Prohexadione-Calcium Controls Vegetative Shoot Growth in Apple

Stephen S. Miller

ABSTRACT. Prohexadione-calcium (Phd-Ca) (BAS 125W or 9054 W) applied at petal fall (PF) or within 10 days of PF to apple trees as a single spray or as multiple low-rate sprays reduced the current season's shoot growth. Sprays applied 2 to 3 weeks after PF were less effective. Timing of the initial spray was more important than rate in achieving early growth suppression, but rate was most important for maximum season-long growth control. Reduced shoot growth enhanced spray coverage and reduced dormant pruning time by as much as 23% over control trees. An effective cumulative dose (ECD) of 250 $mg \cdot L^{-1}$ (based on dilute or tree-row-volume equivalent) active ingredient Phd-Ca applied as a single spray or in several low-rate sprays generally produced season-long control of vigorous shoot growth. However, under some high-vigor growing conditions a higher ECD (500 $mg \cdot L^{-1}$ or greater), applied in multiple low-rate sprays, was required to achieve an acceptable level of growth suppression. When shoots resumed growth in mid-season, a single spray (28 July) at 125 $mg \cdot L^{-1}$ provided additional suppression of shoot growth. During this 5-year study, there were no adverse effects on fruit quality and little or no effect on fruit size. There was no appreciable carryover effect on the next season's shoot growth or fruit size, and there was no additive effect from successive annual applications.

KEYWORDS. Apple, growth control, plant growth regulator, Apogee®, *Malus domestica*

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INTRODUCTION

Climatic and edaphic conditions in most eastern United States fruit producing regions favor vigorous vegetative growth (Greene, 1997). Excessive vegetative growth is a major factor associated with overcrowding, delayed bearing, poor cropping, poor fruit quality (e.g., poor color), and pest problems (e.g., fire blight and aphid infestation) in eastern apple orchards (Forshey and Elfving, 1989; Miller, 1988). Developing and maintaining the delicate balance between vegetative growth and cropping is a major challenge for eastern apple growers (Forshey and Elfving, 1989).

Vegetative growth control by chemical means can help reduce excessive growth, limit tree size, or restrict growth at a particular time to produce a better balance between vegetative growth and fruiting (Miller, 1988). For many years, daminozide (Alar) was the primary plant growth regulator (PGR) used to suppress growth and encourage flowering (Elfving, 1984). Later, a combined spray of daminozide plus ethephon (Ethrel, Rhone-Poulenc, Research Triangle Park, NC) was shown to be effective (Byers and Barden, 1976). Naphthaleneacetic acid, formulated as Tre-Hold (AMVAC Chemical Corp., Los Angeles, CA), is also registered and used for vegetative growth control but has limited application (Miller, 1988). Several triazole derivatives, which inhibit gibberellin biosynthesis, have powerful growth-regulating properties in fruit trees (Miller, 1988), but because of the residual nature of these compounds and their ability to be absorbed quickly through the roots, they never were registered in the U.S. Recently, a new class of compounds, the acylcyclohexanediones (Rademacher et al., 1992), has been shown to possess growth-regulating properties through GA-biosynthesis inhibition (Nakayama et al., 1992). This class includes prohexadione. Preliminary reports indicated that prohexadione-calcium (Phd-Ca) could reduce vegetative growth in apple trees (Greene, 1996a; Greene, 1996b).

The objective of this study was to evaluate the growth-regulating properties of Phd-Ca [product codes: BAS 9054W, BAS 125 10W, and BAS125 11W (trade named Apogee); BASF Corp., Research Triangle Park, NC USA] when applied to apple trees at various times and rates.

MATERIALS AND METHODS

All studies were conducted on bearing apple trees at the Appalachian Fruit Research Station, Kearneysville, WV. All sprays were applied with a single-nozzle handgun roller-pump or piston-pump sprayer at approx. 690 kPa to the point of drip. Sprays applied between 1994 and 1997 were based on a given concentration of active ingredient (a.i.) Phd-Ca (10% dry flowable formulation) in the spray tank [a tree-row-volume (TRV) (Sutton and Unrath, 1984) is provided for the treated trees as information only]. In 1998, spray dose was determined from a specified rate of chemical product (27.5% dry flowable formulation) in a given volume (378 L) of spray solution applied as a dilute spray based on the calculated TRV for the treated trees. Total dose per hectare is a.i. and reported in this study as $g \cdot ha^{-1}$. A non-ionic adjuvant, Regulaid (Kalo, Inc., Overland Park, KS, USA), was included in all sprays at 0.03% (v/v) (0.1% in the 1994 experiment). In the 1998 trials, ammonium sulfate (spray grade) was added to all spray solutions on an equal weight basis with Phd-Ca to counter a hard-water (21 grains) condition. When multiple low-rate sprays were applied to the same tree during the season, the sum of the individual spray applications is termed the "effective cumulative dose" (ECD). The term ECD is used to represent and compare the magnitude of different treatments and does not represent a single spray concentration.

