Grafting onto Tomato Rootstocks Improves Outcomes for Dry-farmed Tomato

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KEYWORDS. blossom-end rot, DRO141TX, drought, Fortamino, *Solanum lycopersicum*

ABSTRACT. Vegetable grafting can mitigate the negative effects of drought on crop production. Dry farming, which is the production of crops without irrigation during a dry growing season, can result in lower yields, smaller fruit, and a higher incidence of blossom-end rot (BER), which is a physiological disorder associated with drought stress. To determine the effects of grafting on yield and fruit quality of dry-farmed tomato (*Solanum lycopersicum*), three years of trials were conducted using different scion–rootstock combinations and ungrafted controls. In 2020, grafting onto rootstocks 'DRO141TX' and 'Fortamino' resulted in greater total yield and average fruit weight and a lower BER incidence for dry-farmed tomato than grafting onto the rootstock 'Shincheonggang' or using ungrafted plants. In 2021, grafting onto the rootstock 'DRO141TX' again increased yields and average fruit weight and decreased BER incidence when compared with ungrafted plants ('Fortamino' was not tested). Interactions were detected between different scion–rootstock combinations in terms of the degree of reduction of necrotic BER (BER resulting in a large, sunken, grey or black spot, making the fruit unmarketable) when grafted onto 'DRO141TX', with the scion 'Azoychka' having a 69% reduction in necrotic BER and the scion 'Astrakhanskie' having a 93% reduction in necrotic BER. In 2022, an interaction was detected between the rootstocks and scions in terms of their effect on large fruit (>0.33 lb) yield, with 'BHN 871' grafted onto 'Fortamino' producing the highest yields of large fruit and 'Big Beef' grafted onto 'Fortamino' producing the lowest yields. Overall, grafting onto the rootstocks 'DRO141TX' or 'Fortamino' improved diverse dry-farmed tomato outcomes in the Willamette Valley of Oregon, USA.

Drought is one of the most important factors limiting crop productivity and food security (Kumar et al. 2017). Vegetable grafting has been proposed as a way to mitigate the effects of drought on crop production (Altunlu and Gul 2011; Fuentes-Merlos et al. 2022; Khapte et al. 2022; Kumar et al. 2017; Poudyal et al. 2015; Schwarz et al. 2010). Tomato (*Solanum lycopersicum*) grafting is a "surgical alternative to breeding" and produces a physical hybrid between a desired rootstock and scion genotype (Albacete et al. 2015). Rootstocks for tomato are often intraspecific hybrids, including crosses between cultivated tomato and *Solanum habrochaites* or cultivated tomato and *Solanum pennellii* (Khapte et al. 2022; Poudyal et al. 2015; Suchoff et al. 2018). Grafting can improve plant performance through increased vigor and improved resistance to soil-borne disease and abiotic stressors such as drought (Altunlu and Gul 2011; Fuentes-Merlos et al. 2022; Khapte et al. 2022; Kumar et al. 2017; Poudyal et al. 2015). Rootstock traits that improve resistance to drought stress include improved root traits such as larger root dry weight and higher root-to-shoot ratio, changes in scion–rootstock communication, i.e., improved signaling and hormonal changes, and changes in scion morphology and physiology such as reduction in stomata density, improved osmoregulation, and higher antioxidant activity (Kumar et al. 2017). Others have suggested that the grafting process (including self-grafting) improves drought stress tolerance through changes in gene expression of the apical meristem (Fuentes-Merlos et al. 2022). Although grafting does increase seedling production costs, and Rivard and Louws (2011) estimated $0.51 to produce an ungrafted seedling and $1.25 to produce a grafted seedling, studies have shown that improved yields and lower input requirements can result in higher net revenue (Suchoff et al. 2018).

Some farmers along the U.S. Pacific Coast practice dry farming, which is the production of crops without the use of irrigation during a dry growing season (Garrett 2019; Leap et al. 2017). Although yields are lower for dry farm crops than irrigated crops, dry farming allows farmers to grow in fields without water rights or investments in irrigation infrastructure. Dry-farmed tomato is a popular crop in coastal California, and the cultivar Early Girl is preferred by growers and consumers (Leap et al. 2017). However, many tomato cultivars, including Early Girl, are susceptible to the physiological disorder blossom-end rot (BER), especially if dry-farmed in hotter, drier climates, as found in the Willamette Valley of Oregon, USA (Davis et al. 2023). Additionally, BER can be delineated by degree of severity. When BER on a fruit is less severe, it results in a grey speckled blemish on the bottom of the fruit (referred to as light BER in this work) (Fig. 1). Some farmers will still sell these fruits (personal observation). When BER is more severe, it results in a large, sunken, grey or black spot, making the fruit unmarketable (referred to as necrotic BER in this work). The direct cause of BER may be either oxidative stress or calcium deficiency (or both), and both have been associated with drought stress (Hagassou et al. 2019; Saure 2014; Taylor and Locascio 2004). Dry farmers are interested in grafting tomato because it may reduce drought stress, increase yields, increase average fruit weight, and reduce the incidence of physiological disorders like BER. The primary purpose of these trials was to determine how different rootstocks affect the yield and fruit quality (both the average fruit weight and incidence of BER in this work) of dry-farmed tomato. The secondary purpose was to identify scion–rootstock combinations that performed best in a dry farm setting.

