Prohexadione-calcium Suppression of Apple Tree Shoot Growth as Affected by Spray Additives

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Abstract. Technical grade prohexadione-calcium (93.2% a.i. P-Ca) applied to 'Fuji'/M.9 trees in three applications in deionized water reduced shoot growth by 25%, but the addition of $(\text{NH}_4)_2\text{SO}_4$ to P-Ca suppressed shoot growth by 47%. If P-Ca was mixed in well water (high in calcium salts), P-Ca did not suppress shoot growth at all. The commercially formulated prohexadione-calcium [Apogee: 27.5% P-Ca + 56.1% $(\text{NH}_4)_2\text{SO}_4$ + 16.4% other proprietary additives] + Regulaid in well water (high calcium) was not as effective (reduced growth by 30%) as when additional $(\text{NH}_4)_2\text{SO}_4$ was added (reduced growth by 53%), and if CaCl_2 (used to control corking) was tank mixed with Apogee + Regulaid, the Ca^{++} interfered with the growth suppression of P-Ca. If $(\text{NH}_4)_2\text{SO}_4$ was added at the same rate as CaCl_2 (w/w), the Apogee growth suppression was completely restored (reduced growth by 50%). Choice (a commercial water conditioner that has $(\text{NH}_4)_2\text{SO}_4$ in the formulation, among other ingredients) + Li-700, or $(\text{NH}_4)_2\text{SO}_4$ + Silwet L-77, or $(\text{NH}_4)_2\text{SO}_4$ + Silwet L-77 + Oil were among the most effective adjuvant combinations with Apogee. The addition of ethephon at 270 $\text{mg}\cdot\text{L}^{-1}$ improved the growth suppression of Apogee + $(\text{NH}_4)_2\text{SO}_4$ + Regulaid. Solubor compromised the effectiveness of Apogee + Regulaid. Adjusting the pH of the Apogee + $(\text{NH}_4)_2\text{SO}_4$ + Regulaid spray to either pH = 4 or pH = 9 did not affect efficacy. The combination of Apogee + $(\text{NH}_4)_2\text{SO}_4$ + Regulaid caused increased fruit cracking of 'Empire' fruit as compared to the control (7%), presumably due to increased absorption of P-Ca. Chemical names used: Prohexadione-calcium (P-Ca, 3-oxido-4-propionyl-5-oxo-3cyclohexenecarboxylate) formulated as BAS-125 (10% P-Ca); Apogee (27.5% P-Ca), or Technical 93.5% P-Ca; Regulaid (polyoxyethylenepolypropoxypropanol, alkyl 2-ethoxethanol, and dihydroxy propane); Silwet L-77 (polyalkyleneoxide modified heptamethyltrisiloxane, silicon surfactant), LI-700 (80%, phosphatidylcholine, methylacetic acid and alkyl polyoxyethylene ether); Superior Oil (Drexel Damoil 70-second delayed dormant spray oil); ethephon (2-chloroethyl phosphonic acid); Solubor (20.5%, Boron equivalent); captan (*N*-Trichloromethylthio-4-cyclohexene-1,2-dicarboximide).

Several plant growth regulators have been used to reduce vegetative growth of fruit trees, thereby reducing pruning costs and improving fruit quality (Faust, 1984; Looney, 1983; Luckwill, 1970; Miller, 1988; Williams, 1984). Apogee [(27.5% P-Ca + 72.5% $(\text{NH}_4)_2\text{SO}_4$) BASF Corp., Research Triangle Park, N.C.], recently registered as a foliar aqueous spray for inhibiting shoot growth of apple [*Malus × sylvestris* (L.) var. *domestica* (Borkh. Mansf.) trees, results in reduced pruning time, tree canopy size and density, and reduced severity of fireblight (Byers and Yoder, 1999; Yoder et al., 1999).

Since prohexadione-calcium (P-Ca) sprays are rather expensive, it is important to maximize the efficacy of the applied dose by promoting absorption, translocation, or both, to the site of GA synthesis (Rademacher, 2000). The reduced effectiveness of many pesticides have been related to chemical stability in aqueous

spray solutions at high or low pH, the sprayer water volume applied per hectare, physical barriers related to the plant cuticle structure, calcium salts in the spray water (Nalewaja et al., 1992), calcium or boron nutrients routinely added to sprays to correct physiological disorders of apple (Raese and Drake, 2002), photo-oxidation at high light intensities (Rademacher unpublished), energetics and/or mechanics of plant growth regulator loading into the phloem or xylem cells, binding or metabolism of the chemical before it reaches the site of action or some other action. Many adjuvants, alone or in combination with other chemicals, added to sprays may potentiate or interfere with the activity of specific PGRs, but frequently their modes of action are not understood.

The objectives of the experiments reported here were to evaluate the effectiveness of P-Ca [formulated as the BAS-125 10% P-Ca), Apogee (27.5% P-Ca), or the technical (93.2% P-Ca)], alone or in combinations with deionized water, well water (high in calcium), calcium chloride, solubor, ammonium sulfate, commercial spray-adjuvants, pH of spray water, and ethephon for influences on tree-growth and subsequent flowering.

