Optimal Spacing of Grafted ‘Primo Red’ High Tunnel Tomato

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KEYWORDS. determinate, in-row, plant spacing, rootstock, *Solanum lycopersicum*

ABSTRACT. Grafted and ungrafted ‘Primo Red’ tomato (*Solanum lycopersicum*) transplants were planted at 16-, 20-, and 24-inch spacing in a commercial high tunnel in central New York, USA, to compare yields. ‘Primo Red’ scions were grafted onto ‘Maxifort’ rootstocks and left to heal in a commercial greenhouse facility. Tomatoes were harvested as they ripened, and the weight and number of fruit per plot was recorded and then calculated out to a per-plant basis. Wider plant spacings resulted in higher yields for both grafted and ungrafted plants. However, economic returns remained highest in the highest density (16 inches in-row) spacing with grafted plants. This indicates that growers may not need to adjust density despite additional foliage from grafted plants. Foliar incidence of Botrytis gray mold (*Botrytis cinerea*) was not significantly different under spacing or grafting treatments. Grafting resulted in higher yields across all plant spacings compared with ungrafted plants. Commercial growers can use this information to make choices on grafting and spacing in high tunnel tomato.

As consumer demand for year-round, local produce increases (Low et al. 2015; Martinez et al. 2010), more growers are investing in high tunnel production to extend their growing season. These inexpensive, passively heated structures protect crops from adverse weather conditions, insects, wildlife, and disease (Blomgren and Frisch 2007). Reduced exposure to these abiotic and biotic stressors often results in higher quality and higher yielding crops compared with those grown in the field, which often translates to increased profits for growers depending on the crop, location, production practices, and markets. Tomato (*Solanum lycopersicum*) is the most commonly cultivated crop in high tunnels worldwide and in the United States (Carey et al. 2009; Lamont 2009). According to the US 2017 Census of Agriculture, there are ~10,849 farms with protected environment operations (up 20% from the 2012 census). Of those farms, 7974 (73%) grow tomatoes in a protected setting with an annual value of more than $418 million (US Department of Agriculture, National Agricultural Statistics Service 2019). These values included heated greenhouses and high tunnels.

High tunnels are well suited for tomato production and, in some research, have demonstrated 3 times more profitability than a field-grown crop (Galinato and Miles 2013). In some geographic regions, the controlled environment allows growers to bring tomatoes to market ~3 to 4 weeks earlier compared with field-grown plants, allowing some growers to charge a premium price (O’Connell et al. 2012). While the exclusion of precipitation allows tomato foliage to remain dry, foliar disease is still common in high tunnel tomato production due in part to vigorous foliar growth, reduced air flow, dense plant spacing, and high humidity within the plant canopy. Intensive, year-round cultivation without rotation can also lead to degradation of many soil health parameters as well as buildup of soilborne disease. According to Blomgren and Frisch (2007), high tunnel tomato growers are increasingly having problems with leaf mold (*Passalora fulva*), powdery mildew (*Oidium lycopersici*), and Verticillium wilt (*Verticillium dahlia*), diseases that are not typically an issue in field production in the northeastern United States. High tunnel growers must take care to keep tunnels weed-free, practice good sanitation, monitor air flow and humidity, and provide adequate plant spacing so that the high tunnel environment does not become favorable for the development of foliar and soilborne pathogens. In addition to the aforementioned cultural practices, growers have the option of grafting desirable cultivars to disease-resistant rootstocks, such as Estamino, Maxifort, or Shin Cheong Gang, to combat the many abiotic and biotic stressors that can hinder tomato vigor in protected agricultural settings.

Research has shown that grafting tomato to resistant rootstocks can help manage soilborne diseases such as Fusarium wilt [*Fusarium oxysporum* f.sp. *lycopersici* (Rivard and Louws 2008)], bacterial wilt [*Ralstonia solanacearum* (McAvoy et al. 2012; Rivard et al. 2012)], southern blight [*Sclerotium rolfsii* (Rivard et al. 2010a)], and root-knot nematodes [*Meloidogyne* sp. (Barrett et al. 2012; Rivard et al. 2010a)].

