horticulturae

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Effect of Grafting Compatibility on Fruit Yield and Quality of Cantaloupe in a Mediterranean-Type Climate

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Abstract: Grafting is effectively used worldwide to overcome abiotic and biotic factors impacting yield, including soil temperature. Field studies were conducted in 2020 and 2021 in a cool Mediterranean climate (average daily air temperature range of 12.8–17.1 °C) to identify suitable rootstock combinations for grafted cantaloupe (*Cucumis melo* var. *reticulatus*) and evaluate fruit yield and quality. Cantaloupe cultivars Sugar Rush (SR), Goddess (G), and Athena (A) were compatible with interspecific hybrid squash (*Cucurbita maxima* × *C. moschata*) rootstock cultivars Super Shintosa (SS) and Carnivor (CN) but were incompatible with 'Carolina Strongback (CS)' (*Citrullus amarus*) and 'Pelop (P)' (*Lagenaria siceraria*) rootstocks. Nongrafted cultivars exhibited vine decline at harvest in 2020 but not in 2021, and grafting tended to delay harvest by 15–18 days. Overall, while grafting with interspecific hybrid squash rootstocks may have delayed fruit harvest, fruit quality was not compromised. Further, yield was increased for 'Goddess' and 'Athena', but not 'Sugar Rush'. 'A/CN' had the highest fruit yield/ha and number per plant. The grafted treatments of each cantaloupe cultivar with interspecific hybrid squash rootstocks met the U.S. fancy grade criteria.

Keywords: *Cucumis melo* var. *reticulatus*; northwest Washington; soil temperature; sudden wilt

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Citation: Shrestha, S.; Mattupalli, C.; Miles, C. Effect of Grafting Compatibility on Fruit Yield and Quality of Cantaloupe in a Mediterranean-Type Climate. *Horticulturae* **2022**, *8*, 888. https://doi.org/10.3390/horticulturae8100888

Received: 30 August 2022
Accepted: 24 September 2022
Published: 28 September 2022

1. Introduction

Cantaloupe (*Cucumis melo* var. *reticulatus*) is a popular fruit in the U.S. currently accounting for 24% of the U.S. melon market [1,2]. Cantaloupe is a warm season crop with optimal growth occurring in the range of 30–35 °C and is sensitive to temperature below 10 °C [3–5]. California is the largest producer of cantaloupe in the U.S. accounting for 64% of the production, while Arizona, Florida, and Georgia also have significant production [2]. Cantaloupe production in a Mediterranean-type climate is limited by the relatively cool summer climate. However, there is a strong market demand for locally produced specialty fruit and vegetable crops throughout the U.S., particularly in urban and metropolitan areas.

Cantaloupe and other specialty melons grown in cooler weather may experience vine decline or sudden wilt, which is characterized by rapid wilting of vines and plant collapse late in the season and can occur due to pathological, cultural, or abiotic factors [6–8]. Similarly, cold stress can cause wilting in addition to reduced leaf expansion and chlorosis leading to necrosis. Grafting has been used for decades in Asia and Europe to prevent biotic and abiotic-induced stresses and promote plant growth [9,10]. For example, cantaloupe grafted onto low temperature tolerant interspecific hybrid squash (*Cucurbita maxima* × *C. moschata*) rootstocks and grown at an average minimum soil temperature of 19.7 °C for a 3-week period after transplanting exhibited improved growth and less wilting than nongrafted plants [11]. Interspecific hybrid squash rootstocks can reduce the risk of severe growth inhibition when melon, watermelon, cucumber, and summer squash are grown at low soil temperatures in a greenhouse production system [12]. Rootstocks of interspecific hybrid squash, *Cucumis melo* genotypes, *Cucumis metuliferus* and *Benincasa hispida* have also provided tolerance against abiotic and biotic stress in melon [13–18].

The performance of a grafted plant depends on the properties of the scion and rootstock genotypes, the compatibility between scion and rootstock, environmental conditions, and cultivation methods [19,20]. Grafting compatibility is generally related to taxonomic affinity but there are noteworthy exceptions [21]. For example, 'Arava' melon (*C. melo* var. *reticulatus*) showed higher compatibility with *C. moschata* × *C. moschata* rootstock cultivars RS59 and RS90 (100% plant stand on average) compared to RS58 and RS60 (34% plant stand on average) [22]. Graft incompatibility has negative impacts on xylem and/or phloem functionality resulting in low survival rate, abnormal growth, and low yield [23–28]. Due to the variation of graft compatibility even between closely related species, it is necessary to evaluate graft compatibility before considering the use of a rootstock with a specific scion genotype [12,29].

Fruit quality is important for cantaloupe marketability. A minimum of 11% and 9% total soluble solids (TSS) are considered 'very good internal quality' (U.S. fancy grade) and 'good internal quality' (U.S. no. 1 grade), respectively [30]. The production environment, cultivation methods, types of scion-rootstock combinations used, and/or fruit maturity at harvest can affect grafted melon fruit yield and quality [31,32]. For example, 'Arava' grafted onto interspecific hybrid squash produced fruit with reduced TSS and decreased sensory ratings while 'Honey Yellow' (*C. melo* var. *inodorus*) grafted onto the same rootstock and grown in the same production environment had TSS and sensory ratings similar to nongrafted plants [33]. 'Supermarket' and 'Proteo' (*C. melo* var. *reticulatus*) grafted onto 'P360' (*C. moschata* × *C. maxima*) rootstock had similar TSS as nongrafted plants, but TSS was reduced when grafted onto *Benincasa hispida* rootstock [18].

Studies on field production of grafted melons in a cool Mediterranean-type climate such as northwest Washington are limited to watermelon but not cantaloupe [34–36]. Rootstocks may have optimal soil temperature and moisture ranges and it is important to assess scion-rootstock combinations under the climatic and geographic conditions where the crop will be produced [31]. Thus, the goal of this study was to provide growers in a Mediterranean-type climate with recommendations for grafted cantaloupe by identifying suitable grafting combinations and evaluating fruit yield and quality.

