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High Tunnel and Grafting Effects on Organic Tomato Plant Disease Severity and Root-knot Nematode Infestation in a Subtropical Climate with Sandy Soils

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***Abstract*. The U.S. fresh-market tomato industry faces increasing competition from Mexico, which achieves greater productivity and quality due to the use of protected structures. Protected agriculture is limited in humid, subtropical regions of the United States. Although grower interest in high tunnel production has increased in recent years, systematic high tunnel research has not yet been conducted in subtropical Florida. Additionally, although tomato grafting has shown the potential to overcome biotic and abiotic stresses, research of high-tunnel, grafted tomato production in subtropical conditions is lacking. During this 2-year study (Citra, FL), a side-by-side comparison of open field and high tunnel organic tomato production was conducted using a split-split plot design. The most significant benefit of high tunnel production was season extension achieved through the reduction of foliar disease severity, which reduced the area under the disease progress curve by 64% across two seasons. This may be largely attributed to the pronounced reduction in the duration of leaf wetness during the wet months of the growing cycle. Grafting with 'Multifort' rootstock reduced the root-knot nematode soil population density by 88% as well as root galling severity, both of which demonstrated the potential for increased levels in the high tunnel production system compared with open field production. The more severe root-knot nematode infestation in high tunnels was likely due to the modification of soil temperatures, which were 2 °C greater during the early part of the season but were reduced after shadecloth application. Compared with the open field, solar radiation was reduced by 23% in the high tunnel before shadecloth application and by 51% after shadecloth application; however, due to the high radiation levels in subtropical Florida, daily light integral levels indicated that light was not limiting for high-quality tomato production. The average wind speed was reduced by 57% in the high tunnel and, together with the reduction in solar radiation, indicated the potential reduction in summer abiotic stress and evapotranspiration within high tunnels. These results revealed that the integrated use of high tunnel and grafting technologies may be important for enhancing fresh-market tomato production in the humid subtropics, especially in organic systems.**

U.S. production of fresh-market tomatoes has been in a state of steady decline, decreasing by 27% in planted acreage and by 32% in production amounts from 2000 to 2015 (USDA-NASS, 2016). In Florida, the top producer of fresh-market tomatoes in the United States, production declined by nearly 40% during the same timeframe (USDA-NASS, 2016). A major factor of the U.S. fresh-market tomato production decline has been increased competition from Mexico, as U.S. imports of Mexican tomatoes nearly tripled between 2000 and 2016 (US-DOC, 2017). Much of the growth in Mexican tomato imports was due to the combination of consistently low labor costs and new favorable governmental policies that included large subsidies for protected agriculture. As a result of protected production, Mexican tomato growers have experienced increasing yields, reduced weather and pest problems, and an extended growing season (Guan et al., 2017; Wu et al., 2017). Protected tomato production totaled 15,000 ha of the 48,000 ha of Mexican fresh-market tomato production in 2016, with 84% of the total Mexican fresh-market tomato sales to the United States coming from protected production (FTC, 2018; USDA-FAS, 2016). In contrast, U.S. protected tomato production comprises less than 10% of the fresh-market category (USDA-NASS, 2017). The consequences of protected agriculture being such a small portion of U.S. tomato production are that U.S. growers are not able to match the quality and production potential of Mexican growers, production acreage is in decline, and multiple large producers and packing houses are closing their businesses (Downs, 2018; USDA-NASS, 2016). In addition to competition from Mexico, U.S. production of fresh-market tomatoes has decreased because of reduced yields (Guan et al., 2017). In Florida alone, yields per ha have decreased by 28% from 2000 to 2015, primarily due to the phase-out of methyl bromide (Guan et al., 2017; USDA-NASS, 2016). Innovative strategies must be implemented to combat challenges and increase production for U.S. growers to compete in the marketplace.

Although conventional tomato production has been declining, organic production has become one of the fastest growing segments of U.S. agriculture, with sales more than doubling from 2008 to 2016 (USDA-NASS, 2008, 2017). Organic tomato sales rank second for organic vegetables nationwide, and Florida is now the second largest organic tomato producer in the United States (USDA-NASS, 2017). However, productivity is a challenge for organic growers because they have fewer tools to overcome pests and diseases compared with conventional growers, and overall productivity is estimated at just 80% of conventional yields (Seufert et al., 2012).

Productivity in the humid subtropics, whether conventional or organic, has additional limitations, including abiotic factors of high humidity, frequent rainfall, temperature extremes, and drastic temperature fluctuations. Moderate winter temperatures may also result in prolonged insect and disease incidence and greater severity. These challenges require growers to use production practices that maximize plant health and productivity. Low-cost high tunnel and grafting technologies may be used as integrative tools to benefit both conventional and organic tomato growers in achieving these goals.

High tunnels are unheated, polyethylene-covered structures that provide an intermediate level of environmental protection compared with open field and greenhouse production. Tomato ranks as the most important high tunnel crop in the United States and worldwide (Carey et al., 2009; Lamont, 2009). Adoption of high tunnel fruit and vegetable production in Florida has increased in the past 15 years from nearly no production reported in 2001 to 75 ha in 2013 (Hochmuth and Toro, 2014). Recent growth in Florida high tunnel fruit and vegetable production includes a few large operations, which have nearly doubled the previously reported acreage (R.C. Hochmuth, personal communication), and small-scale, direct-market expansion, which has been partially fueled by the Natural Resources Conservation Service (NRCS) High Tunnel System Initiative (USDA-NRCS, 2019).

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There are many advantages to high tunnel production systems, with the most significant benefit being extension of the growing season to periods of the year that are less favorable for plant growth (Lamont, 2005, 2009). Crop stress may be reduced due to high tunnel moderation of drastic fluctuations and temperature extremes experienced in Florida and other subtropical growing regions, and active tunnel microclimate management may further ameliorate these conditions. High tunnels have been reported to reduce biotic stresses in tomato production, including foliar diseases, such as early blight (*Alternaria solani*) and bacterial speck (*Pseudomonas syringae* pv. *tomato*), and major arthropod pests, such as whitefly (*Bemisia tabaci*), thrips (*Frankliniella* spp.), and aphids (*Aphis gossypii*) (Antignus et al., 1996; Healy et al., 2017; O'Connell et al., 2012; Waiganjo et al., 2013). However, the high tunnel environment may favor development of certain diseases, such as tomato leaf mold (*Passalora fulva*), when high humidity (>85%) and warm temperatures predominate. Despite the increasing information obtained from high tunnel studies in northern temperate regions in the United States, there is scarce systematic research regarding high tunnel application and adaptation in subtropical organic vegetable production systems, where many disease and pest problems persist as a result of conducive environments. In Florida, root-knot nematodes (*Meloidogyne* spp.) thrive in sandy soils under warm, moist conditions, but little is known regarding the impact of the high tunnel growing system on root-knot nematode management in organic tomato production.

