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The use of grafted plants to lessen the impacts of abiotic and biotic stresses is increasing in U.S. open field- and high tunnel-based production. Growers can purchase or prepare their own grafted plants. Regardless, all who prepare grafted plants benefit from research-based information regarding the compatibility of various rootstock-scion combinations and the growth of rootstock and scion variety seedlings before grafting. Rootstock and scion seedlings can be grafted only when their stem diameters are similar and approximately 1.5-3.0 mm. Therefore, the relative growth rate of rootstock and scion seedlings strongly influences sowing and grafting schedules. Genetically or physically mismatched rootstock and scion seedlings can have significant negative consequences. To our knowledge, the number of commercially available rootstock varieties has increased nearly 10-fold in approximately six years but information regarding rootstock compatibility and seedling vigor is largely unavailable. We documented the growth rate of eighteen tomato rootstock and five scion varieties and tested the graft survivorship and performance of ninety potential rootstock-scion combinations representing growers' production needs and goals.

Materials and Methods

Plant Materials and Seeding Conditions

Eighteen tomato commercial rootstock and five scion varieties were selected based on grower input and our familiarity with varieties. Tomato growers throughout the Midwest and North-Central U.S. were contacted directly through the collaboration and use of 19 organic certifying agencies, 25 grower associations, five trade publications, four listservs, and 11 farmer groups. Information, particularly about disease resistance, of commercial tomato rootstocks was obtained from seed catalogues and seed company websites. Grower input was used in variety selection. Collectively, the rootstock varieties were developed by 12 companies and contain approximately 11 disease tolerance/resistance packages. The selected scion varieties represent hybrid and heirloom and round- and oblong-fruited types. A list of the rootstock varieties included in the study and their characteristics are shown in Table 1 and in a reference table updated annually (www.vegetablegrafting.org/wp/wp-content/uploads/2012/08/usda-scri-etal-tomato-rootstock-table-feb2013-mk-1.pdf).

Two rounds of growth and compatibility evaluations were completed February-April, 2014 in a climate-controlled greenhouse located at the Ohio Agricultural Research and Development Center in Wooster, OH. In the greenhouse, the average temperature was 74 °F, relative humidity

was 37%, and photosynthetically active radiation (PAR) was 130 µmol $m^{-2}s^{-1}$ during round 1; the average temperature was 75°F, relative humidity was 46%, and PAR was 197 µmol $m^{-2}s^{-1}$ during round 2. Seed were sown on February 25, 27, 28, and March 1, 2014 for round 1; and on March 26, 28, and April 2, 2014 for round 2. All seed were sown into 96-cell trays filled with PRO-MIX® MP MYCORRHIZAE™ Organik™ (Premier Tech, Canada) growing medium. Trays were placed on capillary mat on a bench with an automatic irrigation system.

Stem Diameter Growth Measurement

Stem diameter was measured 1 cm below the cotyledons 12, 15, and 18 days after sowing. One more measurement was taken 26 days after sowing on the three slowest-growing varieties (Trooper, Estamino, and RST-04-105) in round 1. The data were fit to a linear model using Proc Reg in SAS (version 9.3; SAS Institute, Cary, NC). R square of each fitting was from 0.47 to 0.90 in round 1 and 0.43 to 0.88 in round 2. Estimated parameters in the linear model were used to calculate predicted days needed to reach 1.5 mm and 3.0 mm (the minimum and maximum stem diameter suitable for grafting) in Microsoft Excel (2010). The days to reach 3.0 mm were out of the range of actual measurement; therefore, they are projections.

Grafting Procedure and Healing Conditions

The day of emergence was noted for each plant. Plants were grafted when they reached 1.5 to 2.5 mm in stem diameter. Plants of each variety that emerged within the same three-day period and that were similar in size were selected in order to minimize within-variety plant to plant variation. In round 1, grafting days were March 19, 21, 24, and 25, 2014; in round 2, grafting days were April 12, 14, 15, 16, 18, and 21, 2014. The cleft graft method (hcs.osu.edu/vpslab/grafting-guide) was used to graft all plants. Rootstock and scion seedlings at similar growth stage and with matching stem diameters were selected.

