‘D’Anjou’ Pear Shoot Growth and Return Bloom, but Not Fruit Size, Are Reduced by Prohexadione-Calcium

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Abstract. Prohexadione-calcium (P-Ca) was applied to ‘Anjou’ pear (*Pyrus communis* L.) trees in the lower and upper Hood River Valley (HRV), Oregon, to determine its effectiveness for managing the excessive vigor of ‘Anjou’ under different growing climates. Vegetative growth and development (weekly shoot growth rate, total annual extension growth, number of initiated shoots, internodal length, and number of nodes), yield (fruit number and fruit size), and return bloom dynamics were evaluated between 2010 and 2013. P-Ca consistently reduced shoot elongation by ≈40% in all years and at both sites when doses of 250 ppm were applied in early spring (i.e., ≈5 cm of annual shoot extension) compared with untreated trees. Shorter shoots were the result of both reduced internodal growth and fewer nodes. In the cooler, upper HRV, a single P-Ca application controlled shoot elongation for the entire season, but in the warmer, lower HRV, a second flush of growth was generally observed ≈60 days after the first application. A subsequent P-Ca application (250 ppm) provided added growth control in some instances. Yield was unaffected by P-Ca the season of application; however, in one year, an increase in fruit number indirectly led to reduced fruit size; otherwise, fruit size was unaffected by P-Ca. Postharvest fruit quality was not influenced substantially by P-Ca. Return bloom, however, was consistently reduced by P-Ca. Return yield, the year after P-Ca application (recorded in 2013 only), was reduced in proportion to the decrease in return bloom relative to untreated trees. In 2012, ethephon was also evaluated, alone or in combination with P-Ca. When applied on its own either once (150 ppm, 5-cm growth), or twice [150 ppm, 5-cm growth; 300 ppm, 57 days after full bloom (DAFB)], ethephon did not affect vegetative growth or yield components but did improve return bloom and return yield relative to other treatments; however, when combined with P-Ca, ethephon did not reverse reductions in return bloom or return yield induced by P-Ca. The most effective ethephon treatment for promoting flowering and return yield (300 ppm, 57 DAFB) was not tested in combination with P-Ca. We conclude that P-Ca is an effective tool for controlling vigor of ‘Anjou’ trees, but the decrease in return bloom requires additional investigation. Further work testing combinations of ethephon and P-Ca are warranted to optimize growth and productivity of ‘Anjou’ trees.

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The inherent, high vigor of commercial pear cultivars is not sufficiently controlled by the semidwarfing rootstocks currently available in the United States. A recent, 10-year performance evaluation of Pacific Northwest (PNW) pear cultivars on promising, semidwarfing rootstocks from international programs did not produce new candidates for the United States (Einhorn et al., 2013). Considerable research effort is ongoing to understand and develop dwarfing in the pear germplasm (Elkins et al., 2012); in the interim, new acreage will continue to be established at low to moderate tree densities because few options

exist to reduce inter- and intracanopy shading previously shown to limit fruit growth and productivity of pear (Einhorn et al., 2012; Garriz et al., 1998; Kappel and Neilsen, 1994). Although these plantings may cost less in the short term, they limit early returns and opportunities to improve harvest efficiencies in the future (i.e., low-density plantings require time to develop large, complex canopies to maximize space efficiency, which, in turn, are dependent on tall ladders for harvest). Alternative solutions to managing vigor of both new and established pear plantings are desperately needed.

The growth-controlling compound, P-Ca, has been shown to effectively manage vegetative growth in several tree-fruit crops, including pear (Asin et al., 2007; Costa et al., 2001, 2004; Elfving et al., 2002, 2003b; Rademacher et al., 2004; Smit et al., 2005), apple (*Malus ×domestica* Borkh.) (Byers and Yoder, 1999; Duyvelshoff and Cline, 2013; Greene, 1999; Owens and Stover, 1999; Unrath, 1999), and sweet cherry (*Prunus avium* L.) (Elfving et al., 2003a), but not peach (*Prunus persica* L.) (Byers and Yoder, 1999). In several cases, P-Ca markedly reduced the vigor of pear cultivars despite the growth-promoting influence of non-dwarfing rootstocks (Elfving et al., 2003b; Smit et al., 2005). Depending on cultivar and environmental conditions, plant response to P-Ca dose and application frequency varied (Costa et al., 2004; Elfving et al., 2002; Rademacher et al., 2004; Smit et al., 2005; Sugar et al., 2004; Unrath, 1999), illustrating a major limitation to extrapolating P-Ca results from one cultivar to another.

