Plant Growth, Fruit Yield and Quality, and Tolerance to Verticillium Wilt of Grafted Watermelon and Tomato in Field Production in the Pacific Northwest

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Abstract. Growth, fruit yield and quality, and potential tolerance to verticillium wilt (Verticillium dahliae) were compared among non-grafted, self-grafted, and grafted triploid watermelon (Citrullus lanatus Thunb., ‘Crisp’n Sweet’) and heirloom tomato (Solanum lycopersicum, ‘Cherokee Purple’). Rootstocks for watermelon were ‘Emphasis’ (Cucurbita maxima × Cucurbita moschata), and rootstocks for tomato were ‘Beaufort’ and ‘Maxifort’ interspecific tomato (Solanum lycopersicum × Solanum habrochaites). Field trials were carried out in 2010 and 2011 at Hermiston and Eltopia (eastern Oregon and Washington, respectively) and Mount Vernon (western Washington). Grafted watermelon had significantly larger stem diameter than non-grafted and self-grafted plants both years at Mount Vernon, whereas there were no differences at Hermiston or Eltopia. Grafted tomato in 2011 had significantly larger stem diameter than non-grafted and self-grafted plants at Eltopia and Mount Vernon, and ‘Beaufort’-grafted plants were significantly taller than other treatments at Mount Vernon. Grafting did not impact watermelon or tomato fruit yield or quality at any location either year. Foliar symptoms of verticillium were not observed on ‘Crisp’n Sweet’ watermelon at the eastern locations either year; however, at Mount Vernon, ‘Emphasis’ and ‘Strong Tosa’-grafted plants had significantly lower verticillium wilt severity than non-grafted and self-grafted plants both years. Microsclerotia were observed in all recovered watermelon stems sampled at Eltopia and Mount Vernon. V. dahliae was isolated from non-grafted and ‘Emphasis’-grafted ‘Crisp’n Sweet’ stems at Eltopia and non-grafted, self-grafted, and ‘Strong Tosa’-grafted stems at Mount Vernon. Foliar symptoms of verticillium wilt and microsclerotia in stems were not observed on ‘Cherokee Purple’ plants at either location both years despite site histories of the disease. Grafting with ‘Emphasis’ and ‘Strong Tosa’ rootstocks may be an effective strategy for managing verticillium wilt on watermelon in western Washington; however, grafting ‘Cherokee Purple’ onto ‘Beaufort’ and ‘Maxifort’ did not provide any advantages for tomato under the field conditions of this study.

Worldwide, watermelon (Citrullus lanatus Thunb.) and tomato (Solanum lycopersicum) are grafted onto vigorous and disease-resistant rootstocks to ensure adequate yields where high salinity, soilborne pathogen populations, and/or unfavorable growing temperatures limit productivity (Dau et al., 2009; Fernandez-Garcia et al., 2002; Kubota et al., 2008; Oda, 2007; Sakata et al., 2007; Venema et al., 2008). Producer adoption of grafting in the United States has been tentative, however, as a result of concerns about added labor costs, limited technical information regarding the grafting process, lack of information on regionally specific rootstock selection, and potential negative impact on fruit quality (Davis et al., 2008a, 2008b; Kubota et al., 2008; Rivard et al., 2010a; Sakata et al., 2007). Watermelon grafted onto interspecific squash rootstock (C. maxima × C. moschata Duchesne) were found to yield fruit that were significantly larger with firmer flesh than fruit from non-grafted plants (Huitron-Ramirez et al., 2009; Lee, 1994; Paroussi et al., 2007). Paroussi et al. (2007) found that ‘Crimson Sweet’ watermelon grafted onto interspecific squash hybrid rootstock (C. maxima × C. moschata ‘Duchesne ‘Mahmoud’) had higher yields but lower total soluble solids (TSS) than when grafted onto bottle gourd rootstocks. Cushman and Huan (2008) found that TSS was unaffected by grafting. Bruton et al. (2009) evaluated fruit quality of nine watermelon cultivars grafted onto five rootstocks and found that grafted onto C. maxima × C. moschata and C. ficifolia rootstocks, watermelon fruit had higher firmness but equivalent lycopene content and TSS compared with non-grafted watermelon. For tomato, Flores et al. (2010) found that fruit from ‘Kyndia’, an indeterminate commercial cultivar, grafted onto ‘UC82B’, a determinate processing cultivar known to have high TSS, had higher TSS compared with fruit harvested from self-grafted tomato plants. Romano and Paratore (2001) found that grafting tomato with ‘Beaufort’ rootstock increased plant vigor and yield, but there was no effect on fruit quality.

