Prohexadione-Ca Reduces Russet and Does Not Negate the Efficacy of GA4+7 Sprays for Russet Control on ‘Golden Delicious’ Apples

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Additional index words: plant growth regulator, Apogee, ProVide, Malus × domestica

Abstract. A series of four experiments were undertaken to evaluate the effects of individual and combined applications of prohexadione-Ca (P-Ca) and GA4+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 GA4+7 at 10-day intervals beginning at PF generally reduced fruit more effectively than P-Ca. P-Ca did not reduce the efficacy of GA4+7 sprays for russet reduction. However, GA4+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 GA4+7 treatment in every experiment, although there was a significant interaction between P-Ca and GA4+7 sprays on mean fruit weight in only one experiment. There were no consistent effects of P-Ca and GA4+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 GA4+7 sprays on russet can be additive. The economic benefits resulting from a reduction in russet severity after combined P-Ca and GA4+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 nonrusseted 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 (GA4+7) can be applied at 7- to 10-d intervals during the first month after bloom to reduce the incidence and severity of russet (Ecccher, 1978; Ecccher and Bottelli, 1981; Taylor, 1975, 1978; Wertheim, 1982). Three to four applications of a proprietary mixture of 15 to 20 mg L−1 GA4+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 GA4+7 sprays to reduce russet, believing that the increase in crop value after multiple GA4+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, 1989) 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 GA4+7 in a russet control program. The greatest effect of P-Ca on gibberellin biosynthesis and metabolism coincides with the period during which GA4+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
russet as effectively as four applications of GA₄+7. When these two plant growth regulators were combined, the russet severity was no better than either material alone (Miller, 1998). However, GA₄+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 GA₄+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 GA₄+7 application (McArthur et al., 2006). However, we also reported that mean fruit weight at harvest was occasionally reduced by the combination of P-Ca and GA₄+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 GA₄+7 sprays for reducing russet of ‘Golden Delicious’ apple; 2) determine if application of P-Ca at this time interferes with the efficacy of GA₄+7 sprays for russet reduction; and 3) determine the effects of combining a single application of P-Ca at PF with multiple GA₄+7 sprays on mean fruit weight at harvest. Lesser objectives of the study were to determine if GA₄+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 ± GA₄+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 treatments: 1) an untreated control; 2) a single application of 167 mg L⁻¹ P-Ca at PF (25 Apr.); 3) 20 mg L⁻¹ GA₄+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 20 mg L⁻¹ GA₄+7 was tank-mixed with 167 mg 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 center tree in each plot 30 d after PF. The surface area affected by russet was determined for each fruit in the lowest russet severity class (Table 1).

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 GA₄+7 sprays. The interaction term in the model was not significant, indicating that P-Ca did not reduce the efficacy of GA₄+7 sprays for russet control (Table 1). P-Ca had no effect on mean fruit weight or fruit maturity parameters. GA₄+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 GA4+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 GA4+7 sprays on russet severity was not significant, indicating their effects were additive. There were no effects of P-Ca or GA4+7 sprays on fruit weight or fruit maturity in Expt. 2 (Table 2). However, there was a significant interaction between the effects of P-Ca and GA4+7 sprays on mean fruit weight in Expt. 3; combining P-Ca and GA4+7 sprays reduced mean fruit weight by 7% (13 g) compared with the control. The treatments had no effect on mean shoot length, measured 30 d after PF (P = 0.08), whereas GA4+7 sprays were without effect on mean shoot length (Table 3). There was a significant interaction between the effects of P-Ca and GA4+7 sprays on shoot length. Mean shoot length was the same on trees treated with both P-Ca and GA4+7 and control trees, indicating that GA4+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 GA4+7 sprays reduced mean fruit weight. However, there was a significant interaction between the effects of P-Ca and GA4+7 sprays on mean fruit weight in Expt. 3; combining P-Ca and GA4+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 GA4+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 GA4+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 GA4+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 GA4+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 GA4+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 GA4+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 GA4+7 sprays on mean fruit weight were additive (data not shown).
All P-Ca and GA4+7 spray treatments reduced russet severity in Exp. 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\(^{-1}\) GA4+7. A factorial analysis of the treatments in Exp. 4 as a 2 \(\times\) 2 factorial design revealed a significant main effect of P-Ca \((P < 0.01)\) and GA4+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 Exp. 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 GA4+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 GA4+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 GA4+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 GA4+7 sprays for russet control. Alternatively, optimum combinations of P-Ca and GA4+7 sprays may enable effective russet control with lower concentrations or a reduced frequency of GA4+7 sprays, although the limited data from Exp. 4 do not bear this out.