Data were analyzed using 2- and 3-way ANOVA and GLM procedures, as appropriate. Regression analysis [linear and/or quadratic (if four or more chemical rates)] was used to evaluate the effect of chemical rate and to determine the coefficient of determination (r^2). Regression analyses did not include the control treatment ($0\ mg \cdot L^{-1}$), except in the 1995 Experiment, since it had been established that any rate of the chemical caused a response. Where appropriate, means were separated by Duncan's new multiple range test.

1994 Experiment: Phd-Ca (BAS 9054W) was applied to 5-year-old 'Mercier Redchief Delicious'/MM.106 at various concentrations and timings arranged in a randomized-complete-block design with four whole-tree replications per treatment (Table 1). The test plot orchard had a TRV of $1730\ L \cdot ha^{-1}$. Shoot growth was recorded on 10 tagged shoots on the outside of the canopy of each tree on four dates during the growing season. At harvest, all fruit were removed from each tree and total weight was recorded. A subsample of 10 fruit was selected at random for determination of fruit quality. Flesh firmness was determined on opposite pared sides of each fruit with a McCormick Model FT-327 penetrometer (McCormick Fruit Tech, Yakima, WA, USA) fitted with an 11.3-mm tip and mounted in a drill-press stand. Soluble solids concentration (SSC) was determined with a hand-held, temperature-compensating refractometer (Reichert-Jung, Cambridge Instruments, Buffalo, NY, USA) on equal aliquots of the juice collected from each of the 10-fruit composite samples. Starch index (SI) was rated by dipping one half of each fruit (cut perpendicular to the core at the equator) in an iodine solution (8.8 g KI + 2.2 g I_2/1.0 L) for one minute. The degree of staining was rated on a scale of 1 to 9 where 1 = entire cut surface stained (fruit fully immature), 4 to 6 = cut surface partially stained but no staining in the core area (mature), and 9 = no staining (fruit fully over-mature) (Smith et al., 1979). Surface pigmentation was estimated visually on each fruit as percent of total fruit surface showing red color. Color intensity was rated on a 1 to 5 scale where 1 = pink, 2 = pinkish/red, 3 = red, 4 = red/dark red, and 5 = dark red color. The crop from each tree was sized on an electronic fruit weight sizer (OmniSort, Durand-Wayland, LaGrange, GA, USA) with fruit separated into 15 weight classes from 48 to 216 count per 19 kg unit. At bloom in 1995, flower clusters were counted, one limb per tree that was at least 10 cm in circumference, and the number of clusters per limb cross sectional area was determined.

1995 Experiment: Three treatments of Phd-Ca (BAS 125 10W) were applied to 16-year-old 'Law Rome'/MM.111 trees: single sprays of 125 $mg \cdot L^{-1}$ or 250 $mg \cdot L^{-1}$ at the 5-to 12-cm growth stage [between 7 and 14 days after petal fall (DAPF)] (15 May) or a multiple spray of 125 $mg \cdot L^{-1}$ applied on 15 May and repeated 4 weeks later on 16 June. Trees were vigorous, central-leader form planted 5.5 m $\times$ 6.1 m with a TRV of 3600 $L \cdot ha^{-1}$, and were carrying a heavy bloom. There were eight single-tree replications per treatment. Twenty terminals were tagged on the periphery of the canopy on each tree between 1 and 3 m above the ground and measured on the day of initial treatment, and again at the end of the growing season. Trees were harvested, total yield recorded, fruit sized, and fruit quality determined from a 10-apple subsample from each tree as in 1994. Spray treatments were not repeated in 1996, but yield and shoot growth measurements were taken from all trees treated in 1995 to assess any carryover effects.

1996 Experiment: Single sprays of Phd-Ca (BAS 125 10W) at 0, 125 or 250 $mg \cdot L^{-1}$ were applied to six whole-tree plots of 8-year-old 'Kidd's Gala'/M.7A apple trees 10 DAPF. Tree-row-volume was approximately 3600 $L \cdot ha^{-1}$. Shoot growth was measured as in the 1994-95 growing seasons. Canopy volume was calculated from canopy depth (across the row), width (within the row), and a height measurement, assuming the canopy was an inverted cone. Pruning time per tree was recorded in the dormant season. In April 1997, one limb per tree 10 to 15 cm in circumference was selected and the blossom clusters counted.

1997 Experiments: An excessively vigorous high-density (1.8 m × 5.5 m, 996 trees/ha) block of 9-year-old 'Starkspur Golden Delicious'/ seedling apple trees trained to a Y canopy form was selected to test multiple spray treatments of Phd-Ca (BAS 125 10W) (Table 4) at a high seasonal dose rate (191 $g \cdot ha^{-1}$). The trees had been pruned annually since planting, were quite open to light (except the lower underside portion of the canopy's Y form), and regularly produced in excess of 60 cm of terminal shoot growth and 100 cm of watersprout growth. Average canopy height at the beginning of the growing season was 2.5 m. Tree-row-volume was determined to be 1730 $L \cdot ha^{-1}$. Sprays were applied to four-tree subplots in each of five rows (treatment blocks) in a randomized complete block design. The initial spray for each treatment was applied on 7 May, one week after petal fall (PF). Successive sprays were applied at 2-week intervals (except the last spray was after a 3-week interval) at various concentrations from 0 to 250 $mg \cdot L^{-1}$. Each treatment received a total dose of 191 $g \cdot ha^{-1}$ (an ECD of 625 $mg \cdot L^{-1}$) for the season with the last spray for each treatment applied on 25 July. At least one guard tree was positioned between each treatment subplot. An unsprayed control plot was included in each block. At harvest (24 Sept.), 20 fruit were collected at random from each side (east and west) of the canopy for fruit size measurements. Shoot growth was measured at the end of the growing season (30 Oct.). Five current-season's watersprouts were removed from the center of each tree and their length was recorded. In addition, five terminal shoots in the lower canopy (up to 1.5 m above ground) and five terminals in the upper canopy (above 2.0 m height) were selected at random on the east and west side of the canopy from each tree, and the current-season's growth was measured.