General. Randomized complete-block designs were used in all experiments. Trees were blocked by location within rows or by trunk cross-sectional area (TCSA). All experiments had six blocks or more. Trees were sprayed with a low pressure hand-wand sprayer to drip. In the dormant season (Expts. 1–4), average shoot length of the longest top two shoots, length of 4 or 10 longest scaffold shoots, weight, and basal and terminal shoot diameters of these scaffold shoots, total length of all shoots longer than 30 cm, time required to prune each tree, number of cuts/tree, and pruning weights/ cm^2 TCSA per tree were recorded. Data were analyzed by analysis of variance (ANOVA) and General Linear Method (GLM) procedures using SAS software (SAS Institute, 1985). Means were compared by single-degree-of-freedom contrasts, by linear and polynomial regressions, or Duncan's New Multiple Range Test depending upon the experimental design.

Expt. 1. In 1999, 102 five-year-old 'Fuji'/M.9 trees (six blocks) were selected for 17 treatments (Table 1). Apogee was applied at petal fall (PF), PF+21 d, and PF+42 d to the same trees at 125 $\text{mg}\cdot\text{L}^{-1}$ either alone or in combination with CaCl_2 , adjuvants [Regulaid (Kalo Agricultural Chemicals, Overland Park, Kans.), Silwet L-77 (OSI Industries, Tarrytown, N.Y.), Superior Oil (Drexel Chemical Co., Memphis, Tenn.)], hard water, or ammonium sulfate. In addition, two P-Ca formulations (Apogee and BAS 125) were evaluated. Shoot length of the four longest scaffold shoots were measured on 15 June 1999. In the dormant season, the total length of shoots longer than 30 cm, weight and time required to prune trees, number of cuts, and pruning weights/ cm^2 TCSA were taken.

Expt. 2. In 2000, 147 six-year-old 'Fuji'/M.9 trees (seven blocks) were selected for 21 treatments (Table 2). Apogee was applied at 125 $\text{mg}\cdot\text{L}^{-1}$ in three applications to the same trees at FB+4, FB+21, and FB+42 d. In addition, ethephon, Regulaid, $(\text{NH}_4)_2\text{SO}_4$, Superior Oil, Choice (Loveland Industries, Greeley, Colo.), Li-700 (Loveland Industries), NaCl, KCl, CaCl_2 , NaOH, HCl and captan were applied in various combinations with Apogee as potential adjuvants, water conditioners, effectors, or to adjust pH (Table 2). On 26 June, 10 of the longest scaffold shoots were tagged around the periphery of each tree and their lengths were measured. During dormancy, these 10 scaffold shoots were removed and the basal diameters and shoot lengths were recorded. In addition, the nodes/cm of the basal 40 cm and nodes/cm of the upper 30 cm of shoots were recorded. Trees were pruned and the total length of the shoots longer than 30 cm, the weight and time required to prune, the number of cuts, and the pruning weights/ cm^2 TCSA per tree were recorded.

Expt. 3. In 2001, 78 six-year-old 'Fuji'/M.9 trees (six blocks) were selected for 13 treatments (Table 3). P-Ca formulations [Apogee 27.5% a.i. P-Ca) or technical pro-hexadione-calcium (93.2% a.i. P-Ca)] were applied at 125 $\text{mg}\cdot\text{L}^{-1}$ P-Ca in three applications to the same trees at FB+7, FB+28, and FB+59

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Table 1. Effect of P-Ca, adjuvants, and nutrient sprays on shoot growth of 'Fuji'/M.9 applied in 1999.^z