Verticillium wilt is a soilborne disease caused by Verticillium dahliae Kleb., that impacts watermelon and tomato production throughout the world (Pegg and Brady, 2002) and is becoming an increasing problem in the Pacific Northwest (Washington, Oregon, and Idaho) (Maynard, 2001; Sunseri and Johnson, 2001). V. dahliae is a fungal pathogen that infects plant roots and rapidly colonizes xylem tissue, restricting water uptake and causing irreversible wilting and plant death (Pegg and Brady, 2002). V. dahliae produces microsclerotia within infected plant tissue and microsclerotia can persist in the soil for up to 14 years (Green, 1980; Menzies and Griebel, 1967; Pegg and Brady, 2002; Schnathorst, 1981).

There are few verticillium wilt-resistant watermelon cultivars available (Maynard, 2001; Pegg and Brady, 2002), and although there are no cucurbit rootstocks known to be resistant to verticillium wilt (Davis et al., 2008b), watermelon grafted onto many commercial cucurbit rootstocks have shown increased tolerance to verticillium wilt and delayed symptom onset of up to 20 d (Papamatos et al., 2000; Paroussi et al., 2007). Rivard and Louws (2008) and Rivard et al. (2010b) found that grafting heirloom tomato onto vigorous rootstocks such as ‘Beaufort’ and ‘Maxifort’ effectively controlled bacterial wilt (caused by Ralstonia solanacearum), fusarium wilt (caused by Fusarium oxysporum f. sp. lyco-persici), southern blight (caused by Sclerotium rolfsii), root-knot nematode (Meloidogyne spp.), and also increased plant vigor and yields. Although most commercial tomato cultivars have resistance to V. dahliae race 1 and some have resistance to race 2 (Bryan, 1925; Pegg and Brady, 2002), growers often choose susceptible cultivars such as heirlooms as a result of high customer demand,
unique fruit color, shape and flavor, and higher market value (Grassbaugh et al., 1999; Rivard and Louws, 2008).

Vegetable grafting research has been conducted in warmer regions of the United States and focused on soilborne pathogens common to those climates. There is limited information on the performance of grafted watermelon and tomato plants in field production in northern temperate climates of the United States. The primary objective of this research was to evaluate plant growth, fruit yield and quality, and verticillium wilt severity of watermelon and tomato in field production at selected sites in the Pacific Northwest. The anticipated benefit of this research was to provide growers with regionally specific information on the potential of grafting to manage verticillium wilt.

Materials and Methods

Field trial locations and experimental designs. Field trials were conducted in two contrasting areas in the Pacific Northwest: the irrigated dryland Columbia Basin and the cool humid Puget Sound. In the Columbia Basin, watermelon plots were located within a commercial watermelon field at Hermiston, OR, in 2010 and within a commercial melon field at Ellopia, WA, in 2011. Tomato plots were located within a commercial tomato field at the Ellopia site both years. In the coastal region, watermelon and tomato plots were located at the Washington State University Northwestern Washington Research and Extension Center (WSU NWREC) at Mount Vernon both years. Soil types are Adkins, Quincy, and Taunton fine sandy loam at Hermiston, classified as coarse-loamy, mixed, superactive, mesic Xeric Hapllocalids, Haplocambids, and Torripsamments; a Taunton very fine sandy loam at Eltopia, classified as coarse-loamy, mixed, superactive, mesic Xeric Hapllocalids, and Haplocambids; and Torripsamments; a Taunton very fine sandy loam at Ellopia, classified as coarse-loamy, mixed, superactive, mesic Xeric Hapllocalids, Haplocambids, and Torripsamments; and a Taunton very fine sandy loam at Ellopia, classified as coarse-loamy, mixed, superactive, mesic Xeric Hapllocalids, and Haplocambids. All plants were propagated at WSU Mount Vernon NWREC and transplanted to the field locations. Both crops at WSU Mount Vernon NWREC and transplanted to the field locations. Both crops at Eltopia, WA, were grafted onto ‘Strong Tosa’ (Solanum lycopersicum × Solanum habrochaites), and grafted onto ‘MaxiFort’ (Solanum lycopersicum × Solanum habrochaites). There were six plants per plot and five replicates at both locations both years. Watermelon was grafted using the one-cotyledon splice technique (Miles et al., 2013), whereas tomato was grafted using the splice technique (Johnson et al., 2011). Self-grafting was included as a positive control treatment (Rivard and Louws, 2008).