An additional study was initiated in 1997 on 18-year-old 'Law Rome'/MM.111. Treatments ranged from no Phd-Ca applied during the season to a total of 3, 4, 5, or 6 individual sprays with concentration per spray ranging from 60 to 250 $mg \cdot L^{-1}$ (Table 5). Total season dosage was 89, 134, or 178 $g \cdot ha^{-1}$ (an ECD of 240, 360, or 480 $mg \cdot L^{-1}$, respectively). Treatments were arranged in randomized complete blocks with six blocks and single whole-tree treatments. Tree-row volume was calculated at 3880 $L \cdot ha^{-1}$ and sprays were applied at approximately 2260 $L \cdot ha^{-1}$. On 2 May, the initial treatment date, 10 terminals were selected on the periphery of the canopy between 1.5 and 2.5 m above the ground, tagged, and shoot growth measurements taken. Shoots were measured again at 4, 8, and 12 weeks after the initial treatment and at the end of the growing season. In early September, measurements on canopy width, depth, and height were recorded for each tree, and the TRV was calculated for each treatment. On a uniform overcast day and again on a cloudless day in early September, light as photosynthetically active radiation (PAR) was measured at the base of each tree under the canopy with a Sunfleck SF80 Ceptometer light bar (Decagon Devices, Inc., Pullman, WA, USA). Four readings were recorded per tree, one each in the north, east, south, and west quadrant of the canopy. Full sun measurements were taken in the open drive middles between tree rows at each of the six blocks. Mean percent full sunlight in the lowest level of the canopy was computed. Five of the trees treated at the 134 $g \cdot ha^{-1}$ rate were selected in September before harvest for detailed spray-coverage data collection. A 4 m tall metal pole was placed in the center of the canopy near the central leader. Water-sensitive paper cards (52×76 mm^2) (Ciba-Geigy Ltd., Application Services, Basle, Switzerland) were secured to the pole with double-sided tape at 1.2, 2.1, 3.0, and 3.7 m above the ground. Trees were sprayed with a PTO-driven airblast sprayer calibrated and driven to deliver 935 $L \cdot ha^{-1}$. Cards were collected and the size of the stained area determined by computer image analysis using Sigma Scan Pro software (Jandel Scientific, San Rafael, CA, USA). Mean percent spray coverage at each of the four heights in the canopy was calculated, and the increase or decrease in spray coverage was compared to check trees. At harvest, a 20-apple fruit sample was collected from each tree for fruit quality assessment as in previous experiments. Harvesting each tree and passing the fruit over the OmniSort electronic fruit grader determined total yield and percent fruit in individual weight classes.

1998 Experiments: The 'Starkspur Golden Delicious'/seedling trees trained to a Y trellis were used to evaluate the growth-control properties of a newer formulation of Phd-Ca (BAS 125 11W). In previous tests using this group of trees, sprays were applied from the ground. In this trial, sprays were applied from a stepladder that allowed the applicator to be elevated above the canopy. This improved coverage of the watersprout growth in the center of the Y form trees. Sprays were applied at 4 rates: 0, 63, 125, and 250 $mg \cdot L^{-1}$ (Table 6) to five four-tree subplots in a spray volume of 1790 $L \cdot ha^{-1}$ with the initial spray applied on 29 April, about 7 DAPF. Successive sprays for each treatment were applied on 26 May and 23 June. A TRV of 1084 $L \cdot ha^{-1}$ was used to calculate the chemical dosage per hectare. Trees received a total dose of 56, 110, or 221 $g \cdot ha^{-1}$ (an ECD of 189, 375, or 750 $mg \cdot L^{-1}$, respectively) Phd-Ca. Four four-tree plots that had been sprayed with Phd-Ca in 1996 and 1997 were left untreated in 1998, and shoot growth was measured at the same time as on treated trees. Favorable weather conditions resulted in a resumption of vigorous shoot growth in early July. One-half of the trees in each treatment plot were selected and treated with an additional spray on 28 July at 125 $mg \cdot L^{-1}$ in a spray volume of 1880 $L \cdot ha^{-1}$ with chemical rate based on a TRV of 2300 $L \cdot ha^{-1}$. Shoot growth measurements were taken on 22 June and 30 Oct. and fruit size determined at harvest as in 1997.

