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Low-Temperature Survival of 'Cresthaven' Peach Flower Buds and Fruit Yield on Eight Rootstocks in the 2017 NC-140 Rootstock Trial

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Abstract

'Cresthaven' budwood was collected from Biglerville, PA on 13 Jan., 24 Feb., and 16 Nov. 2020 and 11 Jan., 1 Mar., and 15 Nov. 2021 for controlled freezing tests to evaluate the relative cold tolerance of peach flower buds on eight *Prunus* rootstocks in the 2017 NC-140 trial. Fruit yield was also recorded annually to determine if crop load affected the low temperature survival of fruit buds in the successive dormant period. Size-controlling rootstocks evaluated were 'Controller™ 6, 7 and 8', 'MP-29', and 'Rootpac® 20' and 40', as well as two seedling rootstocks, Lovell and Guardian® Brand 'BY520-9'. In January 2020, T_{50} values (temperature at which 50% of flower buds are killed) of Lovell trees were ≥ 2.7 °C lower than those of all other rootstocks, except for 'MP-29', 'Controller™ 6', and 'Controller™ 7'. However, in January 2021, only buds of Guardian® trees were less cold-tolerant than those on Lovell. In February 2020, none of the flower buds on any rootstock had T_{50} values lower than those from Lovell trees. Also, flower buds from Lovell trees were 4.4 °C hardier than those of Guardian® trees collected on 1 Mar. 2021. Flower buds from trees on all rootstocks had similar T_{50} values when tested in November 2020 or 2021. Annual fruit yield varied by rootstock in the first two years of bearing, but by the third year, the annual yield was similar among all rootstocks, except 'MP 29'. Based on the early results of this trial, no rootstock was superior to Lovell in cold tolerance with high fruit yield at this site.

Peach production in the United States (U.S.) was 566,847 t with a value of $521 million in 2020 (Agriculture Marketing Resource Center 2021). Although the value of the crop has increased, the number of hectares in production has decreased from 37,583 in 2016 to 29,543 in 2020 in the U.S. due to several factors (Lesmes-Vesga 2022; US Department of Agriculture, National Agricultural Statistics Service 2021). Highly productive trees of improved cultivars, the use of dwarfing rootstocks, and the adoption of intensive cultural practices have led to trees planted at close spacings that are yield efficient (Anthony and Minas 2021). Despite these advances, biotic and abiotic factors, such as poor tolerance to peach tree short life and other diseases, insect pests and nematodes, high pH soils, and tree loss during erratic weather events, limit production.

Several NC-140 Regional Project trials have been conducted to evaluate rootstock performance for efficient peach production and improved tolerance to stress, using sustainable practices on diverse sites across North America since 1984 (Marini 2021; Reighard and NC-140 collaborators, in press). Rootstocks tested in the trials included genotypes from many *Prunus* species, including *P. americana*, *P. cerasifera*, *P. davidiana*, *P. domestica*, *P. dulcis*, *P. mume*, *P. persica*, *P. tomentosa*, *P. umbellata*, and *P. salicina*. Seedling rootstocks, often used as a standard of comparison, as well as clonally-

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propagated genotypes, including interspecific hybrids, were evaluated in long-term NC-140 trials. Results from these peach studies demonstrated that Lovell rootstock generally had greater tree survival and large cumulative yield compared with other rootstocks evaluated (Johnson et al. 2011; Perry et al. 2000; Reighard et al. 2004, 2011, 2020).

In addition to the multi-location NC-140 studies, several ancillary studies have been conducted to evaluate low-temperature survival of overwintering peach flower buds on trees of selected rootstocks, which is a major factor limiting crop production (Brown and Cummins 1988; Davis 2013; Durner 1990; Warmund et al. 2002; Warmund and Slater 1988). In addition to the aforementioned studies, others have evaluated peach flower bud survival as affected by the scion cultivar and/or the rootstock (Harber et al. 1992; Liu 2017; Smith et al. 1994; Szalay et al. 2010; Sterle and Minas 2021). 'Redhaven' and 'Cresthaven' flower buds are considered winter hardy in the U.S. hardiness zones 6a and 6b, whereas 'Piroska' buds are more cold-tolerant than 'Redhaven' in Hungary (Sterle and Minas 2021; Szalay et al. 2010; Warmund et al. 2002). However, many site factors, including tree health, management practices, and climatic factors influence peach flower bud hardiness (Brown and Cummins 1988; Durner and Gianfagna 1988; Warmund et al. 2002).

Previous work conducted at two locations in Virginia demonstrated that the previous season's crop density adversely affected the survival of swollen flower buds on 'Cresthaven'/Lovell trees when assessed two days following exposure to sub-freezing temperatures in early spring (Byers and Marini 1994). Based on these findings, the purpose of our study was to evaluate the relative cold hardiness of 'Cresthaven' flower buds on rootstocks included in the 2017 NC-140 regional rootstock trial at three dates during dormancy and to determine if fruit yield in the growing season preceding each freezing test influenced flower bud survival.