In the United States, P-Ca (trade-name Apogee®; BASF Corp., Research Triangle Park, NC) was initially labeled for use with pear, but substantial reductions in return bloom of ‘Bosc’ (Sugar et al., 2004) and reduced fruit size of ‘Bartlett’ (Elfving et al., 2003b; Sugar et al., 2004) resulted in the removal of pear from the label. ‘D’Anjou’ trees, on the contrary, did not exhibit notable, negative responses to P-Ca with respect to fruit growth, return bloom, or yield (Sugar et al., 2004). Moreover, P-Ca effectively reduced vegetative growth of ‘Anjou’ (Elfving et al., 2002). Of the commercially important pear cultivars currently produced in the PNW, ‘Anjou’ is by far the least precocious and most vigorous and, hence, would benefit the most by techniques that control vigor and/or impart early production. Our main objective, therefore, was to thoroughly evaluate the fruiting and vegetative growth responses of ‘Anjou’ to P-Ca in two distinct yet equally important regions of the HRV to determine if reconsideration of a specimen label solely for ‘Anjou’ pear was warranted.

Materials and Methods

Expt. 1 (2010–11). Trials evaluating different rates and timings of P-Ca on vegetative and reproductive growth of pear trees were performed in 2010 and 2011 at the Oregon State University’s Mid-Columbia Agricultural

Research and Extension Center (MCAREC) in Hood River, OR (lat. 45.7° N, long. 121.5° W) and in a commercial orchard in Parkdale, OR (lat. 45.53° N, long. 121.61° W). In Parkdale, 11-year-old 'Anjou'/OH × F 97 pear trees were selected from an orchard trained to a central-leader system (2.8 m × 4.6 m; 797 trees/ha). Trees at MCAREC were 9-year-old 'Anjou'/OH × F 97 (3.1 × 4.9 m; 672 trees/ha) trained to a multileader system. Solutions of P-Ca (Apogee; BASF Corp.) were prepared in water (pH 6.96) as ppm of active ingredient and supplemented with 0.1% (v:v) nonionic surfactant (Simulaid; Genesis AGRI Products Inc., Union Gap, WA). Solutions were applied to drip to entire primary scaffold limbs (one scaffold per tree) with a CO₂ pressurized hand gun sprayer (Model D Less Boom; Bellspray, Inc., Opelousas, LA).

Experimental units (scaffold limbs) were selected for uniformity of bloom and vegetative growth. Despite these general selection criteria, variability in scaffold size led us to block treatments on basal scaffold circumference, measured at 10 cm from the point of origin to the trunk. In 2010, three treatments were applied to five replicate scaffolds at the MCAREC: 1) control (water + surfactant); 2) P-Ca (125 ppm) applied once; and, 3) P-Ca (125 ppm) + P-Ca (250 ppm) when shoots resumed growth. In Parkdale, two treatments each with six replicates were compared: 1) control (water + surfactant) and 2) P-Ca (250 ppm) applied once.

In 2011, the trials were repeated at both sites on new scaffolds (i.e., different trees). Treatments differed from those applied in 2010 but were identical at both sites: 1) control (water + surfactant); 2) P-Ca (250 ppm)

applied once; 3) P-Ca (250 ppm) applied as needed when shoots resumed growth; and 4) P-Ca (250 ppm) applied every 30 d. The final application of Treatment 4 occurred before the start of the 45 d preharvest interval effective in the United States for apple.

In 2010 and 2011, shoot length was recorded weekly at both sites on ten 1-year-old shoots selected at a similar canopy height and position and tagged at the time of the first application. Shoot length was measured until shoot growth ceased. In the fall, the total

Fig. 1. Effect of 2010 prohexadione-calcium (P-Ca) treatments on 'Anjou' pear annual shoot growth at a lower (A) and higher elevation site (B) in the Hood River Valley, OR. Asterisk on the x-axis denotes time of first application for all treatments; dash above the x-axis denotes application timing of 250 ppm P-Ca for the P-Ca 125 ppm + 250 ppm treatment. Vertical bars represent SE.

