Gibberellic Acid, Fruit Freezing, and Post-freeze Quality of 'Hamlin' Oranges

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SUMMARY. Our objectives were to determine if gibberellic acid (GA₃) application at color break in the fall affected the juice content, soluble solids content (SSC), titratable acid (TA), and ratio of SSC:TA of 'Hamlin' orange (*Citrus sinensis*) fruit following moderate to severe freezes. We also wanted to know if GA₃ affected the post-freeze rate of decrease in juice content, fruit and tree cold hardiness, and the amount of fruit drop following a freeze. GA₃ (18 fl oz/acre) was applied at color break in the fall of 2002, 2003, and 2004 to 'Hamlin' orange trees on Swingle citrumelo (*C. sinensis* × *Poncirus trifoliata*) rootstock planted in 1995 at Gainesville, Fla. Moderate to severe freezes occurred in all three seasons. Fruit were harvested at about 2-week intervals following freezes in each season and the internal fruit quality was determined. GA₃-treated fruit generally had higher juice content compared with nontreated fruit for 8 weeks after moderate to severe freezes in all three seasons, which may be economically important to citrus processors and growers since Florida growers are paid based on fruit pounds-solids (juice content × SSC). The rate of decrease in juice content over time was similar for both treatments in seasons one and two, but was less for GA₃-treated fruit than nontreated fruit in season three. In addition, SSC was equal to or slightly greater for fruit treated with GA₃ than for nontreated fruit. Fruit drop rate and magnitude were also significantly less for the GA-treated compared with nontreated trees in two of three seasons. GA₃ did not affect fruit, leaf, or tree cold hardiness in any season.

Periodic severe freezes have caused significant yield reductions and tree losses in the Florida citrus industry. In response, the industry has moved south and to coastal areas, thus reducing the risk of tree damage and losses. However, fruit are damaged at much higher temperatures than trees (Hendershott, 1962) and it is quite common to have fruit damage even as far south as Basinger and Immokalee, Fla.

Ice formation in fruit following a freeze decreases juice content via dehydration and water loss through the peel (Syvertsen, 1982). Fresh fruit become unmarketable due to section drying and juice content decreases by as much as 25 units (58% to 33%) within 2 weeks after a freeze (Rasmussen et al., 1963), causing a reduction in pounds-solids (juice content × SSC) and grower returns, which are based on pounds-solids for processing fruit in Florida. Juice content is also be-

coming increasingly more important to grower returns for ready-to-serve juice. In addition, fruit drop and yield reductions occur following a severe freeze if fruit are not harvested within a few weeks.

Gibberellic acid (GA₃) applied in fall at or near color break increased juice content by 2% to 10% depending on season and cultivar (Davies et al., 1999). However, GA₃ applied in late fall or winter sometimes delayed flowering and decreased flowering intensity (Fidelibus et al., 2002) and caused trees to be less cold-hardy in Texas (Cooper and Peynado, 1958; Young, 1971) and in southern Florida (E.W. Stover, personal communication).

Our preliminary observations suggest that GA₃ may not only increase juice content initially, but may also delay the rate of decrease in juice

content following a freeze. Post-freeze maintenance of juice levels may be economically important to growers and processors since fruit are paid for based on pounds-solids levels in the juice. This hypothesis has not been tested quantitatively. Our primary objectives were to determine whether fall application of GA₃ increased fruit juice content, delayed the rate of decrease in juice content following a freeze, decreased post-freeze fruit drop, and reduced cold hardiness of 'Hamlin' orange trees compared to nontreated trees. A secondary objective was to determine if GA₃ affected juice SSC, TA, the ratio of SSC:TA, and pounds-solids.

Materials and methods

PLANT MATERIAL AND TEMPERATURE MEASUREMENTS. Mature 'Hamlin' orange trees on Swingle citrumelo rootstock were used in this study. Trees were planted in 1995 at 15 ft within and 20 ft between rows at Gainesville, Fla. The experimental plot consisted of 16 uniform blocks of six trees each. Eight of the blocks were randomly selected and sprayed at fruit color break (hue = 110°) with the equivalent of 18 fl oz/acre of GA₃ (ProGibb; Abbott Laboratories, Chicago) on 28 Oct. 2002, 21 Oct. 2003, and 3 Nov. 2004. The same trees were sprayed each year, but previous studies suggest that there are no long-term effects of repeated application of GA₃ on tree growth or yields (Fidelibus et al., 2002). The GA₃ solution was applied with a backpack sprayer at an equivalent of 125 gal/acre. No adjuvant was used because GA₃ is effective for increasing juice content without it (Davies et al., 1999).