Materials and Methods

Field trial. A peach rootstock trial was planted at the Penn State Fruit Research and Extension Center, Biglerville, PA, USA (lat. 39°934643°N, long. 77°255197° W, elevation 220 m) on 27 Apr 2017 with 'Cresthaven' as the scion cultivar budded onto eight rootstocks, according to guidelines established by the NC-140 Pome and Stone Fruit Research committee (Table 1). Size-controlling rootstocks evaluated in this trial included 'Controller™ 6', 7', and 8', 'MP-29', and 'Rootpac® 20 and 40', as well as two seedling rootstocks, Lovell and Guardian® Brand 'BY520-9'. Trees were spaced at 1.8 m x 5.5 m and trained to a perpendicular V system with four trees of each rootstock in each replication, except for 'MP-29' and 'Rootpac® 40', which were limited to three trees per replicate due to the shortage of trees. Five replications of 'Controller™ 6', 7 and 8', 'Rootpac® 20', Lovell, and Guardian® rootstock, and four replications of 'MP-29' and 'Rootpac® 40' were arranged in a randomized complete block design with the fifth block lacking the latter two rootstocks. In spring 2020, each tree was thinned to a crop density of two fruit/cm^2 of trunk cross-sectional area. Fertilization, irrigation, and pest management followed local guidelines (Crassweller et al., 2020). All trees of each rootstock in each replication were harvested annually in 2019 to 2022 and total fruit weight for each harvested tree was recorded. Only fruit ≥ 5.7 cm-diameter were included in total fruit weights.

Freezing tests. Tissue for the freezing tests was collected on 13 Jan., 24 Feb., and 16 Nov. 2020, and 11 Jan., 1 Mar. and 15 Nov. 2021. Sampling dates were selected to assess floral bud hardiness during mid-winter, just before bud swell in late winter, and in the fall as buds were acclimating to low temperatures. For each sampling date, budwood was collected from all trees per plot in each replication in the trial. Six cuttings, consisting of five nodes each, were collected from the middle portion of one-year-old wood on each tree at approximately 1.5 m above the soil surface. Samples were then placed in sealed polyethylene bags, packed in a cooler containing frozen gel packages, and sent by overnight mail to the University of Missouri-Columbia, where freezing tests were conducted.

Immediately after delivery, a cutting from each rootstock was placed in moist cheesecloth and wrapped in aluminum foil for each of six test temperatures, including an unfrozen control. A 0.01-mm-diameter copper-constantan thermocouple was placed in contact with a bud of one sample of each test temperature to monitor tissue temperature and thermocouple output was read with a digital thermometer (Omega Engineering, Inc., Stamford, CT). Samples were then placed in a programmable freezer (Tenney Benchmaster; Tenney Engineering, Union, NJ) at -2 °C for one hour before cooling at 3 °C/h. The cheesecloth froze and seeded the tissue with ice at about -1 °C. Samples were removed from the freezer at 3 °C intervals, using a range of temperatures (-9 to -24 °C) likely to produce tissue injury (Warmund et al., 2002). After removal from the freezing chamber, samples were thawed at 4 °C for 24 h and placed at 21 °C for 5 d before floral bud evaluation. Unfrozen controls were maintained at 4 °C during the freezing test and then transferred to 21 °C at the same time as samples exposed to sub-freezing temperatures were placed at the latter temperature. To assess floral bud survival, 5 buds per twig were sectioned with a razor blade and examined for oxidative browning under a dissecting microscope at 40X magnification The numbers of injured and uninjured floral primordia were recorded and the modified Spearman-Karber equation was used to calculate T_{50} values for buds at each sampling date (Bittenbender and Howell, 1974).

S*tatistical analyses.* Yield data for each year were subjected to an analysis of variance (ANOVA) using PROC GLIMMIX in SAS (SAS Institute, Cary, NC). Means were separated using Fisher's protected least significant test ($P \leq 0.05$). For the freezing tests, the experiment was also a randomized complete block design and T_{50} values for each collection date were subjected to an analysis of variance using PROC GLIMMIX. Means were separated using Fisher's protected least significant test ($P \leq 0.05$). Next, fruit yield per tree was used in the statistical model as the covariate to determine if floral bud survival at each collection date was affected by fruit yield in the preceding growing season.