Treatment ^y	P-Ca formulation (mg·L ⁻¹)	Added chemicals					June 1999	Dec. 1999			
		Regulaid	Oil	Silwet L-77	CaCl ₂	(NH ₄) ₂ SO ₄	Shoot length (cm)	Shoot length (cm)	Shoot wt (g)	Basal diam (cm)	Cuts/tree
							scaffold ^x	scaffold ^w	scaffold ^w		
1.	No treatment	—	—	—	—	—	51.7 a	53.0 a	10.6 a	0.712 a	75.6 a
2.	BAS 125 (10%)	+	—	—	—	—	36.2 c	37.1 ef	7.3 b-d	0.672 a-d	64.1 ab
3.	BAS 125 (10%)	—	+	+	—	—	32.6 c	33.4 f	5.8 d	0.573 de	63.1 ab
4.	Apogee (27.5%)	—	—	—	—	—	43.6 b	46.7 bc	9.4 a-c	0.669 a-d	66.1 ab
5.	Apogee (27.5%)	+	—	—	—	—	36.3 c	36.9 ef	6.4 cd	0.604 a-e	62.7 ab
6.	Apogee (27.5%)	—	+	+	—	—	34.5 c	34.1 f	5.7 d	0.557 e	60.1 b
7.	Apogee (27.5%)	—	—	—	+	—	46.9 ab	49.7 a-c	9.2 a-c	0.696 ab	67.6 ab
8.	Apogee (27.5%)	—	—	—	—	+	32.1 c	31.4 f	5.1 d	0.586 c-e	59.9 b
9.	Apogee (27.5%)	—	—	—	+	+	35.0 c	35.6 ef	6.7 cd	0.647 a-e	62.0 ab
10.	Apogee (27.5%)	+	—	—	+	—	44.1 b	44.9 cd	7.5 b-d	0.632 a-e	66.0 ab
11.	Apogee (27.5%)	+	—	—	—	+	31.2 c	32.5 f	6.6 cd	0.654 a-e	61.1 b
12.	Apogee (27.5%)	+	—	—	+	+	36.1 c	40.3 de	9.2 a-c	0.692 a-c	62.3 ab
13.	Apogee (27.5%)	—	+	+	+	+	33.1 c	32.0 f	5.4 d	0.589 b-e	64.6 ab
14.	Apogee (27.5%)	—	+	+	+	—	43.2 b	44.1 cd	7.4 b-d	0.607 a-e	58.0 b
15.	Apogee (27.5%)	—	+	+	—	+	31.5 c	32.2 f	6.4 cd	0.645 a-e	61.7 ab
16.	0	+	—	—	+	+	47.1 ab	51.5 ab	10.0 ab	0.680 a-d	66.3 ab
17.	0	—	+	+	+	+	47.8 ab	49.7 a-c	9.3 a-c	0.710 a	64.4 ab
Contrasts		Comparisons					Pr>F ^v	Pr>F	Pr>F	Pr>F	Pr>F
2, 3 vs. 5, 6		BAS 125 10% vs. Apogee 27.5%					NS	NS	NS	NS	NS
2, 5, 12 vs. 3, 6, 13		Regulaid vs. Oil + L-77 (+Apogee)					*	**	**	**	NS
4, 5, 6 vs. 7, 10, 14		CaCl ₂ vs. none (+Apogee)					***	***	NS	NS	NS
4, 5, 6 vs. 8, 11, 15		(NH ₄) ₂ SO ₄ vs. none (+Apogee)					***	***	NS	NS	NS
7, 10, 14 vs. 8, 11, 15		CaCl ₂ vs. (NH ₄) ₂ SO ₄ (+Apogee)					***	***	**	NS	NS
7, 10, 14 vs. 9, 12, 13		CaCl ₂ vs. CaCl ₂ + (NH ₄) ₂ SO ₄ (+Apogee)					***	***	NS	NS	NS

^zFull bloom occurred 30 Apr. 1999. Treatments were applied at PF, PF+21, PF+42 d with a low pressure hand-wand sprayer.^yConcentrations (mg·L⁻¹): P-Ca = 125 mg·L⁻¹; CaCl₂ = 1.8 g·L⁻¹; (NH₄)₂SO₄ = 1.8 g·L⁻¹; Regulaid = 1.257 mL·L⁻¹; Oil = 2.514 mL·L⁻¹; Silwet L-77 = 0.314 mL·L⁻¹.^xFour longest scaffold shoots (15 June 1999).^wFive longest scaffold shoots (16 Dec. 1999).NS, *, **, *** Nonsignificant or significant at $P \leq 0.05, 0.01, 0.001$, respectively.Table 2. Effect of P-Ca (three applications) on shoot growth of 'Fuji'/M.9 applied in 2000 and return bloom in 2001.^z