Plot and field maintenance and plant establishment. All plants were propagated at WSU Mount Vernon NWREC and transplanted to the field locations. Both crops at all locations were planted on raised beds covered with black polyethylene mulch. Beds were spaced 1.4 m center-to-center, and plants were 0.6 m apart in a single row. Plants were drip-irrigated according to commercial practices and crop water use at each site (Hemphill, 2010), about 134 m³ ha⁻¹ twice per week at Hermiston and Ellopia and 66 m³ ha⁻¹ twice per week at Mount Vernon. At Hermiston and Ellopia, watermelon and tomato studies were planted within commercial fields, which served as a buffer. A watermelon pollinator cultivar, SP-4 at Hermiston and Crimson Sweet at Ellopia, was planted every six plants within the study plots. At Mount Vernon, one complete row of ‘Crimson Sweet’ watermelon was planted as outside rows on either side of the study and one plant was planted at the end of each row as a pollinator and a buffer. For tomato at Mount Vernon, one complete row of tomato plants was planted on either side of the study and two plants were planted at the ends of each row as a buffer.

Plant growth. Stem diameter for both crops was measured just below the graft union and about 2.5 cm above the soil line using a digital caliper (Model #700-126; Mitutoyo, Aurora, IL). Watermelon stem diameter was measured in 2010 at 41, 55, and 71 d after transplanting (DAT) at Hermiston and at 57, 65, 72, and 80 DAT at Mount Vernon. Plant growth was delayed at Mount Vernon as a result of cold early summer temperatures. In 2011 watermelon stem diameter was measured 42, 56, 71, and 85 DAT at Elltopia and 22, 38, 55, and 69 DAT at Mount Vernon. There were insufficient watermelon plants for data collection in some treatments later in the season at Mount Vernon as a result of high disease pressure. Tomato stem diameter and plant height were only measured in 2011, at 42, 56, 71, and 85 DAT at Elltopia and 40, 53, 66, and 82 DAT at Mount Vernon. Plant height was measured from the soil line to the top of the plant crown. Area under growth progress curve (AUGPC) values were calculated for stem diameter of both crops and for plant height of tomato at each location following Shaner and Finney (1977).

Harvest and yield. Watermelon fruit were harvested when the tendril and leaflet located at the leaf axil where the fruit stem arises had turned completely brown and dry (Georgia Vegetable Team, 2000) at 56, 71, and 87 DAT at Hermiston in 2010 and 95, 100, and 107 DAT at Elltopia in 2011. At Mount Vernon, no watermelon fruit reached marketable size either year as a result of the low growing degree-days, and so no yield data could be collected. Tomato fruit at both locations were harvested when about 75% ripe. For both crops at each harvest date, the total number and weight of marketable fruit per plot were recorded, and for tomato, number and weight of unmarketable fruit also were recorded.

Fruit characteristics. Three representative marketable watermelon fruit were selected from each plot at each harvest date and average fruit diameter, length, and weight were measured. Each fruit was cut in half along the longitudinal axis, and a 5 cm × 5 cm section of fruit tissue was taken from the center of one half of each fruit just below the latitudinal axis toward the blossom end. Fruit firmness was measured using a drill-press penetrometer (Ametek, Berwyn, PA) with a 4-mm cylindrical blunt-end tip that penetrated to the center of each section at a depth of 3.2 mm. For tomato, five representative marketable fruit were selected from each plot at each harvest date and average fruit diameter, length, and weight were measured. A 1-cm thick laterally cut section was taken from the center of each fruit and firmness in the center of the pcriarp of each section was tested as described previously.