Table 1. The effect of 2010 prohexadione-calcium (P-Ca) application rate on vegetative and reproductive processes of 'Anjou' pear limbs at a lower Hood River Valley site [Mid-Columbia Agricultural Research and Extension Center (MCAREC)] and an upper Hood River Valley site (commercial orchard, Parkdale) in Oregon.^z

Treatment	Annual vegetative growth			Fruiting			2011 Return Bloom	
	Total shoot length (cm·cm ⁻² LCA) ^y	Shoots (no./cm ² LCA)	Avg shoot length (cm)	Fruits (no./scaffold)	Yield (kg/scaffold)	Avg fruit wt (g)	Flowering spurs (%) ^x	Flowering 1-year-old shoots (%) ^w
<i>Lower Hood River Valley (MCAREC)</i>								
0 ppm + surfactant	83.1 a ^v	2.3	37.1 a	35	8.9	255.9	74 a	26.8 a
P-Ca 125 ppm (1×) ^u	61.7 ab	1.8	33.4 ab	38.6	10	255.7	57 ab	9.6 b
P-Ca 125 ppm + 250 ppm	41.1 b	1.6	25.9 b	28.2	7.5	270	49 b	5.3 b
<i>P > F</i>	0.0249	0.2221	0.0315	0.6595	0.7082	0.5717	0.022	0.0081
<i>Upper Hood River Valley (Parkdale)</i>								
0 ppm + surfactant	71.7 a	1.8	38.6 a	10	2.1	219	19.8	6.1 a
P-Ca 250 ppm (1×)	44.1 b	1.5	29.5 b	16	3.4	217.4	12.7	1.7 b
<i>P > F</i>	0.0239	0.2455	0.0123	0.1213	0.1271	0.8595	0.0787	0.0229

^zData are means of five and six replicates at MCAREC and Parkdale, respectively.

^yThe data are expressed as the total growth in centimeters per cross-sectional area (LCA) of scaffold. LCA was calculated from the circumference of the scaffold, 10 cm from its point of origin to the trunk.

^xThe total population of spurs from each scaffold treated in 2010 was observed for the presence or absence of flower clusters in Spring 2011. The data are expressed as the percentage of spurs per scaffold with flower clusters.

^wThe total population of shoots on selected scaffolds with measurable extension growth during 2010 was observed for the presence or absence of apical flower clusters in Spring 2011. The data are expressed as the percentage of 1-year-old shoots with flower clusters.

^vMeans were separated within columns by Fisher's protected least significant difference ($P < 0.05$), whereby means associated with different letters are significantly different.

^uApplication of 125 ppm P-Ca as Apogee (BASF Corp.) was applied to both P-Ca treatments at MCAREC "to drip" to entire scaffolds when new shoots had ≈5 to 10 cm of new growth. For the 125 ppm + 250-ppm treatment, 250 ppm P-Ca was applied when growth of shoots previously treated with 125 ppm had resumed. Application of 250 ppm P-Ca in Parkdale was applied when new shoot growth reached ≈5 to 10 cm.

number of shoots and their annual shoot growth per scaffold were determined and expressed as either the length or number of shoots/cm² of scaffold-limb cross-sectional area. Additionally, in 2011, individual nodes were counted on the total annual extension growth to estimate average internode length (cm) and number of nodes per centimeter of shoot length (nodes/cm).

Fruits were harvested at commercial timing, counted, and weighed. Harvests occurred on 10 Sept. 2010 (150 DAFB) and 18 Sept. 2011 (147 DAFB) at MCAREC and 5 Oct. 2010 (156 DAFB) and 15 Oct. 2011 (152 DAFB) at Parkdale. Return bloom was analyzed each year after the year of treatment from the total population of spurs and 1-year-old shoots on unpruned scaffolds; data are expressed as the percentage of the total population of fruiting spurs or 1-year-old extension shoots with flower clusters. Pruning was performed after measurement of return bloom. Full bloom occurred on 13 Apr. 2010, 24 Apr. 2011, and 21 Apr. 2012 at MCAREC and 2 May 2010, 16 May 2011, and 8 May 2012 at Parkdale.