Treatment ^y	Apogee (27.5% P-Ca)	Added chemicals	Special sprays	pH of mix	June 2000	Dec. 2000			Apr. 2001
					Shoot length (cm) scaffold ^x	Length (cm) scaffold ^w	Basal diam (mm)	Cuts/cm ² /tree	Return bloom (% visual spurs flowering)
1. Control	—	---		---	56.5 ab ⁱ	76.3 a	12.0 ab	82.0 ab	70.7 bc
2.	+	---		7.9	43.5 cd	69.8 a	11.4 ab	65.3 b-d	70.7 bc
3.	+	(NH ₄) ₂ SO ₄		7.6	34.8 e-g	66.3 a	11.5 ab	58.4 cd	83.6 ab
4.	+	Urea		7.8	47.6 cd	75.8 a	12.1 ab	77.9 a-c	72.9 bc
5.	+	(NH ₄) ₂ SO ₄ + Regulaid		7.7	34.3 e-g	64.8 a	10.8 b	57.6 cd	83.3 ab
6.	+	(NH ₄) ₂ SO ₄ + Oil		7.5	31.0 gh	75.4 a	11.4 ab	68.9 a-d	67.1 bc
7.	+	Choice + LI-700		4.7	32.4 f-h	74.7 a	11.4 ab	60.6 b-d	80.7 ab
8.	+	(NH ₄) ₂ SO ₄ + Silwet L-77		7.6	30.7 gh	75.0 a	11.5 ab	57.0 cd	71.4 bc
9.	+	NaCl		7.6	40.3 d-f	66.6 a	11.0 ab	59.4 b-d	77.9 a-c
10.	+	KCl		7.6	45.5 cd	78.0 a	12.0 ab	74.7 a-c	73.3 bc
11.	+	CaCl ₂		7.6	50.6 bc	72.1 a	11.9 ab	73.0 a-d	73.6 bc
12.	+	(NH ₄) ₂ SO ₄ + Regulaid + CaCl ₂	Tank mixed (High rate NH ₄ SO ₄)	7.4	34.1 e-g	77.9 a	11.7 ab	68.9 a-d	74.3 a-c
13.	+	(NH ₄) ₂ SO ₄ + Regulaid + CaCl ₂	Tank mixed (Low rate NH ₄ SO ₄)	7.5	45.8 cd	78.7 a	11.9 ab	66.4 a-d	73.6 bc
14.	+	Regulaid+CaCl ₂		7.5	48.9 b-d	74.3 a	11.5 ab	63.0 b-d	67.9 bc
15.	+	CaCl ₂ + Regulaid	Post-trt ^v	7.5	50.4 bc	81.0 a	12.3 ab	74.8 abc	72.9 bc
16.	+	CaCl ₂ + Regulaid	Pre-trt ^u	8.0	41.9 c-e	71.8 a	11.2 ab	58.6 cd	79.3 a-c
17.	+	(NH ₄) ₂ SO ₄ + HCl	Acidic pH = 4.0	3.9	30.6 gh	66.9 a	11.0 ab	61.1 b-d	78.6 a-c
18.	+	(NH ₄) ₂ SO ₄ + Na OH	Basic pH = 9.0	8.9	31.1 gh	74.0 a	11.5 ab	61.6 b-d	77.9 a-c
19.	+	(NH ₄) ₂ SO ₄ + Regulaid + Captan		7.6	32.8 f-h	68.0 a	11.0 ab	56.6 cd	76.1 a-c
20.	+	(NH ₄) ₂ SO ₄ + Regulaid + Ethephon		6.3	24.6 h	67.1 a	10.9 ab	50.9 d	90.0 a
21.	—	Regulaid + CaCl ₂ + (NH ₄) ₂ SO ₄		7.4	63.4 a	82.2 a	12.7 a	87.9 a	63.6 c

^zFull bloom occurred 16 Apr. 2000. Treatments were applied at PF, PF+21, PF+42 days with a low pressure hand-wand sprayer.^yConcentrations: Apogee (P-Ca) = 125 mg·L⁻¹ (P-Ca); CaCl₂ = 0.454 g·L⁻¹; (NH₄)₂SO₄ = 1.8 g·L⁻¹ (trt 12 only); 0.454 g·L⁻¹ (all other trts); Regulaid = 1.25 mL·L⁻¹; Oil = 2.50 mL·L⁻¹; Silwet L-77 = 0.31 mL·L⁻¹; NaCl = 0.454 g·L⁻¹; KCl = 0.454 g·L⁻¹; Li-700 = 1.25 mL·L⁻¹; Choice = 1.25 mL·L⁻¹; Urea = 0.454 g·L⁻¹; Captan = 2.40 g·L⁻¹; Ethephon = 270 mg·L⁻¹.^xAverage length 10 longest scaffold shoots (26 June 00).^wAverage length and weight of 10 longest scaffold shoots (5 Dec. 2000).^vTreated day after regular spray.^uTreated day of spray and allowed to dry before addition spray treatment was applied.ⁱMean separation in columns by Duncan's New Multiple Range Test; $P \leq 0.05$.

Table 3. Effect of P-Ca (three applications) on shoot growth of 'Fuji'/M.9 applied in 2001.²