Lycopene. Lycopene was quantified using a spectrophotometer method developed by Nagata and Yamashita (1992) and modified by Elena Lon Kan (personal communication, 2010). The sections of fruit tissue used for firmness measurements were frozen in a −10 °C freezer and then homogenized in a blender such that there was one composite sample per plot per harvest date. Three 1-g subsamples were taken from each plot at each harvest date and average fruit diameter, length, and weight were measured. A 1-cm thick laterally cut section was taken from the center of each fruit and firmness in the center of the pcriarp of each section was tested as described previously.

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were extracted with chilled (4 °C) acetone: hexane (2:3) and lycopene was quantified using a Beckman DU-65 spectrophotometer (Beckman Coulter, Inc., Brea, CA).

**Total soluble solids.** TSS was measured as °Brix using a Palm Abbe™ digital refractometer (MISCO, Cleveland, OH). Watermelon juice was extracted directly from the fruit, whereas tomato juice was filtered through a wire mesh strainer into a glass beaker. Measurements were taken in a controlled laboratory environment with temperatures ranging between 21 and 22 °C. The digital refractometer was equipped with automatic temperature compensation, and the digital refractometer was calibrated at the beginning of each day using deionized water.

**Verticillium evaluation.** Severity of verticillium wilt was rated visually for both crops during each growing season. Severity was determined as the total percentage of above-ground plant tissue per plot exhibiting typical symptoms consisting of V-shaped leaf lesions, leaf chlorosis and necrosis, and plant wilting (Pegg and Brady, 2002; Schnathorst, 1981). Verticillium wilt symptoms were evaluated on watermelon at Hermiston at 41, 55, 71, and 87 DAT in 2010 and 42, 56, 71, 85, and 99 DAT at Eltopia in 2011. At Mount Vernon, disease severity was evaluated weekly beginning at 53 DAT and ending at 101 DAT in 2010 and biweekly in 2011 beginning at 42 DAT and ending at 98 DAT. Verticillium wilt severity was evaluated on tomato at Eltopia at 41, 55, 71, and 87 DAT in 2010 and 42, 56, 71, 85, and 99 DAT in 2011. At Mount Vernon, disease severity was rated weekly in 2010 beginning at 21 DAT and ending at 103 DAT and biweekly in 2011 beginning at 35 DAT and ending at 109 DAT. Severity ratings were used to generate area under disease progress curve (AUDPC) values (Shaner and Finney, 1977). After the final rating each year, stems of one symptomatic watermelon and one random tomato plant (no symptoms were observed) from each plot at each field site were cut at the soil line to a 20-cm length, surface-sterilized for 5 min in a 10% bleach solution, rinsed in tap water for 30 s, cut longitudinally, and incubated in moisture chambers for 4 weeks at room temperature in the dark. Microsclerotia that formed in the stems were examined under a dissecting microscope (40×). In 2011, conidia from infected stems were swiped with small sterile filter paper strips and transferred onto ½-potato dextrose agar medium. Isolates with growth characteristic of V. dahliae were sent to the Washington State University Puyallup Plant and Insect Diagnostic Laboratory for DNA sequencing (Applied Biosystems 3730x; Applied Biosystems, Grand Island, NY) to confirm species identification.

**Statistical analyses.** Data were subjected to analysis of variance using PROC MIXED (SAS Version 9.2; SAS Institute, Cary, NC). When there was no significant interaction between grafting treatment and year, data were pooled at each location and analyzed using a split-plot model with grafting treatment as the main plot and year as the subplot. Non-pooled data were analyzed using a one-way model. Homogeneity of variance was assessed in all cases using Levene’s test in SAS (Levene, 1960). Field locations and disease severity were analyzed separately as a result of possible differences in the pathogenicity and host specificity of V. dahliae at each location. Extremely low AUDPC values for rootstock-grafted treatments in field studies resulted in strongly heterogeneous variance; thus, ranked data were used for analysis. Treatment means were separated using LSMeans (SAS Institute, 2009).

