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Prohexadione-Ca Reduces Russet and Does Not Negate the Efficacy of GA_{4+7} Sprays for Russet Control on 'Golden Delicious' Apples

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***Abstract*. A series of four experiments were undertaken to evaluate the effects of individual and combined applications of prohexadione-Ca (P-Ca) and GA_{4+7} primarily on fruit russet, but also on fruit set, fruit weight, early season shoot growth, and fruit maturity of 'Golden Delicious' apples (*Malus* × *domestica* Borkh.). A single application of P-Ca (138 to 167 mg·L^{-1}) at petal fall (PF) reduced the severity of russet in three of the four experiments; however, multiple applications of 20 ppm GA_{4+7} at 10-day intervals beginning at PF generally reduced russet more effectively than P-Ca. P-Ca did not reduce the efficacy of GA_{4+7} sprays for russet reduction. However, GA_{4+7} sprays reduced the inhibitory effects of P-Ca on shoot growth measured 30 days after PF. A single application of P-Ca at PF had no effect on mean fruit weight at harvest. Fruit size was lowest for the combined P-Ca and GA_{4+7} treatment in every experiment, although there was a significant interaction between P-Ca and GA_{4+7} sprays on mean fruit weight in only one experiment. There were no consistent effects of P-Ca and GA_{4+7} sprays, alone or in combination, on fruit maturity parameters at harvest. These data show that a single application of P-Ca at PF reduced russet severity, and the effects of P-Ca and GA_{4+7} sprays on russet can be additive. The economic benefits resulting from a reduction in russet severity after combined P-Ca and GA_{4+7} sprays will need to be balanced against their occasional negative effect on fruit size. Chemical names used: prohexadione-calcium [3-oxido-4-propionyl-5-oxo-3 cyclohexenecarboxylate formulated as Apogee (27.5% a.i.)].**

Russet is a surface defect of apple fruit that can significantly reduce fresh market value. Fruit with an aggregate of more than 10% of the surface area covered with russet are excluded from both the U.S. Extra Fancy and U.S. Fancy grades, and fruit with an aggregate area of russet exceeding 25% of their surface are excluded from the U.S. No. 1 grade (USDA, 2002). Major differences in russet susceptibility exist between varieties (Miller et al., 2004) or even between sports or subclones of a single variety (Cummins et al., 1977; Simons, 1960; 1962). The cultivars 'Golden Delicious', 'Gala', and 'Fuji', collectively representing 32% of current U.S. apple production (U.S. Apple Assoc., 2005), are generally considered to be russet-susceptible.

The developmental anatomy of russet in 'Golden Delicious' apples has been well described over the last 70 years. Bell (1937) observed that nonrusseted portions of 'Golden Delicious' fruit either had a thicker, more convoluted cuticle or a double layer of cuticle than russeted portions. Simons (1960) noted that russet first appeared on 'Golden Delicious' apples 35 to 45 d after full bloom, coincident with a rapid increase in tangential width of the epidermal cells. Simons (1960) also observed that the epidermal cells of russeted fruit increased in tangential width more rapidly than epidermal cells in non-russeted fruit. Ashizawa et al. (1984) reported that russet in 'Golden Delicious' was caused initially by a weakness in cuticle formation that led to microcracks in the cuticle, these microcracks expanding further with fruit enlargement. Exposure of the underlying hypodermal cells to air resulted in formation of the cork cambium that is known as russet.