In a second trial, Phd-Ca (BAS 125 11W) treatments (Table 8) were applied to the 'Law Rome'/MM.111 trees treated in 1997. Treatments included 0, 2, or 3 sprays at 0, 63, 125, and/or 250 $mg \cdot L^{-1}$ based on a TRV of 3300 $L \cdot ha^{-1}$. Total season dosage of Phd-Ca ranged from 101 to 269 $g \cdot ha^{-1}$ (an ECD of 188 to 500 $mg \cdot L^{-1}$). Treatments were arranged as described in 1997. The initial spray was applied on 28 April (7 DAPF) with additional sprays, if scheduled, applied on 19 May and/or 15 June. Shoot growth, canopy volume, fruit size, and spray coverage were determined as in 1997 except spray coverage was an average of three locations per tree. Water-sensitive cards were placed at four heights in the center of the canopy and on each side half way between the tree's center and the drip line of the canopy parallel to the row middle and in-line with the center of the tree row.

RESULTS

1994 Experiment: Phd-Ca reduced total shoot growth at all concentrations and timings on 'Redchief Delicious'/MM.106 apple trees (Table 1). Shoot growth reduction ranged from 39% at 125 $mg \cdot L^{-1}$ to 69% at 375 $mg \cdot L^{-1}$ applied 7 DAPF. Average growth reduction over all treatments was 55%. Differences in growth were affected in the first 8 weeks after treatment. A treatment of four sprays applied at 50 $mg \cdot L^{-1}$ each was as effective as a single spray at 125, 250, or 375 $mg \cdot L^{-1}$. Growth control during the first four weeks after PF was affected by timing, but not by rate (Table 1). Rate of Phd-Ca affected growth control later in the season (8-12 weeks). Phd-Ca treatments had no measurable effect on fruit quality (flesh firmness, SSC, SI, size, or color) or yield per tree (data not shown). No phototoxicity was observed on fruit or foliage in any of the treatments. Blossom cluster density in 1995 was unaffected by the treatments in 1994 (data not shown).

1995 Experiment: When Phd-Ca was applied between the 5 and 12-cm growth stage, the rate applied affected terminal shoot growth in the year of application, but had no effect on shoot growth the year after sprays were applied in 16-year-old 'Law Rome'/MM.111 apple trees

TABLE 1. Shoot growth control with Phd-Ca (BAS 9054W) in 5-year-old 'Mercier Redchief Delicious'/MM.106 apple trees (1994 Experiment).

Treatment[z]			Shoot growth (cm)			
			Weeks after petal fall			Total growth (cm)
Rate (mg/L)	Timing[y]		0-4	4-8	8-12	
0	Control		10.4 a	15.4 a	2.9 ab	29.3 a
125	7 DAPF		6.1 bcd[x]	4.8 b	4.7 a	18.0 b
250	7 DAPF		4.3 bcd	2.3 b	1.8 b	11.4 b
375	7 DAPF		4.2 cd	2.1 b	1.1 b	9.3 b
250	PF		3.2 d	1.9 b	1.9 ab	10.2 b
250	14 DAPF		8.2 ab	4.1 b	2.4 ab	17.2 b
250	21 DAPF		7.4 abc	3.9 b	1.6 b	13.5 b
50	PF, 7, 14, and 21 DAPF		4.9 bcd	2.3 b	2.8 ab	12.0 b
P-values for regression on:						
rate (timing, 7DAPF)		L[w]	0.184	0.030	0.035	0.074
timing (rate, 250 mg/L)		L	0.003	0.007	0.924	0.128
		Q	0.011	0.027	0.872	0.237

[z] Dilute whole-tree handgun sprays.
[y] DAPF = days after petal fall; PF = petal fall.
[x] Means separation within columns by Duncan's new multiple range test ($P = 0.05$).
[w] L = linear; Q = quadratic.

(Table 2). Yields were not affected in the year of treatment or the year after sprays were applied. Fruit size and fruit quality were unaffected in 1995 (year of treatment) or 1996 (year after treatment) (data not shown).

1996 Experiment: Phd-Ca applied 10 DAPF at 0, 125, or 250 $mg \cdot L^{-1}$ affected shoot growth on vigorous 'Kidd's Gala' apple trees (Table 3). Shoot growth was reduced as concentration of Phd-Ca applied increased. There was a trend toward less pruning time where Phd-Ca was applied. Trees treated at the 250 $mg \cdot L^{-1}$ rate required 23% less pruning time per tree compared to control trees. Canopy volume and blossom density were not affected in the year after Phd-Ca treatment (Table 3). Shoot growth measured at the end of the 1997-growing season (the year after treatment) did not differ among treatments (data not shown).

1997 Experiments: Treatment with four or five sprays of Phd-Ca beginning 7 DAPF (7 May) with the final spray on 25 July and a total of 191 $g \cdot ha^{-1}$ applied per treatment reduced watersprout growth and

TABLE 2. Shoot growth control in 16-year-old 'Law Rome'/MM.111 apple trees with single or multiple sprays of Phd-Ca (BAS 125 10W) (1995 Experiment).