2. Materials and Methods

Field studies were carried out in 2020 and 2021 at the Washington State University Mount Vernon Northwestern Washington Research and Extension Center (WSU NWREC), Mount Vernon, WA, USA (lat. 48.438142, long. −122.386337, elevation 6 m). The region has a Mediterranean climate, and the 20-year average air temperature, precipitation, and relative humidity (RH) during the summer growing season (June through September) were 15 °C (average maximum 21 °C and average minimum 10.5 °C), 170 mm, and 80%, respectively [37]. The experimental site has a Skagit silt loam soil with a pH of 6.4 and 2.7% organic matter [38].

The experiment had a randomized complete block design with 15 grafting treatments (Table S1), 3 replications and 12 plants per plot. Raised beds (Rain-Flo 2600; Rain-Flo Irrigation, East Earl, PA, USA) were 15–20 cm high, 0.8 m wide and spaced 3 m center-to-center and were mulched with black soil-biodegradable plastic mulch (BDM) (17.8 µm, 1.2-m-wide; Organix Solutions, Grove, MN, USA). Wide spacing between rows was used to facilitate fruit harvest and data collection. Transplant holes were made with a custom dibble in a single row on the center of the bed with 0.9 m in-row spacing. Cantaloupe cultivars Sugar Rush (SR) (Harris Seeds, Rochester, NY, USA), Goddess (G) (Osborne Quality Seeds, Mount Vernon, WA, USA), and Athena (A) (Syngenta Seeds, Minneapolis, MN, USA) were selected for the study based on their lower number of days to maturity (65–75 d) combined with their market popularity. Cantaloupe cultivars were grafted onto four cold-tolerant commercially available rootstocks: *Citrullus amarus* cultivar Carolina Strongback (CS) (Syngenta Seeds, Minneapolis, MN, USA), two interspecific hybrid squash cultivars Super Shintosa (SS) and Carnivor (CN) (Syngenta Seeds, Minneapolis, MN, USA), and *Lagenaria siceraria* cultivar Pelop (P) (Rijk Zwaan, Salinas, CA, USA). Non-grafted cantaloupe cultivars served as control treatments. 'Carolina Strongback' is a new citron melon rootstock that has not been tested with cantaloupe for grafting. Interspecific hybrid squash and *Lagenaria* rootstocks are generally recommended for melon grafting [39]. One-cotyledon method [40] of grafting was used in both years since this approach has a high survival rate for cucurbit crops. The grafted plants were transplanted in the field with the graft union at least 2.5 cm above the soil line, on 1 June 2020 and 20 May 2021. In 2020, fertilizer (23N-0P-10K-1.9Mg; Wilbur-Ellis, San Francisco, CA, USA) was applied at the rate of 118 kg·ha^{-1} of nitrogen, and in 2021, fertilizer (16N-7P-13K; Wilbur-Ellis, San Francisco, CA, USA) was applied at the rate of 112 kg·ha^{-1} of nitrogen. Fertilizer was applied to the center of each row with a 1.8 m drop-spreader (Gandy, Owatonna, MN, USA) and was incorporated when raised beds were formed. Drip irrigation tape (T-Tape, Model 508-08-340, 0.20 mm, 20-cm emitter spacing, 4.23 L·min^{-1} per 100 m flowrate; Rivulis, San Diego, CA, USA) and BDM were laid out while forming beds. Irrigation was applied once a week for 1 to 3 h, starting 1 week before transplanting and ending 1 week before last harvest each year.

2.1. Environmental Variables

Air temperature, RH, solar radiation, and rainfall data during the 2020 and 2021 cropping seasons were collected from the WSU AgWeatherNet station [37] located approximately 140 m away from the experimental field plots.. Temperature and moisture probes (S-TMB-M002 and S-SMC-M005, respectively; Onset Computer, Corp., Bourne, MA, USA) were placed 10-cm deep in the center of each experimental plot of the second replicate under the nearest drip emitter to the plant, and average soil temperature and volumetric water content were measured every 15 min using data loggers (HOBO; Onset Computer Corp.). Thermal unit accumulation was calculated for both air and soil temperatures with a base temperature of 10 °C [3].

2.2. Plant Growth Assessments

Plant growth assessments made during the 2020 and 2021 growing seasons are described in Table 1.

2.3. Fruit Harvest

Fruit was assessed for maturity two times per week in 2020 and three times per week in 2021 due to higher temperature that accelerated fruit ripening; assessment started at 60 days after transplanting in both years. Fruit was harvested at three-quarters to full-slip stage. Number of days from transplanting to first harvest were recorded for each plot. For the center 10 plants in each plot, total weight and number of harvested fruit per plot were recorded at each harvest and yield/ha and number of fruit per plant were calculated.

2.4. Fruit Quality

Three representative fruit per plot were arbitrarily selected at each harvest and measured for fruit length, diameter, fruit firmness, TSS, titratable acidity (TA) and pH. A drill-press penetrometer (FDIX 10, 50 × 0.02 N; Wagner instruments, Greenwich, CT, USA) fixed with a 6-mm cylindrical blunt-end tip was used to measure fruit firmness (reported as Newton, N). A disc of peel (skin depth) was removed from four sides of each fruit. After calibration, the plunger head was placed against the flesh in the peeled area of the fruit, a steady downward pressure was applied until the plunger penetrated the fruit flesh to the depth-mark on the plunger, and the reading on the penetrometer was recorded [42]. Longitudinal slices from stem-end to calyx-end were taken from each fruit, a piece of fruit flesh was cut from the middle of the slice, the core and peel were removed, and the fruit piece was squeezed using cheesecloth to extract the juice into a 50 mL beaker. For each sample, 2-3 drops of fruit juice were placed on the prism plate of a digital refractometer

(MISCO, Cleveland, OH, USA) to measure TSS (% measured as °Brix). For each sample, 10 mL of juice was placed in a titrator sampling cup for auto titration (HI922 autosampler, Hanna instruments, Smithfield, RI, USA). The maximum titrant volume (0.1 M NaOH) was set at 25 mL and deionized water was dispensed into the sampling cup for 12 s. The sample was titrated until the end point of pH 8.2, and the auto titrator reading (measured as $g \cdot L^{-1}$) was recorded. Lastly, 2–3 drops of juice from each fruit sample were placed on the prism plate of a pocket pH meter (PAL-pH, ATAGO CO., LTD, Tokyo, Japan) and the pH value was recorded.

