Performance of Satsuma Mandarin Protected from Freezing Temperatures by Microsprinkler Irrigation

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Abstract. Several microsprinkler treatments were tested on 5-year-old satsuma mandarin orange (*Citrus unshiu* Marc.) trees to compare survivability of trunks and scaffold limbs in severe freezes. Three damaging freeze events occurred during winter, with two in 1995–96 and one in 1996–97. Air temperature dropped to -9.4 , -5.6 , and -6.7 °C, respectively. Almost 90% of the foliage was dead on the control plants after the first freezing event and 98% after the second. A single microsprinkler 1.6 m high in the canopy delivering $90.8 \text{ L}\cdot\text{h}^{-1}$ reduced injury; only 54% of the canopy was dead after the first freeze and 71% after the second. There was slightly more shoot-tip dieback on the plants in the microsprinkler treatments than on the control plants after the first two freezes. The amount of limb breakage by ice was minor. The third freeze killed 34% of the canopy in the control plants, but only 26% in the plants in the microsprinkler treatments. Use of microsprinklers increased yield in 1996, but yield for all treatments was very low. Yield for all treatments fully recovered in 1997, averaging 153 kg/tree. Although no death of scaffold limbs or trunks occurred, these results demonstrate that microsprinkler irrigation reduces damage to foliage and increases yield somewhat in severe freezes.

Among commercially important citrus cultivars, satsuma mandarin has the greatest genetic ability to tolerate freezing temperatures, surviving temperatures as low as -9.4 °C (Yelenosky, 1985), -11.0 °C (Anderson et al., 1983), and -11.1 °C (Gerber and Hashemi, 1965) in laboratory studies. In the 1920s, Mississippi growers observed that satsumas could tolerate temperatures of -9.9 to -11.0 °C without injury if “absolutely healthy and perfectly dormant” (Ferris and Richardson, 1923). However, with less hardening, widespread killing of bearing satsuma trees occurred in commercial groves in South Alabama at temperatures of -6.7 °C (Wimberg, 1948). Cold tolerance was sufficient to allow development of a commercial industry of satsuma mandarin in the early 1900s in the subtropical climate along the northern coast of the Gulf of Mexico. South Alabama had ≈ 4856 ha of bearing and 2428 ha of nonbearing satsuma mandarin in 1923 (Dozier, 1924). Severe freezes in the late 1920s, 1930s, and 1940s destroyed the sat-

suma industry in Alabama, and subsequent freezes prevented its reestablishment to a commercial level in the state.

Elevated microsprinkler irrigation has been studied as a means of protecting citrus, including satsuma, from freeze injury with minimal structural damage from the weight of ice in comparison with over-tree irrigation (Bourgeois and Adams, 1987; Braud et al., 1981; Parsons et al., 1991). The survival rate of 1-year-old ‘Owari’ satsuma mandarin exposed to -8.9 °C was 80% when a single microsprinkler delivering $114 \text{ L}\cdot\text{h}^{-1}$ was elevated to a height of 0.75 m at the center of each tree (Bourgeois and Adams, 1987). Almost 95% of 4- and 5-year-old trees exposed to -11.1 °C survived when a microsprinkler was positioned at 0.75 or 1.0 m high in the canopy and delivered either 114 or $342 \text{ L}\cdot\text{h}^{-1}$ (Bourgeois et al., 1990). In both reports, fruiting wood was killed above the coverage pattern of the sprinkler, but the trunk, graft union, and major scaffold limbs were protected, resulting in greater fruit production the second growing season.

Rieger et al. (1985) compared delivery rates of three microsprinklers positioned on the ground and found that trunk temperature of 2-year-old ‘Hamlin’ orange trees 20 cm aboveground remained higher when the delivery rate was $37.9 \text{ L}\cdot\text{h}^{-1}$ than when it was 56.8 or $87.0 \text{ L}\cdot\text{h}^{-1}$. They also found that height of live wood, dry weight, and number of new shoots increased with irrigation rate, but proposed that such savings in growth were of little

value, compared with the energy cost. Parsons et al. (1991) compared emitter height, flow rate, and wetting pattern in different groves, and concluded that protection of trees from freeze injury, regrowth after the freeze, and subsequent production were enhanced in orchards where emitters were installed as high as 0.9 m aboveground. They also suggested that freeze protection was adequate at rates lower than those used by Bourgeois and Adams (1987) in Louisiana. Optimum water application rate and emitter height necessary for maximum freeze protection, regrowth, and yield of satsuma mandarin has not been established. A comparison of both emitter heights and water delivery rates has not previously been made in a randomized, replicated test. The objective of this study was to determine the effects of different height and rate of microsprinkler irrigation during freezes on survival and subsequent vegetative and reproductive growth of satsuma mandarin.