Grafted tomato benefits are primarily achieved through rootstock selection and rootstock-scion interactions. Tomato grafting often targets the suppression of diseases caused by soil-borne pathogens, including bacterial wilt (*Ralstonia solanacearum*), fusarium wilt (*Fusarium oxysporum* f. sp. *lycopersici*), and root-knot nematodes (RKN; *Meloidogyne* spp.), among others (Guan et al., 2012; King et al., 2008). Tomato grafting also has the potential to overcome abiotic stresses (e.g., temperature extremes, drought, flooding, salinity), increase crop vigor, and improve fruit yields (Barrett et al., 2012; Djidonou et al., 2013; Guan et al., 2012; Rahmatian et al., 2014; Rivard et al., 2012). Although tomato grafting provides a tool to address many site-specific challenges faced by tomato growers in Florida and other subtropical growing regions, the high cost associated with the use of grafted plants calls for production systems that help maximize and extend the grafting benefits, such as by ameliorating detrimental effects of drastic temperature fluctuations, temperature extremes, and frequent rainfall.

This study was designed to compare grafted and nongrafted organic tomato production in replicated side-by-side open-field and high-tunnel systems. Focused on tomato plant health assessment, the objectives of this 2-year study were to: 1) characterize the high tunnel and open field microclimate conditions, and 2) determine the high tunnel and grafting effects on plant foliar disease severity and RKN infestation in an organic tomato production system.

Materials and Methods

Plant material. The organic tomato trial was performed during Spring 2016 and 2017 on certified organic land at the University of Florida Plant Science Research and Education Unit (PSREU) in Citra, FL. 'Tribute' (determinate, round, slicing tomato; Sakata Seed America, Inc., Morgan Hill, CA) and 'Garden Gem' (semi-determinate, plum-type tomato; Dr. Harry J. Klee, University of Florida, Gainesville, FL) were used as scions, with 'Multifort' (Paramount Seeds, Inc., Stuart, FL) as the rootstock. 'Multifort' is a vigorous, interspecific hybrid tomato rootstock that provides high resistance to fusarium wilt and RKN. 'Tribute', 'Garden Gem', and 'Multifort' were seeded on 26 Jan. 2016 and 27 Jan. 2017 in 72-cell polystyrene trays (Speedling Inc., Sun City, FL) filled with peat-based potting soil (Natural & Organic 10; Fafard, Agawam, MA), and seedlings were fertilized daily after the first true leaf formation with 2N–1.3P–0.8K Fish/Seaweed Blend organic liquid fertilizer (Neptune's Harvest, Gloucester, MA) at 100–200 mg of nitrogen (N) per liter. Greenhouse minimum and maximum temperatures were maintained between 18 and 27 °C until transplanting. Tomato plants were grafted on 18 Feb. 2016 and 23 Feb. 2017 using the splice method (Lee et al., 2010). Grafted seedlings were kept in a healing room at 27 °C, with initial humidity >95%. Humidity was reduced gradually from day 4 onward until atmospheric conditions were met 7 d after grafting; then, plants were returned to the greenhouse and grown together with nongrafted 'Tribute' and 'Garden Gem' seedlings.

Field trial setup and experimental design. Field preparation included compost application, tillage, and bed formation. The soil texture consisted of 96.8% sand, 2% clay, and 1.2% silt. In 2016, composted cow manure (Floyd's Organic Soils, Alachua, FL) was broadcast at 60.5 Mt per ha before tillage and bed formation. Assuming 5% nutrient availability of the compost during the tomato season, the compost addition resulted in a contribution of 16.8 kg N, 16.7 kg P, and 29.8 kg K per ha. Based on soil test results, preplant organic fertilizer 10N–0.9P–6.6K (Nature Safe, Irving, TX) was applied before tillage and bed formation at a rate of 112.3 kg N, 9.8 kg P, and 74.6 kg K per ha. In 2017, plots were tilled and beds were formed before root zone application of compost and preplant fertilizer banding. Compost application occurred by filling planting holes that were 15 cm long (in line with drip tape), 5 cm wide, and 20 cm deep. Composted cow manure was applied at 11.2 Mt per ha, resulting in a contribution of 3.1 kg N, 3.1 kg P, and 5.5 kg K per ha (assuming 5% nutrient availability). Preplant fertilization was adjusted during the 2017 season because very high levels of P were detected according to the soil test. 13N–0P–0K Blending Base Fertilizer (Nature Safe) and 0N–0P–43.2K Allganic Potassium (SQM North America Corp., Atlanta, GA) were applied, contributing 112.3 kg N and 74.6 kg K per ha. Seedlings of nongrafted and grafted 'Tribute' and 'Garden Gem' were transplanted to hay-mulched raised beds in a north-south orientation on 9 Mar. during both seasons. However, the effective transplant date for the 2017 season was considered to be 23 Mar., because a freeze event and herbicide contamination of compost resulted in a large amount of replanting during the first 2 weeks of the 2017 growing season.

A split-split plot design was used, with the production system (high tunnel and open field) as the whole plot factor, the cultivar ('Garden Gem' and 'Tribute') as the subplot factor, and grafting (grafted and nongrafted) as the sub-subplot factor. The experimental unit consisted of 28 plants across four beds in each sub-subplot. Tomato plants were grown with one row per bed, at 45.7 cm spacing between plants, and bed centers were spaced at 1.8 m. Plants were irrigated with a single drip tape per bed with 30.5-cm emitter spacing. Irrigation events targeted a soil volumetric water content (VWC) maintained at >10%. Irrigation events were typically performed for 30 min, two or three times per day, depending on the temperature, cloud cover, and rainfall. VWC was measured with a FieldScout TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc., Aurora, IL) to a depth of 20 cm to monitor soil moisture, and the irrigation schedule was adjusted accordingly. Plants were fertigated weekly through the drip irrigation system at an adjustable rate based on the plant stage (Liu et al., 2016). Aqua Power 5N–0.4P–0.8K Liquid Fish Fertilizer (JH Biotech, Inc., Ventura, CA) and Big-K 0N–0P–41.5K Sulfate of Potash (JH Biotech, Inc., Ventura, CA) were used for in-season fertigation. In 2016, the total season applications of N, P, and K through fertigation were 91.5, 8.0, and 102.2 $kg \cdot ha^{-1}$, respectively, for the open-field plots, and 122.0, 10.7, and 138.6 $kg \cdot ha^{-1}$ for the high-tunnel plots. Differences were due to extended tomato harvests in the high tunnels; weekly fertigation rates per crop stage were the same in each production system. In 2017, total season applications of N, P, and K through fertigation in both production systems were 119.8, 10.5, and 127.1 $kg \cdot ha^{-1}$, respectively. Tomatoes were trellised using the Florida stake and weave method (Thaxton and Hochmuth, 2015).