Treatment[z] Type	Rate (mg/L)	Average terminal shoot growth (cm) 1995	1996	Yield (kg/tree) 1995	1996
Control	0	54.7	42.7	119	84
Single	125	48.1	43.9	165	30
Single	250	41.4	44.1	153	88
Multiple	125 + 125	40.1	44.0	122	161
P-values for linear regression on: rate (single treatments at 0, 125, and 250 mg/L)		0.000	0.553	0.154	0.937
Comparisons (*P*-values): 250 vs. 125 + 125		0.672	0.978	0.197	0.149

[z] Dilute whole-tree handgun sprays. Single sprays applied at 5-12 cm shoot growth (15 May). Multiple sprays applied at 5 to 12-cm growth and again 4 weeks later (16 June).

TABLE 3. Effects of Phd-Ca (BAS 125 10W) on terminal shoot growth, pruning time, and canopy volume in 1996, and return bloom in 1997 in 8-year-old 'Kidd's Gala'/M.7A apple trees (1996 Experiment).

Treatment[z] rate (mg/L)	Mean shoot growth (cm)	Pruning time (min/tree)	Canopy volume[y] (m^3/tree)	Blossom clusters in 1997 (no./cm^2 LCA[x])
0	46.3	7.9	31.2	3.8
125	34.9	7.3	30.9	4.2
250	29.6	6.1	26.5	4.7
P-values				
ANOVA	0.022	0.160	0.290	0.731
Linear Regression	0.004	0.056	0.162	0.420
r^2	0.422	0.210	0.119	0.041

[z] Dilute whole-tree handgun sprays. Sprays applied 10 days after petal fall on 10 May.
[y] Canopy volume = 1/3 (area of base)(height − 0.7 m).
[x] LCA = limb cross-sectional area.

growth of all other shoots on vigorous 9-year-old 'Starkspur Golden Delicious'/seedling apple trees trained to a Y canopy form (Table 4). All treatments were equally effective in reducing shoot growth. Phd-Ca reduced watersprout and lower canopy shoot growth an average of 43% and upper canopy shoot growth by 50%. Growth response did not differ between the east and west sides of the canopy (data not shown). Aver-

TABLE 4. Effects of a high total dose (191 g·ha^{-1}) of Phd-Ca applied in multiple low-rate sprays on shoot growth in vigorous 9-year-old 'Starkspur Golden Delicious' apple trees on seedling rootstock trained to a Y form canopy (1997 Experiment).

Treatment[z]	Mean shoot growth (cm)[y]			
	Watersprouts	Lower canopy	Upper canopy	All shoots
0+0+0+0+0+0	159.4 a[x]	28.2 a	62.5 a	68.1 a
75+75+125+0+250+100	96.5 b	15.7 b	33.0 b	38.8 b
125+125+0+125+0+250	81.3 b	15.9 b	28.0 b	33.8 b
250+0+125+0+125+125	95.5 b	16.5 b	33.1 b	39.0 b

[z] Individual bi-weekly sprays (except last spray applied at 3-week interval) applied at designated mg·L^{-1} per spray beginning 7 DAPF. Effective cumulative dose applied = 625 mg·L^{-1} (191 g·ha^{-1}).
[y] Watersprouts taken from the center of the canopy; lower canopy shoots from the orchard floor to 1.5 m height; upper canopy shoots from above 2 m height.
[x] Means separation within columns by Duncan's new multiple range test ($P = 0.05$).

age growth of untreated shoots in 1997 was about 68 cm compared to 86 cm in 1996. Shoots in the upper canopy were significantly longer ($P = 0.01$) than shoots in the lower canopy for both treated (31.3 cm vs 16.0 cm) and control (62.4 cm vs 28.1 cm) treatments. Phd-Ca treatments had no effect on average fruit weight or the fruit length:diameter ratio (data not shown).

All multiple Phd-Ca spray treatments effectively reduced shoot growth in the 18-year-old 'Law Rome' trees (Table 5). Total growth was affected by the total dosage applied. Total shoot growth was reduced by 70% at the highest dose (178 g·ha^{-1}), by 51% at the lowest dose (89 g·ha^{-1}), and by an average of 61% at the intermediate dose (134 g·ha^{-1}). The total dose applied from the initial spray through 4, 8, or 12 weeks affected the amount of shoot growth measured during the 0 to 4, 4 to 8, and 8 to 12 week periods, respectively. The total dose applied at PF (first spray) had a significant effect on shoot growth measured at 4 weeks, but not the growth that occurred between week 4 and 8 or between week 8 and 12. Total growth was, however, affected by the dose applied in the initial PF spray. Those treatments that initially received a high rate (240 mg·L^{-1}) tended to have less total shoot growth than those that initially received the low rate (60 mg·L^{-1}).

In this experiment, multiple sprays of Phd-Ca had no effect on canopy TRV or light penetration at the lowest level in the canopy (data not shown). However, trees treated with a total dose of 134 g·ha^{-1} Phd-Ca showed an average increase in spray deposition of 10.6%. The major in-

TABLE 5. Effects of multiple Phd-Ca (BAS 125 10W) sprays on shoot growth in 18-year-old 'Law Rome'/MM.111 apple trees (1997 Experiment).