Breeding efforts have produced many disease-resistant rootstocks that can increase plant vigor in grafted scion cultivars compared with ungrafted plants of the same cultivar (Leonardi and Giuffrida 2006; Masterson 2013), although it is not entirely clear which traits contribute to the increased vigor (Guan et al. 2012; Schwarz et al. 2010). It has been hypothesized that the increased plant vigor resulting from the grafted rootstocks may be associated with plant hormone production, the size of the root system and the corresponding increased water uptake, and increased nutrient uptake or efficiency (Albacete et al. 2009; Djidonou

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
0.0149	lb/100 ft	$kg{\cdot}m^{-1}$	67.1969
1.1209	lb/acre	$kg{\cdot}ha^{-1}$	0.8922
0.0254	mil(s)	mm	39.3701
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

et al. 2013; Lee 1994; Leonardi and Giuffrida 2006; Martínez-Ballesta et al. 2010; Rivero et al. 2003; Savvas et al. 2009). One tomato clonal rootstock that has been associated with increased vigor is 'Maxifort'. Numerous studies have found that when used as rootstock, 'Maxifort' resulted in increased total and marketable fruit yields, increased nitrogen-use efficiency, improved water uptake, and reduced disease pressure (Djidonou et al. 2013; Masterson 2013; Rivard et al. 2010a).

Although research has shown that grafting can confer a number of benefits to high tunnel tomato production (Kubota et al. 2008, Lewis et al. 2014; Rivard et al. 2010b), there is a significant cost both to produce and purchase grafted plants. The challenges of using grafted plants include additional labor, cost of seeds, selection of compatible rootstock, fertilizer management, excessive growth, and adventitious scion rooting (Lee 1994). It has been estimated that the production of a grafted tomato transplant costs $0.49 to $0.76 more than an equivalent-sized ungrafted plant; however, the potential savings from reduced pesticide use and increased yields may justify the investment (Rivard et al. 2010b).

The objectives of this study were to determine the effect of plant spacing on yield of grafted vs. ungrafted 'Primo Red' tomato plants and to explore the economics of grafting. 'Maxifort' was selected as the rootstock for this study because it carries resistance genes to many common soilborne diseases in the United States. 'Maxifort' also increases vegetative vigor. Given the additional vigor and foliage of 'Maxifort' grafts, growers may be able to adopt a lower density planting strategy. Suchoff et al. (2015) explored disease susceptibility and production of ungrafted and grafted 'Mountain Fresh' tomato scions onto rootstocks '801' and '802'. Plant spacing and training systems were also evaluated. Although the data they collected was not found to be statistically significant, they noted a trend that grafted plants yield more than ungrafted plants at the same spacing and suggested that further research should be conducted to clarify whether grafted tomato plants will yield more or equal to ungrafted plants at similar spacings. We hypothesized that at a wider spacing (24 inches), the tomato plants will yield more than those planted at a close spacing (16 inches). Furthermore, the yield benefit of grafting will provide an additional boost, such that a smaller population of grafted plants at 24 inches will match or exceed the yield of a higher plant population of ungrafted plants at 16 inches. The excess vigor of grafted plants can result in foliar disease that ultimately reduces the yield benefit of grafting. Wider plant spacing will reduce incidence of foliar disease, allowing grafted plants to realize full yield potential and reduce input costs through fewer transplants and reduced labor.