**Results**

There was an average of 4.0 cfu g⁻¹ soil of V. dahliae at Hermiston in 2010 and 3.0 cfu g⁻¹ soil of V. dahliae at Eltopia in 2011. At Mount Vernon, an average of 18.0 cfu g⁻¹ soil of V. dahliae was counted at the study location in 2010; in 2011, the study was repeated at the same field site and soil was not re-assayed.

**Watermelon plant growth.** Stem diameter at Hermiston in 2010 was measured incorrectly by a farm worker and data were discarded. Heavy winds after transplanting at Eltopia in 2011 reduced the number of plants per replicate below statistical validity. At Mount Vernon in 2010, stem diameter did not differ as a result of treatment at 57 DAT and was greatest for ‘Strong Tosa’-grafted ‘Crisp’n Sweet’ watermelon on the other sample dates and comparable to ‘Emphasis’-grafted watermelon at 65 and 72 DAT (Table 1). ‘Strong Tosa’ and ‘Emphasis’-grafted ‘Crisp’n Sweet’ watermelon had the greatest mean AUDPC values for stem diameter. In 2011, ‘Strong Tosa’-grafted ‘Crisp’n Sweet’ watermelon had the greatest stem diameter early in the season (22 DAT), equal to ‘Emphasis’-grafted plants midseason (38 and 55 DAT), and by the end of the season (69 DAT), there was no difference in stem diameter as a result of treatment. ‘Emphasis’ and ‘Strong Tosa’-grafted ‘Crisp’n Sweet’ plants had the greatest mean AUDPC values for stem diameter.

**Watermelon yield.** Marketable fruit yield and fruit size were unaffected by grafting at Hermiston in 2010 (data not shown). Additionally, fruit firmness, TSS, and lycopene content did not differ as a result of treatment. Yield data at Eltopia in 2011 and Mount Vernon both years were insufficient for statistical analysis; at Eltopia, there were too many missing plants per replicate (as a result of heavy winds), and at Mount Vernon, low growing degree-day accumulation during both summer seasons delayed fruit development such that none were mature by the end of the growing season.

**Verticillium wilt on watermelon.** Verticillium wilt symptoms were not observed at Hermiston in 2010 or Eltopia in 2011. At Mount Vernon, ‘Emphasis’ and ‘Strong Tosa’-grafted ‘Crisp’n Sweet’ watermelon had significantly lower severity ratings for verticillium wilt than non-grafted and self-grafted watermelon (Fig. 1). The severity rating for verticillium wilt reached 90% to 100% for non-grafted and self-grafted ‘Crisp’n Sweet’ watermelon in 2010, and 40% to 50% in 2011, whereas the severity rating for rootstock-grafted ‘Crisp’n Sweet’ watermelon did not exceed 10% either year. Although verticillium wilt severity appeared to decline at the end of the season in 2011, the lowered rating was likely the result of severely affected plants dying and no longer being recorded. In 2010 and 2011, mean AUDPC values for wilt severity were significantly less for ‘Emphasis’ and ‘Strong Tosa’-grafted ‘Crisp’n Sweet’ watermelon than for self- or non-grafted watermelon (Fig. 2).

**Table 1. Mean stem diameter (cm) and area under growth progress curve (AUDPC) values for stem diameter of ‘Crisp’n Sweet’ watermelon non-grafted, self-grafted, grafted on ‘Emphasis’ bottle gourd and grafted on ‘Strong Tosa’ interspecific squash hybrid in open-field production at Mount Vernon in 2010 and 2011.**

| Treatment          | Days after transplant | 2010 Stem diameter (cm) | AUCPC     | 2011 Stem diameter (cm) | AUCPC     |
|--------------------|-----------------------|-------------------------|-----------|-------------------------|-----------|
| Non-grafted        | 0.89                  | 1.04 b                  | 1.14 bc   | 0.97 d                  | 1.19 c    | 25.56 b   |
| Self-grafted       | 0.96                  | 0.87 b                  | 1.00 c    | 0.97 d                  | 1.19 c    | 21.73 b   |
| Emphasis           | 1.11                  | 1.26 a                  | 1.31 ab   | 1.42 b                  | 29.38 a   |           |
| Strong Tosa        | 1.25                  | 1.38 a                  | 1.41 a    | 1.58 a                  | 32.22 a   |           |
| 2010               |                       | 0.48                    | <0.0001   | 0.003                   | <0.0001   | 0.0002    |
| Days after transplant | 22                   | 0.48 c                  | 0.65 b    | 0.96 b                  | 1.17      | 37.54 b   |
| 2011               |                       | 0.49 c                  | 0.65 b    | 0.94 b                  | 1.10      | 36.67 b   |
| Self-grafted       | 0.61 b                | 0.84 a                  | 1.12 a    | 1.27                    | 44.92 a   |           |
| Emphasis           | 0.66 a                | 0.88 a                  | 1.10 a    | 1.26                    | 45.63 a   |           |
| Strong Tosa        | 0.0001                | 0.002                   | 0.03      | 0.12                    | 0.007     |           |