Materials and Methods

One-year-old ‘Owari’ satsuma mandarin trees on *Poncirus trifoliata* (L.) Raf. rootstock were planted in Mar. 1990 at the Alabama Agricultural Experiment Station Gulf Coast Research and Extension Center in Fairhope, Ala. The test site was 1.6 km east of Mobile Bay, a body of water that significantly moderates winter temperatures. Trees were planted at a spacing of 4.6×7.6 m. Fertilization and insect, disease, and weed control were according to current commercial recommendations.

In 1995, seven treatments were randomly assigned from late fall to early spring to four-tree plots and replicated five times in a randomized complete-block design, using trees ≈ 2.2 m tall. Treatments included: 1) unprotected control; 2) soil mounded ≈ 0.45 m high around the trunk and graft union; 3) a single $40.5 \text{ L}\cdot\text{h}^{-1}$ microsprinkler with 90° spray pattern located 1 m from the trunk on the northwest canopy quadrant and elevated to a height of 0.45 m; 4) a single $90.8 \text{ L}\cdot\text{h}^{-1}$ microsprinkler with 360° spray pattern located at canopy center and elevated to a height of 0.86 m; 5) a single $90.8 \text{ L}\cdot\text{h}^{-1}$ microsprinkler with 360° spray pattern located at canopy center and elevated to a height of 1.6 m; 6) treatments 3 and 5 combined giving an output of $131.3 \text{ L}\cdot\text{h}^{-1}$, and 7) treatments 4 and 5 combined giving an output of $181.6 \text{ L}\cdot\text{h}^{-1}$.

Microsprinkler treatments were activated when low temperatures predicted by forecasting agencies were perceived to be potentially injurious. In general, a low temperature forecast of less than -5 °C triggered treatment, except in Mar. 1996, when trees were deemed to be cold-sensitive due to active growth, and thus susceptible to damage at higher temperatures. Irrigation was begun when air temperature declined to 0.6 °C and continued until rapid thawing of ice was observed and the threat of more freezing temperatures had passed.

Air temperature 1.5 m aboveground was measured hourly with a thermocouple and the data were stored using a CR10 automated

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weather station (Campbell Scientific, Logan, Utah). A second thermocouple located on a tower 9 m high was used to determine the extent of temperature inversion. The weather station was located 100 m from the test grove.

Trees were rated for the percentage of damaged foliage following each injurious freeze event. Trees were rated for extent of shoot dieback using a scale where 0 = no dieback of terminals; 1 = 1% to 5% terminals having distal necrosis; 2 = 6% to 10%; 3 = 11% to 25%; 4 = greater than 25%. Broken scaffold branches were counted in Apr. 1996. Yield was measured at normal commercial harvest in Nov. 1996 and Nov. 1997. Mean fruit size was calculated from a random 20-fruit sample each year. The number of fruit per tree was recorded in 1996.

Data were analyzed as a randomized complete-block design with five blocks using the GLM procedure of SAS (SAS Institute, 1985). The significance of differences among means were determined using Duncan's multiple range test.

Results and Discussion

Satsuma mandarin trees become quiescent, characterized by little or no vegetative growth, when nighttime temperatures fall below 15.5 °C (Young and Peynado, 1962). The test grove was exposed to such temperatures from Nov. 1995 through mid-Feb. 1996 (Fig. 1), during which time terminal buds formed. While there were occasional warmer nights during this time, no bud swelling or shoot growth was observed. Subfreezing temperatures were measured on several days in Dec. 1995, but the low temperature forecasts did not trigger treatment. On 7 Jan. 1996, microsprinkler treatments were applied because temperatures below -6.7 °C were projected, but the minimum temperature was -5.6 °C and no freeze damage was observed.

A strongly advective freeze occurred from 2–4 Feb. 1996, with a low of -9.4 °C and wind speeds of 16–32 km·h⁻¹. During 5–6 Feb. the conditions were moderately advective during the day because of wind speeds between 12 and 24 km·h⁻¹, and moderately radiational at night, with a 1.5 to 3 °C difference between ground and tower sensors. Temperatures initially stayed continuously at or below 0 °C for 67 h, rose above freezing for 5 h with a high of 4.0 °C, then dropped below 0 °C for another 13 h. During the treatment period, there were 7- and 10-h periods of temperatures below -6.7 °C. Microsprinklers delivered water continuously for 87 h. Although trees were quiescent, severe foliage injury and some apparent shoot dieback occurred, but a subsequent freeze prevented symptoms from developing fully. Nonirrigated trees lost more foliage than did irrigated trees (Table 1). The higher placement of the microsprinkler increased the amount of foliage covered and therefore reduced damage.