Materials and methods

We conducted trials of dry-farmed tomato in the mid-Willamette Valley during the 2020, 2021, and 2022 growing seasons. Scion–rootstock combinations and ungrafted cultivars were assessed for yield and fruit quality. Scions were selected because they were reported to be BER-resistant or were regional farm or seed company favorites. Rootstock cultivars were selected based on what was grown by regional farms and/or available as organic seed.

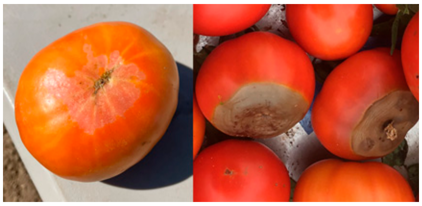

Fig. 1. The severity of blossom-end rot (BER) of tomato can vary. (Left) An example of less severe BER. This results in a grey speckled blemish on the bottom of the fruit referred to as light BER. Some farmers will sell these fruits (personal observation). (Right) An example of more severe BER, resulting in a large, sunken, grey or black spot, making it the fruit unmarketable (referred to as necrotic BER). Adapted from Stone et al. (2024).

The scion–rootstock combinations and ungrafted cultivars analyzed in this work were a subset of those trialed from 2020 to 2022 (additional data are included in Supplemental Table 1).

Each year, transplants were produced at organic farms in the Willamette Valley. The grafted plants were produced at Gathering Together Farm in Philomath, OR, USA (lat. 44.5304°N, long. 123.3713°W). Grafted materials were started approximately 2 weeks before ungrafted materials to compensate for delays in growth during the grafting and healing process. Rootstocks were sown in 2-inch pots, and scions were sown in 200-cell flats. The propagation greenhouse at Gathering Together Farm is 30 ft × 200 ft, custom-made with poly covering, and is heated using a greenhouse heater (GreenGro 220 Plus; L.B. White Company, LLC, Onalaska, WI, USA). Plants were splice-grafted following the protocol of Rosskopf and Pisani (2017). Trays are covered with humidity domes and placed onto covered benches (Fig. 2). The chamber is heated to 82 °F using greenhouse heating tubing (MicroClimate; BioTherm Solutions, Cotati, CA, USA). As the plants healed, light and ambient air were gradually reintroduced into the chambers. After ≈7 d, the plants were removed from the healing chamber and grown in the greenhouse before planting.

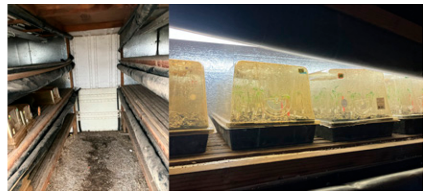

Fig. 2. Healing chambers used for tomato grafting at Gathering Together Farm in Philomath, OR, USA. (Left) The inside of the healing room. Within the room are six benches that can be covered. (Right) One of these benches in use. Grafted plants heal within humidity domes.

Because of space constraints at Gathering Together Farm, we grew ungrafted plants at two additional organic farms. Seeds were sown into 200-cell flats at Eloisa Organic Farm LLC in Albany, OR, USA (lat. 44.6592°N, long. 123.1003°W). This heated greenhouse had a semi-gabled style and was 30 ft wide and 110 ft long (GK Machine Inc., Donald, OR, USA). After developing four true leaves, the plants were moved to Avoca Seed Farm in Corvallis, OR, USA, and up-potted in 2-inch pots. Avoca Seed Farm has an unheated gothic-style greenhouse (OBC Northwest, Canby, OR, USA).

A complete list of all scion–rootstock combinations used in this analysis can be found in Table 1. In 2020, two replications of 18 different scion–rootstock combinations and six ungrafted scions were trialed. One replication was grown at the Oregon State University Vegetable Research Farm (VRF) (lat. 44.5712°N, long 123.2428°W). The second replication was grown at a nearby organic farm. Rootstocks trialed were 'DRO141TX' (De Ruiter, St. Louis, MO, USA), 'Fortamino' (Enza Zaden, Salinas, CA, USA), and 'Shincheonggang' (Banner Greenhouses, Nebo, NC, USA). Scions trialed were 'Big Beef' (Johnny's Selected Seeds, Winslow, ME, USA), 'BHN 871' (Johnny's Selected Seeds), 'Early Girl' (W. Atlee Burpee & Co., Warminster, PA, USA), 'Momotaro' (Fedco Seeds, Clinton, ME, USA), 'New Girl' (Johnny's Selected Seeds), and 'Wisconsin 55' (Johnny's Selected Seeds). The following three of these scion–rootstock combinations were only present at VRF because of low survival after grafting: 'Big Beef'–'Fortamino', 'Momotaro'–'Fortamino', and 'Wisconsin 55'–'Fortamino'. In 2021, there were five replications of grafted (on 'DRO141TX') and ungrafted 'Astrakhanskie' (Adaptive Seeds, Sweet Home, OR, USA), 'Azoychka' (Adaptive Seeds), 'Baylor Paste' (Adaptive Seeds), 'Cosmonaut Volkov' (High Mowing Organic Seeds, Wolcott, VT, USA), and 'Marmande' (Adaptive Seeds). Each replication was grown at a different farm. In 2022, five replications of 'Big Beef' and 'BHN 871' grafted onto 'DRO141TX' and 'Fortamino' were grown. Each replication was grown at a different farm.

