Midwinter Hardiness of Peach and Nectarine Flower Buds and Shoots Across 33 Varieties

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Lack of cold hardiness limits peach flower bud and tree survival in northern climates where winter injury occurs nearly every year. Flower bud mortality directly impacts yield, and shoot injury reduces yield in subsequent years when it leads to tree or limb death (Shane 2020). When winter temperatures reach -13 °F (-25 °C) in more than one out of every seven years, peach production becomes unprofitable (Quamme et al. 1987). In northern New England, midwinter temperature minimums that cause injury occur once every four years (NOAA, Concord, NH station), making peach production risky in this region.

In recent decades, breeding programs have created many new peach and nectarine varieties and a greater diversity of fruit types, such as flat peaches or those with white flesh, many of which are planted by growers due to improved fruit quality and disease resistance (Frecon 2005; Shane, 2005). Preliminary testing has been done to characterize their cold hardiness (Shane 2020), but many varieties remain untested.

Most peach hardiness studies have focused on flower buds, but xylem and cambial tissues within shoots are also subject to cold injury (Figure 1), which can vary among varieties (Shane 2020). Redhaven, one of the most commonly grown varieties in colder regions, has midwinter xylem hardiness that is intermediate to 15 other varieties (Szabó 1992). When injury occurs in older shoot tissues, it can lead to poor tree growth and early tree deaths (Shane, 2020), making shoot hardiness an important factor in identifying varieties with lower winter injury risk.

Figure 1. Freezing injury within peach shoot xylem (left) and cambium (right).

Determining hardiness in peach varieties has often been based on survival following test winters, but this can be confounded by multiple injurious events. To address this, shoots can be subjected to artificial freezing with stepwise temperature decreases followed by injury assessment at each point to create a nonlinear curve, estimating the lethal temperature. Such methods detect varietal differences in hardiness at specific times (Shane 2020). Other factors also affect cold hardiness, complicating differences among varieties. Therefore, both artificial freezing and test winters, along with multiple years of measurement, are needed to characterize hardiness.

The goal of this study was to characterize the midwinter flower bud and shoot (xylem and cambium) cold hardiness in a collection of commercially available peach and nectarine varieties, including older and newer releases.

Materials and Methods

Cold hardiness was measured in 33 peach and nectarine varieties in 2021 (Table 1), and 22 varieties in 2023. Three trees of each variety on Lovell rootstock were planted in 2018 in a commercial orchard located in Concord, NH, USA. Nectafest trees were planted in 2019. Trees were trained to an open center, irrigated as needed, and were given standard pest and disease control measures as well as fruit thinning in early summer. Shoots were collected midmorning Feb. 24, 2021 and Jan. 28, 2023. From each variety, 25 to 30 shoots were cut and placed in buckets with tap water for transport to the laboratory. Transportation took 3 hours, and an additional 2 hours was spent preparing samples. Shoots were then placed in a programmable freezer at 23.2 °F (-4.9 °C) in 2021 and at 17.8 °F (-7.9 °C) in 2023 for 15 hours, after which a set of shoots was removed. Thereafter, freezer temperature was decreased every 24 hours, and a set of shoots was removed at each decrease. Freezer test temperatures were 23.2, 2.1, -4.4, -9.9, -13.2, -21.6, and -30.6 °F (-4.9, -16.6, -20.2, -23.3, -25.1, -29.8, and -34.8 °C) in 2021 and 17.8, 2.5, -2.7, -7.2, -11.9, -16.4, and -21.3 °F (-7.9, -16.4, -19.3, -21.8, -24.4, -26.9 and -29.6 °C) in 2023. Immediately after removal from the freezer, sets of shoots were placed in a cold room at 37 °F (3 °C) until analysis of injury.

A natural freeze to -9.9 °F (-23.3 °C) occurred on Jan. 22, 2022. Shoots were collected Feb. 7 and subjected to the same methods described above, but cold injury prior to collection rendered regression models nonviable. Thus, flower bud survival measured at the first test temperature 20.5 °F (-6.4 °C) is shown in place of artificial freezing data.