Results

Air temperatures. Biglerville PA is within USDA Plant hardiness zone 6b, which has an average minimum temp of -20.6 to -17.8 °C. In the 10-d period preceding the 13 Jan. 2020 collection of peach twigs, minimum daily temperatures were unseasonably warm, ranging from -10 to 5 °C (Fig. 1). The lowest temperature of the dormant period (-13 °C) was not recorded until 15 Feb. 2020 and subsequent minimum daily air temperatures were relatively cold, ranging from -8 to 2 °C until the 24 Feb. sampling date. Sub-zero temperatures were not recorded before the 11 Nov. 2020 collection of budwood and the lowest minimum daily temperature in the 10-d period preceding this date was 2° C. Total precipitation in the 10-d periods before the January, February, and November 2020 tests was 2.9, 0. 1, and 2.9 cm, respectively.
In early Jan. 2021, minimum daily temperatures preceding the freezing test ranged from -3.2 to 2 °C (Fig. 2). The lowest temperature (-10°C) of the dormant season was recorded on 8 Feb. 2021. In the 10-d period preceding the February collection date, the maximum daily temperatures were usually above freezing and the minimum daily temperatures ranged from -7 to 3 °C. Sub-zero minimum daily temperatures were recorded in the 10-d period before the November collection date, but the maximum temperature reached 7 °C the day before sampling the budwood. Total precipitation in the 10-d periods before the January, February, and November 2021 tests were 1.0, 2. 1, and 3.6 cm, respectively.

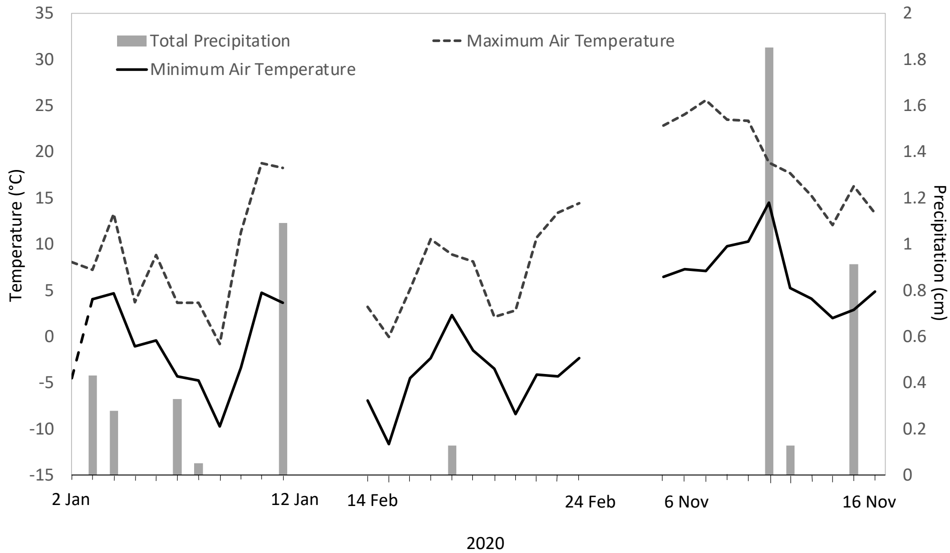

Figure 1. Minimum and maximum daily air temperatures and precipitation for the 10-day period preceding the January, February, and November sample collection dates in 2020.

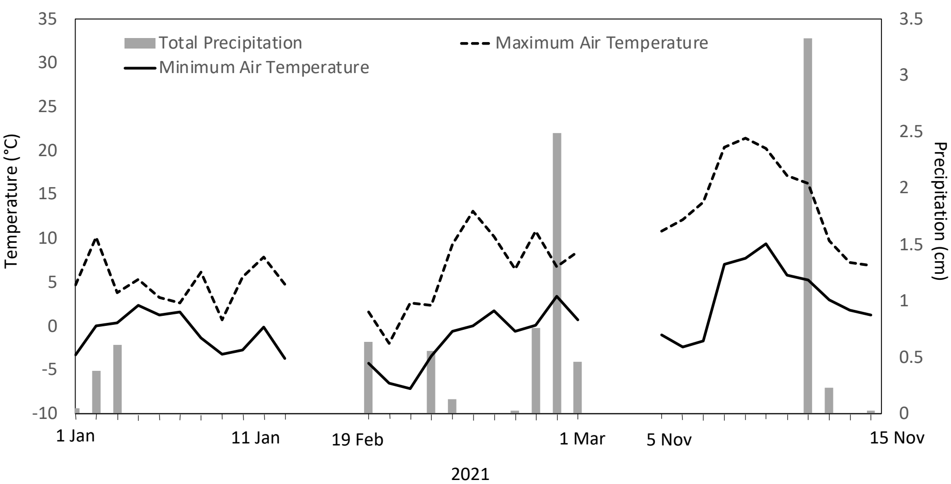

Figure 2. Minimum and maximum daily air temperatures and precipitation for the 10-day period preceding the January, March, and November sample collection dates in 2021.

Floral bud cold hardiness. In Jan. 2020, flower buds of trees on Lovell rootstock had lower T_{50} values than those of trees on all other rootstocks, except 'MP-29', 'Controller™ 7', and Controller™ 6' (Table 2). At the late February collection date, T_{50} values of flower buds from trees on Lovell rootstock were 2.1 to 4.3 °C lower than those from

Table 1. Genetic and regional origin of rootstocks included in the NC-140 trial at Biglerville, PA.