Table 1. Plant growth parameters assessed from field trials conducted at Mount Vernon, WA in 2020 and 2021.

Parameter	Assessment Period	Assessment Criteria
Plant stand	Weekly from one week after transplanting (WAT) until 16 WAT (2020) or 13 WAT (2021)	Total number of live plants per plot
Vine length	Every two weeks from 2 WAT until 10 WAT	Measured from the base of the crown to the tip of the longest vine from center six plants of each plot
Number of lateral vines	Every two weeks from 4 WAT until 10 WAT	Total number of vines growing from the main vine for six plants in the center of each plot
Percent canopy cover	Every two weeks from 2 WAT until 8 WAT	Measured for the center six plants of each plot. After hand weeding, digital photographs were taken at a 65-cm height centered above the plant in each plot. Images were analyzed using Canopeo application (ver. 2.0; Canopeo, Stillwater, OK) developed by the Soil Physics Research Group at Oklahoma State University [41].

2.5. Statistical Analysis

All data obtained from each plot were averaged and then subjected to analysis of variance using a linear mixed effect model procedure in R software ver. 1.4.1106-5 for Windows [43]. Data were analyzed as a randomized complete block design with repeated measures for plant stand, vine length, number of lateral vines, and percent canopy cover. When there was a treatment by year interaction, data were analyzed separately for each year using the same data analysis procedures. The assumptions of normality and homogeneity of variance were tested using the Q-Q plot and the Levene's test (α = 0.05), respectively. Tukey's honestly significant difference test at a significance level $\alpha < 0.05$ was used to compare treatment means for significant differences.

3. Results

3.1. Environmental Variables

All data pertaining to soil and environmental variables recorded during 2020 and 2021 growing seasons are presented in Table 2. Overall, 2021 growing season was a bit warmer compared to 2020 as evident from higher average air temperatures, maximum air temperatures, and average soil temperatures during vegetative growth in the months of June and July (Table 2). The total air thermal accumulation and soil thermal accumulation above 10 °C from transplanting to first harvest was 548 and 958 in 2020 (113 days) and 514 and 948 in 2021 (84 days), respectively. Precipitation and total solar radiation were greater in 2020 (144 mm and 2296 $MJ \cdot m^{-2}$, respectively) than in 2021 (59 mm and 2234 $MJ \cdot m^{-2}$, respectively) as the number of days to first harvest in 2020 was 29 days longer compared to 2021.

Table 2. Environmental and soil conditions during the growing season (1 June to 5 October 2020 and 20 May to 2 September 2021) at Mount Vernon, WA, USA, in 2020 and 2021.

Environmental Variables [z]	2020 [y]						2021					
	June	July	August	September	October	Av./Total	May	June	July	August	September	Av./Total
Average daily air temperature (°C)	14.6	16.4	16.6	15.7	14.0	15.5	12.8	17.1	17.1	17.0	13.3	15.5
Average daily min air temperature (°C)	10.3	11.0	10.3	10.0	10.1	10.3	7.4	11.0	11.2	11.5	4.7	9.2
Average daily max air temperature (°C)	19.4	21.8	23.0	21.7	18.4	20.9	18.0	23.1	24.1	23.5	21.8	22.1
Total air thermal accumulation	134	333	540	715	736	2458	32	244	481	712	719	2188
Total solar radiation ($MJ{\cdot}m^{-2}$)	565	685	636	374	36	2296	225	718	734	515	42	2234
Average relative humidity (%)	79	77	77	81	93	81.4	77	73	75	77	75	75.4
Total rainfall (mm)	78.7	21.0	16.3	27.2	0.75	144	11.4	23.1	0	24.4	0	58.9
Average soil temperature (°C) [x]	19.3	21.5	20.9	17.7	15.9	19.1	17.8	21.9	22.5	20.5	17.3	20
Total soil thermal accumulation	249	608	948	1182	1212	4199	47	402	794	1123	1150	3516
Average volumetric water content ($cm^3{\cdot}cm^{-3}$) [x]	0.28	0.32	0.32	0.32	0.34	0.3	0.21	0.28	0.27	0.28	0.31	0.3

[z] Data from Washington State University's Ag WeatherNet Station located 140 m away from the field site; [y] Seeding date was 23 April in 2020 and 8 April in 2021 due to warmer spring temperature, and first harvest was later in 2020 (1 September) than in 2021 (5 August) due to cooler summer temperature; [x] Measured every 15 min at 10 cm depth with data loggers (Hobo Onset, Bourne, MA, USA) in the center of each experimental plot of the second replicate. Soil temperature and volumetric water content under the soil-biodegradable plastic mulch (BDM) is the average of all BDM plots. BDM was 17.8 µm thick (Organix Solutions, Grove, MN, USA).

3.2. Plant Growth

Grafted treatments with 'Super Shintosa' and 'Carnivor' had 90% to 100% plant stand, while in contrast, grafted treatments with 'Carolina Strongback' and 'Pelop' showed decline throughout the growing season in both growing seasons (Table 3; Figure 1A). In 2020, 'SR/SS' and 'A/CN' had the highest plant stand (100%) at 16 WAT and in 2021, all nongrafted and grafted cantaloupe cultivars with 'Super Shintosa' and 'Carnivor' rootstocks had the highest plant stand (97%) at 13 WAT. An increased plant stand from 5 to 6 WAT was recorded with treatments grafted with 'Carolina Strongback' and 'Pelop' rootstocks in 2020 because the dead plants were thought to be due to transplant shock and were replaced with new transplants. Among grafted treatments with 'Pelop', and 'Carolina Strongback', 'SR/P' (64% and 72% at 3 WAT in 2020 and 2021, respectively) and SR/CS (58% and 78% at 5 WAT and 4 WAT in 2020 and 2021, respectively) were the first to show a major decline in plant stand. There was a sharp decline in plant stand with nongrafted treatments throughout harvest in 2020 (Figure 2A), but such decline was not observed in 2021 (Figure 2B).

Table 3. Results (*p*-values) from analysis of variance of the main factors "treatment", "year", and "weeks after transplanting" (week), and their interactions, for the parameters measured for grafted and nongrafted cantaloupe treatments in 2020 and 2021.