Expt. 2 (2012). A trial to evaluate the timing of P-Ca and ethephon, separately and in combination, was established within the same MCAREC orchard described but to different trees. Trees were selected for uniformity of size (canopy volume) and then grouped within blocks based on trunk circumference. Solutions (ppm of active ingredient) of P-Ca and/or ethephon [Ethrel®; Bayer Crop-Science, Research Triangle Park, NC] were supplemented with 0.1% (v:v) non-ionic surfactant and applied to achieve uniform, complete coverage. A hydraulic pressurized handgun (300 psi) was used to apply treatments to whole canopies.

Single-tree replicates were distributed in a randomized complete block design with six replicates per treatment as follows: 1) control (unsprayed); 2) water + surfactant; 3) P-Ca (250 ppm) applied once; 4) P-Ca (250 ppm) applied twice; 5) ethephon (150 ppm) applied once; 6) ethephon applied twice (150 ppm first application + 300 ppm second application); 7) P-Ca (250 ppm) + ethephon (150 ppm) tank mixed and applied as a single application; and 8) P-Ca (250 ppm) + ethephon (150 ppm) applied twice; ethephon was mixed with both applications of P-Ca. Single application treatments (2, 3, 5, and 7) and the first application of multiple application treatments (4, 6, and 8) were applied when shoots were ≈5 cm long. For those treatments receiving two P-Ca applications (4 and 8), the second application was provided when shoot growth resumed. In Treatment 6, 300 ppm ethephon was applied at 57 DAFB.

Shoot length was recorded weekly on twelve 1-year-old shoots as described previously. In the fall, average internode length (cm) and number of nodes per centimeter of shoot length (nodes/cm) were calculated based on the length of shoots and number of nodes, respectively. One primary scaffold limb per replicate tree was selected before receiving treatment to estimate the total

number of new shoots and the total annual shoot growth of the tree (Forshey and Elfving, 1979).

Trunk and scaffold limb circumference were measured at 25 cm and 10 cm above the graft union and the trunk, respectively, at the inception of the trial and, again, when leaves abscised in the fall. In the spring, a minimum of 200 flower clusters was recorded on each replicate scaffold limb. After June drop, fruits on these scaffolds were counted and fruit set was expressed as the number of fruit per cluster. In accordance with commercial practices, 'Anjou' trees were not thinned. Full bloom occurred on 21 Apr. 2012 and 7 Apr., 2013, respectively.

Whole trees were harvested at commercial timing: 20 Sept. 2012 (152 DAFB) and 30 Aug. 2013 (145 DAFB). The total number of fruit per tree was counted. Fruits from pre-selected scaffolds were counted and weighed separately. Yield and average fruit weight were calculated and a distribution of fruit sizes was generated from individually weighed fruits (100 randomly selected fruit per canopy) and expressed as the number of fruits (less than 60, 60, 70, 80, 90, 100, 110, 120, 135, and greater than 135) per 20-kg commercial packed box. In 2012, fruit firmness (FF) was measured on 40 randomly selected fruit (20 each from the whole canopy and scaffold) at harvest. An additional 40 fruit per tree were immediately placed in regular air cold storage at -1 °C after harvest and analyzed at 3 and 4.5 months for determination of fruit quality attributes [FF; soluble solids concentration (SS); titratable acidity (TA); and

extractable juice (EJ)] according to methods described by Einhorn et al. (2012). EJ has previously been shown as a good ripening indicator (Chen et al., 1983). At each sampling period, a set of 10 fruit was analyzed immediately on removal from cold storage and an additional 10-fruit sample was analyzed after a ripening period of 7 d at 20 °C.

Statistical analyses were performed using the SAS system software (SAS 9.0; SAS Institute, Cary, NC). Data expressed as percentage or counts were transformed by arcsin [square root (n + 1)] and square root (n + 0.5) analysis, respectively. Regression analysis for the relationship between fruit growth and cropload was performed by PROC REG. Treatment means were compared using analysis of variance with PROC GLM and significance was tested at $P \leq 0.05$. Mean separation was determined by Fisher's protected least significant difference test.