Treat- ment ³	P-Ca formulation		Added chemicals	Spray water deionized well	Water ^x hardness ppm (gpg)		pH of mix		July 2001	Dec. 2001					Apr. 2002
	Technical 93.2%	Apogee 27.5%			Pre- mix	Post- mix	Pre- mix	Post- mix	shoots length (cm) ^w	Scaffold shoot length (cm) ^v	Growth after 13 July (%)	Wt (g) ^v	Basal diam (mm)	Pruning cuts /tree	Return bloom (% visual spurs flowering)
1.	—	—	—	—	—	—	—	—	65.3 ab	74.5 a-c	11.5 d	22.4 a-d	9.06 ab	91.8 a	3 e
2.	+	—	—	+	—	—	—	5.4 6.2	48.7 de	70.0 a-c	26.7 a-d	25.3 a-c	9.65 ab	72.0 b	14 b-e
3.	+	—	(NH ₄) ₂ SO ₄	+	—	0(0)	50(3)	5.4 6.3	33.4 gh	61.7 a-d	43.1 a	19.3 b-d	8.72 ab	67.0 b-e	5 e
4.	+	—	—	—	+	250(15)	250(15)	7.7 7.9	66.7 a	85.7 a	18.9 cd	35.4 a	10.42 a	90.2 a	12 c-e
5.	+	—	(NH ₄) ₂ SO ₄	—	+	250(15)	250(15)	7.7 7.9	42.5 ef	58.3 a-d	37.3 ab	23.9 a-c	9.57 ab	64.2 b-f	19 a-e
6.	—	+	Regulaid	—	+	250(15)	425(25)	7.7 7.9	45.8 e	59.0 a-d	30.0 a-c	26.8 a-c	10.06 ab	59.5 b-f	30 a-c
7.	+	—	(NH ₄) ₂ SO ₄	—	+	250(15)	250(15)	7.7 7.8	33.3 gh	62.6 a-d	44.0 a	23.8 a-c	9.08 ab	53.7 c-f	31 ab
8.	—	+	(NH ₄) ₂ SO ₄ +Regulaid	—	+	250(15)	425(25)	7.7 8.1	30.8 gh	49.9 cd	32.2 a-c	17.9 b-d	8.32 b	49.0 f	32 a
9.	—	+	CaCl ₂ +Regulaid	—	+	250(15)	425(25)	7.7 8.0	58.6 bc	83.1 ab	29.4 a-c	31.8 ab	10.24 ab	70.2 bc	15 a-e
10.	—	+	(NH ₄) ₂ SO ₄ +CaCl ₂ +Regulaid	—	+	250(15)	250(15)	7.7 7.7	33.0 gh	56.3 b-d	38.2 ab	15.8 cd	8.41 b	49.8 ef	14 b-e
11.	—	+	Solubor + Regulaid	—	+	250(15)	250(15)	7.7 8.6	55.8 cd	78.1 ab	23.8 b-d	32.5 ab	10.41 a	68.5 b-d	23 a-d
12.	—	+	MgSO ₄ +Regulaid	—	+	250(15)	425(25)	7.7 8.0	36.4 fg	59.6 a-d	35.9 a-c	17.8 b-d	8.79 ab	56.8 b-f	10 de
13.	—	+	Li 700 +Choice	—	+	250(15)	120(7)	7.7 4.9	27.0 h	38.9 d	26.7 a-d	8.6 d	6.59 c	52.2 d-f	7 de
Contrasts: 2, 4 vs. 3, 5	Comparisons: (NH ₄) ₂ SO ₄ vs. none (Apogee and P-Ca)								Pr>F ***	Pr>F *	Pr>F **	Pr>F NS	Pr>F NS	Pr>F **	Pr>F NS

²Full bloom occurred 23 Apr. 2001. Treatments were applied at PF (30 Apr.), 23 d APF (23 May), and 52 d APF (21 June), with a low pressure hand-wand sprayer.

³Concentrations: P-Ca = 125 mg·L⁻¹; Apogee = 125 mg·L⁻¹ (P-Ca); CaCl₂ = 2.4 g·L⁻¹; (NH₄)₂SO₄ = 2.4 g·L⁻¹ (trt 10 only), 0.454 g·L⁻¹ (all other trts); Regulaid = 1.25 ml/L; Oil = 2.514; Solubor = 1.20 g·L⁻¹; MgSO₄ = 6.0 g·L⁻¹; Li-700 = 1.25 mL·L⁻¹; Choice = 2.50 mL·L⁻¹.

⁴Water hardness was determined by dipping a Hach SofCHECK Water Hardness Test Strip into each mix with either deionized or well water. Guidelines for water hardness are as follows: soft = 0–60 ppm; moderate = 61–120 ppm; hard = 121–180 ppm; very hard = 180 ppm & over; (gpg) = grains per gallon: soft = 0–1; slightly hard = 1–3.5; moderately hard = 3.5–7.0; hard = 7.0–10.5; very hard = ≥10.5.

^wAverage length or percentage of 10 longest scaffold shoots (13 July 01).

^vAverage length and weight of 10 longest scaffold shoots (4 Dec. 01).

ns, *, **, ***Nonsignificant or significant at $P \leq 0.05, 0.01, 0.001$, respectively.

days. In addition, Regulaid, (NH₄)₂SO₄, Choice, LI-700, CaCl₂, Solubor (US Borax, Valencia, Calif.), and MgSO₄ were applied in various combinations as potential adjuvants, or water conditioners in deionized water or "hard" well water [well water tested at ≈425 mg·L⁻¹ Calcium ion equivalents (97% Ca and Mg salts)] as indicated in Table 3. Ten of the longest scaffold shoots were tagged around the periphery of each tree and their lengths were measured on 13 July. During dormancy, these 10 scaffold shoots were removed and the basal diameters and shoot lengths were recorded. In addition, the nodes/cm of the basal 40 cm and nodes/cm of the upper 30 cm of shoots were recorded. Trees were pruned and the total length of the shoots longer than 30 cm, the weight and time required to prune, the number of cuts, and the pruning weights/cm² TCSA per tree were recorded.