Plots were randomized within each site, except for the VRF trials during 2021 and 2022. In these trials, grafted and ungrafted tomato plants were grown in adjacent sections of the field, with a border of grafted plants around the grafted section and a border of ungrafted plants around the ungrafted section. This was to maintain more representative growing conditions; we were concerned that grafted plants would outcompete ungrafted plants for water, leading to overyielding in the grafted plants and underyielding in the ungrafted plants. In 2022, the order of plots within these sections at the VRF was randomized; however, in 2021 the plots within the sections were planted in alphabetical order.

Each scion–rootstock combination was grown as a five-plant plot within each farm (except when there were insufficient plant materials to plant a five-plant plot). In 2020 and 2021, trials were planted with 5-ft between-row and 3-ft in-row spacing. The only exception was the 2020 on-farm trial, which was planted with 5.5-ft between-row and 4-ft in-row spacing. In 2022, all

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Table 1. Complete list of all dry-farmed tomato scion–rootstock combinations used in the analysis. Each number indicates the number of replications (plots) included for that scion–rootstock combination for that year. Rootstocks are separated by column. Scions are separated by row for each year. For scion–rootstock combinations with more than one plot in a single year, these plots were at different farms. If there was only one plot, then that plot was at the Oregon State University Vegetable Research Farm.

	'DRO141TX'[i]	'Fortamino'[i]	'Shincheonggang'[i]	'Ungrafted'
Scion	Number of replications			
2020				
'BHN 871'[i]	2	2	2	2
'Big Beef'[i]	2	1	2	2
'Early Girl'[i]	2	2	2	2
'Momotaro'[i]	2	1	2	2
'New Girl'[i]	2	2	2	2
'Wisconsin 55'[i]	2	1	2	2
2021				
'Astrakhanskie'[i]	5			5
'Azoychka'[i]	5			5
'Baylor Paste'[i]	5			5
'Cosmonaut Volkov'[i]	5			5
'Marmande'[i]	5			5
2022				
'BHN 871'	5	5		
'Big Beef'	5	5		

[i] Seed sources for the listed rootstock cultivars are as follows: DRO141TX was from De Ruiter (St. Louis, MO, USA); Fortamino was from Enza Zaden (Salinas, CA, USA); and Shincheonggang was from Banner Greenhouses (Nebo, NC, USA). Seed sources for the listed scion cultivars are as follows: BHN 871, Big Beef, New Girl, and Wisconsin 55 were from Johnny's Selected Seeds (Winslow, ME, USA); Astrakhanskie, Azoychka, Baylor Paste, and Marmande were from Adaptive Seeds (Sweet Home, OR, USA); Cosmonaut Volkov was from High Mowing Organic Seeds (Wolcott, VT, USA); Early Girl was from W. Atlee Burpee & Co. (Warminster, PA, USA); and Momotaro was from Fedco Seeds (Clinton, ME, USA).

trials were planted with 6-ft between-row and 2.5-ft in-row spacing. At each farm, a border was planted around the trial tomato plants.

Soil series and soil available water holding capacity were determined following the protocol found in Davis et al. (2023). Temperature and relative humidity were monitored using temperature and relative humidity dataloggers (Kestrel Drop D2 Wireless Temperature and Humidity Data Logger; Nielsen-Kellerman Co., Boothwyn, PA, USA) at each trial site, with data logged every 10 min. These data were used to determine the average daily maximum temperature (°F), average daily minimum temperature (°F), and average daily maximum vapor pressure deficit (hPa) at each site from 22 Jun to 20 Sep. Rainfall data were collected for each site from 1 Apr to 1 Oct using a weather database (PRISM Climate Group 2023). Soil samples were collected at each site on the day of planting and were analyzed at A&L Laboratories (Portland, OR, USA). Trial site data are provided in Table 2.

The dry-farmed tomato field at the VRF rotated to a new location each year to prevent the buildup of soil-borne diseases. A cover crop of common vetch (*Vicia sativa*), triticale (×*Triticosecale*), and annual fescue (*Vulpa myuros*) was fall-seeded, grown, and incorporated in the VRF field each year before planting. The VRF field was prepared for planting each year by subsoiling (910 5 Shank Ripper; Deere & Company, Moline, IL, USA), disking (Kello-Bilt Model 225; Kello-Bilt Inc, Red Deer County, AB, Canada), and power harrowing (Kuhn HR 3504 D; KUHN Group, Saverne, Bas-Rhin, France). Granular chicken manure (Nutri-Rich 4N–1.3P–1.7K Granular Fertilizer; Stutzman Environmental Products, Inc., Canby, OR, USA) and pelletized feather meal (Pro-Pell-It! Feather Meal 12N–0P–0K; Marion AG Services, Inc., St. Paul, OR, USA) were applied and incorporated before planting to achieve a total rate of 156 lb/acre N (1500 lb/acre of granular chicken manure and 800 lb/acre of pelletized feather meal) at the VRF in 2020 and 2021. In 2022, this was decreased to 120 lb/acre N (1100 lb/acre of granular chicken manure and 630 lb/acre of pelletized feather meal). Farmers participating in on-farm trials used their usual cover cropping, amendments, and bed preparation methods. These are not detailed here.