High tunnels and their management. Three single bay high tunnels that were 14.6 m (length) × 7.3 m (width) and corresponding side-by-side open-field plots were randomly arranged in three blocks (one high tunnel and one open-field plot in each block) with a sufficient intervening distance to avoid shading effects; these served as the three replications in this study. The high tunnels had a height of 4.3 m and Quonset-shaped roofs (Sun Master IV 0.152-mm clear greenhouse film; Lumite, Inc., Alto, GA) with vertical sides. The ends had 2.3-m rolldown openings, and the sides had 1.5-m rolldown openings; the high tunnels did not have any roof-venting mechanisms.

For early season growth, high tunnel sides were kept closed; the ends of the tunnels were closed on days and nights when temperatures were <10 °C. Sides of the high tunnels remained closed until temperatures were >27 °C. When daily high temperatures in the open field were sustained at >32 °C, Aluminet I 40% Greenhouse Shadecloth (Green-Tek Inc., Dinuba, CA) was applied to the high tunnels (2 May 2016 and 17 Apr. 2017).

Disease management. Weekly field scouting and periodic diagnostic tissue sampling were conducted during the tomato production seasons. Tissue samples were submitted to the UF/IFAS Plant Diagnostic Center (Gainesville, FL) for disease diagnosis. Regalia (Marrone Bio Innovations, Inc., Davis, CA) and Double Nickel 55 (Certis USA, LLC, Columbia, MD) were used in rotation on a weekly basis for disease management in 2016. In 2017, early season management included the application of biologicals Actinovate AG (Novozymes BioAg Inc., Milwaukee, WI) and Double Nickel 55TM, which were rotated on a weekly basis to build a competitive microbial environment on plant surfaces. When the 2017 rainy season began, contact fungicides OxiDate 2.0 (BioSafe Systems, LLC, East Hartford, CT) and MilStop were used in rotation on a weekly basis to sanitize the plants; this application was followed within 24 h by either Actinovate or Double Nickel 55TM to re-inoculate plant surfaces.

Microclimate assessment. In 2016, high-tunnel and open-field air temperatures (±0.2 °C accuracy range) and relative humidity (±3.5% accuracy range) were monitored during the first replication of the experimental design with a HOBO U23 Pro v2 Temperature/Relative Humidity Data Logger (Onset Computer Corporation, Bourne, MA). In 2017, air temperature (±0.6 °C accuracy range) and relative humidity (±3% accuracy range) were monitored with a WatchDog 2450 Mini Station Temp/RH (Spectrum Technologies, Inc., Aurora, IL) in all three replications. During both seasons, photosynthetically active radiation (*PAR*; ±5% accuracy range) was measured with a LightScout Quantum Light Sensor (Spectrum Technologies, Inc., Aurora, IL), and soil temperature (±0.8 °C accuracy range) and volumetric water content (±3% accuracy range) were measured with a WaterScout SMEC 300 Soil Moisture/EC/Temperature Sensor (Spectrum Technologies, Inc., Aurora, IL) during the first replication of the experimental design in 2016 and in all three replications in 2017. Additionally, a Decagon ECH2O Em50 datalogger (METER Group USA, Pullman, WA) was used in 2017 to monitor wind speed (±5% accuracy range) and leaf wetness with two Davis Cup anemometers (METER Group, Inc. USA, Pullman, WA) and three PHYTOS 31 leaf wetness sensors (METER Group USA, Pullman, WA) in each whole plot of the first replication. Leaf wetness and wind speed measurement instruments were added 9 May 2017 (halfway through the growing season); therefore, data were only recorded after the shadecloth was applied and when the ends and sides of the high tunnels were fully open. Data were recorded every 15 min for all measurements.

Monitoring stations were placed in a central bed in the middle of each whole plot. Air temperature/humidity and *PAR* sensors were placed in the middle of the raised bed and elevated to 1 m; wind speed sensors were placed at 1.4 m and 1.5 m. Leaf wetness sensors were placed at three different locations to represent inner, canopy margin, and fully exposed leaves at the time of setup (halfway through the growing season). Soil sensors were placed at a depth of 10 cm, directly under the drip tape, and halfway between drip tape emitters. The average daily light integral (DLI) was calculated from the *PAR* data as mol·m^{-2}·d^{-1} using the following equation:

$$DLI = \frac{\sum_{i=1}^{n} \frac{(3600 \times x_i)}{4 \times 10^6}}{d}$$

where x_i = *PAR* measurement (recorded every 15 min) at i^{th} observation (μmol·m^{-2}·s^{-1}); n = number of observations; and d = number of days.

To best interpret production system effects on the microclimates, data were separated for pre- and post-shadecloth application. Datalogger accuracy for each sensor type was also considered when evaluating results.

Plant foliar disease assessment. Tomato plant foliar disease severity was evaluated based on the Horsfall-Barratt disease rating system (Horsfall and Barratt, 1945), which uses 12 intervals, the size of which increase logarithmically from 0% to 50% disease coverage and then logarithmically decrease from 50% to 100% coverage. During both years, four plants per treatment were assessed individually for foliar disease severity beginning at 2-week intervals and transitioning to 1-week intervals as disease severity increased. Ratings were based on the summation of the percent defoliation caused by disease and the percent disease coverage of the remaining foliage. In 2016, seven total assessments commenced on 12 May and continued to 6 July; in 2017, five total assessments were conducted from 10 May to 30 June.

Plant disease severity was reported as the area under the disease progress curve (AUDPC) considering the plant disease coverage as a function of time because early season disease severity not only affects plant biological processes at the time of measurement but also has a cumulative effect. To calculate AUDPC, Horsfall-Barratt ratings were first converted to the midpoint of the percent disease coverage (Bock et al., 2009). AUDPC was then calculated as follows:

$$AUDPC = \sum_{i=1}^{n} \frac{(x_i + x_{i-1})}{2} \times (t_i - t_{i-1})$$

where x_i = Horsfall-Barratt midpoint measurement at i^{th} observation; t_i = time at i^{th} observation; and n = number of observations.

In this study, i = 0 was the initial transplanting date, and the initial disease coverage was assumed to be zero.