Immediately after grafting, plants were placed in a healing chamber in the same greenhouse room used for seedling production for two weeks until evaluation. The healing chamber was constructed and used as described previously (hcs.osu.edu/vpslab/grafting-guide) using a polyvinyl chloride (PVC) frame covered by one layer of clear plastic sheeting overlain by one layer of shade cloth (47% light transmission in PAR). Within the chamber, an automatic irrigation system with drippers and foggers was used to maintain high moisture. The four sides of the healing chamber were opened gradually over time, as weather and plant status allowed, to lower relative humidity and limit adventitious root development. Temperature and relative humidity in the healing chamber were recorded continuously at 5-min intervals with Hobo ProV2 data loggers (version 2.5.0, Onset Computer Co., Pocasset, MA, USA) throughout the study. The average temperature in the healing chamber during round 1 was 73°F and relative humidity was 87%; during round 2, the average temperature and relative humidity was 74°F and 88%, respectively.

Graft Survivorship Assessment

Two weeks after grafting, graft survival was rated based on scion appearance using metrics as described previously (hcs.osu.edu/vpslab/grafting-guide; Johnson and Miles, 2011). Grafted plants with completely wilted scions were regarded as dead while all other plants were scored as living. The number of living plants was counted for each combination, and survivorship was calculated as the number of living plants divided by the total number of plants grafted for each combination.

Survivorship data were collected for 90 rootstock-scion combinations. Due to the limited grafting capacity of a grafter on a day, the experiment was conducted using an augmented design. Ninety rootstock-scion combinations were assigned to grafters randomly, and grafted on different days as soon as plants grew to 1.5-2.5 mm in stem diameter. Each grafter and graft day combination was treated as a block. Self-grafted Cherokee Purple was used as the common control and repeated twice within each block at random. Twelve grafted plants were grafted for each combination. The experiment was repeated twice in February-March and March-April 2014, within the months allotted for commercial propagation of grafted tomato seedlings.

Data analysis was conducted by the Proc Glimmix procedure in SAS (version 9.3; SAS Institute, Cary, NC). Survivorship was the response variable, and rootstock, scion, rootstock*scion interaction and block were treated as fixed effects. Treatment means were separated using a pdiff option in the LSMEANS statement at α=0.05. The Tukey method was applied for multiple comparison adjustment to analyze the differences in least square means.

On-farm Evaluation of Grafted Plants

Growers were invited to nominate their farm as a site for the summertime evaluation of grafted plants prepared in phase 1 of the study. Invitations to self-nominate their farm were issued to growers through the collaboration and use of 24 organic certifying agencies, 13 grower associations, representatives of six industry trade publications, five seed companies, and four grower-oriented listservs operating in the Midwest and North Central U.S. Requests to participate in the evaluation exceeded the number of plants available for distribution by three-fold. A total of 86 growers submitted requests through an online form (www.hcs.osu.edu/vpslab). Growers were selected on a first come, first serve basis by order of receipt of request and then by state the grower was located in. A total of approximately 1,000 grafted plants representing 90 rootstock-scion combinations were shipped in mid-April, 2014 to 31 growers in 13 states for on-farm evaluation.

Results and Discussion

Predicted days needed for each variety to grow to 1.5 mm and 3.0 mm in stem diameter varied among varieties (Table 2). In round 1, Arnold and Trooper needed 16 and 30 days to reach 1.5 mm, the shortest and longest times among tested varieties, respectively. Most varieties needed 17-21 days to reach 1.5 mm stem diameter, although RST-04-105 and Estamino were found to require longer: 23 and 24 days respectively. In round 2, Kaiser and Trooper required 10 and 19 days to reach 1.5 mm diameter (the shortest and longest among all varieties, respectively) while most varieties required 12-15 days to reach 1.5 mm stem diameter. The five scions required an intermediate amount of time to reach 1.5 mm stem diameter (19 or 20 days in round 1 and 13 or 14 days in round 2), although San Marzano 2 was estimated to require 17 and 12 days in rounds 1 and 2, respectively. The amount of time that varieties were found or projected to attain stem diameters of 1.5 m-3.0 mm (the grafting window) ranged from 10 to 25 days in round 1 and 6 to 16 days in round 2.

Survivorship in either round of evaluation did not differ significantly among the 90 rootstock-scion combinations tested here (Table 3). Graft survival exceeded 92% in all combinations (Table 4) with a studywide average of 97%. However, survivorship differed by day of grafting and grafter in round 2 (p=0.02).