Planting dates are listed in Table 2. Seedling trays were sub-irrigated to saturate soil media before planting. Tomato plants were watered-in after planting with 1 L of water per plant. Plants were grown without support, except for at one on-farm trial in 2022, during which a basket weave was used. Tomato plants were not pruned. Fields were clean-cultivated using cultivating tractors (Model G; Allis-Chalmers Manufacturing Company, West Allis, WI, USA), wheel hoes, and hand tools.

Each year at the VRF, a number of plants were infected by an unknown virus and removed from the field. These plots were missing one to three plants. Yield and fruit count data were extrapolated based on the area of the plot, not by the number of plants.

In 2020 and 2021, grafted plants at the VRF showed signs of powdery mildew (*Erysiphe* sp./spp.). In 2022, the fungicide Kaligreen (OAT Agrio Co., Ltd., Tokyo, Japan) was sprayed at the VRF on 3 Aug, 13 Aug, 24 Aug, and 3 Sep using a backpack sprayer (SOLO 451 Backpack Mist Blower; SOLO Incorporated, Newport News, VA, USA) following the label rate.

Tomatoes were harvested weekly. In 2020, weekly harvests occurred from 16 Jul to 29 Sep (11 weeks) at the VRF, and from 30 Jul to 8 Oct for the on-farm trial (10 weeks). Because of wildfire smoke, harvests were suspended on 8 Sep and resumed on 17 Sep. In 2021, weekly harvests occurred from 13 Jul to 20 Sep (10 weeks) at the VRF and 22 Jul to 24 Sep (9 weeks) for on-farm trials. In 2022, weekly harvests occurred from 2 Aug to 4 Oct (9 weeks) at the VRF, and from 5 Aug to 7 Oct (9 weeks) for on-farm trials. All tomatoes that were ripe or at color-break were picked from each plot. The only exception to this occurred at the VRF from 31 Aug to 29 Sep 2020; during this time, only three plants per plot were picked to reduce demand for labor.

For each plot at each weekly harvest, tomatoes were weighed (lb/plot)

Table 2. Data of trial site the following characteristics: soil series; available water holding capacity (AWHC); planting date; soil fertility data including soil pH, soil nitrate concentration (NO_3), soil phosphorus concentration (P), soil potassium concentration (K), and soil calcium concentration (Ca) from a depth of 0 to 6 inches[i]; average daily maximum temperature, average daily minimum temperature, and average daily maximum vapor pressure deficit (VPD) from 22 Jun to 20 Sep; total rainfall from 1 Apr to 1 Oct. Notes for each year of the trial and each farm are also presented. Farms include the Oregon State University Vegetable Research Farm (VRF) and six others. Farms with the same number were included in multiple years of trials.

Yr	Farm	Soil series AWHC (inches)[i]	Planting date	pH	NO_3 (ppm)[i]	P (weak Bray, ppm)[i]	K (ppm)[i]	Ca (ppm)[i]	Avg daily maximum temp (°F)[i]	Avg daily minimum temp (°F)[i]	Avg daily maximum VPD (kPa)[i]	Total rainfall (inches)[i]	Notes
2020	VRF	Chehalis Silty clay loam 12	8, 10, 11 May	5.9	46	93	168	2503	83.4	51.5	2.6	8.68	
	1	Malabon Silty clay loam 12	14 May	6.4	65	128	396	3821	85.0	52.2	2.7	8.63	
2021	VRF	Chehalis Silty clay loam 12	12 May (ungrafted), 17 May (grafted)	6.2	34	81	304	2391	86.0	51.8	2.8	5.66	
	2	Woodburn Silt loam 12	28 May	5.9	8	160	162	1567	87.1	52.8	3.1	7.01	
	3	Chapman Loam 8	18 May	6.7	36	166	900	2193	87.7	52.5	3.1	5.95	
	4	Amity Silty clay loam 11	13 May	6.3	42	148	201	2889	87.6	52.4	3.1	6.33	
	5	Chapman Loam 10	25 May	6.2	24	61	472	2018	87.0	52.4	3.0	6.15	
2022	VRF	Chehalis Silty clay loam 12	24, 25 May	6.0	12	69	240	2818	85.9	53.0	2.7	12.95	Tillage pan from 12–20 inches[i]
	2	Woodburn Silt loam 12	31 May	6.3	21	182	231	1916	87.3	51.9	2.9	14.04	
	3	Chehalis Silt loam 11	16 May	5.2	17	171	1126	2558	87.2	53.3	2.8	13.05	
	4	Amity Silty clay loam 11	16 May	5.7	43	157	277	4054	86.6	53.7	2.9	13.62	
	6	Transitional soil Silt loam 9	17 May	6.5	11	56	943	4514	85.4	51.3	2.7	19.82	