Expt. 4. In 2001, 24 ten-year-old 'Empire'/Mark trees (six blocks) were selected for four treatments (Table 4). P-Ca formulations [Apogee 27.5% a.i. P-Ca) or technical pro-hexadione-calcium (93.2% a.i. P-Ca)] were applied at 125 mg·L⁻¹ P-Ca in three applications to the same trees at FB+9, FB+30, and FB+64 d. In addition Regulaid, (NH₄)₂SO₄, and/or Solubor, were applied in various combinations to determine if fruit cracking would occur (Table 4). On 19 July, 10 of the longest scaffold shoots were tagged around the periphery of each tree and their lengths were measured.

Results and Discussion

Inhibition of shoot growth by P-Ca was potentiated by (NH₄)₂SO₄ in experiments conducted in 1999, 2000, and 2001 on Fuji/M.9 as measured by a suppression of scaffold shoot length, basal diameter, pruning weight (data not shown), and number of pruning cuts (Tables 1–3). The growth retardant diamazide suppressed shoot length in the year of application, but shoots grew longer the year after application and the basal diameter appeared to be increased and shoot weight unchanged in the year of application (Emerson and Byers, unpublished). Since the nature of diamazide growth suppression was not published, comparison of the shoot length, weight, and basal diameter cannot be compared to P-Ca. However, data reported here indicate that P-Ca shoot suppression was not more vigorous in the subsequent season, as may have been with diamazide; thus from one season's applications, P-Ca truly suppressed tree vigor (Byers and Yoder, 1999).

Expt. 1. In 1999, the addition of (NH₄)₂SO₄ (treatments 4, 5, and 6 vs. 8, 11, and 15) to the Apogee sprays using hard well water (high in Ca and Mg) improved efficacy by June 26. The 10% P-Ca (BAS 125W) and the 27.5% P-Ca (Apogee) formulations gave similar shoot growth suppression of scaffold shoot length by June 1999, when applied with Regulaid or Oil + Silwet L-77 (treatments 2 and 3 vs. 5

and 6, Table 1). The addition of CaCl₂ to the Apogee (P-Ca, 125 mg·L⁻¹) formulation caused poorer scaffold shoot inhibition (treatments 4, 5, and 6 vs. 7, 10, and 14), but the addition of (NH₄)₂SO₄ restored the effectiveness of the mixture (treatments 7, 10, and 14, vs. 8, 11, and 15). When using "hard" well water, Apogee plus (NH₄)₂SO₄ promoted better activity (treatments 4, 5, and 6 vs. 8, 11, and 15). The additives, (NH₄)₂SO₄, CaCl₂, Regulaid, or Oil plus Silwet L-77, alone had no effect on scaffold shoot growth (1 vs. 16; 1 vs. 17). Apogee plus Silwet L-77 plus Oil provided additional shoot growth suppression when compared to Apogee plus Regulaid (treatments 2, 5, and 12 vs. 3, 6, and 13).

In 1999, scaffold shoot length grew little from June to December because tree carried a full crop of fruit. Although shoot lengths were significantly reduced for most all Apogee treatments, the basal diameters and the number of cuts required to prune the tree did not show the degree of growth suppression as did scaffold shoot length.

From a 10-fruit sample from each tree for treatments 1 and 11, Apogee + (NH₄)₂SO₄ + Regulaid did not affect fruit diameter, length/diameter ratio, fruit firmness, SSC, starch fruit color, or fruit weight. Trees were thinned to about the same crop load 30 d after bloom (data not shown). No differences in fruit set were found.

Expt. 2. In 2000, the addition of (NH₄)₂SO₄

Table 4. Effect of P-Ca (3 applications) on shoot growth of 'Empire'/Mark applied in 2001^a.

Treat- ment ^y	Prohexadione calcium		Added chemicals	Spray water deionized well		Water hardness ^x ppm (gpg)		pH of mix		Fruit/cm ² trunk cross- sectional area ^w	Oct. 2001		Apr. 2002	
	93.2%	27.5%				Pre- mix	Post- mix	Pre- mix	Post- mix		Cracked fruit		Average single fruit wt	Return bloom (%)
											% fruit /tree	# fruit /tree	fruit wt (g)	visual spurs flowering)
1.										7.21 a ^v	7 b	14.4 ab	140 a	29 a
2.	+	-	-	-	+	0 (0)	0 (0)	5.4	6.7	6.30 a	7 b	13.3 ab	155 a	46 a
3.	-	+	(NH ₄) ₂ SO ₄ +Regulaid	-	+	250 (15 gpg)	250 (15 gpg)	7.5	7.9	4.90 a	21 a	22.8 a	149 a	37 a
4.	-	+	Solubor +Regulaid	-	+	250 (15 gpg)	250 (15 gpg)	7.5	8.6	4.54 a	9 b	9.3 b	150 a	32 a

^aFull bloom occurred 17 Apr. 2001. Treatments were applied at 26 Apr., 17 May, and 22 June with a low pressure hand-wand sprayer.