Shoots were removed from cold storage within one week of artificial freezing and left at room temperature for one day to allow for browning of injured tissues. Flower buds were measured as dead or alive based on visual browning of the pistil in cross-section. Xylem

Table 1. Origin and fruit descriptions of peach varieties included in Concord, NH trial.

Cultivar	Origin	Type	Flesh color
August Rose	New Jersey AES[i]	Peach	White
Avalon	New Jersey AES	Nectarine	Yellow
Brigantine	New Jersey AES	Nectarine	Yellow
BuenOs	New Jersey AES	Flat	Yellow
Contender	North Carolina	Peach	Yellow
Coralstar	Michigan - Stellar	Peach	Yellow
Cresthaven	Michigan – MSU[ii]	Peach	Yellow
Desiree	New Jersey AES	Peach	Yellow
Emeraude	France, Riviera Breeding	Nectarine	White
Evelynn	New Jersey AES	Peach	Yellow
Galaxy	California - USDA	Flat	White
Glenglo	West Virginia	Peach	Yellow
Jade	France, Riviera Breeding	Nectarine	White
John Boy	New Jersey	Peach	Yellow
July Rose	New Jersey AES	Peach	White
Manon	France, Riviera Breeding	Peach	White
Messina	New Jersey AES	Peach	Yellow
Nectafest	West Virginia - USDA	Nectarine	Yellow
PF17	Michigan - PF[iii]	Peach	Yellow
PF23	Michigan - PF	Peach	Yellow
PF5D	Michigan - PF	Peach	Yellow
PF9A 007	Michigan - PF	Peach	Yellow
Redhaven	Michigan - MSU	Peach	Yellow
Saturn	New Jersy AES	Flat	White
Scarlet Rose	New Jersey AES	Peach	White
Selena	New Jersey AES	Peach	Yellow
Silvergem	New Jersey AES	Nectarine	White
Silverglo	New Jersey AES	Nectarine	White
Spring Snow	California - Zaiger	Peach	White
Sugar Giant	California - Zaiger	Peach	White
Sugar May	California - Zaiger	Peach	White
TangOs	New Jersey AES	Flat	Yellow
White Lady	California - Zaiger	Peach	White

i AES is Agricultural Experiment Station.
ii MSU is Michigan State University.
iii PF is from the Flaming Fury® series bred by Paul Friday, Coloma, Michigan.

tissue browning was visually rated using a scale from 0 to 10, where 0 indicated no browning and 10 indicated 100% discoloration of the xylem in cross section (Figure 1). To assess browning of cambium, shoots were cut lengthwise to the depth of the outer xylem on two sides of each shoot and rated on the same scale as xylem. Cambial browning was measured as the relative length and circumference of discolored tissue. Additionally, tissues were rated according to the intensity of browning using a scale of 0 to 5, where 0 indicated no browning and 5 indicated dark browning to blackening of the tissues (Moran and Ginakes 2024). Both ratings were used to calculate an index of injury according to the equation:

$$index\ of\ injury = \frac{(discolored\ area + ((discolored\ intensity * 2))}{2}$$

In May 2024, trees were rated for signs of winter injury by assessing tree vigor, shoot growth, limb death and trunk cracking. A rating of 1 indicated poor vigor, more than half the limbs dead, no shoots growing at the base of the limbs, and obvious trunk cracking. A rating of 5 indicated strong vigor, new shoot growth at the base of the limbs and no trunk cracking. At this time, only one tree death had occurred and for an unknown reason. Some shoot dieback occurred in all the varieties, so this was not used as an indicator of overall tree health.