Russet may result from a variety of stimuli, including growth of fungi (Goffinet et al., 2002; Heidenreich et al., 1997; Zobrist, 1962) or yeasts (Heidenreich et al., 1997) on the fruit surface, insect feeding (Easterbrook and Fuller, 1986), frost around the time of bloom (Simons, 1959), high humidity and precipitation, particularly during the period from 15 to 20 d after bloom (Creasy, 1980), or various crop protection sprays (Kirby and Bennet, 1967; Palmer et al., 2003; Stiles et al., 1958). Multiple sprays of gibberellins A4 and A7 (GA_{4+7}) can be applied at 7- to 10-d intervals during the first month after bloom to reduce the incidence and severity of russet (Eccher, 1978; Eccher and Boffelli, 1981; Taylor, 1975, 1978; Wertheim, 1982). Three to four applications of a proprietary mixture of 15 to 20 mg·L^{-1} GA_{4+7} beginning at petal fall (PF) are recommended to reduce russet severity on susceptible cultivars in the United States. The estimated material cost of such a program ranges from U.S. $300 to $500 per hectare depending on product concentration, number of applications, and water rate. Many growers remain skeptical of the economic benefits arising from the use of GA_{4+7} sprays to reduce russet, believing that the increase in crop value after multiple GA_{4+7} sprays may not be sufficient to offset this additional cost in some years or regions.

Prohexadione-calcium (P-Ca) is a gibberellin biosynthesis inhibitor that is increasingly being used in apple production systems globally to reduce vegetative growth, improve fruit set by reducing June drop, and reduce the incidence of fire blight and other diseases (Rademacher and Kober, 2003). P-Ca is rapidly degraded in plants, having a biologic half-life in the range of 10 to 14 d (Rademacher et al., 2004). Therefore, the effects of P-Ca on shoot growth are short-lived (Byers and Yoder, 1999), and repeat applications at 3- to 5-week intervals are required to achieve season-long control of shoot growth in most environments. P-Ca may increase fruit set (Byers et al., 2004; Glenn and Miller, 2005; Greene, 1999; Unrath, 1999) and was found in one study to reduce the efficacy of some postbloom chemical thinning sprays (Greene, 1999). The initial application of P-Ca is made when two to five leaves are fully developed on each shoot corresponding in most seasons to either at or soon after PF when shoots are 2 to 5 cm in length. The timing of the first P-Ca spray coincides with the initial application of GA_{4+7} in a russet control program. The greatest effect of P-Ca on gibberellin biosynthesis and metabolism coincides with the period during which GA_{4+7} sprays are applied and russet may be initiated on the fruit surface. The current U.S. label specifies that the efficacy of P-Ca sprays for reducing shoot growth or gibberellin sprays for reducing fruit russet or cracking may be reduced if both materials are applied (Apogee; BASF Corp., Research Triangle Park, N.C.). Miller (1998) reported that concentrations of P-Ca above 188 mg·L^{-1} reduced russet of 'Golden Delicious', two applications of P-Ca reducing

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russet as effectively as four applications of GA_{4+7}. When these two plant growth regulators were combined, the russet severity was no better than either material alone (Miller, 1998). However, GA_{4+7} sprays for russet control did reduce the level of shoot growth control normally obtained with multiple P-Ca sprays. We recently reported that a single application of P-Ca at PF reduced the severity of another skin defect of apple (scarf skin) and furthermore, the efficacy of multiple GA_{4+7} sprays for scarf skin control was in fact increased when P-Ca was applied either in mixture or within 2 d of the first GA_{4+7} application (McArtney et al., 2006). However, we also reported that mean fruit weight at harvest was occasionally reduced by the combination of P-Ca and GA_{4+7} sprays.

The primary objectives of the present study were to 1) compare the efficacy of a single PF spray of P-Ca with a standard program of multiple GA_{4+7} sprays for reducing russet of 'Golden Delicious' apple; 2) determine if application of P-Ca at this time interferes with the efficacy of GA_{4+7} sprays for russet reduction; and 3) determine the effects of combining a single application of P-Ca at PF with multiple GA_{4+7} sprays on mean fruit weight at harvest. Lesser objectives of the study were to determine if GA_{4+7} sprays interfere with the effects of P-Ca on shoot growth and to describe effects of these two materials, alone or in combination, on fruit maturity.