Root-knot nematode assessment. Soil samplings to determine the nematode population density were conducted to assess RKN infestation. Eight 30-cm deep soil samples per sub-subplot (two from each bed) were taken from the middle of each bed and halfway between in-row plants with a 2.5-cm diameter soil probe (Oakfield Apparatus Company, Oakfield, WI), composited to form a single representative sample, and stored at 10 °C before being sent to Waters Agricultural Laboratories, Inc. (Camilla, GA) for RKN juvenile counts. Results were reported as the number of nematodes per 100 cm^3 of soil. In 2016, soil nematode assessments were only conducted on 13 July, at the end of the growing season. In 2017, samples were taken at monthly intervals to understand the *Meloidogyne* soil population density changes over time. Initial samples were taken on 30 Mar., 1 week after the effective transplanting date (i.e., 3 weeks after initial planting). Then, sampling was performed on 29 Apr., 2 June, and 30 June, representing 30, 64, and 92 d after the initial assessment, respectively. A final assessment was conducted after the final harvest on 7 July.

Plant root galling ratings were also conducted after the final harvest. In 2016, every other plant in each sub-subplot was assessed. However, in 2017, every plant was assessed. Plants were dug and roots were assessed for root galling using a root gall index of 0–10 (Zeck, 1971).

Statistical analyses. Data were analyzed using a linear mixed model with the GLIMMIX procedure of SAS 9.4 (SAS Institute Inc., Cary, NC). Tests for normality, homogeneity of variances, and linearity were performed to determine the necessity of data transformation; transformations were performed logarithmically when necessary. When transformed data were used for statistical analysis, results were presented using the original data. Fisher's least significant difference test (α = 0.05) was used for multiple comparisons among different treatments.

Results and Discussion

Effects of production systems on the microclimate. Production system air temperature differences before shadecloth application (Table 1) included the minimum high-tunnel air temperature in 2016 at 1.1 °C greater than the minimum open-field temperature (with maximum temperatures essentially equal) and the maximum high-tunnel air temperature in 2017 at 4.2 °C greater than the maximum open-field temperature

Table 1. Monthly air temperatures (°C) during the Spring 2016 and 2017 tomato production seasons in Citra, FL.

		Without shadecloth				With shadecloth[z]			
		March[y]		April[x]		May[x]		June	
	Temp[w]	OF	HT	OF	HT	OF	HT	OF	HT
2016	Average	20.4	20.9	22.3	23.0	25.3	24.8	28.4	27.9
	Maximum	30.5	30.1	34.3	34.3	38.0	34.3	40.3	37.0
	Minimum	13.6	14.6	13.4	14.6	15.5	16.8	20.7	21.7
	Diurnal	16.9	15.5	20.9	19.7	22.5	17.5	19.6	15.3
2017	Average	18.0	19.1	20.6	22.0	25.0	24.9	26.2	26.3
	Maximum	27.7	30.9	28.8	34.3	33.2	32.9	33.0	33.8
	Minimum	10.1	10.4	12.2	12.1	17.8	17.6	22.1	22.1
	Diurnal	17.6	20.5	16.6	22.2	15.4	15.3	10.9	11.7

[z]Shadecloth was applied to the high tunnel treatment only.
[y]Data logging began on 18 Mar. 2016 and on 10 Mar. 2017, 9 d and 2 d after transplanting, respectively.
[x]Due to shade application, 2 d at the beginning of May were included in the April data in 2016 and 13 d at the end of April were included in the May data in 2017.
[w]Data reported are the average of the daily maximum, minimum, average, and diurnal temperatures for each month.
OF = open field; HT = high tunnel.

Table 2. Monthly soil temperatures (°C) during the Spring 2016 and 2017 tomato production seasons in Citra, FL.

		Without shadecloth				With shadecloth[z]			
		March[y]		April[x]		May[x]		June	
	Temp[w]	OF	HT	OF	HT	OF	HT	OF	HT
2016	Average	—	—	—	—	24.9	25.1	29.1	27.7
	Maximum	—	—	—	—	28.2	26.7	32.1	29.2
	Minimum	—	—	—	—	21.9	23.6	26.7	26.6
	Diurnal	—	—	—	—	6.3	3.1	5.4	2.6
2017	Average	21.0	22.8	24.0	25.6	27.3	26.8	29.3	29.3
	Maximum	27.7	29.0	29.0	30.6	31.0	28.4	32.6	30.5
	Minimum	15.9	18.1	19.6	21.6	24.4	25.4	27.3	28.4
	Diurnal	11.8	10.9	9.4	9.0	6.6	3.0	5.3	2.1

[z]Shadecloth was applied to the high tunnel treatment only.
[y]Data logging began on 3 May 2016 due to initial logger failure, and on 10 Mar. 2017, 2 d after transplanting.
[x]Due to shade application, 13 d at the end of April were included in the May data in 2017.
[w]Data reported are the average of the daily maximum, minimum, average, and diurnal temperatures for each month.
OF = open field; HT = high tunnel.

(with minimum temperatures essentially equal). This resulted in a diurnal temperature range that was 1.3 °C less in the high tunnel than in the open field in 2016; however, it was 4.0 °C greater in the high tunnel in 2017. This occurred because lower early-season temperatures in 2017 required more intensive microclimate management (through lowering of the sides and/or ends of the tunnels on cold days and nights <10 °C), and tunnels were kept closed for longer durations to help increase temperatures to optimal growing conditions. Interestingly, the observed minimum air temperatures were only slightly greater in the high-tunnel system, indicating that the ability to retain heat through cold nights may be limited for some high-tunnel systems, particularly for small, stand-alone high tunnels with a single-layer poly system, as used in this study. However, even with minimum temperatures being negligibly different on cold nights, the amount of damage that occurred during those cold nights was greatly reduced in the high tunnel. It was hypothesized that this was heavily influenced by the wind protection within the high tunnel, which presumably increased the effectiveness of the retained soil heat and better maintained the leaf thermal boundary layer. More research is necessary to quantify these effects.

After shadecloth application, maximum air temperatures in the high tunnels were 3.3 °C lower than those in the open field in 2016, whereas minimum temperatures were 1.1 °C greater in the high tunnels (Table 1). This resulted in a diurnal temperature range that was 4.4 °C less in the high tunnel in 2016. In 2017, however, the maximum, minimum, and diurnal high-tunnel air temperatures appeared to be similar to open-field temperatures.

The high tunnel production system had a more consistent effect on soil temperatures (Table 2). Before shadecloth application, maximum and minimum high tunnel soil temperatures were 1.5 and 2.3 °C greater, respectively, than the open-field soil temperatures (data only available for the 2017 season). After shadecloth application, maximum soil temperatures in the high tunnel were 2.1 and 2.3 °C less than open-field soil temperatures in 2016 and 2017, respectively. However, considering datalogger temperature accuracy, minimum soil temperatures were essentially equivalent. This resulted in average soil temperatures in the high tunnel that were 1.8 °C greater than those in the open field before shadecloth application (2017 only) and 1.0 °C lower than those in the open field after shadecloth application (averaged across both seasons). Soil temperature differences may be important for understanding the production system effects on nutrient cycling and soil pathogen and nematode ecology. With consistent soil temperature differences recorded at 10 cm, it was assumed that the magnitude of differences would increase at shallower depths, with increasingly greater high tunnel temperatures before shadecloth application and increasingly greater open field temperatures after shadecloth application. Additionally, it is likely that the hay-mulched beds mitigated soil temperature differences between production systems, and that grower use of black plastic mulch could possibly alter soil temperature differences. Soil temperature differences at varying depths and interaction effects of mulch types and production systems on soil temperatures were not investigated in this study. Future research of these topics is needed.