Results

Expt. 1. In 2010, extension growth of 'Anjou' shoots treated on 28 DAFB with 125 ppm P-Ca was significantly reduced by 60 DAFB at the MCAREC (Fig. 1A). The slope of shoot growth for P-Ca-treated shoots between 44 and 60 DAFB, however, indicated limited growth suppression; therefore, a second application of P-Ca (250 ppm) was applied to one of the two P-Ca treatments at 60 DAFB (i.e., P-Ca 125 ppm + 250 ppm). Growth cessation persisted for ≈55 d after the second application. At the end of the season, P-Ca 125 ppm + 250 ppm shoots were

Fig. 2. Effect of 2011 prohexadione-calcium (P-Ca) applied once, twice or every 30 d on 'Anjou' pear annual shoot growth at a lower (A) and higher elevation site (B) in the Hood River Valley, OR. Asterisk on the x-axis denotes time of first application for all treatments; dashes above the x-axis denote successive 250 ppm P-Ca applications for the P-Ca 250 ppm 30-d treatment; plus symbol above the x-axis denotes the second application for the P-Ca 250 ppm (twice) treatment. Vertical bars represent SE.

≈15% shorter than Control shoots. Shoots treated only once with 125 ppm P-Ca, however, showed a marked growth phase between 90 and 120 DAFB and, ultimately, surpassed untreated shoots, although the difference between the treatments was not significant. 'D'Anjou' scaffolds in Parkdale received an initial application of 250 ppm P-Ca. The 3-week lag phase in bloom between the upper elevation Parkdale site and MCAREC afforded time to assess the growth response to 125 ppm P-Ca at MCAREC and alter the application rate at Parkdale accordingly. Shoot growth at Parkdale was suppressed for the entire season by 250 ppm P-Ca applied at 37 DAFB (Fig. 1B). P-Ca-treated shoots were ≈46% of control shoots after cessation of growth in late summer.

At MCAREC, scaffolds treated with P-Ca 125 ppm + 250 ppm had significantly less cumulative vegetative growth (total shoot growth and average length) than controls (Table 1). Vegetative growth on scaffolds treated once with P-Ca 125 ppm was intermediate but not significantly different from the other treatments. Shoot number, yield components (fruit weight and fruit number), and average fruit size were unaffected by P-Ca treatment. Return bloom on spurs treated with P-Ca 125 ppm + 250 ppm was significantly reduced ≈32% relative to controls, but not for spurs receiving only a single application of 125 ppm P-Ca. Flowering on 1-year-old shoots was markedly reduced by P-Ca, irrespective of dose.

At Parkdale, one application of 250 ppm P-Ca reduced total annual shoot length and average shoot length compared with the control (Table 1). The response of shoots to 250 ppm P-Ca in Parkdale was similar to that induced by the 125 ppm + 250 ppm P-Ca treatment at MCAREC (Table 1). P-Ca did not significantly reduce the number of shoots or the yield and size of fruit on Parkdale scaffolds. Return bloom of spurs was numerically reduced by P-Ca relative to controls, albeit nonsignificantly ($P = 0.0787$). The percentage of 1-year-old shoots with return bloom was significantly reduced by P-Ca.

In 2011, 'Anjou' growth at MCAREC and Parkdale was significantly lowest for shoots treated with 250 ppm P-Ca at 30-d intervals (Fig. 2A). At both sites, growth of shoots treated with P-Ca once (1×) was reduced to ≈70% of control shoots. Shoots treated a second time with P-Ca at MCAREC (2×) were not significantly shorter than shoots treated only once. The decision to delay the second P-Ca application of the 2× treatment at MCAREC until 89 DAFB was associated with the high variability of this population (as shown by SE bars), which limited detectable differences between the growth of 2×-treated shoots and those treated every 30 d before 89 DAFB. In Parkdale, extension growth ceased for the entirety of the season after the initial 250 ppm P-Ca application at 35 DAFB (Fig. 2B), as similarly observed in 2010. Consequently, a second P-Ca application

Table 2. The effect of 2011 prohexadione-calcium (P-Ca) application rate on vegetative and reproductive processes of 'Anjou' pear limbs at a lower Hood River Valley site [Mid-Columbia Agricultural Research and Extension Center (MCAREC)] and an upper Hood River Valley site (commercial orchard, Parkdale) in Oregon.^z

