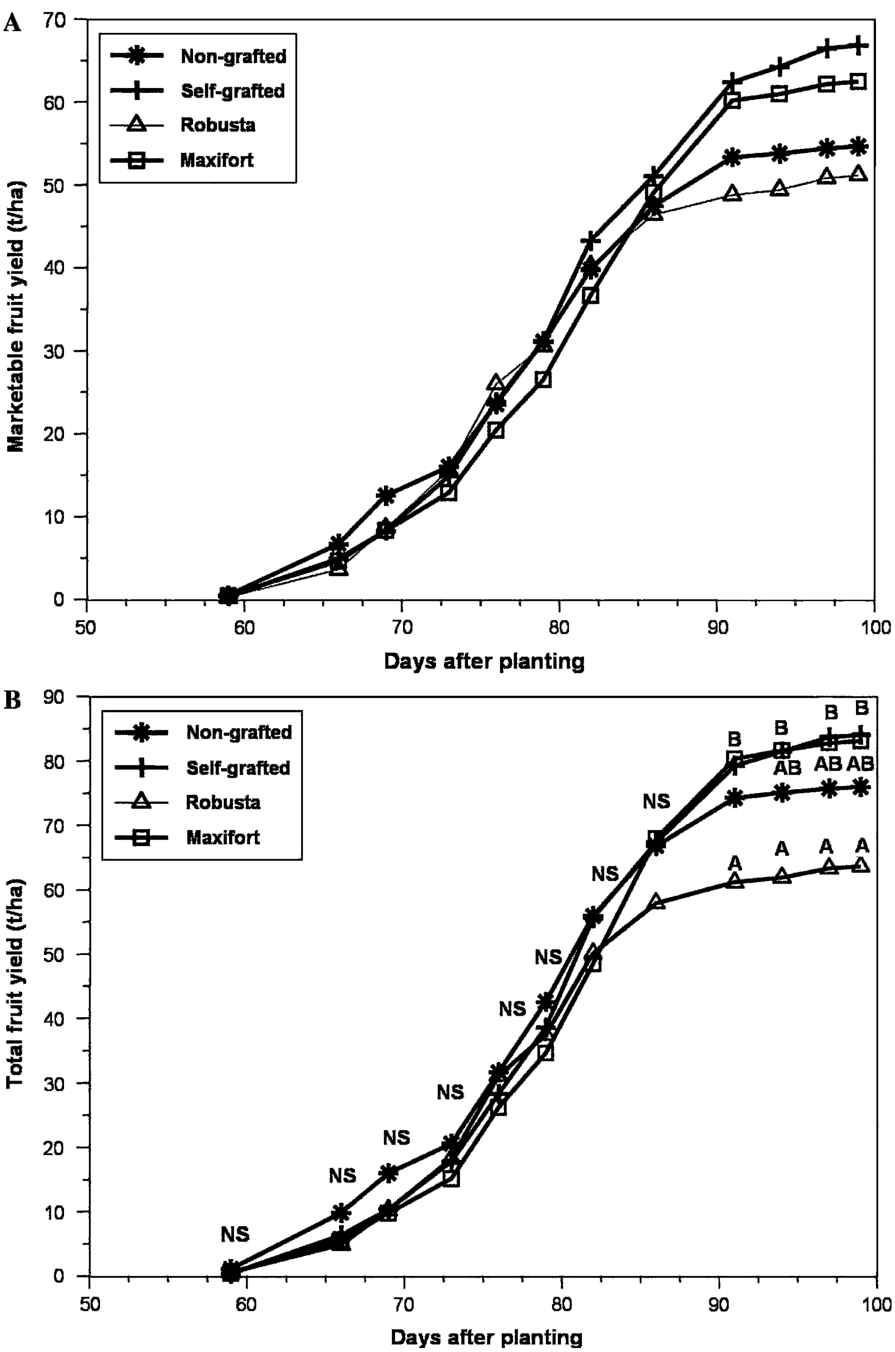

Fig. 5. Cumulative marketable (**A**) and total (**B**) fruit yield of grafted and nongrafted heirloom tomato cv. German Johnson (Orange County, NC). Cumulative marketable yield showed no significant treatment effects. Cumulative total yield was analyzed for each harvest date, and the results of a mean separation test with a protected least significant difference ($P = 0.05$) are shown.