* Treatment differences were analyzed using the LSMeans statement to analyze differences in least square means. Treatments followed by the same letter in a column are not significantly different at α = 0.05.

* Significance of block and treatment effects analyzed using SAS (Version 9.2; SAS Institute, Cary, NC) with PROC GLM at α = 0.05.
Verticillium wilt on tomato. Symptoms of verticillium wilt were not observed on any plants of ‘Cherokee Purple’ at either location in either year. Additionally, no microsclerotia or verticillate conidia were observed in assayed ‘Cherokee Purple’ stems from either location either year.

Discussion

Although other studies have found significant increases in watermelon fruit firmness, fruit size, and yield as a result of grafting (Huitron-Ramirez et al., 2009; Lee, 1994; Paroussi et al., 2007), there were no differences in these parameters for ‘Crisp’n Sweet’ watermelon grafted onto ‘Emphasis’ and ‘Strong Tosa’ rootstocks in this study in the Pacific Northwest. TSS and lycopene content were also similar between grafted and non-grafted ‘Crisp’n Sweet’ watermelon, as has been reported by Bruton et al. (2009) and Cushman and Huan (2008). As a result of plant mortality and delayed maturity associated with unfavorable weather conditions, watermelon yield and fruit quality results in this study were limited to 1 year and one location. Although bottle gourd and squash rootstocks have been reported to increase cold tolerance of grafted watermelon plants (Lee, 1994), no such effect was observed in this study where the average soil temperature at Mount Vernon between 14 June and 15 Sept. in 2010 and 2011 was 18.2 °C and

No microsclerotia were observed in any of the four sampled ‘Crisp’n Sweet’ watermelon stems per treatment from Hermiston in 2010. At Eltopia in 2011, microsclerotia were observed in all sampled ‘Crisp’n Sweet’ stems from non-grafted and self-grafted plants, three of six ‘Emphasis’-grafted plants, and none of the four ‘Strong Tosa’-grafted plants. ‘Crisp’n Sweet’ watermelon were self-grafted and grafted onto ‘Emphasis’ bottle gourd and ‘Strong Tosa’ interspecific squash rootstocks with non-grafted ‘Crisp’n Sweet’ watermelon as the control. SE bars show significant differences in verticillium wilt severity among treatments (least square means, $P \leq 0.05$).

Verticillium colonies were isolated from ‘Crisp’n Sweet’ stems from all infected plants except ‘Emphasis’-grafted plants. Identity of five isolates, one from Eltopia and four from Mount Vernon, was confirmed as *V. dahliae* by DNA sequencing.

**Tomato yield.** There were no differences in tomato yield among treatments at Eltopia in 2010 and 2011, and there was no interaction between grafting treatment and year for marketable or unmarketable yields (Table 3). Greater marketable fruit yield in 2011 than in 2010 was likely the result of more frequent harvesting in 2011. Fruit size and fruit quality at Eltopia were unaffected by grafting treatment either year, and there was no significant interaction between grafting treatment and year (Table 3). Fruit diameter, length, and weight were significantly smaller in 2010 than 2011. There was no significant difference in firmness and TSS between years, but lycopene content was significantly higher in 2010. Tomato plants at Mount Vernon were severely impacted by late blight (*Phytophthora infestans*) in 2010, and in 2011, the growing season was unseasonably cool; therefore, both years, there was insufficient yield for statistical evaluation.