	Plant Stand	**Vine Length**	**No. of Lateral Vines**		**Canopy Cover**	
Treatment	<0.0001	<0.0001	<0.0001		<0.0001	
Year	0.91	<0.0001	<0.0001		<0.0001	
Week	<0.0001	<0.0001	<0.0001		<0.0001	
Treatment × Year	<0.0001	0.08	0.23		0.52	
Year × Week	<0.0001	0.0006	0.04		<0.0001	
Treatment × Week	<0.0001	<0.0001	<0.0001		<0.0001	
Treatment × Year × Week	0.01	<0.0001	<0.0001		<0.0001	
	Days to first harvest	Yield/ha	Total fruit no per plant		Fruit wt	
Treatment	<0.0001	<0.0001	0.003		<0.0001	
Year	<0.0001	<0.0001	<0.0001		0.01	
Treatment × Year	0.52	0.40	0.74		0.001	
	Fruit length	Fruit diameter	TSS	Firmness	TA	pH
Treatment	<0.0001	<0.0001	<0.0001	<0.0001	0.002	0.002
Year	0.02	0.53	0.02	<0.0001	<0.0001	<0.0001
Treatment × Year	0.36	0.08	0.02	0.002	0.17	0.38

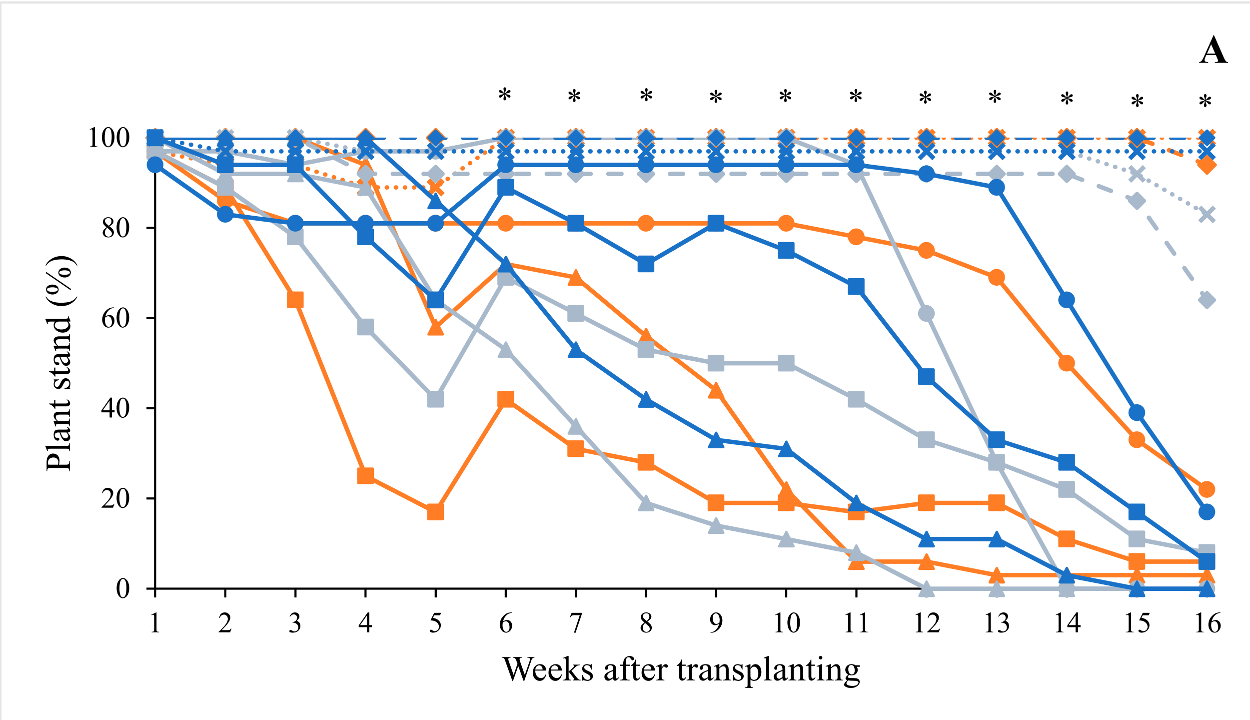

Figure 1. *Cont.*

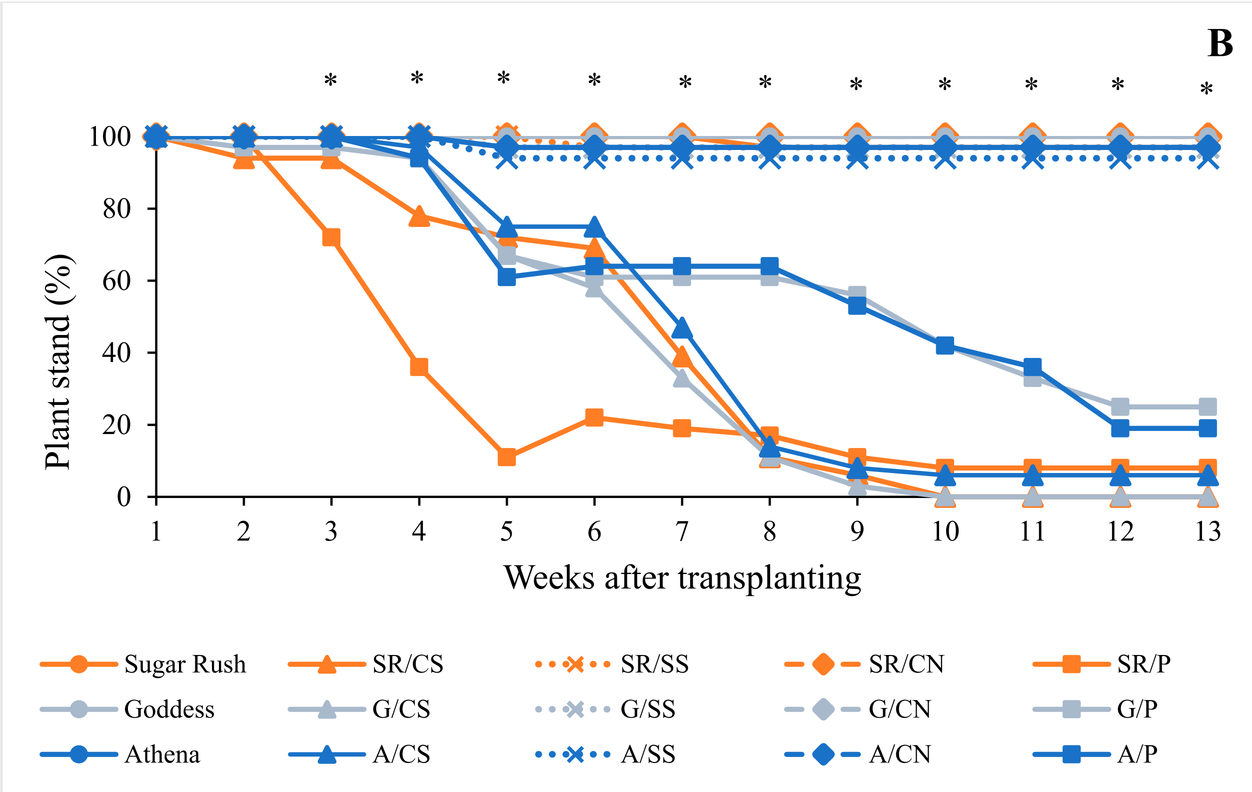

Figure 1. Plant stand of cantaloupe cultivars Sugar Rush (SR), Goddess (G) and Athena (A) nongrafted and grafted onto four rootstock cultivars Carolina Strongback (CS), Super Shintosa (SS), Carnivor (CN), and Pelop (P) grown with black soil-biodegradable plastic mulch (BDM) and measured every week from 1 June to 30 September 2020 (**A**) and 20 May to 15 August 2021 (**B**) at Mount Vernon, WA, USA. * Represent significant differences at $p < 0.05$.

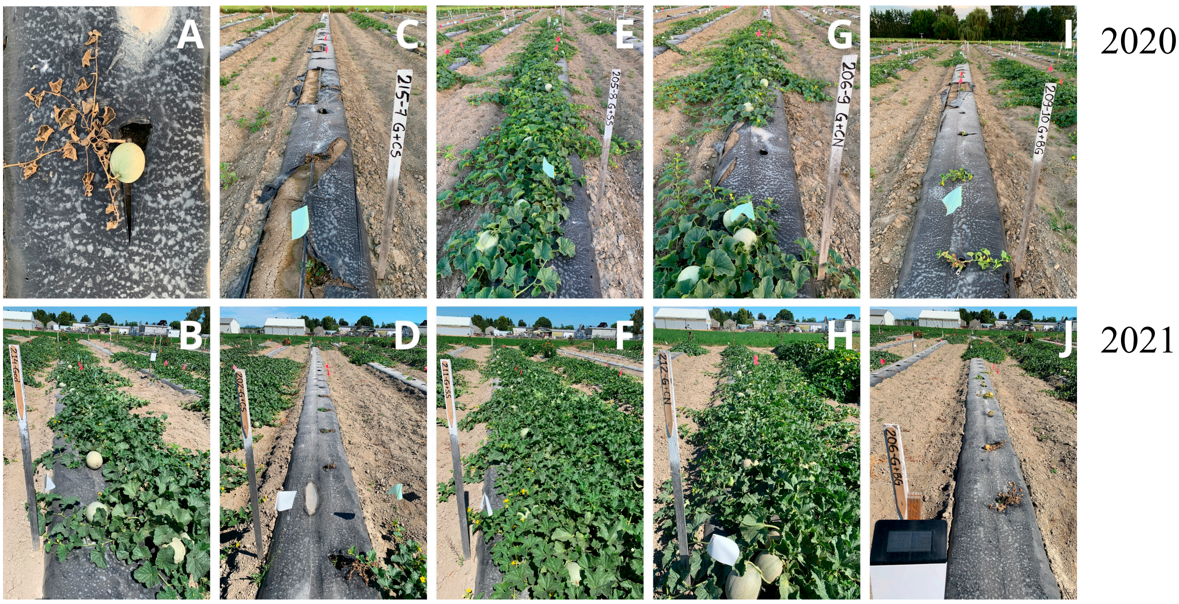