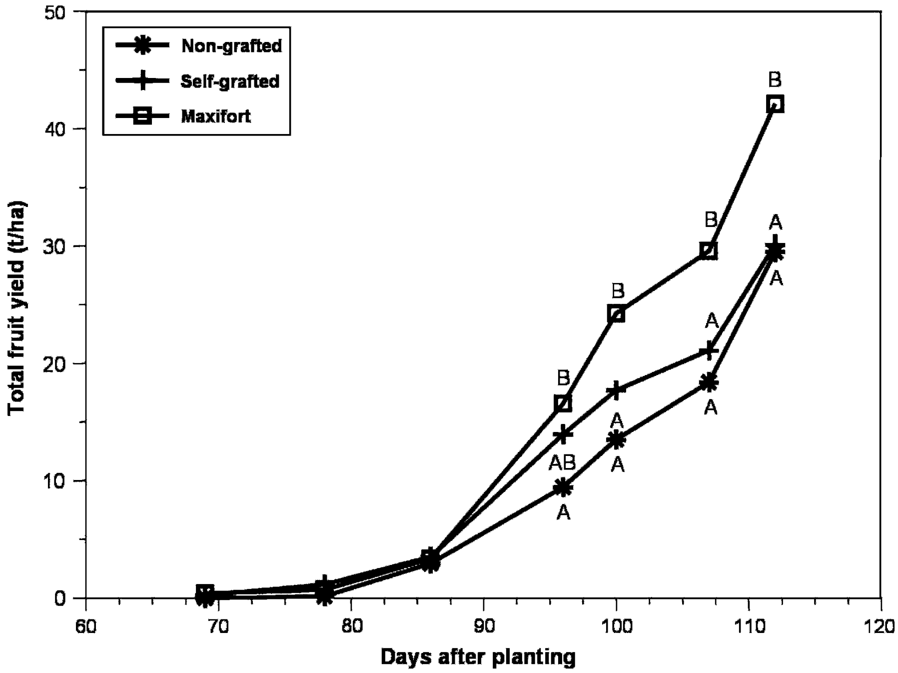

Fig. 6. Total fruit yield of grafted and nongrafted tomato cv. German Johnson for standard and twin-row cultural training systems (CEFS, 2006). Cumulative total yield was analyzed for each harvest date, and the results of a mean separation test with a protected least significant difference (P = 0.05) are shown.

our knowledge, this is the first report of fusarium wilt management in the field through grafting of tomato in the United States. The reduced risk of fusarium wilt can be of great value to organic and conventional growers of heirloom cultivars. Major resistance genes have been deployed in modern hybrid cultivars to manage this disease (Jones, 1991). However, because heirloom varieties do not carry genetic resistance to fusarium wilt, grafting could be a primary component to integrate these genetic control mechanisms into an heirloom production system. In tomato, fusarium can reduce yields significantly in severely infested soils (Fuchs et al., 1999; Khan and Khan, 2002). In Alamance County, yields were unaffected by 'Maxifort', which showed complete resistance to *F. oxysporum* f.sp. *lycopersici*. Fusarium wilt increased ≈25% in the nongrafted and self-grafted controls 2 weeks after harvesting had begun. This specific timing of this late epidemic helps understand yield effects. The crop canopy was in place and much of the fruit sized before complete wilt set in. If the epidemic started earlier, then wilt would have occurred before full harvest and yield could have been negatively impacted.

The main goal of organic and other heirloom tomato growers is to reduce risk of crop failure without compromising yield and preferably increasing yield. A key question in the mind of local growers would relate to the economics of grafting. Clearly, if major crop losses would recur as a result of soilborne disease, then grafting would be viable (this study; (Grimault et al., 1994; Tikoo et al., 1979). The use of host resistance as a disease management tactic often leads to a tradeoff resulting in reduced crop productivity by resistant genotypes when there is an absence of disease (Bergelson and Purrington, 1996; Brown, 2002). Growers may be willing to accept this trend as a result of enhanced long-term economic stability with the use of resistant cultivars. In our work, we observed no negative effects resulting from grafting in terms of crop productivity. The primary economic tradeoff associated with grafting is the grafted transplant production cost. Because of the increase in transplant production costs, growers would benefit most from rootstock if yields were elevated enough to offset this cost even during years with little disease pressure.

The results from this study are not clear as to whether grafting with 'Maxifort' under little or no soilborne disease pressure would be advantageous. In the CEFS trial, cumulative total yield was significantly higher (P = 0.05) and was elevated, particularly late in the season (Fig. 6). Sustained production may be very beneficial to growers as fruit production often declines late in the season, although markets still may be suitable. At the two organic on-farm trials, 'Maxifort' and 'Robusta' did not consistently impact cumulative yield. In one trial, 'Maxifort' tended to delay early fruit set, whereas 'Robusta' increased early fruit set as compared with all other treatments. In contrast, 'Robusta' was not as effective in sustaining late-season yield in the Orange County trial. The dynamics of rootstock on early- versus late-season productivity is an important consideration for growers seeking to sell on an early or late market and is a productive avenue for future research.

Grafting is an effective integrated pest management tool for growers that face heavy disease pressure from soilborne pathogens and are constrained by market demands to supply high-value heirloom fruit. Growers who have eliminated or who are limited to short crop rotations, like those operating in tunnels, may benefit greatly from this emerging technology. Likewise, grafting could be very important for growers that are transitioning production areas from conventional to organic management. These conditions can lead to elevated pest pressure (Zinati, 2002), and root-knot nematodes can be particularly problematic (McSorley, 2002). 'Maxifort' contains the *Mi* gene, conferring tolerance to root-knot nematode and therefore offers tolerance for this important soilborne plant pathogen (Lopez-Perez et al., 2006).

The reason for yield benefit in the organic system at CEFS compared with the on-farm experiment is not clear and is a productive question for future research. Cultural management for American production systems may need to be adjusted to capture increased yields. This has been done in commercial soil-based tunnel systems in the Mediterranean (Besri, 2003). A productive component of future research is to explore plant training systems that maintain or enhance yield on a per plant basis leading to reduced rootstock density and therefore reduced economic constraints for a grafted tomato production system.

In this study, we have documented the benefit of grafting heirloom tomato cultivars onto rootstock that confer resistance to indigenous soilborne pathogens. In one case, the presence of fusarium was unexpected, highlighting the usefulness of rootstocks to reduce risk of production losses. Grafting increased yield or did not impact yield in organic production systems. Thus, grafting heirloom tomatoes onto well-selected rootstocks decreases risk of catastrophic plant losses and provides similar or greater yields, which should add to the stability of farm income.

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