Treatment	Annual vegetative growth						Fruiting ^y			2012 return bloom		
	Total shoot length (cm·cm ⁻² LCA) ^s	Shoots (no./cm ² LCA)	Avg shoot length (cm)	Nodes (no./shoot)	Avg internode length (cm)	Nodes (no./cm shoot) ^w	Fruits (no./scaffold)	Yield (kg/scaffold)	Avg fruit wt (g)	Flowering spurs (%) ^v	Flowering 1-year-old shoots (%) ^u	
<i>Lower Hood River Valley (MCAREC)</i>												
Control	73.1 a ^t	2.4	29.9 ab	9 ab	3.2 a	0.3 b	44.8	9	201.3	53.5	40.2 a	
0 ppm + surfactant	72 a	2	35.9 a	10.5 a	3.1 a	0.3 b	43.7	8.9	209.2	55.5	28.5 ab	
P-Ca 250 ppm (1×) ^s	49.9 b	2.2	22.6 bc	8.1 b	2.6 b	0.36 a	52.3	10.6	199.7	31.8	4.2 c	
P-Ca 250 ppm (2×)	47.8 b	1.9	24.7 bc	8.2 b	2.6 b	0.34 a	51.7	10.9	209.8	39.8	15.2 bc	
P-Ca 250 ppm (every 30 d)	40 b	1.9	20.5 c	7.1 b	2.6 b	0.35 a	43.5	8.9	198.7	36.2	3 c	
<i>P</i> > <i>F</i>	0.0114	0.2168	0.0045	0.0392	0.0004	0.0022	0.9309	0.9132	0.7651	0.0592	0.0002	
<i>Upper Hood River Valley (Parkdale)</i>												
Control	55.4 a ^u	2	27.5 a	9.0 a	2.8 a	0.33 c	6.2	1.1	186.1	70.7	23.5	
0 ppm + surfactant	52 ab	2.2	23.4 a	8.1 a	2.7 a	0.35 bc	4	0.7	183.4	70.8	23.8	
P-Ca 250 ppm (1×)	37.2 b	2.3	16.7 b	6 b	2.6 a	0.36 b	7	1.2	174.9	65	13.3	
P-Ca 250 ppm (2×)	36.3 b	2.5	14.6 bc	5.8 b	2.3 b	0.4 a	5	0.8	164.4	57.7	17.5	
P-Ca 250 ppm (every 30 d)	19.8 c	1.7	11.4 c	4.8 b	2.2 b	0.42 a	3.7	0.5	143.2	63	14.8	
<i>P</i> > <i>F</i>	0.0007	0.3474	<0.0001	<0.0001	<0.0001	<0.0001	0.59	0.3704	0.1167	0.3653	0.3024	

^zData are means of five and six replicates at MCAREC and Parkdale, respectively.

^yFrost events in Nov. 2010 and Feb. 2011 resulted in significant flower mortality and low fruit set in Parkdale.

^xThe data are expressed as the total growth in centimeters per cross-sectional area (LCA) of scaffold. LCA was calculated from the circumference of the scaffold, 10 cm from its point of origin to the trunk.

^wThe number of nodes per cm of 2011 annual shoots from selected scaffolds.

^uThe total population of spurs from each scaffold treated in 2011 were observed for the presence or absence of flower clusters in Spring 2012. The data are expressed as the percentage of spurs per scaffold with flower clusters.

^vThe total population of shoots on selected scaffolds with measurable extension growth during 2011 were observed for the presence or absence of apical flower clusters in Spring 2012. The data are expressed as the percentage of 1-year-old shoots with flower clusters.

^zMeans were separated within columns by Fisher's protected least significant difference ($P < 0.05$), whereby means associated with different letters are significantly different.

^sThe first application for all 250 ppm P-Ca treatments as Apogee (BASF Corp.) was applied "to drip" to entire scaffolds when new shoots had ≈5 to 10 cm of new growth. For the 250-ppm (2×) treatment at MCAREC, P-Ca was applied when growth of shoots previously treated with P-Ca had resumed (89 d after full bloom). At Parkdale, the 250 ppm (2×) treatment was not applied as a result of the season-long control of shoot growth from the first treatment timing; however, the P-Ca every 30-d treatment was provided.

was not provided to limbs of the 2× treatment, as was performed at MCAREC.

The number of nodes per unit length of shoot was increased, and the total annual shoot length, average shoot length, and average internode length of shoots borne on scaffolds were all significantly reduced by P-Ca at both sites, the effect being numerically more pronounced with increasing application frequency although not always significantly (Table 2). The number of shoots initiated on scaffolds, however, was not influenced by P-Ca at either site. Yield characteristics (number of fruit, yield, and average fruit size) were also unaffected by P-Ca treatments at either site. Return bloom was numerically lower, albeit nonsignificantly, for spur populations of P-Ca-treated scaffolds relative to controls at both sites. Flowering on 1-year-old shoots was reduced by P-Ca compared with controls at both sites but only significantly at MCAREC.