Fruit, leaf, and trunk temperatures were monitored on freeze nights using copper constantin T-type thermocouples attached to a Doric 245 data logger (InterTechnology Inc., Don Mills, Ont., Canada). Thermocouples were attached to the proximal side of the fruit equator at a 4.5-ft height in the canopy of one tree/block (16

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
73.0778	fl oz/acre	mL·ha ⁻¹	0.0137
0.3048	ft	m	3.2808
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.54	inch(es)	cm	0.3937
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

trees total). Thermocouples were also attached with tape to the abaxial leaf surface and the trunk at the same 4.5-ft height for each of the 16 trees. Standard air temperatures were taken at a 4.5-ft height. Initially fruit temperatures were greater than air temperatures, but minimum air and fruit temperatures and durations were the same during the critical low-temperature periods.

Temperatures were carefully monitored on prospective freeze nights. On 7–8 Jan. 2003 minimum air and fruit temperatures reached 27 °F for 3 h with 7 h <32 °F. Ice was observed after making a 1/4-inch cut from the stem end in about 10% of the fruit. A severe freeze occurred on 23–24 Jan. with a minimum air and fruit temperature of 21 °F for 4 h with 14 h <32 °F. Fruit were frozen throughout following this freeze (i.e., hard ice was found in the center of the fruit). Fruit were harvested and analyzed for internal quality (juice content, SSC, TA, and SSC:TA ratio) at about 2-week intervals (8 Jan., 21 Jan., 4 Feb., 18 Feb., and 4 Mar. 2003).

In 2003–04 there were 10 dates where temperatures were below 32 °F. However, the only moderate freezes occurred on 20 Dec. 2003 with 10 h <32 °F and a minimum air and fruit temperature of 25 °F for 3 h, and on 29 Jan. with 6 h <32 °F and a minimum air and fruit temperature of 25 °F for 1 h. Fruit were harvested and internal quality analyzed at about 2-week intervals (6 Jan., 20 Jan., 2 Feb., 18 Feb., and 1 Mar. 2004).

During the winter of 2004–05 there were five dates where air and fruit temperatures were less than 32 °F. However, minimum air temperature fell to 25 °F for only 1 h on 26 Jan. 2005. This minimum temperature and duration did not cause extensive fruit damage. Fruit were harvested and internal quality analyzed at about 2-week intervals (18 Jan., 2 Feb., 15 Feb., 1 Mar., and 15 Mar.).

FRUIT DROP AND FREEZE DAMAGE MEASUREMENTS. Fruit were counted under each tree at about 2-week intervals from 8 Jan. to 13 Mar. 2003. The total number of fruit on each tree was counted on 13 Mar. 2003 and percent fruit drop for each date determined. The rate of fruit drop and final fruit drop were also determined. Fruit were raked from under each tree following counts. Only final percent drop was

determined for each treatment in season two (2 Mar. 2004) and season three (17 Mar. 2005) for two trees/block for each of eight GA₃-treated and nontreated blocks due to time constraints.

Freeze damage was assessed subjectively on a 1 to 5 scale (1 = no damage; 5 = 100% leaf drop) at weekly intervals following each moderate to severe freeze until mid-March of each season. Overall tree health and vigor were also assessed subjectively using a 1 to 5 scale (1 = healthy; 5 = unhealthy, defoliation, and wood damage) in March of each season.

FRUIT QUALITY MEASUREMENTS. A randomly selected 23-fruit sample was harvested around one tree/block at a 3- to 6-ft height, as described previously (Davies et al., 2004). A standard sample typically consists of 20 fruit of similar size (Reitz and Sites, 1948). The three extra fruit were used to remove any residual juice from the juicer before each new sample was run. Fruit were weighed and then juiced using an FMC Fresh and Squeeze juicer (FMC Inc., Lakeland, Fla.), following which juice weight was determined. A refractometer (Bellingham and Stanley, Tunbridge Wells, U.K.) was used to determine uncorrected SSC. Titratable acidity was determined using an automatic titrator containing 0.3125 N sodium hydroxide (Denver Instruments, Denver, Colo.). Corrected SSC, which will be referred to as SSC in the text, was

calculated by adjusting SSC for TA levels and SSC:TA ratio was calculated (Wardowski et al., 1995).

EXPERIMENTAL DESIGN AND STATISTICAL ANALYSIS. The experiment was arranged as a randomized complete-block design with eight blocks of six trees each for GA₃-treated and nontreated trees. Fruit were harvested at five dates for each season as described previously and data were initially analyzed by analysis of variance to determine main effects of time and treatment and their interactions. Linear regression was performed using Sigma Plot software (SYSTAT Software Inc., Richmond, Calif.).