Growers continue to provide quantitative and qualitative information from on-farm evaluations of grafted plants provided to them. The information will be submitted for inclusion in the 2015

Midwest Vegetable Trial Report. A preliminary assessment of information available to date suggests that grafted plant performance varied by rootstock-scion combination and farm and that growers remain interested in additional evaluations and data on grafted plant performance.

We documented the seedling growth rate of 18 commercial rootstock and five scion varieties and the percent survivorship of 90 grafted combinations. We also tracked graft survivorship by grafter and day of grafting and provided grafted plants to 31 growers in 13 states for evaluation. We learned that: a.) growth rates, including stem diameters, which are important in grafting, vary significantly among rootstock varieties; b.) that the growth rates of many rootstock varieties may differ from scion varieties; c.) that graft survivorship may differ less than growth rates; d.) that grafter and grafting-day conditions may influence survivorship; e.) that on-farm performance of grafted plants is likely to differ among rootstock-scion combinations and locations; and f). that growers remain strongly interested in grafted plants as production tools. Based on these findings, genetic incompatibility may be less of a concern than scheduling rootstock and scion sowing and grafting periods, identifying skilled grafters, and optimizing the condition of grafting stock and grafting-healing room conditions.

Acknowledgments

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Table 1. List of 18 commercial tomato rootstock and five scion varieties used in this study.

Rootstock Variety	Seed Company/ Distributor	Rootstock Variety	Seed Company/ Distributor	Scion Variety	Seed Company/ Distributor
Aiboh	Asahi Industries	Kaiser	Rijk Zwaan	Brandywine	NE Seed
Akaoni	Asahi Industries	Maxifort	DeRuiter Seeds	Better Boy	NE Seed
Aooni	Asahi Industries	Resistar	Hazera Seeds	Celebrity	NE Seed
Armada	Takii Seed	RST-04-105	DP Seeds	Cherokee Purple	NE Seed
Arnold	Siegers Seed Co.	RST-04-106	DP Seeds	San Marzano 2	NE Seed
B.B.	Takii Seed	Shield	Rijk Zwaan		
Beaufort	DeRuiter Seeds	Stallone	Rijk Zwaan		
Cheong Gang	Seminis Vegetable	Supernatural	A.P. Whaley Seeds		
Estamino	Enza Zaden	Trooper	Seedway		

Note 1. None of the seed used in this study were treated.
Note 2. Seed of only Kaiser and Stallone were pelleted; all other seed were not pelleted.
Note 3. Seed of only Arnold, Beaufort, Kaiser, Maxifort, Shield, and Stallone were primed; all other seed were not primed.

Table 2. Predicted days after sowing to reach 1.5 mm and 3.0 mm stem diameter (the range over which plants can be grafted reliably) of 18 tomato rootstock and 5 scion varieties. Each bar is bounded on the left and right by the days at which stem diameter is expected to be 1.5 mm and 3.0 mm, respectively. White color bars represent round 1 and gray color bars represent round 2.