[i] 1 inch = 2.54 cm, 1 ppm = 1 $mg \cdot kg^{-1}$, (°F-32) ÷ 1.8 = °C, 1 kPa = 1 cbar.

and counted (fruit/plot), and then fruit were sorted by the level of BER (no BER, light BER, and necrotic BER), and fruit with BER were counted and weighed again. Tomatoes with light BER had gray speckling on the blossom end, whereas tomatoes with necrotic BER had a black sunken spot. These data were used to determine total yield (ton/acre), total fruit (fruit/acre), average fruit weight (lb/fruit), proportion of fruit with BER (based on fruit count, not fruit weight), and proportion of fruit with necrotic BER. Total yield and total fruit data included fruit with and without BER. In 2020, BER data collection at the VRF was suspended after the harvest on 7 Sep. In 2022, we also separated fruit based on weight, with large fruit being those with a weight greater than 0.33 lb. The total weight of these large fruit was used to determine the total large fruit yield (ton/acre).

A data analysis was performed using statistical software (R version 4.1.3) (R Core Team 2022; RStudio Team 2018). Data from each year were analyzed separately because they were unbalanced between years. Mixed-effects models were used to test the main effects of rootstock and scion, as well as their interactions, on the mean total yield, mean total large fruit yield, mean total fruit count, and mean average fruit weight (Bates et al. 2015). For these models, scion, rootstock, and scion:rootstock were included as fixed effects, and farm was included as a random intercept. Thus, each year was tested as if it had a randomized complete block design with each farm being a block. Unequal variance suggested linear model assumptions were not met for the response variables "average fruit weight" in 2020 and "total fruit count" and "average fruit weight" in 2021; therefore, data were log-transformed. A type III analysis of variance with Satterthwaite's method was used to determine whether the effect of scion:rootstock, rootstock, and scion were statistically significant at an α level 0.1 (Fox and Weisberg 2018). Generalized linear mixed-effects modeling with a binomial distribution was used to determine the effects of scion, rootstock, and scion:rootstock on proportional metrics, including the mean proportion of fruit with BER and mean proportion of fruit with necrotic BER, with farm included as the random intercept and total plot fruit count used as weights (Bates et al. 2015). However, these models were overdispersed; therefore, they were refit using a beta-binomial distribution (Brooks et al. 2017). Type III Wald χ^2 tests were used to determine whether the effects of scion:rootstock, scion, and rootstock were statistically significant. The estimated marginal means and *SE* were calculated for each model, and mean separation was conducted using Tukey's honest significant difference (Lenth 2020). Means and *SE*s were back-transformed for presentation. All means reported are from the full models.

Results

In 2020, the main effect of rootstock was statistically significant for the response variables total yield ($P < 0.001$), total fruit count ($P = 0.001$), average fruit weight ($P < 0.001$), BER incidence ($P < 0.001$), and necrotic BER incidence ($P < 0.001$) (Table 3). No interactions between rootstocks and scions were detected during the 2020 growing season; therefore, the main effect of rootstock is presented for that year (Table 4). Grafting scions onto 'DRO141TX' increased the mean total yield by 109%, mean total fruit count by 41%, and mean average fruit weight by 48%, and decreased the mean BER incidence by 77% and mean necrotic BER incidence by 85% for dry-farmed tomato compared with ungrafted controls. Grafting onto 'Fortamino' increased the mean total yield by 71% and mean average fruit weight by 52%, and decreased the mean BER incidence by 77%. 'DRO141TX' also resulted in a higher mean total yield than 'Fortamino'. Grafting onto the rootstock 'Shincheonggang' did not affect the dry farm performance when compared with ungrafted controls.

In 2021, the main effect of rootstock was statistically significant for the response variables total yield, total fruit count, average fruit weight, BER incidence, and necrotic BER incidence (all $P < 0.001$). Grafting scions onto 'DRO141TX' increased mean total yield by 108%, mean total fruit count by 52%, and mean average fruit weight by 40%, and decreased the mean BER incidence by 78% for dry-farmed tomato compared with ungrafted controls (Table 4).

Interactions between rootstock and scion were not statistically significant for the response variables total yield, total fruit count, average fruit weight, and BER incidence. However, there was an interaction detected between rootstock and scion in terms of their effect on the mean necrotic BER incidence ($P = 0.048$). After investigating this interaction, we found that tomato scions differed in the degree of improvement, with the largest decrease in necrotic BER for the scion 'Astrakhanskie' (93% decrease in necrotic BER), which also had the highest mean necrotic BER incidence when grown as an ungrafted plant (Table 5).