^xConcentrations (mg·L⁻¹): PHCA = 125 mg·L⁻¹; Apogee = 125 mg·L⁻¹; (NH₄)₂SO₄ = 0.454 g·L⁻¹; Regulaid = 1.25 mL·L⁻¹; Solubor = 1.20 g·L⁻¹.

^yWater hardness was determined by dipping a Hach Sofchek Water Hardness Test Strip into each mix with either deionized or well water. Guidelines for water hardness are as follows: soft = 0–60 ppm; moderate = 61–120 ppm; hard = 121–180 ppm; very hard = 180 ppm & over; (gpg) = grains per gallon: soft = 0–1; slightly hard = 1–3.5; moderately hard = 3.5–7.0; hard = 7.0–10.5; very hard = ≥10.5.

^wTotal fruit harvested.

^vMean separation within columns by Duncan's New Multiple Range Test ($P \leq 0.05$).

(treatment 2 vs. 3) or Choice + Li700 (treatment 2 vs. 7) to the Apogee sprays using hard well water (high in Ca and Mg) improved efficacy on 26 June; but the addition of Urea, NaCl, KCl, or CaCl₂ (treatment 2 vs. either treatments 4, 9, 10, or 11) to Apogee was no better than Apogee alone (Table 2). The addition of Silwet L-77 to (NH₄)₂SO₄ + Apogee further may not have improved efficacy (treatment 3 vs. 8). The addition of CaCl₂ to the (NH₄)₂SO₄ + Apogee spray was not detrimental to shoot growth suppression if a high rate of (NH₄)₂SO₄ (equivalent to the CaCl₂ rate w/w) was used (treatment 5 vs. 12). However, the addition of (NH₄)₂SO₄ at a low rate (equivalent to the Apogee rate w/w) to a tank mix of Apogee + (NH₄)₂SO₄ + Regulaid (treatment 5 vs. 13) efficacy was reduced. In addition, CaCl₂ applied before or after Apogee + Regulaid did not reduce efficacy in this experiment (treatment 14 vs. 15, 14 vs. 16). Adjusting the pH of the Apogee + (NH₄)₂SO₄ + Regulaid spray to either pH = 4 or pH = 9 did not affect efficacy (treatment 17 vs. 5, and 18 vs. 5). Tank mixing captan with Apogee + (NH₄)₂SO₄ + Regulaid did not cause foliage injury or affect efficacy (treatment 19 vs. 5). The addition of ethephon at 270 mg·L⁻¹ improved the growth suppression of Apogee + (NH₄)₂SO₄ + Regulaid (treatment 20 vs. 5). The additives Regulaid + CaCl₂ + (NH₄)₂SO₄ alone (treatment 21 vs. 1) did not cause shoot growth suppression or injury.

Data taken 5 Dec. 2000 on the average shoot length of the 10 longest shoots tagged on 26 June, showed no shoot inhibition by any of the Apogee sprays (Table 2); however, pruning cuts/cm² TCSA reflected similar growth suppression to shoot length data taken on 26 June. Those trees inhibited most by the treatments (based on the 10 tagged shoots on 26 June) also grew the most from 26 June to 5 Dec. 2000. Tagging the strongest shoots on the tree for measurements ignored less vigorous shoots that were reflected by the pruning cut data. Regrowth was probably related to no crop existing on the trees in this experiment. This was in contrast to Expt. 1, which had a full crop and did not have a significant regrowth.

Ethephon tank mixed with Apogee + (NH₄)₂SO₄ + Regulaid (treatment 20) promoted additional suppression of shoot growth.

Numerically shoot length, shoot diameter, and pruning weights were reduced more than any other treatment, and it was the only treatment to significantly increase return bloom.

Expt. 3. In 2001, prohexadione-calcium technical grade (93.2% P-Ca) applied at 125 mg·L⁻¹ to 'Fuji'/M.9 trees in three applications in deionized water reduced shoot growth by June 2001 (treatment 1 vs. 2), and the addition of (NH₄)₂SO₄ to P-CA further suppressed shoot growth (treatment 2 vs. 3) (Table 3). However, if P-CA was mixed in well water (250 mg·L⁻¹ hardness), P-CA did not suppress shoot growth (treatment 2 vs. 4). Apogee (27.5% a.i., +72.5% (NH₄)₂SO₄ in the formulation) + Regulaid in well water was not as effective as simply adding more (NH₄)₂SO₄ (treatment 6 vs. 7); however, the Regulaid may have had some additional influence, but not statistically (treatment 7 vs. 8). If CaCl₂ was added, the calcium completely inhibited the effect of the Apogee + Regulaid (treatment 6 vs. 9); but if (NH₄)₂SO₄ was added at the same rate (w/w), the effectiveness was completely restored (treatment 9 vs. 10). When Solubor was added to Apogee + Regulaid, effectiveness was compromised (treatment 6 vs. 11), but MgSO₄ did not (treatment 6 vs. 12). Apogee + Li-700 + Choice, a commercial water conditioner, numerically was the most effective treatment (treatment 13). Choice, among other ingredients, has (NH₄)₂SO₄ in the formulation. In the dormant season, additional measurements were taken to document the amount of re-growth after 13 July. The amount of growth after 13 July was inversely related to amount of growth suppression from April to July. Nontreated trees that grew the most in the early season had the least amount of growth after 13 July. This was probably related to no crop existing on the trees in this experiment in contrast to Expt. 1 where a full crop may have greatly reduce re-growth after July.