Rootstock	Genetic and regional origin of rootstock
Controller™ 6	clonal rootstock from an open-pollinated plant originating from *Prunus persica* 'Harrow Blood' × *P. persica* 'Okinawa' in 1994, tested as 94-94-27 and HBOK 27, and released from the University of California Rootstock Breeding Program in 2012 (Foundation Plant Services 2022c)
Controller™ 7	clonal rootstock from an open-pollinated plant originating from *Prunus persica* 'Harrow Blood' × *P. persica* 'Okinawa' in 1994, tested as 94-94-32 and HBOK 32, and released from the University of California Rootstock Breeding Program in 2010 (Foundation Plant Services 2022a)
Controller™ 8	clonal rootstock from an open-pollinated plant originating from *Prunus persica* 'Harrow Blood' × *P. persica* 'Okinawa' in 1994, tested as 94-94-10 and HBOK 10, and released from the University of California Rootstock Breeding Program in 2010 (Foundation Plant Services 2022b)
Guardian® Brand BY520-9	peach seedling derived from 69 open-pollinated selections from B594520-9 and was introduced by the United States Department of Agriculture, Agricultural Research Service, Byron, GA, and Clemson University, Clemson, GA in 1994 (Okie et al. 1994)
Lovell	peach seedling found by G.W. Thissell in Winters, CA in 1882 (Foundation Plant Services 2022d)
MP-29	clonal rootstock from a plum (*P. umbellata* 'Edible Sloe') × peach (*P. persica* 'SL0014' cross released from United States Department of Agriculture, Agricultural Research Service, Byron, GA and the Florida Agricultural Experiment Station in 2011 (Beckman et al. 2012)
Rootpac® 20	clonal rootstock from a sand cherry (*P. besseyi*) × myrobalan plum (*P. cerasifera*) cross, originally tested as PAC 9801-02 and patented as Densipac and introduced in 2011 from the Agromillora Catalana Breeding Program, Subirats, Barcelona, Spain (Gasic and Preece 2014)
Rootpac® 40	clonal rootstock from an almond × peach hybrid [*P. dulcis* × *P. persica*) 'Felinem' (*P. dulcis* 'Marcona' × *P. persica* Nemaguard)], originally tested and patented as Nanopac from the Agromillora Catalana Breeding Program, Subirats, Barcelona, Spain (Anthony and Minas 2021)

Table 2. Mean T50 values of 'Cresthaven' peach floral buds on eight rootstocks at selected dates.

	T_{50} value					
Rootstock	13 Jan. 2020	24 Feb. 2020	16 Nov. 2020	11 Jan. 2021	1 Mar. 2021	15 Nov. 2021
Lovell	-16.3 a [i]	-16.1 a	-15.2 a	-19.9 a	-16.0 a	-16.7 a
MP-29	-15.2 ab	-12.9 bc	-16.3 a	-19.1 a	-13.2 c	-16.2 a
Controller™ 7	-15.0 ab	-14.0 b	-15.1 a	-19.5 a	-14.2 bc	-16.5 a
Controller™ 6	-14.8 ab	-11.8 c	-15.9 a	-19.2 a	-13.3 c	-16.1 a
Guardian®	-13.6 bc	-12.7 bc	-15.9 a	-17.1 b	-11.6 d	-16.3 a
Controller™ 8	-13.5 bc	-12.8 bc	-15.7 a	-19.4 a	-16.0 a	-15.9 a
Rootpac 40®	-13.2 c	-12.3 c	-14.9 a	-19.2 a	-14.6 abc	-15.6 a
Rootpac 20®	-13.0 c	-11.8 c	-15.9 a	-19.7 a	-15.3 ab	-16.1 a

[i] Means represent 5 replications of each 5-node cutting for each rootstock. LSmeans within columns followed by common letters do not differ at the 5% level of significance, by Fisher's protected LSD.

trees on all other rootstocks. However, bud hardiness was similar on trees of all rootstocks in November with T_{50} values ranging from -16.3 to -14.9 °C.

For Jan. 2021, T_{50} values of flower buds from trees on all rootstocks were 2.0 to 2.8 °C lower than the T_{50} value of buds on trees of Guardian® rootstock (Table 2). At the March collection date, flower bud T_{50} values from Lovell and 'Controller™ 8' trees were 4.4 °C lower than that of Guardian® trees. Flower bud T_{50} values were similar on trees from all rootstocks at the November test date.

Fruit yield. Trees on Lovell and Guardian® rootstocks produced greater fruit yield than 'MP-29', 'Rootpac® 20', and 'Rootpac® 40' trees in 2019 (Table 3). The following year, trees on Lovell, 'Controller™ 7', and Guardian® had higher yields than those on all other rootstocks, except for 'Controller™ 6' and 8'. 'MP-29' rootstock produced lower yield than all others in 2021.

In the covariate analysis, T_{50} values of flower buds were not affected by fruit yield in the preceding growing season (data not presented).