Soil moisture was somewhat variable. Although trends demonstrated that moisture was greater in the high tunnel in 2016 and lower in 2017, production system differences were always within accuracy limits of the sensors; therefore, they were effectively equivalent (data not shown). This was to be expected because soil VWC was also monitored on a regular basis during the season to advise irrigation scheduling, and open field irrigation was adjusted for rainfall events to reduce overwatering. Relative humidity was also variable. Data indicated that the average daily relative humidity was higher in the high tunnel in 2016 than in the open field (77.2% compared with 71.5%); however, the average daily relative humidity was lower in the high tunnel than in the open field in 2017 (69.2% and 75.4%, respectively; data not shown). The relatively small differences found each season were most likely insignificant and did not have much of an effect on plant transpiration or plant growth.

Leaf wetness data in 2017 indicated that the leaf wetness duration was much shorter in the high tunnel than the open field (average, 1.91 vs. 10.93 h, respectively) (Fig. 1). In fact, the longest duration of leaf wetness in the high tunnel (7.79 h) was shorter than the average duration of leaf wetness in the open field during the 68 d of monitoring, and far less than the open field maximum of 24 h. A comparison of leaf wetness duration with rainfall data from the Florida Automated Weather Network indicated that open-field leaf wetness may have been influenced by heavy dew at least as much as it was influenced by rainfall because extended periods without rain continued to have long durations of leaf wetness in the open-field

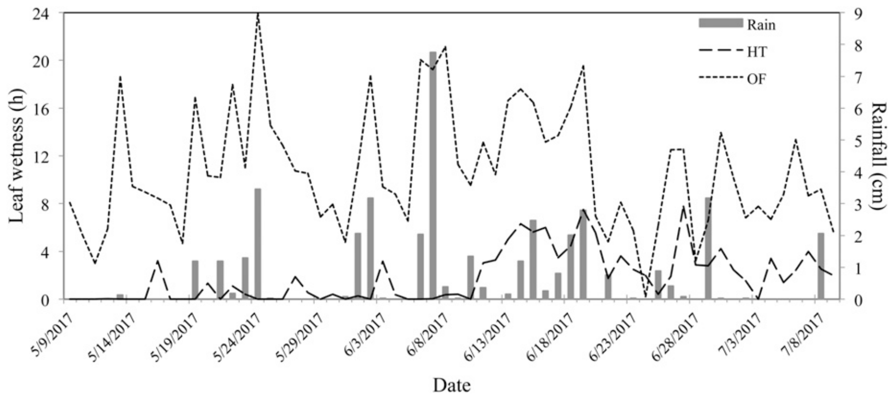

Fig. 1. Leaf wetness duration during the last 2 months of the Spring 2017 tomato production season in Citra, FL, in perspective with daily rainfall data. HT = high tunnel; OF = open field.

Table 3. Monthly averages for *PAR* and DLI during the Spring 2016 and 2017 tomato production seasons in Citra, FL.

		Without shadecloth				With shadecloth[z]			
		March[y]		April[x]		May[x]		June	
	Light measurement[w]	OF	HT	OF	HT	OF	HT	OF	HT
2016	Maximum *PAR*	—	—	—	—	2321	1237	2331	1120
	Average DLI	—	—	—	—	51.5	26.2	48.5	23.9
	Maximum DLI	—	—	—	—	64.0	31.0	65.9	31.3
	Minimum DLI	—	—	—	—	13.7	5.90	16.3	7.0
2017	Maximum *PAR*	2042	1602	2193	1660	2292	1041	2170	994
	Average DLI	42.2	33.3	49.7	37.5	51.9	23.8	42.3	18.9
	Maximum DLI	57.9	42.6	60.2	46.8	67.4	32.5	63.1	28.3
	Minimum DLI	12.9	10.0	3.9	3.0	13.4	6.0	15.3	8.1

[z]Shadecloth was applied to the high tunnel treatment only.
[y]Data logging began on 3 May 2016 due to initial logger failure and on 10 Mar. 2017, 2 d after transplanting.
[x]Due to shade application, 13 d at the end of April were included in the May data in 2017.
[w]*PAR* = photosynthetically active radiation; DLI = daily light integral. Data reported for *PAR* is the monthly average of the daily maximum values (μmol·m^{-2}·s^{-1}), and data reported for DLI is the monthly average and the value of the maximum and minimum day of the month (mol·m^{-2}·d^{-1}).
OF = open field; HT = high tunnel.

production system, whereas little or no leaf wetness was found in the high tunnels (Fig. 1). The presence of moisture is critical for pathogen growth, and it is considered the dominant factor of disease development for most oomycete, fungal, bacterial, and nematode pathogens (Agros, 2015). As such, leaf wetness duration is a key factor influencing infection, lesion number, incidence, and severity of numerous pathogens (Huber and Gillespie, 1992). Therefore, high tunnel reduction of free moisture from heavy dews may be a key benefit in the subtopics; however, this benefit is not typically realized in temperate climates.

Wind speed data were only recorded during the timeframe when the sides and ends of the high tunnel were kept fully open. Maximum wind speeds were 33.3% less in the high tunnel than in the open field, with the daily maximum averaging 2.46 vs. 3.68 m·s^{-1}, respectively. Average wind speeds were 56.5% lower in the high tunnel production system, with a daily average of 0.33 m·s^{-1} compared with 0.76 m·s^{-1} in the open field. Although higher windspeeds would be expected to result in quicker drying of leaf surfaces, its contribution to reducing the duration of leaf wetness appeared to be less significant than high tunnel reduction of leaf wetness in this study. Plant transpiration would be expected to be greater with higher windspeeds because the boundary layer around the stomata would be more rapidly removed, which would also affect water and nutrient uptake. None of these parameters was measured in this study; therefore, future research is warranted.

PAR data showed a relatively consistent difference between high tunnel and open field systems each day. Maximum *PAR* was reduced in the high tunnel by 22.8% before shadecloth application in 2017 (data were not recorded for 2016); after shadecloth application, it was reduced by 47.0% and 54.4% in 2016 and 2017, respectively. Results indicated a progressive reduction in light over multiple seasons, indicating a deterioration of the plastic film and the necessity for high tunnel growers to monitor light levels to assure that a sufficient level of light intensity is available for the specific crops grown (Table 3). The average DLI for the high tunnel and open field were 34.8 and 45.0 mol·m^{-2}·d^{-1}, respectively, before shadecloth was applied (2017 data only). After shadecloth application, 2016 high tunnel and open field average DLI values were 24.9 and 50.5 mol·m^{-2}·d^{-1}, respectively; they were 22.1 and 47.3 mol·m^{-2}·d^{-1}, respectively, for the 2017 season.