Treatment[z] (mg/L sprays)	Total dose applied ($g{\cdot}ha^{-1}$)		Shoot growth (cm) weeks after petal fall 0-4	4-8	8-12	Total growth (cm)
0 + 0 + 0 + 0 + 0 + 0 + 0	0		19.7	11.3	1.3	34.5
60 + 60 + 0 + 120 + 0 + 0 + 0	89		10.6	2.8	1.1	16.8
60 + 60 + 60 + 60 + 0 + 60 + 60	134		9.0	1.4	0.5	13.4
60 + 60 + 120 + 0 + 0 + 120 + 0	134		9.7	1.2	0.4	14.4
120 + 60 + 60 + 60 + 60 + 0 + 0	134		7.7	1.5	0.7	13.6
120 + 0 + 0 + 120 + 0 + 120 + 0	134		7.4	1.8	0.5	13.4
240 + 0 + 0 + 120 + 0 + 0 + 0	134		7.1	1.4	0.5	12.4
240 + 0 + 120 + 0 + 120 + 0 + 0	178		6.0	1.5	0.4	10.1
P-values for regression on cumulative dose applied to:						
petal fall		L[y]	0.000	0.355	0.345	0.002
		Q	0.000	0.656	0.632	0.009
day 10 (2 treatments)		L	0.000	0.306	0.472	0.004
		Q	0.001	0.587	0.586	0.015
date shoot growth was measured		L	0.003	0.076	0.025	0.000
		Q	0.008	0.048	0.044	0.001

[z] Three to six individual sprays applied at 10-day intervals beginning at petal fall at the designated rate ($mg{\cdot}L^{-1}$) per spray. Dilute whole-tree handgun sprays. Tree-row volume was calculated at 3880 $L{\cdot}ha^{-1}$ and sprays were applied at approximately 2260 $L{\cdot}ha^{-1}$.
[y] L = linear; Q = quadratic.

crease in spray deposition occurred in the lower portion of the canopy (28.9% at 1.2 m height and 19.8% at 2.1 m height). There was a decrease (9.1%) in spray deposition in the Phd-Ca treated trees in the highest part of the canopy (3.7 m height). Fruit quality and fruit size of 'Law Rome' were unaffected by the multiple Phd-Ca spray treatments (data not shown).

1998 Experiments: Two (22 June) or three (30 Oct.) sprays of the 27.5% formulation of Phd-Ca (BAS 125 11W) reduced shoot growth in vigorous 10-year-old 'Starkspur Golden Delicious' apple trees (Table 6). Multiple sprays at 250 $mg{\cdot}L^{-1}$ were the most effective for controlling watersprouts and shoots in the upper and lower canopy. Trees previously treated in 1996 and 1997, but not treated in 1998, showed little or no difference in shoot growth compared to controls (Table 6) on 22

TABLE 6. Effects of Phd-Ca (BAS 125 11W) sprays on current-season shoot growth measured on two dates in 10-year-old 'Starkspur Golden Delicious' apple trees on seedling rootstock trained to a Y canopy form (1998 Experiment).

Treatment[z] rate/spray (mg/L)	Total dose applied ($g \cdot ha^{-1}$)	Mean shoot growth (cm)			Mean shoot growth of (cm)		
		Water-sprouts	Upper canopy[y]	Lower canopy	Water-sprouts	Upper canopy	Lower canopy
		22 June			30 October		
0	0	75 a[x]	49 a	34 a	222 a	127 a	27 a
63	56	77 a	58 a	35 a	206 ab	127 a	26 a
125	110	61 b	52 a	26 b	209 ab	121 ab	20 ab
250	221	46 c	39 b	22 b	155 c	100 bc	16 b
0–(treated in 1996-'97)		79 a	49 a	26 b	183 bc	87 c	22 ab
P-values for linear regression on rate (63, 125, and 250 mg/L)		0.000	0.000	0.004	0.010	0.032	0.015
Comparisons (*P*-values):							
2, 3, 4 vs. 5		0.002	0.829	0.456	0.768	0.024	0.355
1 vs. 5		0.435	0.924	0.010	0.046	0.008	0.497

[z] Dilute handgun application based on TRV of 1084 $L \cdot ha^{-1}$. Sprays were applied on 29 April, 26 May, and 23 June 1998 in 1790 $L \cdot ha^{-1}$ at the designated rate ($mg \cdot L^{-1}$). Total dose applied was 56, 110, and 221 $g \cdot ha^{-1}$ for treatments 2, 3 and 4, respectively.
[y] Upper canopy = above 2 m; Lower canopy = ground to height of 1.5 m.
[x] Mean separation by Duncan's new multiple range test, $P \leq 0.05$.