Figure 2. Plant growth of cantaloupe cultivar Goddess nongrafted (**A**,**B**), grafted with 'Carolina Strongback' (**C**,**D**), with 'Super Shintosa' (**E**,**F**), with 'Carnivor' (**G**,**H**), and with 'Pelop' (**I**,**J**) rootstocks at 10 WAT in 2020 and 2021, respectively, at Mount Vernon, WA, USA.

Vine length increased for all treatments except for grafted treatments with 'Carolina Strongback' and 'Pelop' rootstocks, which completely collapsed by 10 WAT (Table 3; Figure 3A). At 10 WAT, 'G/SS', 'G/CN', and 'A/CN' had the longest vine length (average 183 cm) followed by 'A/SS' (167 cm; Table 3 and Figure 3A).

At 10 WAT, 'A/CN' had the highest number of lateral vines (6 vines) followed by 'G/CN' and 'A/SS' (average 5.6 vines) (Table 3; Figure 3B). Number of lateral vines did not increase for grafted treatments with 'Carolina Strongback' and 'Pelop' until 8 WAT (0.8 on average). However, at 10 WAT, all cantaloupe cultivars grafted onto 'Pelop' showed a decline in the number of lateral vines (0.9 on average) while those grafted onto 'Carolina Strongback' completely collapsed.

At 6 WAT, 'A/CN' had the highest canopy cover (37%) (Table 3; Figure 3C). At 8 WAT, 'A/CN' had the highest canopy cover (65%) followed by all nongrafted cantaloupe cultivars, 'SR/CN', 'G/SS', 'G/CN', and 'A/SS' (50%) (Table 3; Figure 3C). Canopy cover of grafted treatments with 'Carolina Strongback' and 'Pelop' did not change much throughout the growing season and was 2% at 6 WAT and 1% at 8 WAT.