Results indicated that even with the great reduction in irradiance in the high-tunnel production system after shadecloth application, the average DLI was generally greater than the 22 mol·m^{-2}·d^{-1} threshold required for high-quality tomato production (Faust, 2001; Morgan, 2013). The one exception was for the month of June in 2017, during which the average DLI decreased to 18.9 mol·m^{-2}·d^{-1} (Table 3). This was likely due to the high frequency of rain showers that month (Fig. 1), which was more frequent than in June 2016 (data not shown) and resulted in a year-over-year monthly reduction of DLI by 21.2% in the high tunnel (and 12.8% in the open field). Transpiration rates may be affected by the decrease in light intensity in high tunnels because lower light generally results in thinner, larger leaves with lower stomatal densities (Royer, 2001); therefore, season extension into the summer rainy season may require light management for optimal tomato production.

It is also possible that the high irradiance in the open field was detrimental to plant growth because high levels may lead to photoinhibition. In extreme cases, after photosynthesis is totally inhibited, high irradiance can cause photo-oxidation of chloroplast and carotenoids (Powles, 1984). Photoinhibition and photo-oxidation are complex and involve other environmental factors such as temperature, nutrient and water availability, and CO_2 levels (Waterkeyn, 2017). Optimum tomato irradiance conditions are 500–800 μmol·m^{-2}·s^{-1}, yet photoinhibition has been reported within this optimum range at moderately high temperatures of 35 °C (Lu et al., 2017; Zhang et al., 2005). Conversely, optimum tomato temperature conditions are 15 to 32 °C, and irreversible photoinhibition has been reported within this range at irradiance levels of 1000 μmol·m^{-2}·s^{-1} (Lu et al., 2017; Zhang et al., 2005). In this study, although the air temperature difference was relatively small between production systems, *PAR* values were >1000 μmol·m^{-2}·s^{-1} for a total of 159 and 218 h in the high tunnel and open field, respectively, before shadecloth was applied (2017 data only). After shadecloth application, high tunnel and open field *PAR* values were greater than this threshold for 128 and 304 h, respectively, in 2016, and 67 and 435 h, respectively, for the 2017 season. These results clearly indicate the potential for high tunnels to reduce the effects of photoinhibition in Florida and other subtropical environments. Future research is needed to determine the effects of high tunnel temperatures and irradiance modifications on tomato photosynthesis, plant growth, and yield under subtropical environmental conditions.

Assessment of plant disease development. The predominant disease in this study was early blight (*A. solani*), verified by the UF/IFAS Plant Diagnostic Center (Gainesville, FL), and a low incidence of bacterial spot (*Xanthomonas vesicatoria*) was also confirmed.

Table 4. Effects of the production system, grafting, and tomato cultivar on end-of-season foliar disease and root-knot nematode assessment in the Spring 2016 and 2017 tomato production trials in Citra, FL.

	AUDPC		RKN[z] population		RKN root galling	
Factor	2016[y]	2017[y]	2016[y]	2017	2016[y]	2017[y]
PS	***	*	0.059	0.074	NS	NS
C	***	*	NS	NS	NS	NS
G	*	*	***	***	***	***
PS × C	NS	NS	NS	NS	NS	NS
PS × G	NS	NS	NS	NS	***	NS
C × G	NS	NS	*	NS	*	NS
PS × C × G	NS	NS	NS	NS	NS	NS

[z]Measurements were RKN juvenile soil population densities (no. per 100cm^3 soil) and Zeck's RKN root galling ratings (0–10).

[y]Data were logarithmically transformed to satisfy statistical assumptions.

AUDPC = area under the disease progress curve; RKN = root-knot nematode; PS = production system; C = cultivar; G = grafting.

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively. Actual P values are indicated if $0.05 < P \leq 0.10$ to show data trends when consistent results were found in both seasons.

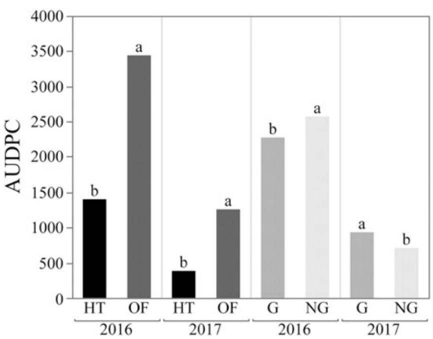

Fig. 2. Tomato foliar disease severity as affected by the production system and grafting during the Spring 2016 and 2017 tomato production seasons in Citra, FL. AUDPC = area under the disease progress curve; HT = high tunnel; OF = open field; G = grafted plants; NG = nongrafted plants. Treatment analyses were separated by season, and the same letters within a single season indicate that the treatments are not significantly different.

Tomato plant disease assessment results were greatly impacted by seasonal weather patterns and affected the length of time from transplanting to final harvest. During both seasons, the AUDPC was affected by the production system, cultivar, and grafting (Table 4). Disease severity was much less in 2017 than in 2016. High tunnels significantly reduced the AUDPC compared with the open field, by 59.2% and 69.4% in 2016 and 2017, respectively (Fig. 2). The high tunnel effect could be attributed to the reduction in the duration of leaf wetness, which was the disease-related parameter most affected by the high tunnel production system in this study (Fig. 1). The AUDPC was 11.6% less in grafted plants in 2016, whereas it was 31.4% greater for grafted plants in 2017. 'Garden Gem' had AUDPC values 27.5% and 31.1% less than 'Tribute' in 2016 and 2017, respectively. The seasonal variation was predominately due to weather differences because the rainy season started 3 weeks earlier in 2016, although an improved spray regimen with additional fungicides approved for organic tomato production may have also benefited the 2017 crop. The greater severity of fungal disease on plant foliage in 2016 resulted in the open field harvest ending 22 d before the high tunnel final harvest; however, in 2017, disease severity did not limit the duration of the high tunnel or open field harvest.

In this study, the high tunnel system had a greater role in reducing tomato plant foliar diseases compared with the use of grafted plants. High tunnel effects on disease severity were expected because previous research spanning from Wisconsin to North Carolina has demonstrated the effectiveness of high tunnels to reduce early blight (Healy, et al., 2017; O'Connell et al., 2012; Rogers and Wszelaki, 2012). The 2016 grafting effects confirmed the potential for the increased vigor of grafted plants to reduce the severity of foliar diseases (Yamakawa, 1983). However, the higher disease severity of grafted plants in 2017 might have also indicated the possibility of increased infection due to enlarged vegetative foliage as a result of using vigorous rootstocks.