Materials and Methods

Expts. 1 and 2: P-Ca ± GA_{4+7} (2005). Two studies with identical experimental designs were conducted on commercial orchards at two locations in Henderson Co., N.C. The crop at one location (Expt. 1) was produced using standard management practices for fresh market production, whereas at the other location (Expt. 2), the crop was produced using standard management practices for a processed market. Each study used mature 'Golden Delicious' trees on M.7 rootstock and included the following four treatments: 1) an untreated control; 2) a single application of 138 $mg \cdot L^{-1}$ P-Ca (50 g Apogee in 100 L water; BASF Corp.) at PF (27 Apr.); 3) 15 $mg \cdot L^{-1}$ GA_{4+7} (15.9 g ProVide 10SG per 100 L water; Valent BioSciences Corp., Libertyville, Ill.) applied 0, 10, and 20 d after PF; and 4) a combined treatment in which the initial GA_{4+7} application was tank-mixed with P-Ca at the same concentrations. No additional adjuvants or water conditioners other than those present in the formulated products were included with the spray treatments. At each location, the spray treatments were applied to six-tree plots with an axial fan air-blast sprayer calibrated to deliver water at 1680 $L \cdot ha^{-1}$. The treatments were arranged in a randomized complete-block design with either six (Expt. 1) or four (Expt. 2) replications. A random sample of 100 fruit was removed from each plot at harvest representing a pooled sample of 25 fruit from each of the middle four trees. Mean fruit weight was calculated from the total weight of the 100-fruit sample per plot. The aggregate area of russet was assessed for each fruit in the random sample in 20% increments. An additional sample of 20 unblemished fruit per plot was removed for assessment of treatment effects on fruit maturity. Firmness was measured on opposite pared sides of each fruit using a mechanized pressure tester [FTA Model GS-20; GUSS Manufacturing (Pty) Ltd., Strand, South Africa] fitted with an 11.1-mm-diameter probe. Soluble solids concentration (SSC) was measured from the expressed juice with a digital refractometer (Atago Palette PR-32α; Atago U.S.A., Bellevue, Wash.). The starch index at harvest was determined using the method described by Watkins et al. (2005) and the rating system described by Blanpied and Silsby (1992) in which 1 = 100% staining and 8 = 0% staining.

Expt. 3: P-Ca ± GA_{4+7} (2006). Eighty uniform, mature 'Golden Delicious'/M.7 trees were selected from within a commercial orchard in Henderson Co., N.C., in Spring 2006 from different rows within the same orchard that was used in Expt. 2. Apart from the growth regulator treatments, the trees were managed according to standard commercial practice for a processed market. The trees were grouped into 20 plots with four trees in each. The following four treatments were applied to five plots with an axial fan air-blast sprayer calibrated to deliver water at 1400 $L \cdot ha^{-1}$: 1) an untreated control; 2) a single application of 167 $mg \cdot L^{-1}$ P-Ca at PF (24 Apr.); 3) 20 $mg \cdot L^{-1}$ GA_{4+7} (21.1 g ProVide 10SG per 100 L water) applied 0, 10, 20, and 30 d after PF; and 4) a combined treatment in which the PF application of 20 $mg \cdot L^{-1}$ GA_{4+7} was tank-mixed with 167 $mg \cdot L^{-1}$ P-Ca. The treatments were arranged in a randomized complete-block design experiment with five replications. Shoot length was measured on a random sample of 10 shoots per tree on the middle two trees in each plot 30 d after PF. At harvest, a random sample of 50 fruit was removed from each of the middle two trees in each plot and pooled. The surface area affected by russet on each fruit was rated in 20% increments. Mean fruit weight was estimated from the total weight of the 100-fruit sample per plot. An additional sample of 20 fruit per plot was removed for assessment of treatment effects on fruit firmness, SSC, and starch index. Firmness was measured on opposite pared sides of each fruit using a mechanized pressure tester [FTA Model GS-20, GUSS Manufacturing (Pty) Ltd.] fitted with an 11.1-mm-diameter probe. A pooled juice sample was obtained by placing a vertical wedge of tissue from each fruit into a kitchen juicer and the SSC was measured with a digital refractometer (Atago Palette PR-32α; Atago U.S.A.). The starch index at harvest was determined like in the previous experiments.