Because GA4+7 sprays are routinely used in commercial practice to reduce russet, it seems somewhat paradoxical that russet can be 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 GA20\(\beta\)-hydroxylase and certain \(2\Beta\)-hydroxylases (Rademacher and Kober, 2003). GA20\(\beta\)-hydroxylase is the most important target enzyme inhibited by P-Ca in most plant species, catalyzing the conversion of inactive GA20 into highly active GA1. P-Ca may also inhibit the \(2\Beta\)-hydroxylase enzymes responsible for metabolic inactivation of endogenously active GAs such as GA1 and GA3 (Rademacher and Kober, 2003). Such inactivation by P-Ca could conceivably result in elevated levels of endogenous GA2 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 GA4+7 program.

The effects of combining a single application of P-Ca at PF with three or four GA4+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 GA4+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 GA4+7 program for russet control on ‘Golden Delicious’ in two different experiments. However, in one of these experiments, the initial GA4+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 GA4 by \(2\Beta\)-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 GA4+7 were combined compared with a GA4+7 program alone.

Data from the present study indicate that GA4+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 GA4+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 GA4+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 GA4+7 sprays on fruit weight in Exp. 3, the data indicating that the combination of P-Ca and GA4+7 sprays had a

### Table 4. Effects of 167 mg L\(^{-1}\) prohexadione-Ca (P-Ca) at petal fall, alone or combined with different rates of GA4+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 (Exp. 4).\(^4\)

<table>
<thead>
<tr>
<th>Treatment (mg L(^{-1}))</th>
<th>Mean shoot length (cm)</th>
<th>Fruit set (%)</th>
<th>Mean fruit wt (g)</th>
<th>Firmness (N)</th>
<th>SSC (°Brix)</th>
<th>Starch index (1–8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-Ca</td>
<td>GA4+7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>17.4 bc(^6)</td>
<td>41</td>
<td>189 a</td>
<td>65.5 c</td>
<td>12.0</td>
</tr>
<tr>
<td>167</td>
<td>0</td>
<td>15.3 c</td>
<td>54</td>
<td>175 ab</td>
<td>66.8 d</td>
<td>12.0</td>
</tr>
<tr>
<td>0</td>
<td>20</td>
<td>20.5 a</td>
<td>39</td>
<td>169 bc</td>
<td>68.1 b</td>
<td>12.2</td>
</tr>
<tr>
<td>167</td>
<td>20</td>
<td>21.4 a</td>
<td>59</td>
<td>156 bc</td>
<td>69.9 a</td>
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<tr>
<td>167</td>
<td>5</td>
<td>19.3 ab</td>
<td>57</td>
<td>165 bc</td>
<td>67.0 cd</td>
<td>12.5</td>
</tr>
</tbody>
</table>

\(^4\)Russet data were analyzed after arcsine-square root transformation. Back-transformed weighted means are presented.

\(^5\)Means within columns with different letters are significantly different at \(P = 0.05\) using the Waller-Duncan k-ratio t test \((n = 6)\).

\(^6\)SSC = soluble solids concentration.
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.

**Literature Cited**


Miller, S.S. 1998. The influence of prohexadione-Ca, an anti-gibberellin, on efficacy of giberrellins used for control of fruit cracking and fruit russet. Proc. 74th Cumberland Shenandoah Fruit Workers Conf.