3.3. Fruit Harvest

Since 'Carolina Strongback' and 'Pelop' rootstocks were incompatible with all three tested cantaloupe cultivars, no fruit was harvested from these graft combination treatments. Delayed first harvest dates were observed in grafting treatments with interspecific hybrid squash rootstock except for treatment 'G/CN' (89 DAT). Grafting increased yield by 68% to 93% and fruit number per plant by 15% to 53% for all three cultivars (Tables 3 and 4). 'A/CN' had the highest yield and fruit number per plant (40.2 $t \cdot ha^{-1}$ and 5.9, respectively) while nongrafted 'Sugar Rush' and 'Goddess' had the lowest (13.7 $t \cdot ha^{-1}$ and 3.5 on average, respectively). Both years, grafting increased the weight per fruit and was highest for 'G/SS', 'G/CN', 'A/SS' and 'A/CN' (1.8 kg on average; Tables 3 and 4).

3.4. Fruit Quality

Due to graft incompatibility of all cantaloupe cultivars with 'Carolina Strongback' and 'Pelop' rootstocks, there are no data on fruit quality attributes of these grafting combinations. Grafting with interspecific hybrid squash increased fruit length by 11% on average and fruit diameter by 14% on average. 'G/SS', 'G/CN', 'A/SS' and 'A/CN' tended to have the largest fruit length and diameter (16 and 15 cm on average, respectively), while nongrafted 'Sugar Rush' had the lowest (12 and 11 cm, respectively) (Tables 2 and 4). For nongrafted treatments that had decline in plant stand in 2020, fruit were small and damaged by sun scald due to lack of canopy cover (Figure 2A). Fruit firmness was not impacted by grafting for 'Goddess' both years, for 'Sugar Rush' in 2021, and for 'Athena' in 2020 (Tables 3 and 5). In 2020, nongrafted 'Sugar Rush' had the highest fruit firmness (56.6 N) followed by 'SR/SS' and 'SR/CN' (48.6 N on average). In 2021, nongrafted 'Sugar Rush', SR/SS' and 'SR/CN' had the highest fruit firmness (47.5 N on average) followed by 'A/SS' and 'A/CN' (38.5 N on average). Grafting increased TSS by up to 2.7% for all cantaloupe cultivars (Tables 3 and 5). Both years, all nongrafted and grafted treatments had fruit with TSS more than 11% indicating U.S. fancy grade quality except for nongrafted 'Athena' in 2020 (10.6%). The TA and pH were not impacted by grafting for each cantaloupe cultivar. 'A/SS' and 'A/CN' had the highest TA (0.77 $g \cdot L^{-1}$ on average), while pH of fruit harvested from all treatments ranged between 6.4–7.0. (Tables 3 and 5).

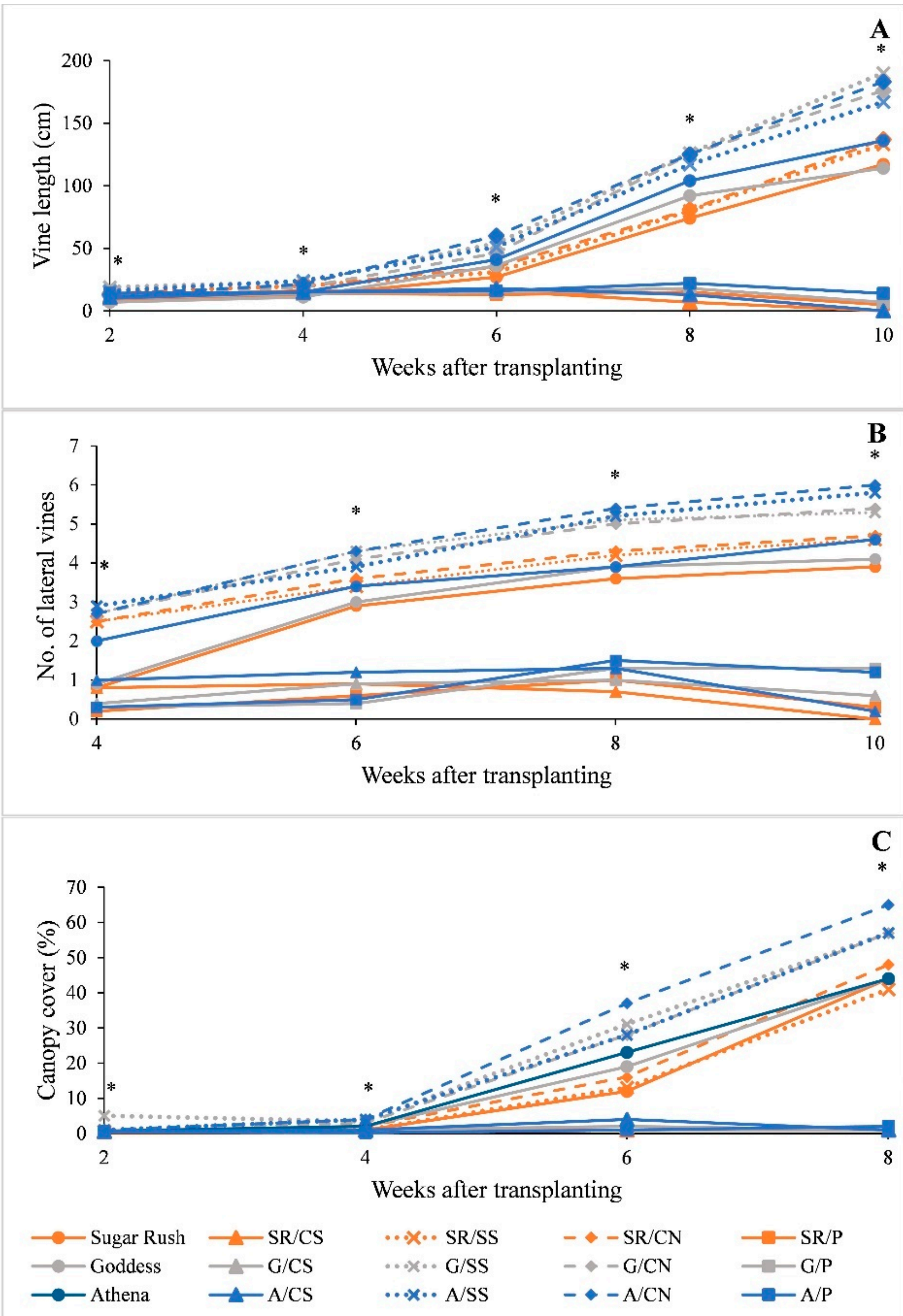

Figure 3. Vine length (**A**), number of lateral vines (**B**), and percent canopy cover (**C**) of cantaloupe cultivars Sugar Rush (SR), Goddess (G) and Athena (A) nongrafted and grafted onto four rootstock cultivars Carolina Strongback (CS), Super Shintosa (SS), Carnivor (CN), and Pelop (P) grown with black soil-biodegradable plastic mulch (BDM) and measured every two weeks until 10 weeks after transplanting from 1 June to 15 August 2020 and 20 May to 31 July 2021 (years combined) at Mount Vernon, WA, USA. * represents significant differences at $p < 0.05$.