Assessment of root-knot nematode infestation. After the 2017 season, root samples from several plants were composited to form a single representative sample for polymerase chain reaction (PCR) analysis by the University of Florida Nematode Diagnostic Laboratory (Gainesville, FL). *M. javanica* was identified as the main RKN species affecting tomato plants in this study.

Correlations between RKN root galling ratings and nematode population density in the soil have been previously reported (Bélair and Boivin, 1988; Starr, 1988), and the results of this study showed similarities between the two methods of analysis (Table 4). High tunnel end-of-season *M. javanica* juvenile counts in the soil were greater than open field counts in both seasons, by 250% and 95% in 2016 and 2017, respectively (Fig. 3A). Although results were not significantly different at $P \leq 0.05$, the P values of 0.059 and 0.074 in 2016 and 2017, respectively, demonstrated a strong trend for increased soil RKN population density under high tunnel production (Table 5). Additionally, the production system and grafting interactions in 2016 indicated that RKN root galling ratings were higher in the high tunnel compared with the open field for nongrafted tomato plants (ratings of 4.0 and 0.7, respectively) (Fig. 3B), and that grafting onto 'Multifort' rootstock overcame the apparent negative impacts of the high tunnel, essentially eliminating galling in both high tunnel (0.1 rating) and open field (0.0 rating) plots. Conversely, 2017 root galling ratings for nongrafted plants were not significantly different between production systems. Grafted treatments led to significantly lower end-of-season RKN soil population densities than nongrafted treatments in both seasons, with 89.5% and 86.7% reductions in 2016 and 2017, respectively (Fig. 3A). The RKN root galling rating was also significantly lower for grafted plants in both seasons (Fig. 3B). Additionally, cultivar and grafting interactions occurred in 2016 for both RKN soil population density and RKN galling rating, indicating that nongrafted 'Garden Gem' was more susceptible than nongrafted 'Tribute', and that grafting mitigated this genotype effect. However, such interaction effects were not significant in 2017.

Bridge and Page (1980) indicated that galling ratings of ≥4 (based on a 0–10 scale) may result in significant yield reductions. In 2016, grafted plants were not rated with this range; however, ratings of ≥4 were observed for 6.0% and 59.5% of nongrafted plants in open field and high tunnel plots, respectively. The root-knot nematode infestation severity appeared to be greater in 2017, as reflected by higher RKN population densities in the soil and root galling ratings. Some grafted plants had root galling ratings in the yield limiting range, at 3.5% and 3.4% of the total open field and high tunnel grafted plants, respectively, indicating the possible breakdown of Mi gene resistance. Nongrafted plants with ratings ≥4 comprised an average of 56.8% and 60.4% of the total open field and high tunnel nongrafted plants, respectively, indicating that yields of nongrafted plants in both open-field and high-tunnel systems may have been reduced by RKN. Interestingly, with galling severity thresholds of ≥5, ≥6, and ≥7, the differences between the percentages of affected plants in high tunnel and open field nongrafted treatments were progressively greater (data not shown), confirming the presumption that RKN severity was greater in high tunnel than in open field production for nongrafted plants.

The RKN soil population densities were evaluated throughout the 2017 season, in addition to the end-of-season assessments. At the time of the initial sampling and 30 d after initial sampling (DAIS), the soil RKN population density averaged only 1.0 and 0.2 juveniles per 100 cm^3 of soil, respectively, with no significant difference between treatments (Table 5). However, RKN population densities increased as the tomato production season progressed. At 64 DAIS, the production system and grafting effects were identified, with high tunnel and open field RKN population densities at 14.3 and 2.3 juveniles per 100 cm^3 of soil, respectively, and nongrafted and grafted tomato plots resulting in RKN population densities at 12.8 and 4.4 juveniles per 100 cm^3