Expt. 4. In 2001, Prohexadione-calcium [formulated as 27.5% P-Ca (Apogee) or the technical PHCA (93.2% P-Ca)] applied at 125 mg·L⁻¹ to 'Empire'/Mark trees in three applications at FB+9, FB+30, and FB+64 d in deionized water did not reduce tree growth (data not shown) due to heavily cropping trees. Only the combination of Apogee + (NH₄)₂SO₄ + Regulaid caused fruit cracking (21%; treatment

3) as compared to in the control (Table 4, treatment 1 = 7%). Data from Expts. 1–3 suggest that this combination was more effective as a result of increased absorption or activation of P-Ca; thus, the cracking of 'Empire' may be related to a higher concentration of P-Ca in the fruit or the tree.

Conclusions

The past three seasons' experiments support the benefit of adding additional (NH₄)₂SO₄ to the Apogee formulation [27.5% P-Ca + 72.5% (NH₄)₂SO₄] sprays, especially when using high calcium content well water. However, since (NH₄)₂SO₄ improved Apogee efficacy in deionized water, the additional benefit of (NH₄)₂SO₄ to all water sources may be important to maximizing efficacy. Ammonium sulfate is used to improve the uptake of many herbicides (Kapusta, 1996). Scanning electron micrographs of spray deposits of glyphosate + CaCl₂ showed an amorphous, thick, and non-crystalline deposit which may act to physically entrap glyphosate. When ammonium sulfate is added, leaf contact, thickness, and crystalline content was correlated with increasing toxicity in the leaf surface of wheat, sunflower, and kochia (Nalewaja et al., 1992). However, the function of (NH₄)₂SO₄ may be to provide a more efficient cation (NH₄⁺ vs. Ca⁺⁺) for the prohexadion anion. In addition, NH₄ ions may increase the loading, transport, or both, of the P-Ca molecule to the site of GA inhibition by supplying a proton pump with sufficient inorganic energy (Harold, 1986; Sze et al., 1999). The adjustment of pH to 4 or to 9 (with HCl or NaOH) did not result in a change in Apogee response (Expt. 2). However, during drying, the pH of the spray/plant surface was not known. A different result may have been obtained if pH buffered solutions were used. Mixing of CaCl₂ with Apogee, in a beaker in the laboratory, did not produce a precipitate with well water or deionized water. For this reason, (NH₄)₂SO₄ probably affected P-Ca absorption, translocation, or both, to the site of GA synthesis.

Hardness of water is frequently referred to as Ca⁺⁺ concentration equivalents, but also may be referred to by the precipitation

of a soap with Ca^{++} or other cations, such as Mg^{++} . A water conditioner may change the precipitation properties of a calcium solution while not affecting the calcium concentration in the solution. When well-water "hardness" was increased by adding CaCl_2 to the Apogee spray solution, the growth inhibition properties of P-Ca was almost completely negated; however, MgSO_4 did not have the same effect as CaCl_2 . The addition of an equal weight $(\text{NH}_4)_2\text{SO}_4$ restored the P-Ca activity, but adding either NaCl or KCl to the spray did not influence P-Ca activity even though both are used in cation exchange water softeners. $(\text{NH}_4)_2\text{SO}_4$ may have had a direct effect on uptake and/or activity of the P-Ca molecule by substituting the NH_4^+ for Ca^{++} . The commercial water conditioner, Choice + LI-700 was also as effective as $(\text{NH}_4)_2\text{SO}_4$ + Regulaid for counteracting the effect of high calcium well water. Since Solubor also inhibited the activity of Apogee, additional studies on the nature of P-Ca absorption, translocation, and/or action could provide useful information for increasing efficacy of Apogee sprays.

The combination of ethephon + Apogee provided some additional suppression of shoot growth and increased flowering (Table 2). Since ethephon can cause fruit thinning during the period when P-Ca is recommended, either low ethephon rates must be chosen in the 40 d AFB or it should be applied only during the ethephon insensitive fruit thinning period

from ≈ 40 to 70 d AFB (1 June–15 July).

Shoot growth suppression by P-Ca in comparison to the control was considerably different between years (Expts. 1–3). Shoot inhibition measured 3 weeks after the last three sprays (in mid-June) appeared to be similar for the three experiments. However, in the latter half of the season, shoot growth was greatest in Expts. 2 and 3 when trees carried no fruit. The heavy crop load in Expt. 1 probably controlled shoot growth during the second half of the season. Soil moisture as affected by summer rain, humidity, and temperatures were different between the three seasons, but crop load was considered to be the primary factor leading to regrowth after the third P-Ca application.

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