Table 4. Days to first harvest, yield (t·ha^{-1}), total fruit number per plant, and weight per fruit of cantaloupe cultivars Sugar Rush (SR), Goddess (G) and Athena (A) nongrafted and grafted onto two rootstock cultivars Super Shintosa (SS) and Carnivor (CN) at Mount Vernon, WA, USA, in 2020 and 2021 (years combined).

Treatment [z]	Days to First Harvest	Yield (t·ha^{-1})	Tot. Fruit Number per Plant	Weight per Fruit (kg)	
				2020	2021
Sugar Rush	97 abc [y]	11.4 d	3.9 bc	0.6 d	0.9 d
SR/SS	105 c	18.8 cd	4.5 abc	1.1 bc	1.1 cd
SR/CN	102 bc	19.4 cd	4.5 abc	1.0 bc	1.1 cd
Goddess	90 a	15.9 d	3.0 c	1.5 ab	1.5 b
G/SS	92 ab	33.6 ab	4.9 abc	1.8 a	1.8 a
G/CN	89 a	27.9 bc	4.3 abc	1.8 a	1.8 a
Athena	100 abc	18.8 cd	4.3 abc	0.9 cd	1.4 bc
A/SS	107 c	31.7 ab	5.0 ab	1.8 a	1.6 ab
A/CN	103 bc	40.2 a	5.9 a	2.0 a	1.8 a
p-value	<0.0001	<0.0001	0.004	<0.0001	<0.0001

[z] Grafted treatments are abbreviated as scion/rootstock; [y] Means followed by the same letter in the same column are not significantly different at $p < 0.05$; means were discriminated using Tukey's honestly significant difference.

Table 5. Fruit length and diameter, fruit firmness, total soluble solids, titratable acidity, and pH of cantaloupe cultivars Sugar Rush (SR), Goddess (G) and Athena (A) nongrafted and grafted onto two rootstock cultivars Super Shintosa (SS) and Carnivor (CN) at Mount Vernon, WA, USA, in 2020 and 2021 (years combined when there was no treatment by year interaction).

Treatment [z]	Fruit Length (cm)	Fruit Diameter (cm)	Fruit Firmness (N)		TSS (%)		TA (g·L^{-1})	pH
			2020	2021	2020	2021		
Sugar Rush	12 e [y]	11 c	56.6 a	47.3 a	13.1 abc	15.7 a	0.56 ab	7.0 a
SR/SS	14 d	13 b	49.0 b	48.4 a	14.7 a	15.0 ab	0.60 ab	6.8 ab
SR/CN	13 d	13 b	48.2 b	46.8 a	14.8 a	15.1 a	0.51 b	7.0 a
Goddess	15 bc	14 ab	41.5 c	31.4 b	11.9 bc	11.6 c	0.64 ab	6.6 ab
G/SS	16 a	15 a	42.3 c	33.3 b	12.5 abc	12.4 c	0.55 ab	6.7 ab
G/CN	16 ab	15 a	43.6 c	32.4 b	12.4 abc	12.7 c	0.54 ab	6.8 ab
Athena	14 cd	13 b	44.5 c	30.9 b	10.6 c	12.5 c	0.65 ab	6.5 b
A/SS	16 a	15 a	49.7 c	39.0 ab	13.9 ab	13.2 bc	0.77 a	6.4 b
A/CN	16 a	15 a	43.5 c	37.9 ab	12.6 abc	13.1 bc	0.77 a	6.5 b
p-value	<0.0001	<0.0001	<0.0001	<0.0001	0.0004	<0.0001	0.002	0.002

[z] Grafted treatments are abbreviated as scion/rootstock; [y] Means followed by the same letter in the same column are not significantly different at $p < 0.05$; means were discriminated using Tukey's honestly significant difference.

4. Discussion

This study demonstrates that plant growth and yield of cantaloupe grafted with interspecific hybrid squash are higher than nongrafted plants in a Mediterranean-type climate. Findings from this study also reiterate that the success of grafting and the performance of grafted plants depend on scion-rootstock compatibility.

'Carolina Strongback', a new citron rootstock cultivar used in this study, is resistant to fusarium wilt (caused by *Fusarium oxysporum* f. sp. *niveum*) and root knot nematode (*Meloidogyne* sp.) [44]. While there are no published reports on grafting cantaloupe with 'Carolina Strongback', melon grafted with 'Carolina Strongback' in South Carolina were observed to collapse and die after reaching the soft ball fruit size (R. Hassell, personal communication). Likewise, other studies have reported that melon plants grafted with bottle gourd rootstocks such as 'Pelop' wilted shortly after transplanting [45].

In this study grafted plants with 'Pelop' and 'Carolina Strongback' showed decline in plant stand at 2 and 4 to 5 WAT, respectively and decline continued throughout the growing season in both years for both grafted treatments. Furthermore, vine length, number of lateral vines and canopy cover of grafted plants with 'Carolina Strongback' and 'Pelop' were on average 85%, 76% and 98% less, respectively, at 8 WAT compared to all other treatments both years. Data from this study are congruent with earlier findings. For example, 'Arava' melon grafted onto bottle gourd (*L. siceraria*) rootstock cultivar SUS had the lowest number of leaves, plant height, and plant fresh weight compared to plants grafted with interspecific hybrid squash rootstocks at 3 WAT in the greenhouse, indicating grafting incompatibility [22]. Another study also reported incompatibility of 'Akekekouqi' melon with bottle gourd and watermelon rootstock cultivars, evidenced by significantly lower scion dry weight, scion height, and scion and rootstock stem diameters at 4 WAT in the greenhouse [28].