Damaging freezes occurred again 7–11 Mar. 1996, with minimum temperatures of -2.8, -5.6, -5, and 0 °C, respectively. The conditions were moderate to strongly advective,

Fig. 1. Daily maximum and minimum temperatures from a weather station located 1.5 m high and 100 m from the test grove during the 1995–96 and 1996–97 winter seasons.

with wind speeds ranging from 12–32 km·h⁻¹. Acclimation of the trees was considered to be poor, as evidenced by breaking buds and emerging shoots, although no floral parts had yet emerged. Factors contributing to the growth activity at this date included the stress of defoliation from the previous freeze, 9.7 cm rainfall accumulated over 20 d, and a 7-d period (22–28 Feb. 1996) of unseasonably warm temperatures, which can cause resumption of growth and loss of cold hardiness (Young, 1970). Because of the perceived lack of hardiness, microsprinklers were activated in late afternoon on 7 Mar. 1996 and operated continuously for 90 h. The same pattern of foliage damage occurred as after the first freeze. The sprinkled trees retained most of the foliage that had been retained after the first freeze, which was within the spray pattern of the microsprinklers, whereas the control trees were almost completely defoliated. A second microsprinkler positioned lower in the canopy

did not increase foliage retention after the February freeze more than did a single microsprinkler positioned at 1.6 m; however, having a second 90.8 L·h⁻¹ emitter at 0.86 m in the March freeze reduced damage an additional 10%, which may have been related to loss of hardiness. The much higher output of this treatment (181.6 L·h⁻¹) would be expected to provide greater protection during freezes.

Shoot dieback, measured after the February and March freezes, was low (<10% for all treatments), indicating that the freezes were not severe enough to greatly affect woody tissues. The greater sensitivity of leaves over woody tissues has been demonstrated in previous studies (Yelenosky, 1978; Yelenosky and Horanic, 1969). Trees with the high-output microsprinklers suffered the most shoot dieback, which might be explained by the dynamic wetting pattern of the emitters. The pattern shrank somewhat as ice built up on the

Table 1. Mitigation of satsuma orange damage by soil mounding around the lower scaffold limbs and by microsprinkler irrigation at two heights and two rates following three damaging freeze events in 1996. The freezes occurred 2–6 Feb., 7–11 Mar., and 19–21 Dec.

Treatment	Sprinkler		Irrigation		Foliage killed (%)			Limb damage by Mar. 7–11 freeze		Yield components in 1996				Yield 1997
	ht (cm)		rate (L·h ⁻¹)		Feb.	Mar.	Dec.	No. broken		Yield (kg/tree)	No. of fruit/tree	Fruit wt (g)	Fruit diam (cm)	
	1 ^z	2 ^z	1	2				2–6	7–11					
Control	---	---	---	---	88 c ^a	98 d	36 c	1.1 c	0.0 b	0.5 c	3 b	145 b	7.2 ab	140
Soil mound	---	---	---	---	89 c	98 d	33 bc	1.3 bc	0.0 b	0.1 c	1 b	186 a	6.8 b	144
Irrigation	0.45	---	40.5	---	76 b	91 d	28 ab	1.2 c	0.1 b	1.6 c	9 b	177 a	7.0 b	161
	0.86	---	90.8	---	69 b	80 c	29 ab	1.7 ab	0.1 b	1.7 bc	9 b	195 a	7.7 a	163
	1.60	---	90.8	---	54 a	71 b	27 ab	1.8 ab	0.4 b	3.9 a	22 a	182 a	7.6 a	163
	0.45	1.6	40.5	90.8	54 a	70 b	23 ab	2.0 a	0.8 a	3.7 ab	20 a	191 a	7.6 a	137
	0.86	1.6	90.8	90.8	46 a	60 a	26 ab	1.6 abc	0.3 b	5.6 a	31 a	182 a	7.5 a	161

^z1 = first sprinkler; 2 = second sprinkler.

^y0 = no dieback of terminals; 1 = 1% to 5% terminals having distal necrosis; 2 = 6% to 10%; 3 = 11% to 25%; 4 = greater than 25%.

^xMean separation within columns by Duncan's multiple range test, $P \leq 0.05$.

branches nearest the emitter, so the proportion of the canopy protected declined as freezing progressed. Plant tissues not continually wetted during subfreezing temperatures and windy conditions may be severely damaged by evaporative cooling (Parsons, 1998).