Discussion

'Cresthaven' flower bud hardiness varied among the rootstocks tested in mid- and late-winter (Table 2). In both years of the study, flower buds on Lovell trees had relatively low T_{50} values in January and in late February or early March compared with most other rootstocks when the temperatures preceding the freezing test resulted in discrimination of rootstock T_{50} values (Table 2). The mean maximum air temperature near 19 °C in the two days preceding the Jan. 2020 freezing test likely contributed to higher T_{50} values in 2020 versus that recorded in Jan. 2021 when the mean 2-d maximum air temperature immediately before sample collection was nearly 12 °C colder. Although Biglerville has been placed in the U.S. hardiness zone 6b (i.e., average temperature minimum of -21 to -18 °C), minimum temperatures recorded during this study were consistent with those typical of zone 8 (-9 to -12°C). In January 2020, flower buds from Lovell trees were more cold-tolerant than those of all other rootstocks, except for 'MP-29' and 'Controller™ 7'. However, in the following year, all flower buds on trees of all rootstocks had similar T_{50} values, except for Guardian®, which were injured at ≥ 2 °C warmer than all other rootstocks. In previous studies conducted in Missouri with similar experimental

Table 3. Mean yield (kg/tree) of 'Cresthaven' peach trees on eight rootstocks in 2019, 2020, and 2021.

Rootstock	Year 2019	2020	2021
Lovell	9.4 ab [i]	18.2 a	24.2 a
MP 29	4.4 cd	5.3 d	10.5 b
Controller™ 7	6.8 bc	17.8 a	21.4 a
Controller™ 6	7.6 bc	15.9 ab	26.2 a
Guardian®	10.5 a	18.1 a	23.8 a
Controller™ 8	7.1 bc	15.7 ab	21.6 a
Rootpac 40®	3.3 d	11.6 c	23.6 a
Rootpac 20®	5.7 cd	13.9 bc	23.1 a

[i] Means represent 4 tree replicates within 5 replications of each rootstock. LSmeans within columns followed by common letters do not differ at the 5% level of significance, by Fisher's protected LSD.

methods, trees on Lovell and Guardian® had similar T_{50} values near -19 °C when tested in mid-January (Davis 2013; Warmund et al. 2002). However, flower buds on Lovell trees can survive as low as -26 °C in Colorado when exposed to cold air temperatures before sampling (Sterle and Minas 2021). Although rootstocks most likely did not reach their maximum mid-winter hardiness in the present study due to a lack of exposure to very low temperatures before sampling, relative differences were detected.

Proebsting (1963, 1970) found that peach flower buds gain and lose cold hardiness as temperatures fluctuate during winter. In Washington, the T_{50} values of 'Elberta' peach flower buds were correlated with the mean air temperature of the two days preceding the freezing test (Probesting 1963). However, this type of relationship was not evident in the present study. For example, the mean two-day air temperature before collection on 13 Jan., 24 Feb., and 16 Nov. 2020 was 11.4, 3.9, and 16.7 °C, respectively at Biglerville (Fig. 1). However, the mean T_{50} values for all rootstocks for January, February, and November 2020 collection dates were -14.3, -13.1, and -15.6 °C, respectively, (Table 2). Specifically, the mean T_{50} values for rootstocks in November 2020 were relatively low compared with those from other sampling dates that year despite the warm mean two-day temperature of 16.7°C before the freezing test.

During the deacclimation period in late February, flower buds on Lovell trees were more cold-tolerant than those on 'MP-29', 'Controller™ 6 and 7', and Guardian® in both years of the experiment (Table 2). In a 1999 study, using samples from South Carolina, flower bud T_{50} values on Lovell trees were lower than that on Guardian® trees when tested in late February, but in other tests conducted similarly with samples from Missouri and Ohio, flower bud hardiness on trees of these two rootstocks did not differ (Davis, 2013; Warmund et al. 2002). Previous work has shown that the temperature at which flower buds are injured depends on temperatures preceding sample collection and their stage of development, among other factors (Ballard et al. 1981; Proebsting

1963). In a few studies, scion buds of peach cultivars with later floral organ differentiation and a delayed bloom date had greater survival after exposure to a spring frost than those with earlier organ development and an early bloom date, but this result has not been reported in other studies (Harber et al. 1992; Palonen and Buszard 1997; Szalay et al. 2018). In the 1994 NC-140 peach trial, trees on Lovell and Guardian® rootstocks had similar dates for 90% full bloom at 10 of 13 sites (Reighard et al. 2004). In the present study, buds had not yet swollen at the time of collection and differences in floral organ development were not apparent when buds were examined after freezing.

Ashworth (1982) found that xylem discontinuity at the base of the flower primordium prevented the migration of ice through the vascular tissue and into the primordium, which resulted in supercooling during early and mid-winter. However, as procambial cells differentiated into xylem vessel elements and vascular continuity was established between flower primordium and the adjacent stem tissue of deacclimating buds, the floral tissue no longer supercooled to a low temperature in the spring.