June. However, when measured on 30 Oct. these trees did have significantly less growth of watersprouts and upper canopy shoots. A single spray at 125 $mg \cdot L^{-1}$ on 28 July to all treatments reduced the growth of watersprouts compared to trees not treated on that date (Table 7). The 28 July spray on control trees and those receiving three earlier season sprays at 125 $mg \cdot L^{-1}$ reduced the growth of all other (whole canopy) shoots. A 3-way ANOVA showed no interaction between the early spray concentration and the mid-season spray ($P = 0.601$). Fruit size was not affected by Phd-Ca (data not shown).

An initial spray of Phd-Ca (BAS 125 11W) at rates of 63 to 250 $mg \cdot L^{-1}$ reduced shoot growth on 19-year-old 'Law Rome'/MM.111 trees when measured 4 weeks after treatment in 1998 (Table 8). The initial application or a second spray (19 May) did not affect shoot growth that occurred between 4 and 6 weeks after the initial spray (28 Apr.). Growth between 6 and 14 weeks and total growth was not affected by the rate of the initial spray; however, the total dose applied affected shoot growth measured on these two dates (3 Aug. and 30 Oct.). Total shoot growth was slightly greater (24%) for trees.

TABLE 7. Effects of a mid-season Phd-Ca spray on current season shoot growth (30 Oct.) in 'Starkspur Golden Delicious' apple trees on seedling rootstock previously treated in the same growing year with Phd-Ca (1998 Experiment).

Spray treatment (mg/L)[z]		Mean shoot growth (cm)	
Early	Mid-season	Watersprouts	Whole canopy[y]
0	0	222	106
	125[x]	161	88
	P =	0.002[w]	0.050
63 (×3)[v]	0	206	102
63 (×3)	125	164	90
	P =	0.022	0.180
125 (×3)	0	209	98
125 (×3)	125	141	77
	P =	0.001	0.027
250 (×3)	0	155	77
250 (×3)	125	115	64
	P =	0.033	0.162

[z] Dilute handgun application based on TRV.
[y] Whole canopy includes terminal shoots in lower and upper canopy plus watersprout growth.
[x] Mid-season spray was applied 28 July in 1880 $L \cdot ha^{-1}$. TRV = 2300 $L \cdot ha^{-1}$.
[w] Single degree of freedom contrast probability.
[v] Early season sprays were applied on 29 April, 26 May, and 23 June in 1790 $L \cdot ha^{-1}$ at the designated rate ($mg \cdot L^{-1}$). TRV = 1084 $L \cdot ha^{-1}$.

treated in 1997 and not treated in 1998 compared to control trees. While Phd-Ca reduced shoot growth (Table 8), canopy volume did not differ among treatments (data not shown). Spray deposition was increased by 7.5% on a whole tree basis for trees treated at the highest rate (269 $g \cdot ha^{-1}$) compared to control trees (data not shown). There was no treatment effect on fruit size at harvest (data not shown).

DISCUSSION

The initial experiment (1994) demonstrated the potential of Phd-Ca as an effective inhibitor of current-season shoot growth in apple. Experiments from 1995 through 1998 confirmed the shoot-growth-regulating properties of Phd-Ca and demonstrated other effects associated with this PGR. During the 5 years of this study, reduction in shoot growth ranged from 21% to 71% of control trees depending on dose applied,

TABLE 8. Effects of multiple Phd-Ca (BAS 125 11W) sprays in 1998 on the current season growth in 19-year-old 'Law Rome'/MM.111 apple trees previously treated with Phd-Ca in 1997 (1998 Experiment).

Treatment		Total dose applied 1998 (g/ha)		Shoot growth (cm) in 1998 weeks after initial spray[y]			Total growth (cm)
1997 Total dose (g/ha)	1998[z] (mg/L)			0-4	4-6	6-14	
0	0	0		22.5	4.2	4.1	35.0
178	0	0		25.0	6.4	5.2	43.4
134	63 + 63 + 63	101		16.0	0.9	5.5	26.6
134	125 + 63	101		15.0	1.2	10.5	33.8
134	63 + 125	101		16.2	1.3	6.4	27.6
134	125 + 0 + 125	134		15.0	0.7	4.9	24.3
134	125 + 125 + 125	202		14.5	0.9	2.6	20.9
89	250 + 125 + 125	269		13.5	0.6	2.3	20.2
P-values for regression on dose applied:							
to date shoot growth measured			L[x]	0.037	0.462	0.001	0.001
			Q	0.105	0.278	0.001	0.003
for initial application only			L	0.013	0.194	0.067	0.058

[z] Dilute handgun application based on a TRV of 3300 $L \cdot ha^{-1}$. Treatment applied at the designated rate ($mg \cdot L^{-1}$) on the following dates (if scheduled) in a spray volume of 2400 $L \cdot ha^{-1}$: 28 April (PF) (1st spray), 19 May (2nd spray), and 15 June (3rd spray).
[y] Date of shoot growth measurement for week: 4 = 26 May; 6 = 8 June; and 14 = 3 August. Total growth recorded on 30 Oct. 1998.
[x] L = linear; Q = quadratic.

time of application, and vigor of the cultivar treated. There was no attempt to make direct comparisons between the three formulations used over the course of this study.