`*Statistical analysis.* Each shoot was considered an experimental unit with 4 to 5 replicate shoots for each variety and temperature combination during controlled freezing. Prior injury was measured in 4 to 5 additional shoots as a measure of ambient injury that occurred before the experiment, and was included in the model for the temperature 32 °F (0 °C). Flower bud and shoot tissue hardiness were estimated by nonlinear regression with differences among varieties based on the 95% confidence interval of the inflection point. Nonlinear regression was used to estimate the four parameters of an adjusted logistic sigmoid function:

$$y = \frac{a}{(1 + e^{b(c-x)})} + d$$

where y is the survival or index of injury, a the maximum injury or upper asymptote, b the slope at the inflection point, c the temperature at the inflection point, x as the controlled freezing temperature, and d the lower asymptote or injury that occurred prior to testing. When no prior injury occurred, d was not included in the model. Lethal temperatures for 50% of the flower buds (LT_{50}), and xylem and cambium tissue temperature of maximum increase in injury (TI) were calculated as parameter c. Varietal differences in cold hardiness were evaluated based on the LT_{50} for flower buds or TI for xylem and cambium, and their 95% confidence intervals. Significant injury differences among varieties were also based on means separation within a temperature using Tukey's HSD at $P \leq 0.05$. Differences among varieties in 2022 were likewise analyzed.