A third damaging freeze occurred 19–21 Dec. 1996. The freeze was a weak radiational freeze; the maximum difference in temperature between ground and tower sensors was only 1 °C and windspeeds were <8 km·h⁻¹. The temperature was -6.7 to -5 °C for 3 h on the morning of 20 Dec. 1996, but otherwise not colder than -3.9 °C during the 68-h period of continuous sprinkling. As in Dec. 1995, the trees were quiescent, but they were not exposed to the same duration of subfreezing temperatures as in the previous two freezes. The test trees had 23% to 36% of the foliage killed, with the same pattern of foliage protection by treatments found in the Feb. and Mar. 1996 freezes. Defoliation was greater on nonirrigated trees, but the difference was not always significant. Most of the leaf damage after this freeze was in the top portion of the tree in all treatments, which is usually the case in a radiational freeze because leaves directly exposed to the sky become colder (Davies and Albrigo, 1994).

A disadvantage of elevated microsprinkler freeze protection of satsuma mandarin is scaffold limb breakage from ice loading (Bourgeois and Adams, 1987). In our study, the number of broken scaffold limbs after all treatments during the February and March freezes was less than one per tree. Increasing emitter height increases risk of structural damage from ice loading (Parsons et al., 1991). In this trial, two of the three treatments with emitters set at 1.6 m reduced limb breakage relative to the control or to treatments with low sprinklers, and few limbs were broken. The data parallel those of Bourgeois and Adams (1987), and indicate that breakage is a minor concern for this method of freeze protection for satsuma.

While freeze injury in 1996 was confined to foliage loss and small terminal branches in this study, satsuma mandarin in another nonirrigated plot on the same experiment station and in other area farms sustained both major limb loss and some tree mortality. Some passive heat was probably transferred from irrigated plots to the controls in this study. However, trees in the test plot may have been

more cold hardy than trees at other locations, or temperatures may not have been sufficiently low to kill woody tissues. The lowest recorded temperature in this study was -9.4 °C, which was lethal for quiescent and acclimated satsumas in other studies (Yelenosky, 1985). Other researchers have found the lethal temperature for satsumas to be even lower (Anderson et al., 1983; Gerber and Hashemi, 1965).

The 1996 freezes substantially reduced yield to levels well below those of the previous 4 years. Average yields were 111 kg/tree in 1995 vs. <6 kg/tree for all treatments in 1996. Although yield was severely reduced in all treatments, trees with high microsprinklers bore more fruit than did the control trees, which had almost none. Trees with a high output (90.8 L·h⁻¹) emitter at 1.6 m produced the best yields. The spray pattern of the microsprinkler treatments reached only a small portion of the fruiting wood, since the primary objective of the irrigation design was to ensure survival of the trunk and scaffold limbs in a severe freeze. Consequently, almost all of the fruit was produced on shoots arising from the interior of the canopy where the ice buildup was greatest and foliage was preserved. We assume that the March freeze was more destructive to the flower crop than was the February freeze, since budbreak was occurring and flower buds should have been differentiated at this time (Davenport, 1990). However, buds were not examined before the freezes to verify which one killed them. Nevertheless, at the relative stage of hardiness in this study and the temperatures and durations of the freezes in 1996, the elevated microsprinklers protected flower buds, indicating that an expanded spray coverage to include flower buds might be useful in preserving yield.

Neither yield nor fruit size in 1997 was affected by treatment. Average yields were 153 kg/tree in 1997 vs. 111 in 1995, indicating that the trees were back to full production. Thus, satsuma mandarins can withstand a reduction in foliage of as much as 35% by December freezes with no reduction in yield. When and how much foliage can be killed before yields are reduced is not known. Furthermore, the flower buds were not killed by this freeze, indicating that they were harder than the leaves.

None of the freeze events were severe

enough to kill trunks and scaffolds, but this study demonstrates the potential advantage of elevated microsprinkler irrigation in protecting bearing-age satsuma mandarin from freeze injury. The survival of flower buds within the spray pattern of the microsprinklers indicates that in freezes such as those experienced here, elevated microsprinklers can prevent some loss of yield. We do not know at this time whether yields could be increased in a similar freeze by placing additional microsprinklers to target shoots on the outer portions of the canopy that typically flower profusely. Having multiple microsprinklers at each tree to protect portions of the outer canopy as well as the trunk and scaffold limbs would be more costly, and the load-bearing ability of scaffolds to ice is not well understood. This study shows that when a microsprinkler is elevated to 1.6 m, a second microsprinkler located near the lower trunk is not necessary at the level of tree cold hardiness observed in this study. The best foliage and flower bud retention were obtained with a single, high-volume microsprinkler elevated to 1.6 m. Some might question that such placement would leave the lower trunk and graft union unprotected; however, Bourgeois and Adams (1987) found that satsuma mandarin trees survived in all instances where water ran down the trunk.

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