**Discussion**

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Symptoms of verticillium wilt were not observed in ‘Crisp’n Sweet’ watermelon at Hermiston in 2010 or Eltopia in 2011 where *V. dahliae* soil inoculum levels were relatively low, 3.0 cfu·g⁻¹ soil. At Mount Vernon where *V. dahliae* soil inoculum levels were higher, 18.0 cfu·g⁻¹ soil, disease severity for non-grafted and self-grafted ‘Crisp’n Sweet’ reached 60% to 100%. Microsclerotia were observed in stems of all treatments at Eltopia. These results suggest that ‘Crisp’n Sweet’ watermelon may not be affected by verticillium wilt when the soil population of *V. dahliae* averages less than 4.0 cfu·g⁻¹ soil at planting. Davis et al. (2008b) and Paplomatas et al. (2000) suggested that although cucurbit rootstocks have susceptibility to *V. dahliae*, plants grafted onto these rootstocks may exhibit delayed symptom expression.

For tomato, ‘Cherokee Purple’ grafted onto ‘Beaufort’ and ‘Maxifort’ rootstocks at both locations had increased stem diameter and plant height throughout the growing season and cumulatively as compared with non-grafted and self-grafted plants. However, there were no increases in yield, fruit size, or fruit quality as a result of grafting in this study. Leonardi and Giuffrida (2006) similarly observed that ‘Beaufort’-grafted tomato plants had significantly greater stem diameter and plant height relative to self-grafted tomato plants. Although other studies have found increased TSS and lycopene content in fruit of grafted tomato plants (Flores et al., 2010), the results of our research showed no increase in either TSS or lycopene content.

Verticillium wilt symptoms were not observed in non-grafted, self-grafted, or grafted ‘Crisp’n Sweet’ heirloom tomato at either location in either year. However, eggplant planted immediately adjacent to the tomato study at both locations in both years developed severe and obvious symptoms of verticillium wilt (Johnson et al., 2013). Although eggplant is reported to be very susceptible to *V. dahliae* (O’Brien, 1983), higher soil populations may be required to cause damage on tomato. Pegg and Brady (2002) stated that *V. dahliae* microsclerotial counts of 100 cfu·g⁻¹ of soil led to 100% tomato crop loss. Bhat and Subbarao (1999) compared the host specificity of *V. dahliae* isolates obtained from 14 different vegetables, including eggplant, and found that none of the isolates caused wilting or reduced plant height in tomato. The authors concluded that many isolates of *Verticillium* cause severe vascular discoloration and wilting only if they are aggressive to the host. Tsror et al. (2001) found that *V. dahliae* from vegetative compatibility group (VCG) 2A isolated from eggplant caused a higher incidence of verticillium wilt in tomato than *V. dahliae* VCG 2B or the VCG 4B isolates from eggplant. The VCG of *V. dahliae* was not determined at either location in our study because the identification of VCG required expertise that was beyond the scope of this study. Under the cool environmental conditions of the Pacific Northwest, ‘Beaufort’ and ‘Maxifort’ provided no tomato yield or fruit quality advantages when grafted with ‘Cherokee Purple.’

**Table 2.** Mean stem diameter (cm), mean plant height, and area under growth progress curve (AUGPC) values for stem diameter and plant height of ‘Cherokee Purple’ heirloom tomato non-grafted, self-grafted, and grafted on ‘Beaufort’ and grafted on ‘Maxifort’ interspecific tomato hybrid rootstocks in open-field production at Eltopia and Mount Vernon in 2011.

| Etopia  | Days after transplanting | Stem diam (cm) | Etopia  | Days after transplanting | Plant ht (cm) | Mount Vernon | Days after transplanting | Stem diam (cm) | Mount Vernon | Days after transplanting | Stem diam (cm) |
|--------|--------------------------|----------------|--------|--------------------------|---------------|--------------|--------------------------|----------------|--------------|--------------------------|----------------|
|        | 42                       | 53             | 66     | 82                       |                |              | 42                       | 53             | 66           | 82                       |                |
| Non-grafted | 0.71 b                 | 1.78 b         | 2.24   | 80.00 b                  | Non-grafted   | 28.90         | 92.40         | 108.77         | 117.17        | 3939.4       |
| Self-grafted | 0.71 b                 | 1.80 b         | 2.37   | 80.76 b                  | Self-grafted  | 25.40         | 91.53         | 110.47         | 119.73        | 3944.9       |
| Beaufort    | 0.76 b                 | 2.05 a         | 2.44   | 87.60 a                  | Beaufort      | 26.23         | 100.00        | 119.03         | 120.37        | 4202.2       |
| Maxifort    | 0.83 a                 | 2.12 a         | 2.49   | 91.69 a                  | Maxifort      | 28.27         | 100.07        | 116.53         | 121.77        | 4190.9       |
| P value     | 0.01                   | 0.0007         | 0.12   | 0.0003                   | P value       | 0.06          | 0.07          | 0.11           | 0.8           | 0.15         |