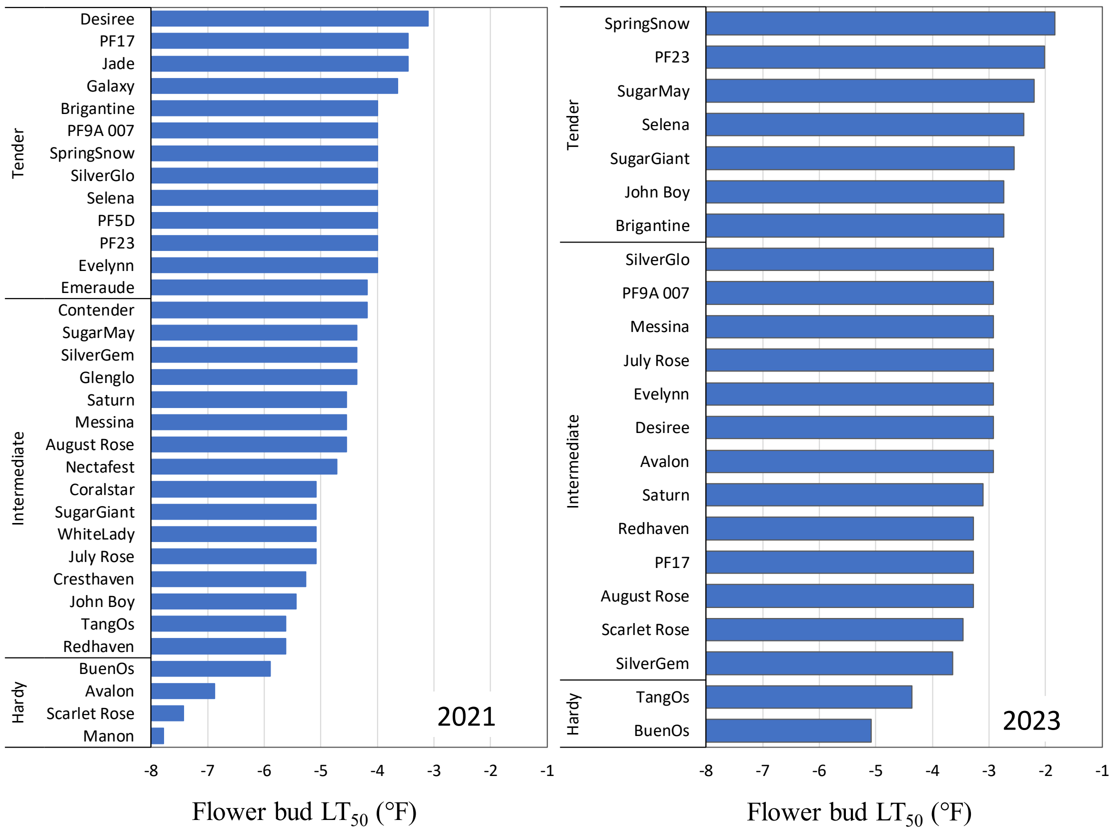
Results and Discussion

Flower bud LT50 ranged from -3.1 to -7.8 °F (-19.5 to -22.1 °C) in 2021 and from -1.8 to -5.1 °F (-18.8 to -20.6 °C) in 2023 (Figure 2). The LT50 is the temperature that kills 50% of flower buds. Hardiness rankings were based on statistical analysis, with intermediate varieties generally not significantly different from tender or hardy varieties. In 2021, the LT50 was coldest in Manon, with BuenOs, Avalon, and Scarlet Rose similarly hardy. Redhaven and varieties like Cresthaven and Contender were intermediate. The warmest LT50 occurred in Desiree, with several varieties as tender as Desiree. In 2023, BuenOs and TangOs had the coldest LT50. Redhaven remained intermediate, with many other varieties following suit. Spring Snow had the warmest LT50 in 2023, matching its ranking as tender in 2021.

A severe freeze to -10 ºF in Feb. 2022 prevented artificial freezing tests but was useful for measuring survival following a natural freeze. Flower bud survival was greatest in Contender and Redhaven (Figure 3). Varieties that had no survival included Brigantine, Galaxy, Glenglo, Jade, PF5D, Saturn, and Spring Snow. Several varieties had low survival (0.6 to 10%), including BuenOs, ranked as hardy in artificial tests. Other varieties had intermediate survival (12.3% to 20.5%). Silverglo had too few buds to measure in 2022.

Some varieties had a warmer LT50 in 2023 than in 2021. Redhaven buds were hardy to -5.6 °F in 2021 but -3.2 °F in 2023. This difference likely stemmed from warmer temperatures just before testing in 2023, which can reduce hardiness (Moran and Ginakes 2024). Flower bud hardiness varied by 10 °F (5.5 °C) between contrasting varieties (Szalay et al. 2010). The narrow range of LT50s in 2021 reflected low variability among

Figure 2. Temperature for 50% flower bud mortality (LT_{50}) in 33 peach varieties in 2021 and 22 peach varieties in 2023 following exposure to subfreezing temperatures.



the varieties. The range was even smaller in 2023, excluding the least hardy varieties.

Varieties differ in flower bud hardiness based on their timing of bud development, with some varieties as early as mid-January (Szabó et al. 2002). We measured hardiness in midwinter, assuming it was near its seasonal maximum, though some buds may have been fully chilled and more responsive to warm temperatures. PF23 and Galaxy, with low chill requirements, had relatively low hardiness, while Redhaven and Contender, requiring more chill, had greater hardiness. Other varieties with long chill requirements like Cresthaven and Coralstar were also hardy. Some varieties' chill requirements could not be found or are undetermined.

Cambial tissue appeared less hardy in some varieties in 2021 than in 2023 (Figure 4). Cambial injury temperatures ranged from -2 to -11 °F in 2021 and from -8 to -15 °F in 2023. TangOs and John Boy were hardiest in 2021 but tender in 2023, while July Rose was the hardiest in 2023 but intermediate in 2021. Cambial injury in Feb. 2022 varied among varieties. Some varieties had high injury levels, consistent with controlled freezing results. Severe cambial damage is typically followed by rapid tree decline (Shane 2020) or subsequent Cytospora cankers (Chang et al. 1989).

Xylem temperature response was similar in both years for Redhaven and most other varieties (Figure 5). Xylem TIs spanned 8 °F (4.5 °C) in 2021 and 3.6 °F (2.0 °C) in 2023. In 2021, BuenOs, Emeraude, Jade, John Boy, PF17, Redhaven, Silvergem, Silverglo, and Sugar Giant had the hardiest xylem with TIs below -11 °F (-24.0 °C). Tender xylem varieties included August Rose, Coralstar, Galaxy, Messina, Nectafest, PF23, Scarlet Rose, Selena, and Spring Snow, with TIs of -10 °F (-23.2 °C) or warmer. In 2023, Silvergem had the hardiest xylem with a TI of -14.1 °F (-25.6 °C). Other tender xylem varieties in 2023 included August Rose, Brigantine, Evelynn, July Rose, Saturn, Scarlet Rose, Selena, Spring Snow, Sugar Giant, and Sugar May.