Results and discussion

SEASON ONE, 2002–03. The overall analysis of the juice content data showed a highly significant time (date) effect and a significant treatment effect and interaction ($P < 0.01$). However, there was no consistent pattern to the interaction and data were further analyzed by regression. There was a steady linear decline in juice content for the GA₃-treated and nontreated fruit (Fig. 1). The juice content of GA₃-treated fruit was significantly greater than that of the nontreated fruit on 8 Jan. (8.5% increase) and 21 Jan. (4.9% increase), and 4 Feb. (13.1% increase) ($P < 0.05$), but no significant treatment differences occurred on 18 Feb. and 4 Mar. The slopes of the regression lines were similar for both treatments and r^2 values were very high. These trends

Fig. 1. Effects of gibberellic acid (GA₃) and fruit freezing on post-freeze juice content of 'Hamlin' orange fruit in 2003. Nontreated (○) $y = 50.81 - 0.45x$, $r^2 = 0.96$; GA₃-treated (●) $y = 53.61 - 0.46x$, $r^2 = 0.98$; n = eight blocks of six trees for each date.

suggest that while GA₃ increased juice content initially, it did not affect the rate of change in juice content over time as we had hypothesized. The juice content 6 weeks after the severe freeze had decreased from 52.2% to 27.8% for GA-treated fruit (24.4 units) and from 49.0% to 26.2% for nontreated fruit (22.8 units). The magnitude of these decreases in juice content following a freeze is similar to that reported by Rasmussen et al. (1963) of 25 units after the 1962 freeze in Florida.

There was no effect of GA₃ on juice SSC for the first three harvest dates, but SSC of GA₃-treated fruit was higher than that of nontreated fruit on 18 Feb. and 4 Mar. ($P < 0.05$) (Fig. 2). These results differ from those of Fidelibus et al. (2002), who found that GA₃ decreased SSC relative to nontreated fruit. Titratable acidity and SSC:TA ratio were not affected by GA₃ treatment (data not shown).

Fruit drop began in early Feb. 2003 and continued at a steady rate until 13 Mar. (Fig. 3). The rate of drop was much lower for GA₃-treated than nontreated trees and final percent drop was significantly less for GA₃-treated (63.6%) vs. nontreated trees (72.9%) ($P < 0.05$). 'Hamlin' oranges typically would not be held on the tree this late into March following a severe freeze. However, some citrus processors are interested in holding 'Hamlin' fruit into March to fill a harvesting gap between midseason and late-season orange cultivars. Nevertheless, the data clearly demonstrate how extensive the fruit drop can be following a severe freeze. GA₃ application generally has much less effect on fruit drop of citrus than other plant growth regulators like 2,4-D, as observed previously (Davies, 1986).

SEASON TWO, 2003–04. The overall analysis of the data showed a highly significant time (date) effect and a significant treatment effect and interaction ($P < 0.01$). Again the interaction showed no clear trend and data were analyzed by regression. There was again a steady linear decline in juice content for the GA₃-treated and nontreated fruit (Fig. 4). The juice content of GA₃-treated fruit was significantly greater than that of nontreated fruit on 20 Jan. (3.4% increase) and 18 Feb. (3.3% increase) ($P < 0.05$). The juice content after a moderate freeze of 20 Dec. 2003 decreased from 49.4% to 45.5% for the GA₃-treated and 48.1%

Fig. 2. Effects of gibberellic acid (GA₃) and fruit freezing on post-freeze soluble solids content (SSC) of 'Hamlin' orange fruit in 2003. Nontreated (○) $y = 11.02 + 0.02x$, $r^2 = 0.88$; GA₃-treated (●) $y = 10.77 + 0.38x$, $r^2 = 0.94$; $n =$ eight blocks of six trees for each date.

Fig. 3. Effects of gibberellic acid (GA₃) on cumulative post-freeze fruit drop of 'Hamlin' oranges in 2003. Nontreated (○) $y = 1.65 + 2.0x$, $r^2 = 0.99$; GA₃-treated (●) $y = 3.42 - 1.60x$, $r^2 = 0.98$; $n =$ eight blocks of six trees for each date.

to 45.1% for nontreated fruit. The slope of the regression line was slightly greater for the GA₃ treatment than for the control, and GA₃ treatment had no effect on juice content late into the season, which is similar to that observed by Fidelibus et al. (2002). These data again suggest, as in 2002–03, that while GA₃ increased juice content initially it did not significantly affect the rate of change in juice content over time.

There was no significant effect of GA₃ on juice SSC for any harvest date, but SSC of GA₃-treated fruit was always numerically higher than that of

nontreated fruit (Fig. 5). The general lack of effect of GA₃ on SSC was similar to that found in 2002–03 but differs from results of Fidelibus et al. (2002), who found that GA₃ decreased SSC, possibly by delaying maturity. TA and SSC:TA ratio were once again not affected by GA₃ treatment (data not shown).

Fruit drop was similar for both treatments and much lower than that in 2002–03 because freeze severity was much less. Final fruit drop averaged 8.7% and 7.9% for GA₃-treated and nontreated trees, respectively.