Expt. 4. P-Ca ± GA_{4+7} rate (2006). A group of 108 uniform "Golden Delicious'/M.26 trees were selected from within an orchard planted at the Mountain Horticultural Crops Research and Extension Center in Fletcher, N.C., in 1999. The trees were split into 36 plots of three adjacent trees. The following six treatments, arranged in a randomized complete-block design experiment, were applied to six plots (replications) with an axial fan air-blast sprayer calibrated to deliver water at 1400 $L \cdot ha^{-1}$: 1) an untreated control; 2) a single application of 167 $mg \cdot L^{-1}$ P-Ca at PF (25 Apr.); 3) 20 $mg \cdot L^{-1}$ GA_{4+7} (21.1 g ProVide 10SG per 100 L water) applied 0, 10, 20, and 30 d after PF; 4) a combined treatment in which the PF application of 167 $mg \cdot L^{-1}$ P-Ca was tank-mixed with the first of four 20 $mg \cdot L^{-1}$ GA_{4+7} sprays; 5) a combined treatment in which the PF application of 167 $mg \cdot L^{-1}$ P-Ca was tank-mixed with the first of four 10 $mg \cdot L^{-1}$ GA_{4+7} sprays; and 6) a combined treatment in which the PF application of 167 $mg \cdot L^{-1}$ P-Ca was tank-mixed with the first of four 5 $mg \cdot L^{-1}$ GA_{4+7} sprays. Two sample limbs were tagged on the center tree of each plot for counts of flower cluster number at bloom and fruit number at the completion of fruit drop, and fruit set was calculated from these data as the number of fruit per 100 flower clusters. The trees received a standard chemical thinning program and were hand-thinned to a commercial crop load after fruit counts were completed. Shoot length was measured on a random sample of 10 shoots per tree on the center tree in each plot 30 d after PF. The surface area affected by russet was rated on each fruit harvested from the center tree in each plot in 20% increments. Mean fruit weight was calculated from total fruit number and weight data. Twenty fruit were removed from the center tree in each plot for assessment of treatment effects on fruit maturity as in Expt. 3.

Statistical analysis. Data were analyzed by analysis of variance using the general linear models procedure of the Statistical Analysis System (SAS Institute, Cary, N.C.). Russet data were analyzed after arcsine-square root transformation. Means separations were determined using the Waller-Duncan k-ratio *t* test at the 5% significance level where appropriate.

Results

Expt. 1. There was a low natural incidence of russet at the location used in Expt. 1 with all treatments having more than 90% of fruit in the lowest russet severity class (Table 1). There was a 7% increase in the proportion of fruit in the lowest russet severity class after GA_{4+7} sprays. The interaction term in the model was not significant, indicating that P-Ca did not reduce the efficacy of GA_{4+7} sprays for russet control (Table 1). P-Ca had no effect on mean fruit weight or fruit maturity parameters. GA_{4+7} sprays significantly reduced mean fruit weight, increased fruit firmness, but had no effect on SSC or starch index (Table 1).

Expt. 2. The general level of russet was higher in Expt. 2 (Table 2) compared with

Expt. 1 (Table 1). In this high-russet scenario, there was a significant main effect of P-Ca on russet severity, increasing the proportion of fruit in the lowest severity class by 26% (Table 2). A standard program of GA_{4+7} sprays reduced russet severity more effectively than a single PF application of P-Ca, increasing the proportion of fruit in the lowest severity class by 45%. Again, the interaction between P-Ca and GA_{4+7} sprays on russet severity was not significant, indicating their effects were additive. There were no effects of P-Ca or GA_{4+7} sprays on fruit weight or fruit maturity in Expt. 2 (Table 2).