Materials and methods

'Primo Red F1' (Harris Seed, Rochester, NY, USA) tomato transplants were raised in a heated greenhouse on a grower-cooperator's farm in Yates County, NY, USA. Seeds were sown on 27 Jan 2016 into an open tray and were grafted onto 'Maxifort' rootstock on 24 Feb 2016. Seedling stems at the two-leaf stage were cut on a 45° angle with a double-sided shaving razor blade 1 to 2 cm above cotyledons and held together with a 2.0-mm silicon clip (Silicone Top-Grafting Clip; Johnny's Selected Seeds, Fairfield, ME, USA). First and second true leaves were removed with the razor blade to facilitate clip placement and avoid disturbance of the graft union. Grafted plants were then placed in a grower-built healing chamber for 2 d at 100% relative humidity and an ambient temperature of ~73 °F. At 3 d, plants were placed under shaded greenhouse benches and misted two to three times daily. Healed plants were moved to an upper greenhouse bench surface at ambient temperature and relative humidity by 7 d and misted as needed by the commercial grower. The grafting success rate was 99%. Additional 'Primo Red' transplants were seeded on 13 Feb 2016, potted on 14 Mar 2016, and were left ungrafted. On 11 Apr 2016, the trial was transplanted into a Lima silt loam under a farm-fabricated 34 × 144-ft galvanized steel high tunnel covered with a 6-mil polyethylene film covering (Tufflite IV; Berry Global Inc., Evansville, IN, USA). This soil did not have a documented history of soilborne disease. Transplants were planted at 16-, 20-, or 24-inch in-row spacing into 42-inch-wide, 4-inch-tall raised beds fitted with grower provided black mulch film. Between-row spacing was 5 ft on-center. Walkways were mulched with grower-provided straw. Although light competition between rows is possible with this spacing, the research team adopted this spacing based on the grower standard. This spacing permitted harvest and pruning labor to navigate the rows and treatments without impediment and therefore was not a likely influence on data from parallel rows. The trial occupied the inner three rows of the high tunnel, which had nine rows total. The trial was planted in a randomized complete block design with four blocks and six treatments. The six treatments included 'Primo Red' grafted onto 'Maxifort' planted at 16-, 20-, and 24-inch in-row spacings, and ungrafted 'Primo Red' planted at 16-, 20-, and 24-inch in-row spacings. Each plot contained a total of six plants, for a total of 24 plants representing each treatment. Plot width remained constant as bed width remained constant at 42 inches wide. Plot length varied to accommodate spacing treatments and was either 80, 100, or 120 inches long. Plants were watered via drip tape with 4-inch emitter spacing to root zone saturation three to seven times per week, depending on crop demand. Crop demand for water varied weekly with changes in solar radiation, temperature, and crop maturity. Supplemental forced air heat with a thermostat set point of 54 °F was provided as needed to protect transplants during cold weather events through April and May. Roll-up sides were the primary method of ventilation. The cooperating grower manually rolled side curtains upward to a maximum of 5 ft when indoor air temperature approached 80 °F. Pruning was carried out via the "strong Y" method. In this method, the grower removed lateral growth with a clean, manual snap up the stem, until reaching the first lateral immediately below the first flower cluster. This lateral was left on the plant and became a "strong Y" bifurcation in the stem. Leaves below this "strong Y" were removed manually, flush with the stem. The "strong Y" pruning method was carried out ~4 weeks after transplant. Plants were trellised with commercially obtained twine around a 6-ft wooden stake driven into the soil between every two plants in-row, the twine running horizontally every 6 to 8 inches of the stake. A preplant soil test was not conducted. Fertility was managed uniformly throughout the trial per grower standards. No preplant fertilizers were added to the high tunnel and plots were fertilized with 5 lb/acre nitrogen (N) per week, applied with soluble 9N–6.5P–24.9K plus micronutrients

Table 1. Average yield of grafted and ungrafted 'Primo Red' tomato plants grown at 16-, 20-, and 24-inch in-row spacings in a commercial high tunnel in Yates County, NY, USA, in 2016.

'Primo Red' treatment and in-row spacing[i]	Yield[ii]		Mean fruit wt (lb)[ii]
	Wt (lb/plant)	Fruit (no./plant)	
Grafted to 'Maxifort' rootstock—24 inches	41.6 a[iii]	70.0 a	0.6 a
Grafted to 'Maxifort' rootstock—20 inches	38.4 ab	62.5 ab	0.6 a
Grafted to 'Maxifort' rootstock—16 inches	33.3 bc	56.1 bc	0.6 a
Ungrafted—24 inches	32.6 bc	54.0 bc	0.6 a
Ungrafted—20 inches	33.1 bc	56.0 bc	0.6 a
Ungrafted—16 inches	28.5 c	46.5 c	0.6 a
P value	<0.001	0.001	0.327

[i] The trial was set up in a randomized complete block design with four replications and six plants per treatment per block. Plants were grown in beds equipped with black plastic, drip tape irrigation, and were supported using a stake-and-weave trellis system; 1 inch = 2.54 cm.
[ii] Tomato fruit was harvested at sign of ripening. Weight and fruit number per plot were recorded by the grower-cooperator and then calculated out to a per plant basis; 1 lb = 0.4536 kg.
[iii] Means followed by the same letter in each column are not significantly different according to Fisher's protected leaset significant difference at $\alpha = 0.05$.