*a* Treatment differences were analyzed using the LSMeans statement to analyze differences in least square means. Treatments followed by the same letter in a column are not significantly different at *P* ≤ 0.05.

*b* Significance of block and treatment effects analyzed using SAS (Version 9.2; SAS Institute, Cary, NC) with PROC GLM at α = 0.05.
Table 3. Mean effects of grafting treatment and year on mean number and weight of marketable and unmarketable fruit and fruit diameter (cm), length (cm), weight (g) per marketable fruit, firmness (N), total soluble solids (TSS, °Brix), and lycopene (μg g⁻¹) for ‘Cherokee Purple’ heirloom tomato non-grafted, self-grafted, grafted on ‘Beaufort’, and grafted on ‘Maxifort’ interspecific tomato rootstocks in field production at Eltopia in 2010 and 2011.

| Treatment   | Number (10⁴ ha⁻¹) | Wt (Mt ha⁻¹) | Number (10⁴ ha⁻¹) | Wt (Mt ha⁻¹) | Diam (cm) | Length (cm) | Wt (g) | Firmness (N) | TSS (°Brix) | Lycopene (μg g⁻¹) |
|-------------|--------------------|---------------|--------------------|---------------|-----------|-------------|--------|--------------|-------------|-----------------|
| Treatment x Year |                    |               |                    |               |           |             |        |              |             |                 |
| Treatment    |                    |               |                    |               |           |             |        |              |             |                 |
| Non-grafted  | 30                 | 4.96          | 0.80               | 4.5           | 8.44      | 6.07        | 0.17   | 211          | 3.74        | 15.6            |
| Self-grafted | 29                 | 4.73          | 0.74               | 3.5           | 9.64      | 5.88        | 0.16   | 234          | 4.33        | 15.4            |
| Beaufort     | 32                 | 5.38          | 0.73               | 3.5           | 8.77      | 5.96        | 0.19   | 227          | 4.30        | 15.6            |
| Maxifort     | 26                 | 4.67          | 0.75               | 4.4           | 9.50      | 5.91        | 0.18   | 240          | 4.00        | 12.0            |
| Year 2010    | 26 b               | 4.65 b        | 0.64               | 4.5           | 7.71 b    | 5.57 b      | 0.03 b | 218          | 4.03        | 18.1 a          |
| Year 2011    | 31 a               | 5.22 a        | 0.87               | 3.5           | 10.40 a   | 6.33 a      | 0.32 a | 238          | 4.16        | 11.2 b          |

Conclusions

In this study in the Pacific Northwest, there were no differences in fruit yield or quality for ‘Crisp’n Sweet’ watermelon grafted onto ‘Emphasis’ and ‘Strong Tosa’ rootstocks or for ‘Cherokee Purple’ tomato grafted onto ‘Beaufort’ and ‘Maxifort’ rootstocks. Although ‘Crisp’n Sweet’ watermelon grafted onto these two rootstocks had a higher rate of growth and increased tolerance to *V. dahliae* than non-grafted and self-grafted plants at Mount Vernon, these advantages did not translate into earlier fruit set or fruit maturity. ‘Cherokee Purple’ tomato may have resistance to *V. dahliae* or require high soil populations of the pathogen; thus, successful cultivation in Washington soils infested with *V. dahliae* may not require intensive verticillium wilt management strategies. Further studies are needed to determine if ‘Beaufort’ and ‘Maxifort’ rootstocks have resistance or tolerance to *V. dahliae*.

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