Expt. 3. P-Ca resulted in a slight reduction in mean shoot length, measured 30 d after PF (P = 0.08), whereas GA_{4+7} sprays were without effect on mean shoot length (Table 3). There was a significant interaction between the effects of P-Ca and GA_{4+7} sprays on shoot length. Mean shoot length was the same on trees treated with both P-Ca and GA_{4+7} and control trees, indicating that GA_{4+7} sprays reduced the inhibitory effect of P-Ca on shoot growth. Like in Expt. 1, P-Ca was without effect on mean fruit weight, whereas GA_{4+7} sprays reduced mean fruit weight. However, there was a significant interaction between the effects of P-Ca and GA_{4+7} sprays on mean fruit weight in Expt. 3; combining P-Ca and GA_{4+7} sprays reduced mean fruit weight by 7% (13 g) compared with the control. The treatments had no effect on flesh firmness or SSC and had only minor effects on starch index (Table 3).

The general level of russet was much lower in Expt. 3 (Table 3) than in Expt. 2 (Table 2), which was the same orchard in the previous year. Like in the previous experiment, the main effects of P-Ca and GA_{4+7} sprays on russet severity were significant, increasing the proportion of fruit in the lowest russet severity class by 10% and 21%, respectively (Table 3). These data indicate again that GA_{4+7} sprays reduced russet more effectively than a single spray of P-Ca at PF. Like in Expt. 2, the interaction term between P-Ca and GA_{4+7} was not significant, indicating their effects on russet were additive.

Expt. 4. Application of P-Ca at PF reduced mean shoot length 30 d later compared with the control, although this difference was not statistically significant (Table 4). Surprisingly, mean shoot length measured 30 d after PF was increased compared with the control by GA_{4+7} sprays either alone or in combination with P-Ca (Table 4). There were no treatment effects on fruit set, although there was a trend for higher fruit set on trees sprayed with P-Ca. Both P-Ca (P = 0.08) and GA_{4+7} sprays reduced mean fruit weight compared with the control (Table 4). Analysis of a subset of the treatments in Expt. 4 as a 2 × 2 factorial design revealed significant (negative) main effects of P-Ca (P = 0.07) and GA_{4+7} sprays (P = 0.01) on mean fruit weight. The interaction term in the model was not significant, indicating the effects of combining P-Ca and GA_{4+7} sprays on mean fruit weight were additive (data not shown).

Table 1. Main effects of three applications of 15 $mg \cdot L^{-1}$ GA_{4+7} at 10-d intervals beginning at petal fall or a single application of 138 $mg \cdot L^{-1}$ prohexadione-Ca (P-Ca) at petal fall on the distribution of fruit within different russet severity classes, fruit weight, and harvest maturity of Golden Delicious/M.7 in 2005 (Expt. 1).[z]

	Russet severity class[y] (% fruit surface area covered)						
Main effect	0–20	21–40	41–60	Mean fruit wt. (g)	Firmness (N)	SSC (°Brix)	Starch index (1–8)
GA_{4+7}							
No GA_{4+7}	92	7	0	150	73.0	9.8	4.6
GA_{4+7}	99	1	0	142	75.0	9.9	4.6
P-Ca							
No P-Ca	96	4	0	145	73.7	9.9	4.5
P-Ca	96	4	0	147	74.2	9.8	4.8
Significance							
GA_{4+7}	0.01	0.01	0.07	0.01	<0.01	0.14	0.96
P-Ca	0.80	0.80	0.39	0.49	0.45	0.69	0.10
Interaction	0.65	0.66	0.39	0.30	0.08	0.07	0.37

[z]Russet data were analyzed after arcsine-square root transformation. Back-transformed weighted means are presented.
[y]Russet assessed on a random sample of 100 fruit per plot.
SSC = soluble solids concentration.