(Nutrichem; Miller Chemical & Fertilizer, LLC, Hanover, PA, USA) via 1:100 injector and drip tape system for a season total of 110 lb/acre N. Application was divided between two to three irrigation events per week until September. No insecticides or fungicides were applied to this trial.

One plot (ungrafted 'Primo Red' at the 20-inch spacing in the third replicate) lost two plants to mechanical injury over the course of the trial and was dropped from the trial. To balance the data analysis, an average of the three healthy plots of the same treatment was generated and substituted for the lost data.

Fruit was harvested at sign of ripening by the grower. The grower harvested on 5, 11, 19, and 27 Jul; 1, 9, 15, 25, and 31 Aug; and 7 and 15 Sep 2016. The weight and number of fruit per plot was recorded then calculated out to a per plant basis. Gray mold (*Botrytis cinerea*) severity was rated on an ordinal scale from 0 to 9, where 0 represented no visible infection symptoms, and 9 represented complete plant death. Disease severity was visually rated on 18 Jul, 29 Jul, 11 Aug, 23 Aug, and 13 Sep 2016. Ambient temperatures were not tracked in this study. Our research examined the effect of grafting and spacing on foliar disease, not seasonal influence. Data analysis was conducted using analysis of variance (ANOVA) procedure, with significance determined using Tukey's honestly significant difference test (JMP Pro ver. 14; JMP Statistical Discovery LLC, Cary, NC, USA). There was no interaction between grafting and spacing; therefore, only main effects of spacing and grafting are presented. An economic analysis was conducted using grower-provided data on costs of ungrafted and grafted transplants and labor, which included time spent transplanting, pruning, and harvesting. Price and labor data were not analyzed statistically because it is a single set from a single source.

Results

Wider spacings (20 and 24 inches) generally resulted in higher yields from both ungrafted 'Primo Red' and grafted 'Primo Red' plants in terms of fruit number per plant and yield per plant. We observed a 27% increase in yield between grafted and ungrafted tomato plants at the 16-inch spacing, a 16% increase at the 20-inch spacing, and a 17% increase at the 24-inch spacing (Table 1). The mean individual fruit weights of 'Primo Red' grafted to 'Maxifort' were not significantly higher than mean fruit weight of ungrafted 'Primo Red' at any

Table 2. Yield difference per row of grafted and ungrafted 'Primo Red' tomato plants grown at 16-, 20-, and 24-inch in-row spacings in a commercial high tunnel in Yates County, NY, USA, in 2016.

'Primo Red' treatment and in-row spacing[i]	Plants (no./row)[ii]	Yield (lb/plant)[iii]	Yield (lb/row)[iv]	Yield difference per row (lb)			Yield difference grafted vs. ungrafted (lb)
				From 16 inches	From 20 inches	From 24 inches	
Grafted to 'Maxifort' rootstock—24 inches	50	41.6	2080.0	−425	−224	NA	+535 vs. 24-inch ungrafted
Grafted to 'Maxifort' rootstock—20 inches	60	38.4	2304.0	−201	NA	+224	+318 vs. 20-inch ungrafted
Grafted to 'Maxifort' rootstock—16 inches	75	33.4	2505.0	NA	+201	+425	+368 vs. 16-inch ungrafted
Ungrafted—24 inches	50	30.9	1545.0	−593	−441	NA	−535 vs. 24-inch grafted
Ungrafted—20 inches	60	33.1	1986.0	−152	NA	+441	−318 vs. 20-inch grafted
Ungrafted—16 inches	75	28.5	2137.5	NA	+152	+593	−368 vs. 16-inch grafted