Shoot growth rate in apple generally is more rapid in the 3-4 weeks after full bloom than later in the growing season (Forshey et al., 1983). Application of Phd-Ca at the beginning of this rapid growth stage (near PF) suppressed the initial surge of current-season's growth more than a similar application 2-3 weeks after PF. This response to Phd-Ca has been reported recently by others (Byers and Yoder, 1999; Unrath, 1999) and is similar to the response obtained with other retardants like daminozide (Rogers and Thompson, 1968) and paclobutrazol (Miller, 1988).

Periodic measurement of current-season shoot growth (experiments in 1994, 1997, and 1998) indicated that a reduction in growth could be expected within 4 weeks of applying Phd-Ca. This period coincides with the primary shoot-growth period in apple. In some years (1998), when conditions favored renewed vegetative growth in mid-season, an additional spray at this time further reduced the amount of growth that occurred over the growing season (Table 7). It would therefore appear that while maximum response to Phd-Ca should be expected when applied during the early shoot-growth period, this PGR has a broad range of response time that is associated with active vegetative growth.

Results from these experiments clearly indicate that response to Phd-Ca is dependent on early timing (near PF) and total dosage applied as a single spray or as multiple sprays over an extended period. Multiple sprays at low concentration were often as effective as a single spray at a higher concentration applied near PF as demonstrated in the 1994 and 1995 Experiments. Multiple spray treatments of an equal ECD were generally comparable in growth control (Tables 4 and 5). These treatments suggested that growth control might be improved if the initial spray was at a higher (250 $mg \cdot L^{-1}$) rate. However, not all experiments supported this theory (Table 8), suggesting that growing conditions may determine the level and time sequence of treatments for optimum growth suppression. Carryover effects on shoot growth varied from no effect (Table 2) to a small decrease (Table 6) or slight increase (Table 8) in growth. This response might be mere random effect, but deserves additional study with particular emphasis on the potential for increased growth once application is discontinued, a common problem with daminozide (Miller, 1988). Unrath (1997) initially reported an additive effect from successive annual applications of Phd-Ca, but later (Unrath, 1999) found no such effect. In this study, there was no evidence of an additive response when trees were treated in two consecutive years (Table 8).

The 'Starkspur Golden Delicious' trees trained to a Y form canopy presented a unique and extreme shoot-growth situation (but not unlike what is often seen in the mid-Atlantic growing region). Because the trees' upper and central canopy were fully exposed to light and they were growing on a vigorous rootstock, shoot-growth was uniformly strong through the first 8-10 weeks of the season and often continued past mid-season (July). Under these circumstances, multiple sprays were considered appropriate for shoot growth control. Applications of 191 $g \cdot ha^{-1}$ (an ECD of 625 $mg \cdot L^{-1}$) or greater total season dose (Tables 4 and 6) reduced shoot growth on the average by 34%. Multiple sprays at a lower dose were ineffective. In North Carolina, Unrath (1999) reported an ECD of about 250 $mg \cdot L^{-1}$ was equally or more effective than an ECD of 500 mg·L^{-1} for controlling shoot-growth on the vigorous cultivar 'Granny Smith'. Considering Unrath's (1999) findings, the results reported in this paper suggest a need to tailor applications to specific growing conditions and further suggests that very high rates may be necessary under some conditions. No adverse effects on fruit quality were found with the high rates used in these experiments.

Prohexadione-Ca, at the rates and timings used in this study, had no effect on fruit quality (flesh firmness, SSC, starch index, or color) and little or no effect on fruit size. This is in contrast to daminozide that affected numerous quality attributes (Miller, 1988) and fruit size (Looney et al., 1967; Williams et al., 1970). The fruit-size reduction by Phd-Ca in the 1994 experiment may have been associated with increased fruit set. Studies by others have shown that Phd-Ca may increase fruit set (Greene, 1999; Unrath, 1999). There were no carryover effects on fruit quality or fruit size as was often observed with daminozide or paclobutrazol (Miller, 1988).

Canopy size and density influence spray deposit (Byers et al., 1984; Ferree and Hall, 1980). As tree size and canopy density decrease, spray deposition within the canopy increases. Reduced shoot growth from Phd-Ca in these studies resulted in an average increase in spray deposit from 7.5% to more than 10%. Reduced shoot growth was also associated with what one would consider a practical reduction in dormant pruning time as reported by Byers and Yoder (1997) and Evans et al. (1999).

This study, over a 5-year period, demonstrated Phd-Ca is a very effective growth retardant for apples and an attractive choice, since there were no apparent adverse effects on fruit quality and minimal or no effects on fruit size. Since Phd-Ca is short lived in apple-tree tissues, applications need to be made soon after petal fall for optimum response, and multiple low-rate sprays may be needed to obtain season-long suppression of shoot growth. Response to Phd-Ca is rate dependent. A single dose of 250 mg·L^{-1} applied dilute based on the calculated TRV will suppress shoot growth in most situations but an ECD as high as 500 mg·L^{-1} or greater may be required for unusually long growing seasons or under exceptionally vigorous growing conditions. Reduced shoot growth as a result of Phd-Ca spray is likely to increase spray distribution within the canopy in the year of treatment and may reduce dormant-pruning time.

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