Table 2. Main effects of three applications of 15 $mg \cdot L^{-1}$ GA_{4+7} at 10-d intervals beginning at petal fall or a single application of 138 $mg \cdot L^{-1}$ prohexadione-Ca (P-Ca) at petal fall on the distribution within different russet severity classes, fruit weight, and harvest maturity of Golden Delicious/M.7 in 2005 (Expt. 2).[z]

	Russet severity class[y] (% fruit surface area covered)								
Main effect	0–20	21–40	41–60	61–80	81–100	Mean fruit wt. (g)	Firmness (N)	SSC (°Brix)	Starch index (1–8)
GA_{4+7}									
No GA_{4+7}	27	30	27	12	5	183	74.2	12.2	2.3
GA_{4+7}	72	19	4	1	0	178	73.7	12.1	2.4
P-Ca									
No P-Ca	38	28	18	6	2	183	74.5	12.2	2.4
P-Ca	64	21	11	4	2	178	73.5	12.2	2.3
Significance									
GA_{4+7}	<0.001	0.057	0.0005	0.0005	0.0016	0.30	0.51	0.88	0.20
P-Ca	0.05	0.16	0.11	0.29	0.95	0.23	0.26	0.93	0.28
Interaction	0.55	0.56	0.60	0.16	0.72	0.34	0.31	0.55	0.07

[z]Russet data were analyzed after arcsine-square root transformation. Back-transformed weighted means are presented.
[y]Russet assessed on a random sample of 100 fruit per plot.
SSC = soluble solids concentration.

Table 3. Effects of four applications of 20 $mg \cdot L^{-1}$ GA_{4+7} at 10-d intervals beginning at petal fall or a single application of 167 $mg \cdot L^{-1}$ prohexadione-Ca (P-Ca) at petal fall, alone or in combination, on shoot length 30 d after petal fall, the distribution of Golden Delicious/M.7 apple fruit within different russet severity classes, fruit weight, and harvest maturity of Golden Delicious/M.7 in 2006 (Expt. 3).[z]

		Russet severity class[y] (% fruit surface area covered)						
Main effects	Mean shoot length (cm)	0–20	21–40	41–60	Mean fruit wt (g)	Firmness (N)	SSC (°Brix)	Starch index (1–8)
GA_{4+7}								
No GA_{4+7}	25.0	75	22	2	199	72.6	11.9	2.7
GA_{4+7}	25.6	96	4	0	189	72.1	11.8	3.4
P-Ca								
No P-Ca	26.1	82	15	0	195	72.7	12.0	3.0
P-Ca	24.5	92	8	0	192	71.9	11.7	3.0
Significance								
GA_{4+7}	0.52	<0.0001	<0.0001	<0.0001	<0.01	0.60	0.41	<0.01
P-Ca	0.08	<0.001	<0.001	0.22	0.34	0.43	0.08	1.00
Interaction	<0.001	0.58	0.35	0.22	<0.01	0.61	0.13	0.67

[z]Russet data were analyzed after arcsine-square root transformation. Back-transformed weighted means are presented.
[y]Russet assessed on a random sample of 100 fruit per plot.
SSC = soluble solids concentration.

All P-Ca and GA_{4+7} spray treatments increased fruit firmness relative to the control in Expt. 4 with the combination of P-Ca and 20 $mg \cdot L^{-1}$ GA_{4+7} sprays resulting in significantly firmer fruit at harvest compared with either material alone (Table 4). There was no effect of treatment on SSC or starch index in Expt. 4.

Table 4. Effects of 167 mg·L^{-1} prohexadione-Ca (P-Ca) at petal fall, alone or combined with different rates of GA_{4+7}, on shoot length 30 d after bloom, fruit set, the distribution of Golden Delicious/M.26 apple fruit within different russet severity classes, fruit weight, and harvest maturity of Golden Delicious/M.26 apple fruit at harvest in 2006 (Expt. 4).[z]