Winter minimum temperatures in southern New Hampshire ranged from -5 to -21 °F (-20.6 to -29.4 °C) in the last 12 years (NOAA), cold enough to

Figure 3. Percent flower bud survival after a freeze to -10 ºF in February 2022.

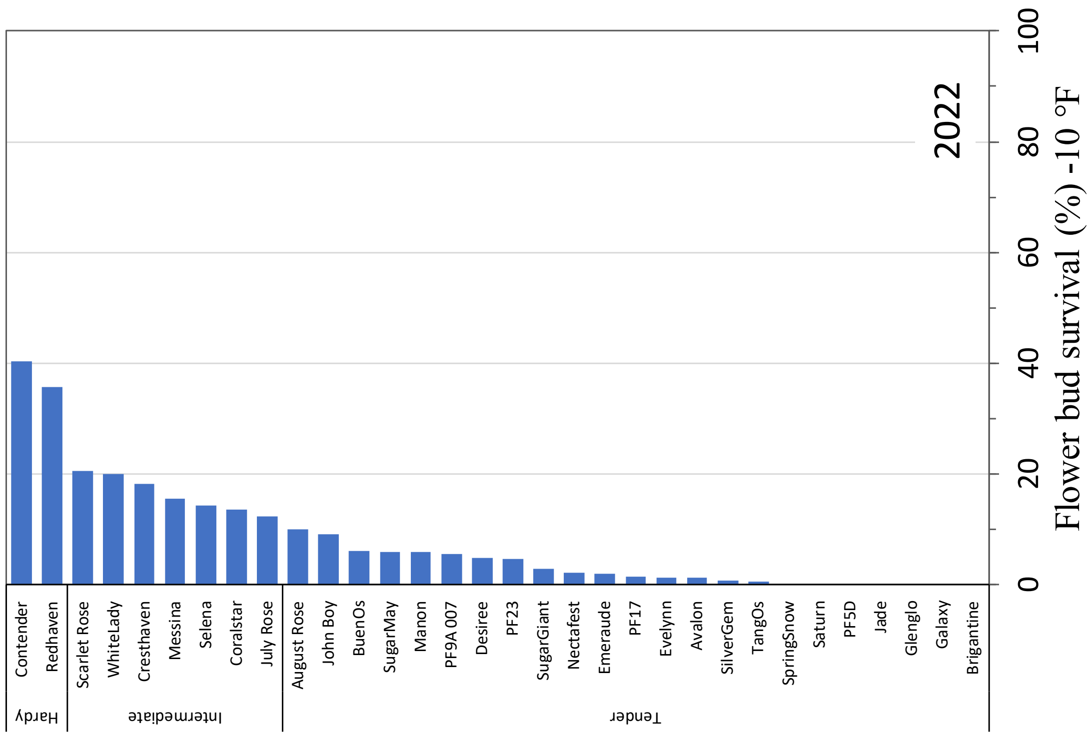


Figure 4. Temperature that causes injury (TI) to cambial tissues in peach shoots of 33 varieties in 2021 and 22 varieties in 2023.