Andrews et al. (1983) suggested that deacclimation of peach flower buds occurs in four stages. In the first period, supercooling occurs and is followed by a transition period during early bud swell when buds are injured at progressively warmer temperatures. In the third period before petal tip emergence, the floral primordium is injured at temperatures when ice nucleation occurs (about -2 to -8 °C), but buds are still relatively cold-tolerant until the final period when flowers are frost-sensitive.

Recently, North et al. (2022) suggested that deacclimation occurs in three phases, which was based on a model to describe the deacclimation potential of grape buds in Wisconsin. In the first phase, deacclimation does not occur or is negligible at any air temperature. During the second phase, deacclimation increases rapidly as chilling units accumulate. In the last phase, the rate of deacclimation slows to a point where there is little change. Because buds acclimate, harden, and deacclimate based on low temperatures by location and plant species, it is unlikely that any one model can be used across broad geographic regions (Warmund 2015).

In mid-November freezing tests, the low temperature tolerance of flower buds was similar among all rootstocks (Table 2). A similar lack of discrimination in peach flower bud cold hardness among rootstocks has been reported in previous studies at various NC-140 trial locations, which may be attributed to the 3 °C temperature intervals at which samples are evaluated (Davis 2013; Warmund et al. 2002). In future studies on the effect of rootstocks on flower bud hardiness, differential thermal analysis (DTA) tests may be preferable to the standard method previously used for NC-140 trials. Fewer buds per test may be sampled in DTA tests and the precise temperatures at which floral organs freeze (i.e., low temperature exotherms) can be readily detected by DTA. However, several temperature sensors, as well as an adequate temperature recorder, are needed for DTA to test multiple buds from each rootstock simultaneously at each sampling date.

Although fruit yield varied among rootstocks in the first three years of the trial, the crop load (i.e., fruit yield) on trees in this study did not affect flower bud hardiness during the subsequent dormant period. The reason for this result may be attributed to the pruning and thinning protocols. For pruning, the number of fruiting lateral shoots per tree was adjusted by pruning based on tree size. Flowers on each lateral were later thinned, leaving a crop density of two fruit/cm^2 of trunk cross-sectional area to prevent overcropping trees. High crop densities, such as ≥ 7 fruit/cm^2, on 'Cresthaven'/Lovell peach trees adversely affected survival of swollen flower buds following exposure to air temperatures as low -3 to -8 °C during a three-night period in March (Byers and Marini 1994).

In this trial, vigorous Lovell and Guardian® trees produced high fruit yield per tree (Table 3). 'MP-29' trees, which were considerably smaller in size (32%) than Lovell and Guardian® trees, produced less fruit per tree than the latter seedling rootstocks (data not shown). In all NC-140 trials, which have included several different seedling and hybrid rootstocks, Lovell trees consistently produced high cumulative yields and tree survival (Perry 2000; Johnson et al. 2011; Reighard et al. 2004, 2011, 2020). However, in the southeastern U.S., Guardian® rootstock was selected as a replacement for Lovell due to its tolerance to peach tree short life and root-knot nematodes (Beckman et al. 1996). Subsequent NC-140 trials conducted across North America have shown that Lovell and Guardian® cumulative yields were similar at nearly all sites (Reighard et al. 2004, 2011, 2020). Based on the early results of the present NC-140 trial, 'Cresthaven' flower buds on Lovell trees were about 3 °C more tolerant than those on Guardian® in mid-January and 3 to 4 °C hardier than Guardian® in late February or early March, respectively. Hence, Lovell rootstock may be preferred over Guardian® at sites where low-temperature minima during mid-winter are near -10 to -15 °C, vigorous trees are desired, and the site does not have a history of peach tree short life.

A consistent trend in the flower bud hardiness of trees on size-controlling rootstocks was not apparent. The relatively warm temperatures during the dormant periods of this study likely prevented flower buds on trees from acclimating to their full potential. Thus, further examination of flower bud hardiness on these dwarfing rootstocks during periods of colder temperatures than those experienced during this study may be warranted.

Literature Cited

Agriculture Marketing Resource Center. 2021. Peaches.https://www.agmrc.org/commodities-products/fruits/peaches#:~:text=BY%202020%20the%20United%20States,down%20from%20%24279%2C790%20in%202018. [accessed 5 Sept 2022].

Anthony BM, Minas IS. 2021. Optimizing peach tree canopy architecture for efficient light use, increased productivity and improved fruit quality. Agron. 11(10):1961. https://doi.org/ 10.3390/agronomy11101961.

Andrews PK, Proebsting EL, Gross DC. 1983. Differential thermal analysis and freezing injury of deacclimating peach and sweet cherry reproductive organs. J Am Soc Hortic Sci. 108:755-759. https://doi.org/10.21273/JASHS.108.5.755.

Ashworth EN. 1982. Properties of peach flower buds which facilitate supercooling. Plant Physiol. 70:1475-1479.

Ballard JK, Proebsting EL Jr, Tukey RB. 1981. Critical temperatures for blossom buds. Wash State Univ Coop Ext Bull 0914.