Treatment (mg·L^{-1})		Mean shoot	Fruit	Russet severity class[y] (% fruit surface area covered)		Mean fruit	Firmness	SSC	Starch index
P-Ca	GA_{4+7}[x]	length (cm)	set (%)	0–20	21–40	wt (g)	(N)	(°Brix)	(1–8)
0	0	17.4 bc[w]	41	80 a	18 a	189 a	65.5 e	12.0	4.3
167	0	15.3 c	54	90 b	10 b	175 ab	66.8 d	12.0	3.9
0	20	20.5 a	39	93 b	7 b	169 bc	68.1 b	12.2	4.1
167	20	21.4 a	58	95 b	5 b	156 bc	69.9 a	11.9	3.9
167	10	21.8 a	50	95 b	5 b	150 c	67.9 bc	12.0	3.9
167	5	19.3 ab	57	92 b	7 b	165 bc	67.0 cd	12.5	4.1
Significance	<0.001	0.59	0.58	<0.01	<0.01	<0.0001	0.20	0.64	

[z]Russet data were analyzed after arcsine-square root transformation. Back-transformed weighted means are presented.
[y]Russet assessed on a random sample of 100 fruit per plot.
[x]GA_{4+7} applied at 0, 10, 20, and 30 d after petal fall.
[w]Means within columns with different letters are significantly different at $P \leq 0.05$ using the Waller-Duncan k-ratio *t* test (n = 6).
SSC = soluble solids concentration.

All P-Ca and GA_{4+7} spray treatments reduced russet severity in Expt. 4, resulting in a significant increase in the proportion of fruit in the lowest russet severity class compared with the control (Table 4). However, in this experiment, there were no differences between the spray treatments; a single application of P-Ca at PF reduced russet severity equally as effectively as four sprays of 20 mg·L^{-1} GA_{4+7}. Analysis of a subset of the treatments in Expt. 4 as a 2 × 2 factorial design revealed a significant main effect of P-Ca ($P = 0.01$) and GA_{4+7} sprays ($P < 0.001$) on the proportion of fruit in the lowest russet severity class, but the interaction term between these two factors was not significant.

Discussion

Application of P-Ca at PF reduced the severity of russet on 'Golden Delicious' apples in three of four experiments in the present study. P-Ca did not influence russet severity in Expt. 1, in which the background level of russet was very low. A single application of P-Ca at PF increased the proportion of fruit in the lowest russet severity class by 0% to 26% compared with 7% to 45% for a standard program of multiple GA_{4+7} sprays. Miller (1998) also reported that P-Ca reduced russet, finding that the level of russet control achieved with two or three sprays of P-Ca at concentrations greater than 188 mg·L^{-1} was similar to that achieved with four sprays of GA_{4+7}. The greater efficacy of P-Ca against russet reported by Miller (1998) may be attributable to either (or a combination of) the higher concentrations that were used in the initial application or to the fact that multiple applications of P-Ca were made. Because P-Ca is relatively short-lived in plants, with a biologic half-life of 10 to 14 d (Rademacher et al., 2004), then the effects of a PF application on GA metabolism would have dissipated by the time of the third and fourth applications of GA_{4+7} in a russet prevention program in which these applications are made at 10-d intervals. If the concentration and timing/frequency of P-Ca sprays required for optimizing russet reduction were known, then this strategy may provide a more cost-effective alternative to the current industry standard of three or four GA_{4+7} sprays for russet control. Alternatively, optimum combinations of P-Ca and GA_{4+7} sprays may enable effective russet control with lower concentrations or a reduced frequency of GA_{4+7} sprays, although the limited data from Expt. 4 do not bear this out.

Because GA_{4+7} sprays are routinely used in commercial practice to reduce russet, it seems somewhat paradoxic that russet can also be reduced by application of a GA biosynthesis inhibitor such as P-Ca. This paradox may be explained by examining the effects of P-Ca on GA metabolism. P-Ca inhibits several key enzymes involved in GA metabolism, including GA_{20}-3β-hydroxylase and certain 2β-hydroxylases (Rademacher and Kober, 2003). GA_{20}-3β-hydroxylase is the most important target enzyme inhibited by P-Ca in most plant species, catalyzing the conversion of inactive GA_{20} into highly active GA_1. P-Ca may also inhibit the 2β-hydroxylase enzymes responsible for metabolic inactivation of endogenously active GAs such as GA_1 and GA_4 (Rademacher and Kober, 2003). Such inactivation by P-Ca could conceivably result in elevated levels of endogenous GA_4 as a result of its protection from conversion to inactive forms. The effects of a PF application of P-Ca on GA metabolism would clearly be coincident with the initial period during which russet is initiated (Creasy, 1980; Simons, 1960). With a half-life in plants of less than 14 d (Rademacher et al., 2004) it would appear that at least two applications of P-Ca would be required to alter GA metabolism throughout the period of russet initiation, explaining why Miller (1998) reported that two or three applications of P-Ca resulted in a level of russet reduction that was equivalent to a standard GA_{4+7} program.