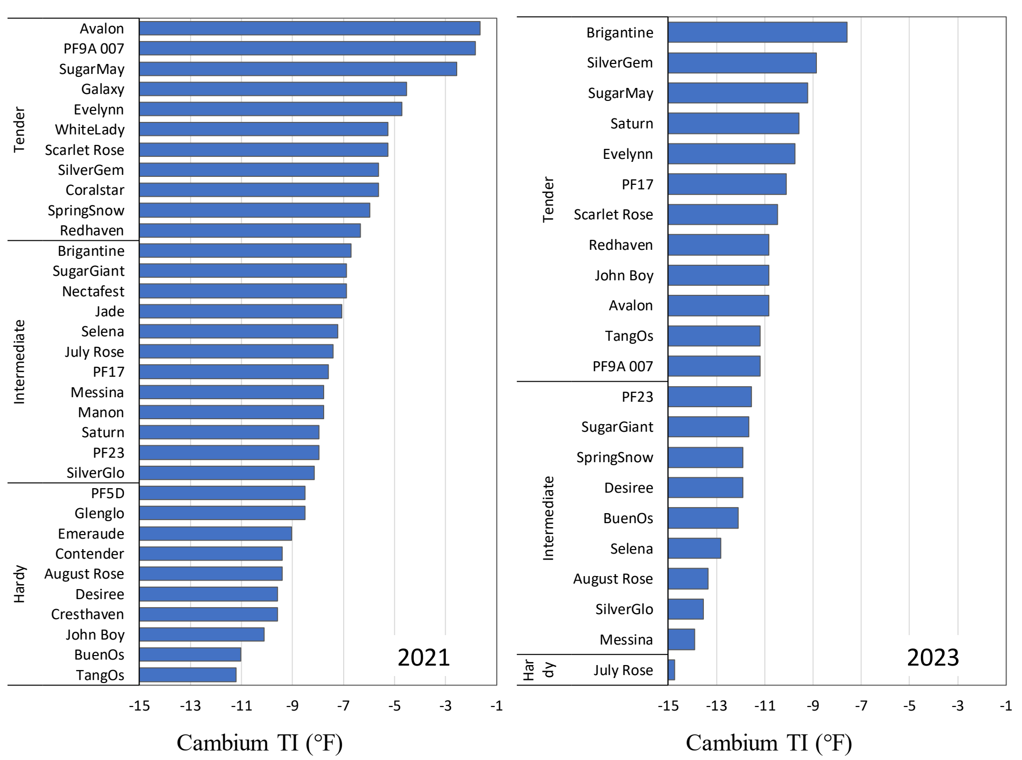
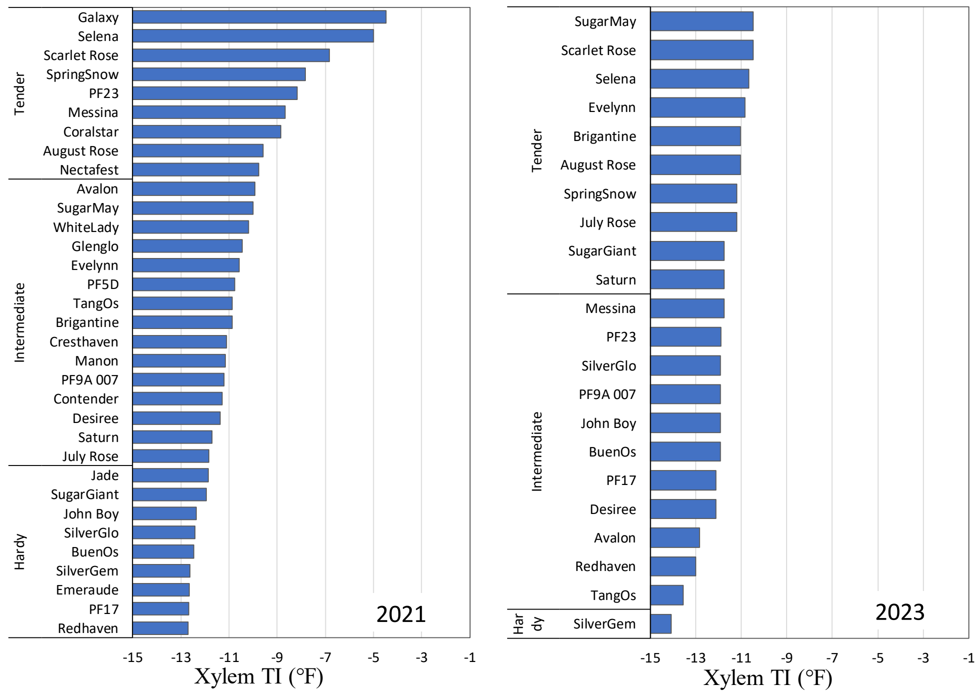


Figure 5. Temperature that causes injury (TI) to xylem tissues in peach shoots of 33 varieties in 2021 and 22 varieties in 2023.



damage xylem in hardiest varieties in four years. Redhaven's shoot xylem was hardy to -18 to -27 °F when artificially hardened (Layne 1989) but suffered severe injury after a freeze to -15 °F (Layne 1982). Cold tolerance reflects acclimation to ambient temperatures prior to testing.