SEASON THREE, 2004–05. The overall analysis of the data showed highly significant time (date) and treatment effects ($P < 0.01$) and there were no interactions. The juice content for the GA_3 -treated fruit was significantly greater than for nontreated fruit on 18 Jan. (3.5% increase), 15 Feb. (5.9% increase), and 15 Mar. (15.1% increase). The 15 Mar. value represents a much larger percent increase in late-season juice content than observed previously for sweet oranges in Florida (Davies et al., 1999; Fidelibus et al., 2002). There was again a steady linear decline in juice content for GA_3 -treated and nontreated fruit, but the juice content decreased much less rapidly for the GA_3 -treated compared with nontreated fruit (Fig. 6). There were no significant differences between treatments for SSC, TA, and SSC:TA ratios (data not shown) and percent fruit drop was significantly greater for nontreated compared with GA_3 -treated fruit, 8.7% vs. 6.0%, respectively ($P < 0.05$), although the differences in percent drop are relatively small. The percent drop was again much less than in the 2002–03 season because the severity of the freezes was much less.

FREEZE DAMAGE TO TREES, 2003–05. There was no difference in leaf or wood freeze damage for GA_3 -treated compared with nontreated trees in any season or time of the study, based on subjective evaluations of the trees (data not shown). Our observations differ from those of Cooper and Peynado (1958) and Young (1971) in Texas, where GA_3 application promoted shoot growth and decreased citrus tree cold hardiness. E.W. Stover (unpublished) also observed decreased cold hardiness for GA_3 -treated compared with nontreated orange trees in southern Florida. Under our temperature regimes in north-central Florida, GA_3 never induced a new growth flush, possibly due to lower average temperatures than found in the other locations. Therefore, it is feasible that there is an interaction between GA_3 and temperature as related to citrus cold hardiness.

Conclusions

Spray application of GA_3 at or near color break consistently increased juice content of 'Hamlin' orange fruit over that of nonsprayed fruit in all three seasons. The increase ranged from 0% to 15.1%, the latter of which is

Fig. 4. Effects of gibberellic acid (GA_3) and fruit freezing on post-freeze juice content of 'Hamlin' orange fruit in 2004. Nontreated (○) $y = 47.41 - 0.05x$, $r^2 = 0.76$; GA_3 -treated (●) $y = 49.03 - 0.06x$, $r^2 = 0.92$; n = eight blocks of six trees for each date.

Fig. 5. Effects of gibberellic acid (GA_3) and fruit freezing on post-freeze soluble solids content (SSC) of 'Hamlin' orange fruit in 2004. Nontreated (○) $y = 10.97 + 0.21x$, $r^2 = 0.97$; GA_3 -treated (●) $y = 11.10 + 0.20x$, $r^2 = 0.97$; n = eight blocks of six trees for each date.

considerably greater than that reported by Davies et al. (1999). The large variation in juice content related to GA_3 treatment was also found previously for oranges in Florida (Davies et al., 1999; Fidelibus et al., 2002). We speculate that the large differences in response to GA_3 are related to seasonal environmental differences.

One of our hypotheses was that GA_3 application would also delay the rate of decrease in juice content following a freeze. Such a delay would allow fruit to be harvested over a lon-

ger period of time following a freeze. This was not the case in two of three seasons. Nevertheless, the higher juice content for GA_3 -treated fruit may be of potential value to growers and processors following a freeze. Moreover, SSC for GA_3 -treated fruit was greater than or equal to that of nontreated fruit in all three seasons. An increase in both variables would also increase pounds-solids (juice content $\times$ SSC), which is the basis for fruit payment in Florida. However, we observed a statistically significant increase in pounds-solids

Fig. 6. Effects of gibberellic acid (GA₃) and fruit freezing on post-freeze juice content of 'Hamlin' orange fruit in 2005. Nontreated (○) $y = 55.02 - 0.16x$, $r^2 = 0.94$; GA₃-treated (●) $y = 55.94 - 0.08x$, $r^2 = 0.82$; $n =$ eight blocks of six trees for each date.

in only one season. Similarly, Davies et al. (1999) generally observed no consistent effect of GA₃ on pounds-solids. In contrast, Fidelibus et al. (2002) found that GA₃ application consistently decreased SSC and pounds-solids. We do not know the reason for the differences in response to GA₃ between these studies. TA and SSC:TA ratios were not affected by GA₃ application. Under our environmental conditions in north-central Florida, GA₃ application had no short- or long-term effects on leaf, stem, trunk, or fruit cold hardiness. Therefore, fall application of GA₃ increases juice content over that of nontreated fruit and sometimes perpetuates this increase following

a freeze. This increase may improve post-freeze returns for citrus growers and processors depending on the cost of GA₃ application and pounds-solids prices.

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