[i] The trial was set up in a randomized complete block design with four replications and six plants per treatment per block. Plants were grown in beds equipped with black plastic and drip tape irrigation and were supported using a stake-and-weave trellis system; 1 inch = 2.54 cm.
[ii] Plant number calculated out to a standard 100-ft (30.48 m) row; 1 plant/100 ft = 0.0328 plant/m.
[iii] Tomato fruit was harvested at sign of ripening. Weight and fruit number per plot were recorded by the grower-cooperator and then calculated out to a per plant basis; 1 lb = 0.4536 kg.
[iv] Yield weight calculated out to a standard 100-ft row; 1 lb/100 ft = 0.0149 $kg \cdot m^{-1}$.
NA = not applicable.

spacing. Across all treatments, fruit produced by 'Primo Red' plants weighed, on average, 1/2 lb. This cultivar normally yields fruits that weigh 1/2 lb (Reid 2012).

Wider plant spacings at 20 and 24 inches resulted in increased yield per plant but not enough to confer a total yield increase per unit of space (row feet). In Table 2, we see that planting at 24 inches instead of 16 inches reduced total plant number by one-third (75 plants per 100-ft row at 16 inches vs. 50 plants per 100-ft row at 24 inches). This decreased plant population translated into labor and seedling cost savings, but these savings did not fully offset the reduced total yield due to a smaller plant population (Table 3). Net revenue per 100-ft row is highest at the 16-inch spacing in both grafted and ungrafted settings, with grafted 'Primo Red' netting the highest revenue ($2005 per 100-ft row). In all plant spacings, grafted plants outperformed ungrafted plants, such that in 100-ft rows, 50 grafted plants at the widest spacing (24 inches) produced a near equivalent yield to 75 ungrafted plants at the narrowest spacing of 16 inches. With the higher foliar density created by the 16- and 20-inch spacings, as well as grafting vigor, there was an opportunity for increased diseases such as gray mold. However, we found no significant differences in disease severity between the treatments in this trial (Table 4).

Discussion

Despite the higher cost of production associated with grafted tomato transplants, high tunnel growers experiencing problems with soilborne diseases can benefit from the increased plant vigor and yields. Comparing yields in this 1-year trial to ungrafted field plantings of 'Primo Red', we see an increase of up to 28.7 lb/plant [41.6 vs. 12.9 lb/plant (Johnson and Ernest 2019)]. Given the additional vigor of grafted plants, commercial growers may consider lower density plantings to avoid foliar diseases and maximize yield per plant. However, yield must be considered over commercial plant spacings. Our study finds that 'Primo Red' grafted tomato transplants will out-yield ungrafted transplants at 16-, 20-, and 24-inch spacings. Furthermore, we find that the additional cost of grafted transplants is offset by the higher yields, resulting in higher

Table 3. Differences in net revenue of grafted and ungrafted 'Primo Red' tomato plants grown at 16-, 20-, and 24-inch in-row spacings in a commercial high tunnel in Yates County, NY, USA, in 2016.

'Primo Red' treatment and in-row spacing[i]	Gross revenue ($/row)[ii]	Trans-plant cost ($/row)[iii]	Labor cost ($/row)[iv]	Net revenue ($/row)[v]	Revenue difference ($/row)[vi] From 16 inches	From 20 inches	From 24 inches	Revenue difference grafted vs. ungrafted ($/row)[vi]
Grafted to 'Maxifort' rootstock—24 inches	$2,080	$150	$180	$1,750	–$255	–$154	NA	+$435
Grafted to 'Maxifort' rootstock—20 inches	$2,304	$180	$220	$1,904	–$101	NA	+$154	+$198
Grafted to 'Maxifort' rootstock—16 inches	$2,505	$225	$275	$2,005	NA	+$101	+$255	+$217
Ungrafted—24 inches	$1,545	$50	$180	$1,315	–$473	–$391	NA	–$435
Ungrafted—20 inches	$1,986	$60	$220	$1,706	–$82	NA	+$391	–$198
Ungrafted—16 inches	$2,138	$75	$275	$1,788	NA	+$82	+$473	–$217