In 2022, we tested the scions 'Big Beef' and 'BHN 871' grafted onto both 'DRO141TX' and 'Fortamino'. The main effect of rootstock was not statistically significant for any of the response variables. When modeling the mean total tomato yield, there was evidence of an interaction between rootstock and scion (at an α level of 0.1). However, Tukey's honest significant difference tests did not find statistically significant differences between the scion–rootstock combinations in terms of the mean total tomato yield (Table 6). There was an interaction between the scion–rootstock combinations in the mean total large fruit yield (at an α level of 0.05). 'BHN 871' on 'Fortamino' had the highest mean total large fruit yield, whereas 'Big Beef' on 'Fortamino' had the lowest. Scions differed in terms of the mean incidence of necrotic BER. The scion 'BHN 871' had a higher mean necrotic BER incidence (11% for BHN 871, 6% for Big Beef).

Discussion

Grafting onto the rootstocks 'DRO141TX' and 'Fortamino' improved dry-farmed tomato yields. Although improvements in dry-farmed tomato total yield, total fruit count, and average fruit weight may be the result of reduced drought stress, improved vigor and growth of grafted plants may also be factors. Studies have found that grafting increases yields and average fruit weight under drip irrigation (Jenkins et al. 2022; Reid et al. 2023; Turhan et al. 2011) and overhead irrigation (Caradonia et al. 2023).

Grafting onto 'DRO141TX' and 'Fortamino' also reduced the incidence of BER for dry-farmed tomato. Reductions in BER are likely the result of improved resistance to drought stress conferred by the rootstock (Saure 2014). However, for some scion–rootstock

Table 3. **Probability values from the type III analysis of variance (ANOVA) using Satterthwaite's method and type III Wald χ^2 tests of main effects (scion and rootstock) and scion–rootstock interaction for dry-farmed tomato yield and fruit quality parameters.**

	Scion	Rootstock	Scion–rootstock interaction
	2020		
Total yield (ton/acre)[i,ii]	0.033**[iii]	<0.001****	0.522
Total fruit count (fruit/acre)[i,ii]	<0.001****	0.001***	0.515
Avg fruit weight (lb/fruit)[i]	<0.001****	<0.001****	0.360
BER incidence (proportion)	0.043**	<0.001****	0.209
Necrotic BER incidence (proportion)	0.003***	<0.001****	0.143
	2021		
Total yield (ton/acre)	<0.001****	<0.001****	0.396
Total fruit count (fruit/acre)	<0.001****	<0.001****	0.911
Avg fruit weight (lb/fruit)	<0.001****	<0.001****	0.123
BER incidence (proportion)	0.094*	<0.001****	0.251
Necrotic BER incidence (proportion)	0.262	<0.001****	0.048**
	2022		
Total yield (ton/acre)	0.512	0.647	0.068*
Total large fruit yield (ton/acre)[i,ii]	0.055*	0.240	0.024**
Total fruit count (fruit/acre)	0.989	0.745	0.242
Avg fruit weight (lb/fruit)	0.983	0.535	0.320
BER incidence (proportion)	0.268	0.247	0.993
Necrotic BER incidence (proportion)	0.045**	0.289	0.972

[i] 1 ton/acre = 2.2417 $Mg\cdot ha^{-1}$, 1 fruit/acre = 2.4711 fruit/ha, 1 lb = 0.4536 kg.
[ii] Per-acre total yield and total fruit count were extrapolated from five-plant plot data (not shown) based on the area of each plot.
[iii] Statistical significance of type III ANOVA with Satterthwaite's method and type III Wald χ^2 tests is indicated.
*, **, ***, **** Significant at $P < 0.1$, 0.05, 0.01, or 0.001 respectively.
BER = blossom-end rot.

combinations on certain farms, BER was still a problem. For example, grafted 'Big Beef' and 'BHN 871' in 2022 had a relatively high mean BER incidence, ranging from 21% (95% confidence interval, 14%–32%) for 'Big Beef'–'Fortamino' to 30% (95% confidence interval, 20%–42%) for 'BHN 871'–'DRO141TX'. The mean BER incidence for 'BHN 871'–'DRO141TX' was not that different from the mean BER incidence found by Davis et al. (2023) for ungrafted dry-farmed 'Early Girl' tomato of 38%. The increased BER incidence in 2022 may have been a result of the effect of the farm because the BER incidence can vary considerably by farm (Davis et al. 2023). Although grafting onto certain rootstocks appears to reduce BER, site factors and management practices at a given farm may also contribute to BER incidence.

It should be noted that ungrafted controls were not "self-grafted"; therefore, some of the improvements in yield and fruit quality may have been the result of the grafting process itself (i.e., cutting the scion and reattaching to the rootstock), and not the genetics of the rootstock per se. Although Fuentes-Merlos et al. (2022) found that the grafting process (including self-grafting) generated drought stress tolerance through gene expression changes in the apical meristems, the majority of studies have not found any effect of self-grafting on yield when compared with ungrafted plants (Grieneisen et al. 2018). The varying efficacy of different rootstocks and scion–rootstock interactions indicates that genetics are at least partially responsible for the effect of grafting.