Beckman TG, Chaparro JX, Sherman WB. 2012. 'MP-29', a clonal interspecific hybrid rootstock for peach. HortScience. 47:128-131. https://doi.org/10.21273/ HORTSCI.47.1.128.

Beckman TG, Okie WR, Nyczepir AP, Reighard GL, Zehr EI, Newall WC. 1996. History, current status, and future potential of Guardian™ (BY520–9) peach rootstock. Acta Hortic. 451:251-258.

Bittenbender HC, Howell GS Jr. 1974. Adaptation of the Spearman-Karber method of estimating T_{50} of cold stressed flower buds. J Am Soc Hortic Sci. 99:187-189.https://doi.org/10.21273/JASHS.99.2.187.

Brown SK, Cummins JN. 1988. Rootstock influenced peach flower bud survival after a natural freeze. HortScience. 23:846-847.

Byers RE, Marini RP. 1994. Influence of blossom and fruit thinning on peach flower bud tolerance to an early spring freeze. HortScience. 29:146-148. https://doi.org/10.21273/HORTSCI.29.3.146.

Crassweller R, Peter K, Krawczyk G, Schupp J, Ford T, Brittingham M, Johnson J, LaBorde L, Harper J, Kephart K, Pifer R, Kelley K, He L, Heinemann P, Biddinger D, Lopez-Uribe M, Marini R, Baugher T, Weber D, Kime L, Crow E, Weaver E, Lehman B. 2020. 2020-2021 Penn State Tree Fruit Production Guide. Publ AGRS-045. Pennsylvania State Extension.

Davis AL. 2013. Low temperature survival of 'Redhaven' peach floral buds on selected rootstocks (M.S. thesis). University of Missouri., Columbia.

Durner EF. 1990. Rootstock influence on flower bud hardiness and yield of 'Redhaven' peach. HortScience.25:172-173.https://doi.org/10.21273/HORTSCI.25.2.172.

Durner EF, Gianfagna TJ. 1988. Fall ethephon application increases peach flower bud resistance to low-temperature stress. J Amer Soc Hort Sci. 113:404-

406. https:// doi.org/10.21273/JASHS.113.3.404.

Foundation Plant Services. 2022a. Prunus cultivar: Controller 7. University of California, Davis, CA. https://fps.ucdavis.edu/treedetails.cfm?v=3489. [accessed 3 Sept 2022].

Foundation Plant Services. 2022b. Prunus cultivar: Controller 8. University of California, Davis, CA. https://fps.ucdavis.edu/treedetails.cfm?v=3490. [accessed 3 Sept 2022].

Foundation Plant Services. 2022c. Prunus cultivar: Controller 6. University of California, Davis, CA. https://fps.ucdavis.edu/treedetails.cfm?v=3493. [accessed 3 Sept 2022].

Foundation Plant Services. 2022d. Prunus cultivar:Lovell. University of California, Davis, CA. https://fps.ucdavis.edu/treedetails.cfm?v=905#:~:text=Origin%3A%201882%2C%20G.W.,Thissell%2C%20Winters%2C%20CA. [accessed 3 Sept 2022].

Gasic K, Preece JE. 2014. Register of new fruit and nut cultivars list 47. HortScience. 49:396-421. https://doi.org/10.21273/HORTSCI.49.4.396.

Harber RM, Nyczepir AP, Yadava UL, and Sharpe RR. 1992. Rootstock, pruning, and soil fumigation in relation to dormancy and cold hardiness of 'Redhaven' peach. HortScience. 27:99-100. https://doi.org/10.21273/HORTSCI.27.2.99.

Johnson S, Andersen R, Autio W, Beckman T, Black B, Byers P, Cline J, Chavez-Gonzalez C, Cowgill W, Godin R, Greene G, Kaps M, Kamas J, Larsen H, Lindstrom T, Miller D, Newell M, Ophardt D, Ouellette D, Parra-Quezada R, Pokharel R, Reighard G, Robinson T, Schupp J, L Stein, Taylor K, Walsh C, Ward D, Warmund M, Whiting M. 2011. Performance of the 2002 NC-140 cooperative peach rootstock planting. J Am Pomol Soc. 65:17-25.

Lesmes-Vesga RA, Cano LM, Ritenour MA, Sarkhosh A, Chaparro JX, Rossi L. 2022. Rootstocks for commercial peach production in the southeastern United States: current research, challenges, and opportunities. Hortic. 8:602. https://doi.org/10.3390/horticulturae8070602.

Liu J. 2017. Revisiting cold hardiness of peach in Georgia (PhD Diss). University of Georgia, Athens.

Marini R. 2021. The changing peach rootstock picture. Penn State Extension. https://extension.psu.edu/the-changing-peach-rootstock-picture. [accessed 5 Sept 2022].

North M, Workmaster BA, Atucha A. 2022. Effects of chill unit accumulation and temperature on woody plant deacclimation kinetics. Physiol Plant. https://doi.org/10.1111/ppl. 13717.