[i] The trial was set up in a randomized complete block design with four replications and six plants per treatment per block. Plants were grown in beds equipped with black plastic and drip tape irrigation and were supported using a stake-and-weave trellis system. Data presented per row is based on a 100-ft (30.48 m) row; 1 inch = 2.54 cm.
[ii] Gross revenue was calculated by multiplying the estimated total yield per treatment on a 100-ft row basis by $1.00/lb ($2.2046/kg). The price of $1.00/lb was provided by the grower. This price was based on the average wholesale value of tomatoes sold 3× per week over the course of the growing season at the Finger Lakes Produce Auction, Penn Yan, NY, USA; $1/100 ft = $0.0328/m.
[iii] Data on cost of the ungrafted transplants and grafted transplants was provided by the grower. The ungrafted 'Primo Red' transplants cost $1.00/plant, and the grafted 'Primo Red' to 'Maxifort' rootstock transplants cost $3.00/plant. Total cost of transplants was calculated out on a 100-ft row basis.
[iv] The cost of labor was calculated based on an hourly rate of $10.00 per hour. Labor was calculated via grower interview and local prevailing farm labor wage at the time of the trial. Labor included transplanting, pruning, and harvesting. Management is not included in the estimate. Labor costs were calculated out on a 100-ft row basis.
[v] Net revenue was calculated by subtracting production costs (including transplant costs and labor costs) from the gross revenue (price per unit × marketable yield per 100-ft row).
[vi] Row length used in calculations is 100 ft. Revenue difference per 100-ft row was calculated by comparing the net revenue of grafted and ungrafted 'Primo Red' at 16-, 20, and 24-inch in-row plant spacings.
NA = not applicable.

Table 4. Gray mold severity on grafted and ungrafted 'Primo Red' tomato plants grown at 16-, 20-, and 24-inch in-row spacings in a commercial high tunnel in Yates County, NY, USA, in 2016.

'Primo Red' treatment and in-row spacing[i]	Gray mold severity (0–9 scale)[ii]				
	18 Jul	29 Jul	11 Aug	23 Aug	13 Sep
Grafted to 'Maxifort' rootstock—24 inches	1.6[iii]	1.4	3.3	4.0	4.0
Grafted to 'Maxifort' rootstock—20 inches	1.8	1.5	3.8	4.0	4.0
Grafted to 'Maxifort' rootstock—16 inches	1.8	1.5	3.3	4.0	3.9
Ungrafted—24 inches	2.0	1.5	3.0	4.1	3.8
Ungrafted—20 inches	2.1	1.3	3.0	3.9	3.8
Ungrafted—16 inches	1.6	1.0	2.8	3.8	3.3

[i] The trial was set up in a randomized complete block design with four replications and six plants per treatment per block. Plants were grown in beds equipped with black plastic and drip tape irrigation and were supported using a stake-and-weave trellis system; 1 inch = 2.54 cm.

[ii] Botrytis gray mold rated on a 0–9 ordinal scale, where 0 represented no visible infection symptoms and 9 represented complete plant death. Ratings are averaged over four replicates.

[iii] No significant differences were found at $\alpha = 0.05$, using Tukey's honestly significant difference.

net revenues for grafted tomato systems at all plant spacings. We find that net revenue is highest for grafted and ungrafted transplants at the 16-inch plant spacing, despite the additional foliage of the grafted plants. The data also show that although not as profitable, the 20-inch spacing of grafted transplants was more profitable than all of the ungrafted transplants. Previous research has found that the economic viability of tomato grafting differs depending on the type of tomato production system, with net returns lowest in conventional field production and organic high tunnel tomato production systems and highest net returns in conventional multibay tunnel production (Rysin et al. 2015). Economic viability of tomato grafting may also be influenced by the scion cultivar and rootstock cultivar, soilborne disease pressure, increases in farm labor costs, and economies of scale. Our data demonstrate that the additional cost and labor of grafting tomato plants is justified while maintaining a dense plant spacing of 16 inches in-row.

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