Overall, 'Carolina Strongback' and 'Pelop' were incompatible with the three cantaloupe cultivars grafted in this study. The mechanism of graft incompatibility is not yet fully understood though researchers have put forward several possible explanations such as differences in anatomical, physiological and genetic attributes of both the scion and the rootstock [21,22], auxin and ethylene level imbalances in the root system following the establishment of the grafting connections [46], callose deposition in newly formed phloem leading to the blockage of photoassimilate transportation [28], and climatic factors [22]. Since the cause of graft incompatibility was not assessed in our study, it cannot be specified. However, graft incompatibility of melons with the same rootstocks was observed in other studies, suggesting that it is not likely due to environmental factors.

Interestingly, in 2020, plant stand declined for nongrafted treatments due to sudden wilt prior to harvest. Sudden wilt may be caused by fungi such as *Monosporascus cannonballus* and *Acremonium cucurbitacearum*, or by production practices that result in a poorly developed root system, or due to abiotic factors such as heat and drought stress, cool weather, and excessive moisture [8,11,47–50]. In our study, plant samples were not assessed for pathogens, hence it is unknown if biotic factors caused the sudden wilt symptoms observed in 2020. However, sudden wilt symptoms in 2020 may have occurred due to cooler weather as the average temperature in June was 2 °C lower in 2020 than in 2021 and was 1 °C lower in July. Similarly, soil temperature under the BDM was lower by 3 °C in June and 1 °C in July 2020 than in 2021. At first harvest, the thermal accumulation above 10 °C was 548 (air) and 958 (soil) in 2020 (113 DAT) and 514 (air) and 948 (soil) in 2021 (84 DAT). Thus, it took approximately 4 weeks longer for thermal accumulation in 2020 than in 2021, and those cool soil conditions may have caused sudden wilt. However, a longer-term study is required to discern if abiotic factors could be involved in sudden wilt symptoms observed at this site.

Compatible grafting combinations observed in this study included interspecific hybrid squash rootstocks such as 'Super Shintosa' and 'Carnivor'. Almost 100% plant stand throughout the growing season in both years were observed in grafted treatments with these rootstocks. However, days to first harvest for grafted 'Sugar Rush' and 'Athena' with interspecific hybrid squash were delayed by 6 days on average compared with nongrafted plants but was not affected for 'Goddess'. Vigorous rootstocks have been shown to affect flowering and harvest time, causing a delay in fruit maturity, and harvesting of watermelon and muskmelon [31,51]. Delayed ripening of watermelons in plants grafted with interspecific hybrid squash rootstock was linked in other studies to increased fruit load that burdened source-sink relations [52,53].

Overall yield/ha, weight per fruit, and number of fruit per plant of grafted treatments with interspecific hybrid squash rootstocks were 303%, 58% and 100% higher, respectively, than those of nongrafted treatments in 2020, and 49%, 21% and 13% higher, respectively, in 2021. Higher yield increase observed in 2020 can be attributed to sudden wilt that resulted in plant stand decline in nongrafted treatments. The *inodorus* F_1 hybrid Incas when grafted with interspecific hybrid squash rootstock cultivar RS 841 had 29% higher total yield and 24% higher fruit weight compared to nongrafted plants, but no significant difference for number of fruit was observed [15]. In contrast, other studies with interspecific hybrid squash rootstocks indicated total yields and number of fruit per plant to be similar as nongrafted treatments [33,54].

It is worth noting that in our study, grafting with interspecific hybrid squash rootstocks resulted in either equivalent or improved fruit quality for the three cantaloupe cultivars in most of the cases. Overall fruit firmness, TSS, TA and pH were 42 N, 12.6%, 0.62 and 6.7, respectively, for nongrafted treatments and 43 N, 13.5%, 0.62 and 6.7, respectively, for grafted treatments. Similar trends were observed among *inodorus* F_1 hybrid cultivar Incas nongrafted and grafted with interspecific hybrid squash rootstock cultivar RS 841 [15]. However, a separate study reported higher TSS, pH and TA in nongrafted melon cultivar Cyrano compared to grafted Cyrano with interspecific hybrid squash rootstock cultivar P360 [55]. Reduced TSS and decreased sensory ratings of galia melon 'Arava' grafted with interspecific hybrid squash rootstock were also reported with no significant differences between nongrafted and grafted honeydew melon 'Honey Yellow' with the same hybrid rootstock [33].

In conclusion, grafting increased plant growth and yield of cantaloupe in a cool Mediterranean-type climate without compromising fruit quality. Cantaloupe cultivars Sugar Rush, Goddess, and Athena were compatible with interspecific hybrid squash rootstock cultivars Carnivor and Super Shintosa, but incompatible with rootstock cultivars Carolina Strongback and Pelop. Thus, growers need to be careful when selecting rootstocks for grafting, and further research is needed to identify more rootstock options for cantaloupe. 'Goddess' and 'Athena' grafted with interspecific hybrid squash produced the highest yield while maintaining U.S. fancy grade quality. Overall, grafting may be viewed as a risk management tool to protect the crop from decline in plant stand that results in reduced yield. Further research is needed to understand if abiotic and/or biotic factors are involved in sudden wilt as well as to determine the profitability of using grafted cantaloupe in this region.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae8100888/s1, Table S1: Cultivars, abbreviation, seed source, and sowing date of cantaloupe and rootstock cultivars used for grafted and nongrafted treatments at Mount Vernon, WA, USA, in 2020 and 2021.

Author Contributions: Conceptualization, S.S. and C.M. (Carol Miles); methodology, S.S. and C.M. (Carol Miles); formal analysis, S.S.; writing—original draft preparation, S.S.; writing—review and editing, S.S., C.M. (Carol Miles) and C.M. (Chakradhar Mattupalli); funding acquisition, C.M. (Carol Miles). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by U.S. Department of Agriculture National Institute of Food and Agriculture (NIFA) Specialty Crop Research Initiative Grant 2016-51181-25404 and NIFA Hatch Projects 1017286 and 1016563.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors would like to thank Patricia Kreider, Ed Scheenstra, and Rachael Schick for technical assistance, Syngenta, Osborne, Rijk Zwaan, and Harris Seeds for providing the seed used in this study.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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