General tree health ratings in 2024 varied (Table 2). Scarlet Rose and Sugar Giant showed signs of tree decline and trunk injury (Figure 6). This aligns with the lack of hardiness in cambial tissues of Scarlet Rose in 2022 and artificial freezing tests. Other varieties with low ratings included Desiree, Emeraude, Galaxy, and PF5D. Ratings were highest in BuenOs and Contender, with most other varieties similar.

Factors other than genetics, such as crop load and prior temperatures, influence hardiness and may explain year-to-year variability. Warm temperatures can induce deacclimation, making buds and shoots vulnerable to freezes (Moran and Ginakes 2024; Minas and Sterle 2020). Two features of hardiness are important: maximum cold tolerance during dormancy and long chill requirements to prevent premature bud development. Varieties with the greatest cold tolerance during dormancy may not maintain high hardiness in late winter, explaining year-to-year inconsistencies in rankings.

Varieties consistently among the least hardy are more likely to experience 100% bud mortality in southern NH based on expected minimum temperatures in northern New England. Evelynn, Galaxy, PF5D, and Sugar May had consistently tender flower buds and shoot tissues, making them high-risk choices (Table 3). BuenOs, a flat peach, was the only variety consistently cold-hardy. Contender, Cresthaven, and Redhaven had consistently hardy flower buds but were not always hardy in shoot cambium and xylem tissues.

Table 2. Tree health rating in five-year-old peach trees measured in May 2024. Trees were rated on a scale of 1 to 5 with 1 indicating signs of severe injury and 5 indicating intact tree trunks, good vigor and surviving limbs.

Severe <3.5	**Moderate** 3.5 to 4.0	**Mild** 4.1 to 4.5	**Little or None** >4.5
Desiree	Avalon	Coralstar	August Rose
Galaxy	Brigantine	Cresthaven	BuenOs
PF5D	Glenglo	Emeraude	Contender
Scarlet Rose	Jade	Evelynn	
Sugar Giant	Johnboy	July Rose	
	Manon	PF23	
	Messina	Redhaven	
	Nectafest	Selena	
	PF17	Silvergem	
	PF9A 007	Silverglo	
	Saturn	TangOs	
	Spring Snow		
	Sugar May		
	White Lady		

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Figure 6. Trunk and limb injury that was likely caused by cold temperatures.

Table 3. Relative rankings for midwinter hardiness in 33 peach varieties.

	Hardy	Intermediate	Tender	Inconsistent
Flower buds	BuenOs	August Rose	Brigantine	Manon
	Contender	Avalon	Desiree	PF17
	Cresthaven	Coralstar	Emeraude	Saturn
	Redhaven	John Boy	Evelynn	Selena
	Scarlet Rose	July Rose	Galaxy	Silvergem
		Messina	Glenglo	Sugar Giant
		Nectafest	Jade	TangOs
		PF9A-007	PF5D	White Lady
			PF23	
			Silverglo	
			Spring Snow	
			Sugar May	
Cambium	August Rose	Emeraude	Avalon	Brigantine
	BuenOs	Jade	Evelynn	Contender
	Cresthaven	Nectafest	Galaxy	Coralstar
	Desiree	PF23	PF5D	Glenglo
	Silverglo	Redhaven	PF9A-007	John Boy
		Sugar Giant	PF17	July Rose
			Scarlet Rose	Manon
			Silvergem	Messina
			Sugar May	Saturn
				Selena
				Spring Snow
				TangOs
				White Lady

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