Although the rootstocks 'Fortamino' and 'DRO141TX' improved the dry-farmed tomato performance in 2020, the rootstock 'Shincheonggang' did not. The improved performance of certain rootstock cultivars over others in grafted tomato has been correlated with rootstock traits such as total root length, root surface area, root dry weight, and other measures of root architecture (Bayındır and Kandemir 2023).

Table 4. **Main effect of rootstock on the estimated marginal means for total yield, total fruit count, average fruit weight, blossom-end rot (BER) incidence, and necrotic BER incidence for dry-farmed tomato in 2020 (two replications) and 2021 (five replications).**

Rootstock	Total yield (ton/acre)[i,ii]	Total fruit count (10,000 fruit/acre)[i,ii]	Avg fruit wt (lb/fruit)[i]	BER incidence (proportion)	Necrotic BER incidence (proportion)
			Mean (*SE*)[iii]		
			2020		
'DRO141TX'[iv]	46.3 (9.4) A[v]	30.4 (5.1) A	0.31 (0.04) A	0.077 (0.016) B	0.018 (0.006) B
'Fortamino'[iv]	38.0 (9.5) B	25.0 (5.3) AB	0.32 (0.04) A	0.078 (0.019) B	0.001 (1.119) AB
None	22.2 (9.4) C	21.6 (5.1) B	0.21 (0.02) B	0.336 (0.035) A	0.117 (0.027) A
'Shincheonggang'[iv]	25.0 (9.4) C	22.4 (5.1) B	0.23 (0.03) B	0.323 (0.027) A	0.095 (0.022) A
			2021		
'DRO141TX'	32.4 (2.8) A	22.0 (1.8) A	0.28 (0.03) A	0.046 (0.013) B	Interaction (Table 5)
'None'	15.6 (2.8) B	14.5 (1.2) B	0.20 (0.02) B	0.212 (0.036) A	

[i] 1 ton/acre = 2.2417 $Mg\cdot ha^{-1}$, 1 fruit/acre = 2.4711 fruit/ha, 1 lb = 0.4536 kg.
[ii] Per-acre total yield and total fruit count were extrapolated from five-plant plot data (not shown) based on the area of each plot.
[iii] Values are estimated marginal means ± *SE*. Estimated marginal means and *SE*s reported for average fruit weight (both 2020 and 2021) and total fruit count (2021 only) data back-transformed from log-transformed data.
[iv] Seed sources for listed rootstock cultivars are as follows: DRO141TX was from De Ruiter (St. Louis, MO, USA); Fortamino was from Enza Zaden (Salinas, CA, USA); and Shincheonggang was from Banner Greenhouses (Nebo, NC, USA).
[v] Values not sharing a common letter within a column are significantly different (Tukey's honest significant difference; $P < 0.05$).

Table 5. Effect of scion–rootstock interaction on the estimated marginal means for necrotic blossom-end rot (BER) incidence for dry-farmed tomato in 2021, with five replications.

Scion–rootstock	Necrotic BER incidence (proportion)
	Mean (*SE*)[i]
'Astrakhanskie'[ii]–'DRO141TX'[ii]	0.024 (0.011) CD[iii]
'Azoychka'[ii]–'DRO141TX'	0.023 (0.011) CD
'Baylor Paste'[ii]–'DRO141TX'	0.038 (0.014) BCD
'Cosmonaut Volkov'[ii]–'DRO141TX'	0.018 (0.009) CD
'Marmande'[ii]–'DRO141TX'	0.010 (0.005) D
'Astrakhanskie'–None	0.335 (0.050) A
'Azoychka'–None	0.074 (0.022) BC
'Baylor Paste'–None	0.126 (0.029) B
'Cosmonaut Volkov'–None	0.059 (0.019) BCD
'Marmande'–None	0.045 (0.016) BCD

[i] Values are estimated marginal means ± *SE*.
[ii] Seed sources for listed cultivars are as follows: DRO141TX was from De Ruiter (St. Louis, MO, USA); Astrakhanskie, Azoychka, Baylor Paste, and Marmande were from Adaptive Seeds (Sweet Home, OR, USA); and Cosmonaut Volkov was from High Mowing Organic Seeds (Wolcott, VT, USA).
[iii] Values not sharing a common letter within a column are significantly different (Tukey's honest significant difference; $P < 0.05$).

Farmers benefit from understanding which rootstocks maximize the performance of each scion (Clingeleffer et al. 2019). Thus, interactions between rootstocks and scions must be examined. We found some evidence for scion–rootstock interactions. For example, in 2022 the scion 'BHN 871' had higher yields of large fruit when grafted onto 'Fortamino', whereas 'Big Beef' had higher yields of large fruit when grafted onto 'DRO141TX'. Others who have examined scion–rootstock interactions in tomato have found effects on fruit yield (Mauro et al. 2020), fruit count (Gong et al. 2022a) fruit quality (Gong et al. 2022b; Mauro et al. 2020), sensory evaluation (Jukić Špika et al. 2021), volatile compound concentration (Jukić Špika et al. 2021), and fruit titratable acidity (Ingram et al. 2022; Mauro et al. 2020). However, others have found no evidence of interactions between rootstocks and scions in terms of their effect on yield (Gong et al. 2022a; Ingram et al. 2022). It should be noted that all of these studies were conducted with irrigation supplied.