Okie WR, Beckman TG, Nyczepir AP, Reighard GL, Newall WC Jr, Zehr EI. 1994. BY520-9, a peach rootstock for the southeastern United States that increases scion longevity. HortScience. 29:705-706. https://doi.org/10.21273/HORTSCI.29.6.705.

Palonen P, Buszard D. 1997. Current state of cold hardiness research on fruit crops. Can J Plant Sci. 77:399-420.

Perry R, Reighard G, Ferree D, Barden J, Beckman T, Brown G, Cummins J, Durner E, Greene G, Johnson S, Layne R, Morrison F, Myers S, Okie WR, Rom C, Rom R, Taylor B, Walker D, Warmund M, Yu K. 2000. Performance of the 1984 NC-140 cooperative peach rootstock planting. J Am Pomol Soc. 54:6-10.

Proebsting EL Jr. 1963. The role of air temperatures and bud development in determining hardiness of dormant 'Elberta' peach fruit buds. Proc Am Soc Hortic Sci. 83:259-269. https://doi.org/10.21273/HORTSCI.5.5.422.

Proebsting EL Jr. 1970. Relation of fall and winter temperatures to flower bud behavior and wood hardiness of deciduous fruit trees. HortScience. 5:422-424.

Reighard GL, NC-140 collaborators. 2022. Thirty-three years evaluating rootstocks for peach in the NC-140: what have we learned? Acta Hortic. 1346:655-660. https://doi.org/10.17660/ActaHortic.2022.1346.82.

Reighard GL, Andersen RL, Anderson J, Beckman T, Baker T, Belding R, Brown G, Byers P, Cowgill W, Deyton D, Durner E, Erb A, Ferree D, Gaus A, Godin R, Hayden R, Hirst P, Kadir S, Kaps M, Larsen H, Lindstrom T, Miles N, Morrison F, Myers S, Ouellette D, Rom C, Shane W, Taylor B, Taylor K, Walsh C, Warmund M. 2004. Growth and yield of 'Redhaven' peach on 19 rootstocks at 20 North American locations. J Am Pomol Soc. 58:174-202.

Reighard GL, Beckman T, Belding R, Black B, Cline J, Cowgill W, Godin R, Johnson RS, Kamas J, Kaps M, Larsen H, Lindstrom T, Newell M, Ouellette D, Pokharel R, Stein L, Taylor K, Walsh C, Ward D, Whiting M. 2011. Six-year performance of 14 Prunus rootstocks at 11 sites in the 2001 NC-140 peach trial. J Am Pomol Soc. 65:26-41.

Reighard GL, Bridges W Jr , Archbold D, Atucha A, Autio W, Beckman T, Black B, Chavez DJ, Coneva E, Day K, Francescatto P, Kushad M, Johnson RS, Lindstrom T, Lorean J, Minas IS, Ouellette D, Parker M, Pokharel R, Robinson T, Schupp J, Warmund M, Wolfe D. 2020. Nine-year rootstock performance of the NC-140 'Redhaven' peach trial across 13 states. J Am Pomol Soc. 74: 45-56.

Smith MW, Carroll BL, Taylor GG. 1994. Cold injury of peach and nectarine cultivars after a fall freeze. HortScience. 29:821. https://doi.org/10.21273/HORTSCI.29.7.821.24.

Sterle D, Minas IS. 2021. Cold hardiness assessment of peach flower buds using differential thermal analysis (DTA) in western Colorado (dormant season 2019-2021). Colorado State University. https://agsci.colostate.edu/minas/wp-content/uploads/sites/60/2020/11/Peach-floral-bud-cold-hardiness-update-21-2_14_20.pdf. [accessed 5 Aug 2022].

Szalay L, Gyökös IG, Békefi Z. 2018. Cold hardiness of peach flowers at different phenological stages. Hortic Sci. 45:119-124. https://doi:10.17221/146/2016-HORTSCI.

Szalay L, Timon B, Németh S, Papp J, and Tóth M. 2010. Hardening and dehardening of peach flower buds. HortScience. 45:761-765. https://doi.org/10.21273/HORTSCI.45.5.761.

US Department of Agriculture, National Agricultural Statistics Service. 2021. Noncitrus fruits and nuts 2020 summary. https://downloads.usda.library.cornell.edu/usda-esmis/files/zs25x846c/sf269213r/6t054c23t/ncit0521.pdf [accessed 3 Sept 2022].

Warmund MR. 2015. Blueberry chilling model dilemmas. J Am Pom Soc. 69:26-30.

Warmund, M., G.L. Reighard, and D.C. Ferree. 2002. Low-temperature susceptibility of 'Redhaven' peach floral buds on various rootstocks in the 1994 NC-140 trial. J Am Pomol Soc. 56:235-241.

Warmund MR, Slater, JV. 1988. Hardiness of apple and peach trees in the NC-140 rootstock trials. Fruit Var J. 42:20-24.