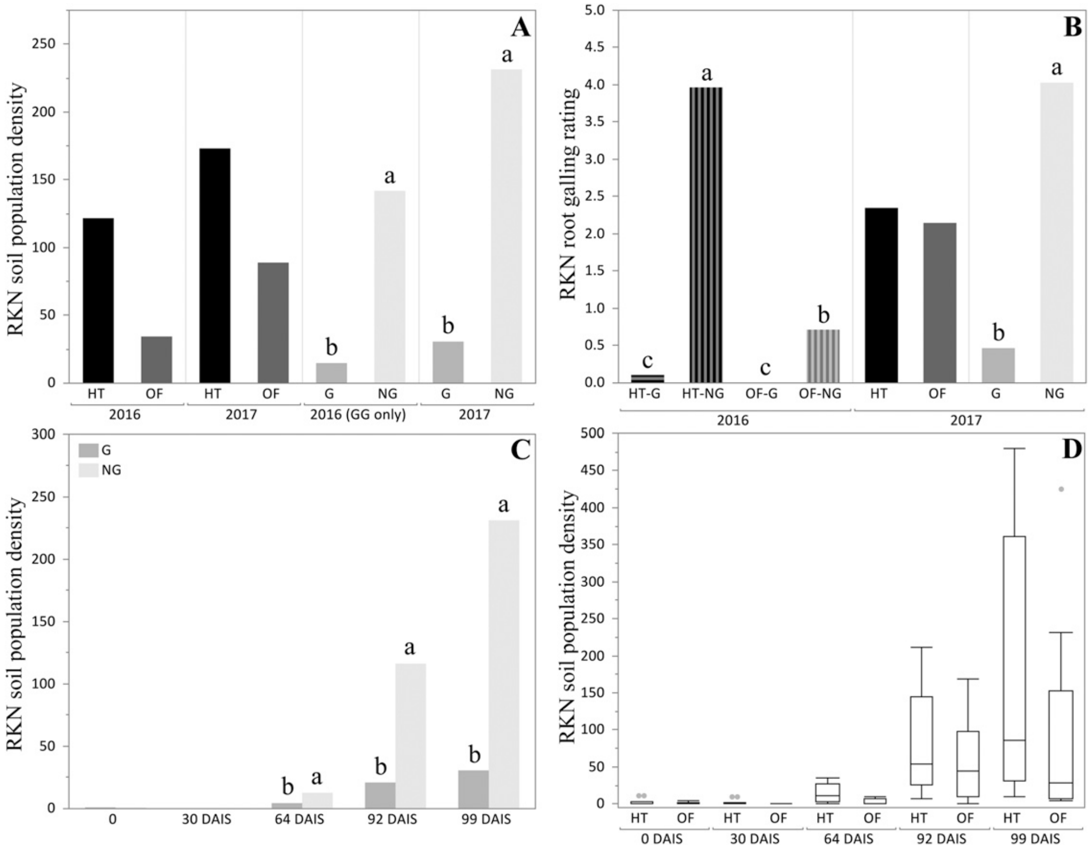

Fig. 3. Root-knot nematode soil population density and tomato root galling rating as affected by the production system and grafting during Spring 2016 and 2017 tomato production seasons in Citra, FL. HT = high tunnel; OF = open field; G = grafted plants; NG = nongrafted plants; DAIS = days after initial sampling. Treatment analyses were separated by date, and the same letters within a single date indicate that the treatments are not significantly different. (**A**) High tunnel and grafting effects on end-of-season root-knot nematode soil population density (juvenile no. per 100 cm^3). (**B**) Root-knot nematode root galling rating (Zeck's 0–10 scale), production system × grafting effects in 2016, and main effects of production system and grafting in 2017. (**C**) Grafting effects on root-knot nematode soil population density (juvenile no. per 100 cm^3) in 2017. (**D**) Box plot of production system effects on root-knot nematode soil population density (juvenile no. per 100 cm^3) in 2017.

Table 5. Effects of the production system, grafting, and tomato cultivar on the soil population density of juvenile root-knot nematodes during the Spring 2017 tomato production season in Citra, FL.

Factor	Initial[z]	30 DAIS	64 DAIS[y]	92 DAIS[y]	99 DAIS[x]
PS	NS	NS	*	NS	0.074
C	NS	NS	NS	NS	NS
G	NS	NS	**	***	***
PS × C	NS	NS	NS	NS	NS
PS × G	NS	NS	NS	NS	NS
C × G	NS	NS	NS	NS	NS
PS × C × G	NS	NS	NS	NS	NS

[z]Initial sampling occurred on 30 Mar., 1 week after the effective transplant date and 3 weeks after the initial planting date.
[y]Data were logarithmically transformed to satisfy statistical assumptions.
[x]99 DAIS is the same as the final sampling date reported in Table 4.
PS = production system; C = cultivar; G = grafting; DAIS = days after initial sampling.
NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively. Actual P values are indicated if $0.05 < P \leq 0.10$ to show data trends when consistent results were found across multiple dates.

of soil, respectively (Fig. 3C). Interestingly, the magnitude of production system differences was greater than that of grafting differences at 64 DAIS. At 92 DAIS, however, only grafting effects were found, with an 81.9% reduction in the population density of RKN. Final sampling occurred just 1 week later, and the production system exhibited a trending difference at P = 0.074; however, grafting continued to show a significant effect on suppressing soil RKN population.

It is important to note that *Meloidogyne* spp. have a very heterogeneous spatial distribution (Duncan and Phillips, 2009). Intensive soil sampling was attempted in the present study to overcome heterogeneity and to obtain better identification of treatment effects, but the variability of the RKN population density remained high (Fig. 3D); therefore, a confidence interval of 90% may be better suited to adequately identify treatment effects. It has not been previously reported that high tunnels increase RKN infestation. Although soil moisture conditions may affect RKN population dynamics, with even slight desiccation greatly affecting RKN juvenile survival and egg viability (Wallace, 1968), soil moisture data indicated that production system differences were negligible; therefore, it was not considered a contributor to the production system differences. It was hypothesized that the differences in RKN incidence and severity were due to a combination of management practices that affect soil temperatures, including the higher soil temperatures in the high tunnels early in the growing season (before the shadecloth was applied) and lower maximum soil temperatures after the shadecloth was applied.

Madulu and Trudgill (1994) reported a base temperature for *M. javanica* of 12.9 °C, and they demonstrated that when soil temperatures were within 12.9 to 30 °C, the thermal time required for a completed life cycle was 350 degree days. At ≥30 °C, the development rate of *M. javanica* declines, requiring more degree days for development. Before the shadecloth was applied, soil microclimate data from the 2017 season indicated that high tunnel temperatures accumulated 12.1% more heat units (range, 12.9 to 30 °C), or 34 additional degree days, than the open field system. After shadecloth application, reduced soil temperatures in the high tunnels resulted in 18.8% more heat units (range, 12.9 to 30 °C), or 137 additional degree days, than the open field. Therefore, the high tunnel production system had a total of 171 more degree days than the open field, which is an addition of almost half of that required for the *M. javanica* life cycle during concurrent growing seasons. At the same time, the high tunnel experienced 28.7% less time at temperatures ≥30 °C, at which development rates of *M. javanica* are expected to be reduced.

Although additional research is needed to confirm the results of this study, findings showed that grafting consistently mitigated the potential disadvantageous high tunnel effects on RKN infestation. This is especially important for growers seeking to use high tunnels for season extension because RKN presence over time clearly demonstrated an exponential trend for nongrafted tomato plants (Fig. 3C). It is unknown, however, if the early-season delay in RKN presence in the tomato crop was primarily due to the time necessary to break dormancy and complete multiple life cycles in the presence of a suitable host, or if it was due to cool spring soil temperatures delaying the onset of dormancy break. Future research is needed to assess time and temperature relations in high tunnel tomato production to understand the implications of the effects of earlier planting dates on RKN populations and plant injury.

The magnitude of root galling as a function of the percent of roots impacted was less than the disease severity ratings as a function of the percent of foliage impacted (data not shown), suggesting that early blight likely had a greater impact on growth and yield parameters than RKN infestation. This may differ during seasons of low foliar disease incidence and severity, or when the nematode population density is high. Soil temperature likely influenced nematode population density and damage in this study, and different mulching systems (black plastic, white plastic, silver plastic, etc.) may have varying effects compared with the hay-mulch system used in this study. Future research is needed to understand production systems, grafting, and mulch-type interactions and to enable growers to maximize high tunnel benefits and minimize potential drawbacks.

Conclusions

Future research is warranted to maximize integrated pest management benefits of high tunnel and grafting technologies in both organic and conventional growing systems and to conduct cost-benefit analyses of each. The primary advantage of high tunnel tomato production in the subtropics was season extension, which was achieved in this study by significantly reducing foliar disease severity compared with that in the open field. Because summer season extension may be challenging in humid subtropical climates, early high tunnel planting should be the primary goal to maximize the high tunnel benefits for spring season tomato production. Future research is needed to establish target high tunnel planting dates and evaluate different tomato trellis systems for optimizing tomato performance while taking into consideration production and market economics.

The primary negative effects of high tunnel production in Florida sandy soils are the potential increase of RKN soil populations and RKN root galling. This new finding demonstrated the need for future research to gain a better understanding of the impact of high tunnel production on RKN infestation and potential management practices in relation to high tunnel season extension. With proper rootstock-scion selection, grafting may reduce potentially unfavorable high tunnel effects of increased RKN infestation; therefore, it may be an important cultural management strategy that can complement high tunnel tomato production, especially in organic systems.

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