The effects of combining a single application of P-Ca at PF with three or four GA_{4+7} sprays on russet were additive as determined by the lack of an interaction term in a factorial analysis of the data in the present experiments. This result is in agreement with previous studies on a different skin disorder of apple fruit (scarf skin), in which the combination of P-Ca with the first of three GA_{4+7} sprays was more effective than either material alone (McArtney et al., 2006). These results are not consistent with the findings of Miller (1998), who reported that P-Ca sprays did not affect the activity of a GA_{4+7} program for russet control on 'Golden Delicious' in two different experiments. However, in one of these experiments, the initial GA_{4+7} application was made at PF, whereas the first P-Ca application was not made until 7 d after PF. Rademacher and Kober (2003) suggested that the inactivation of exogenously applied GA_4 by 2β-hydroxylation could be inhibited by simultaneous treatment with P-Ca resulting in increased GA activity. This suggestion provides a logical explanation for why russet might be reduced more effectively when P-Ca and GA_{4+7} were combined compared with a GA_{4+7} program alone.

Data from the present study indicate that GA_{4+7} sprays nullified the inhibitory effect of a single PF application of P-Ca on shoot growth measured 30 d after PF. Tromp (1982) found that GA_{4+7} did not actively promote shoot growth in apples, even at concentrations as high as 500 mg·L^{-1}. Others have reported a slight antagonizing effect on shoot growth when P-Ca was applied with GA_{4+7} (McArtney et al., 2006; Miller, 1998; Miller et al., 2002; Schroeder et al., 2003). Treatment effects on shoot length were only recorded 30 d after PF in the present study, and it would be logical to assume that final shoot length should not be greatly affected by a single application of P-Ca at PF.

The main effect of P-Ca on mean fruit weight at harvest was neutral; however, P-Ca reduced fruit weight in three of the four experiments in the current study. In a previous study, we also found that P-Ca reduced mean fruit weight (McArtney et al., 2006). Because the effects of P-Ca on fruit set were only measured in one of the four experiments reported here, it is not known at this time if the fruit size response is a direct effect of the combined treatment on fruit growth or if it is mediated by a crop load effect. There was a significant interaction between the effects of P-Ca and GA_{4+7} sprays on fruit weight in Expt. 3, the data indicating that the combination of P-Ca and GA_{4+7} sprays had a negative effect on mean fruit weight. In related unpublished studies, we have found that the combination of P-Ca and GA_{4+7} sprays during this period can significantly reduce the number of fully developed seeds per fruit. Regrettably, seed number was not measured in any of the present experiments.

In conclusion, application of a single P-Ca spray at PF did not negate the effects of a standard program of multiple GA_{4+7} sprays on fruit russet. P-Ca directly reduced the severity of russet on 'Golden Delicious' apple fruit and the effects of combining a PF spray of P-Ca with multiple GA_{4+7} sprays could be additive. The effects of P-Ca and GA_{4+7} sprays on fruit maturity parameters were minor. However, the positive effects of combining P-Ca and GA_{4+7} sprays on fruit russet will need to be weighed against a potential loss of efficacy of shoot growth control and a reduction in mean fruit weight. Further studies may determine strategies for reducing russet that are based on P-Ca alone. Such an approach may prove to be more cost-effective than current GA_{4+7} programs and would alleviate the concern of reducing mean fruit weight when combining these two plant growth regulators.

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