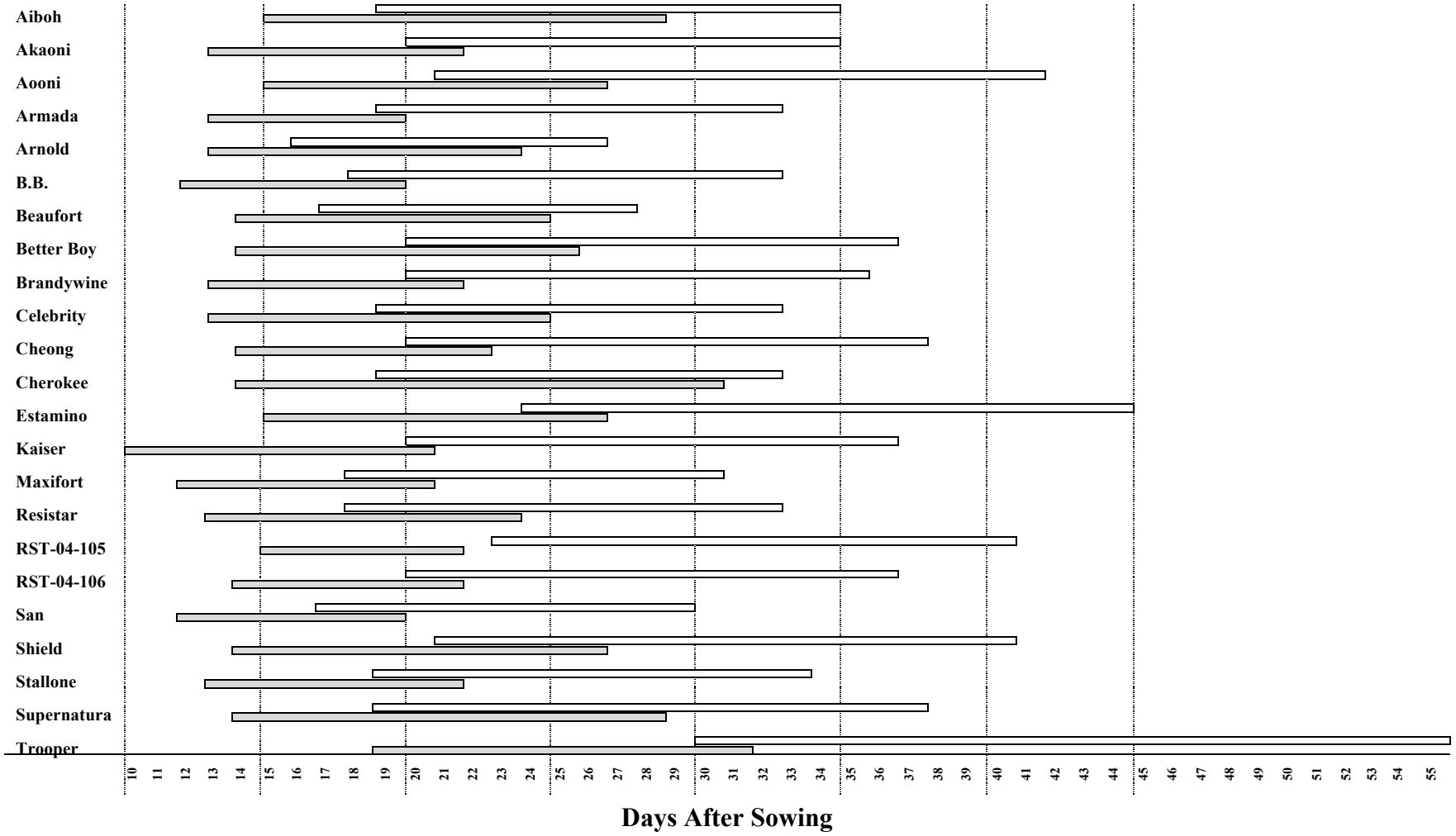

Table 3. Type III tests of fixed effects (rootstock, scion, rootstock*scion interaction, and block) on survivorship using the GLIMMIX procedure (SAS version 9.3; SAS Institute, Cary, NC).

Effect	Survivorship			
	Round 1		Round 2	
	DF	*p*	DF	*p*
rootstock	17	0.65	17	0.52
scion	4	0.82	4	0.97
rootstock*scion	68	0.99	68	0.64
block	17	0.52	14	0.02

Table 4. Graft survivorship (%) of 18 tomato rootstocks and five scions. N=10 for rootstock, N=36 for scion, N=66 for self-grafted control. Data are presented as means ± SE.

Variety	Survivorship
Rootstock	
Aiboh	97 ± 1
Akaoni	100 ± 0
Aooni	97 ± 1
Armada	97 ± 1
Arnold	97 ± 1
B.B.	92 ± 3
Beaufort	99 ± 1
Cheong Gang	98 ± 1
Estamino	98 ± 1
Kaiser	96 ± 3
Maxifort	98 ± 1
Resistar	98 ± 1
RST-04-105	99 ± 1
RST-04-106	97 ± 1
Shield	95 ± 3
Stallone	98 ± 2
Supernatural	95 ± 3
Trooper	100 ± 0
Self-grafted control	95 ± 1
Scion	
Brandywine	97 ± 1
Better Boy	98 ± 1
Celebrity	95 ± 1
Cherokee Purple	98 ± 1
San Marzano 2	97 ± 1
Self-grafted control	95 ± 1