It is also important to investigate interactions between rootstocks, scions, and environment. This work aimed to explore grafting under a particular environmental context, i.e., dry farming. It is easy to imagine that if the farms had been irrigated, then there would not have been an improvement in BER from grafting (Moreno et al. 2019). Although we did not explore the effect of farm during this study, there may be interactions between rootstock, scion, and farm, with some scion–rootstock combinations performing better on certain farms. The readers should understand that the degree of improvement in dry-farmed tomato production observed during this study are not guaranteed; however, grafting onto 'DRO141TX' and 'Fortamino' did appear to improve outcomes of dry-farmed tomato when compared with ungrafted scions.

Although grafting onto 'DRO141TX' and 'Fortamino' increased yield and reduced BER, other considerations and tradeoffs should be investigated. Grafting may also affect the dry matter, soluble solids concentration, titratable acidity, and texture, and these may affect consumer preference (Al-Harbi et al. 2017; Ingram et al. 2022; Turhan et al. 2011; Urlić et al. 2020). This is especially important because the increased intensity of flavor is cited as a reason to dry-farm tomato (Leap et al. 2017). Additionally, the effect of grafting on other physiological disorders of dry-farmed tomato, including yellow shoulder, cracking, and sunscald, should be investigated. Finally, grafting may affect the susceptibility of dry-farmed tomato to certain soil-borne diseases and foliar diseases such as powdery mildew. During the course of this study, we observed that grafted dry-farmed tomato seemed to be more susceptible to powdery mildew than ungrafted dry-farmed tomato. This was noted during both 2020 and 2021 at the VRF. It is possible that grafted plants are more susceptible to powdery mildew because increased aboveground growth reduces airflow (Calabro et al. 2009; Hong et al. 2012).

Table 6. Effect of scion–rootstock interaction on the estimated marginal means for total yield, total large fruit yield (yield of fruit with weight >0.33 lb), total fruit count, average fruit weight, blossom-end rot (BER) incidence, and necrotic BER incidence for dry-farmed tomato in 2022, with five replications.

Scion–rootstock	Total yield (ton/acre)[i,ii]	Total large fruit yield (ton/acre)[i,ii]	Total fruit count (10,000 fruit/acre)[i,ii]	Avg fruit wt (lb/fruit)[i]	BER incidence (proportion)	Necrotic BER incidence (proportion)
	Mean (*SE*)[iii]					
'BHN 871'[iv]–'DRO141TX'[iv]	33.7 (5.2)	26.8 (5.5) AB[v]	15.6 (2.1)	0.41 (0.04)	0.300 (0.051)	0.129 (0.030)
'Big Beef'[iv]–'DRO141TX'	36.1 (5.2)	27.5 (5.5) AB	17.4 (2.1)	0.43 (0.04)	0.255 (0.047)	0.069 (0.021)
'BHN 871'–'Fortamino'[iv]	36.5 (5.2)	28.7 (5.5) A	17.1 (2.1)	0.42 (0.04)	0.253 (0.046)	0.095 (0.025)
'Big Beef'–'Fortamino'	31.6 (5.2)	22.0 (5.5) B	16.0 (2.1)	0.41 (0.04)	0.214 (0.042)	0.049 (0.018)

[i] 1 ton/acre = 2.2417 $Mg \cdot ha^{-1}$, 1 fruit/acre = 2.4711 fruit/ha, 1 lb = 0.4536 kg.
[ii] Per-acre total yield, total large fruit yield, and total fruit count were extrapolated from five-plant plot data (not shown) based on the area of each plot.
[iii] Values are estimated marginal means ± *SE*.
[iv] Seed sources for listed cultivars are as follows: DRO141TX was from De Ruiter (St. Louis, MO, USA); Fortamino was from Enza Zaden (Salinas, CA, USA); and BHN 871 and Big Beef were from Johnny's Selected Seeds (Winslow, ME, USA).
[v] Values not sharing a common letter within a column are significantly different (Tukey's honest significant difference; $P < 0.05$).

Conclusions

In 2020, grafting scions onto 'Fortamino' and 'DRO141TX' rootstocks improved dry-farmed tomato yield and average fruit weight and reduced BER incidence when compared with ungrafted plants. That same year, the rootstock 'Shincheonggang' did not improve the dry farm performance. In 2021, grafting on 'DRO141TX' tended to improve the dry-farmed tomato performance, and Fortamino was not tested. In 2022, there were few differences detected between 'DRO141TX' and 'Fortamino' in terms of their effect on dry-farmed tomato performance.

Climate change is creating hotter and drier summers in the Willamette Valley of Oregon, which will make dry-farmed tomato production riskier (Davis et al. 2023). Grafting has the potential to increase yield and reduce the BER incidence of dry-farmed tomato. Therefore, it will be a critical tool for reducing the risk of dry-farmed tomato crop failure under conditions of increased drought stress.

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