Expt. 2. In 2012, P-Ca applied once, twice, or in combination with ethephon significantly reduced the growth of extension shoots compared with control shoots or shoots treated with only ethephon (Fig. 3). A second treatment of P-Ca on 87 DAFB resulted in significant but minimal additive growth regulation relative to a single application of P-Ca. Ethephon did not improve the growth control elicited by P-Ca when the two chemicals were combined.

Shoots from P-Ca-treated trees had more nodes per unit shoot length but fewer nodes and shorter internodal length than shoots from either untreated controls or ethephon-treated trees (Table 3). Scaffolds of trees treated with P-Ca alone or in combination with ethephon had significantly less total annual shoot growth than those of controls or ethephon-treated trees (Table 3). Ethephon did not affect the responses observed with P-Ca treatments when the two chemicals were combined. The number of shoots initiated on scaffold limbs was not altered by any of the treatments.

The number of fruits per tree was increased, albeit inconsistently, and in most

cases nonsignificantly by P-Ca, ethephon, or combination treatments relative to the controls. Yield was numerically higher for P-Ca treatments (alone or in combination with ethephon) and ethephon (applied once), but results were not significant ($P = 0.068$). Average fruit size was reduced by P-Ca treatments, alone or in combination with ethephon, and when ethephon was applied 57 DAFB compared with control treatments. Control and ethephon (applied once) yielded significantly more large fruits (size 60) and significantly fewer small fruits (size 100, 110, and 120) than P-Ca treatments or ethephon when applied at 57 DAFB. The negative effect on fruit size observed for P-Ca treatments compared with controls was attributed to the markedly higher number of fruit per tree. Ethephon, when applied at 57 DAFB, however, seemed to have a direct, negative effect on fruit size. When applied at 57 DAFB, ethephon-treated trees had the highest percentage of spurs with return bloom. P-Ca applied either once or twice reduced the percentage of spurs with return bloom relative to controls. Ethephon, in the presence of P-Ca, appeared to counteract the effect, but not when P-Ca was applied twice. Bloom of 1-year-old shoots was significantly and markedly reduced by treatment with P-Ca. Return yield followed a similar trend as return bloom; ethephon applied twice (150 ppm + 300 ppm) significantly improved yield, but P-Ca treatments significantly reduced yield relative to untreated trees. The improvement in return bloom from ethephon (when combined with P-Ca in the single application) did not translate to an improvement in return yield. Average fruit weight was inversely related to yield the year after treatments.

No clear trends were apparent in the post-harvest quality of fruits treated with P-Ca relative to control fruit (Table 4). Ethephon, when applied at 57 DAFB, resulted in higher TA and SS after 3 and 4.5 months of regular air storage relative to all other treatments. The relative increase in TA and SS of 57 DAFB-treated ethephon fruit compared with

other treatments remained after 7-d ripening periods.

Discussion

When scaffolds or entire canopies of 'Anjou' were treated with 250 ppm P-Ca early in the season (shoots ≈5 cm of new growth), we consistently observed a 32% to 39% decrease in the total annual vegetative growth (Tables 1 to 3). A trend toward greater control of growth when an additional P-Ca application was provided was evident. Similar reductions in shoot growth by P-Ca have been reported for several pear cultivars (Costa et al., 2004; Elfving et al., 2002, 2003b; Rademacher et al., 2004; Smit et al., 2005); however, in general, significant growth reductions in those studies were achieved primarily through multiple applications of P-Ca. Despite the relatively rapid metabolism of P-Ca in plant tissue (2 to 3 weeks; Evans et al., 1999), extension growth of 'Anjou' was effectively reduced for the entire season by a single P-Ca application, except when applied at 125 ppm (Fig. 1A). Initial application doses between 50 and 125 ppm have been effective for inhibiting shoot growth of apple (Duyvelshoff and Cline, 2013; Greene, 1999; Unrath, 1999) and pear (Costa et al., 2004; Smit et al., 2005), but the excessive vigor of 'Anjou' necessitated higher rates as similarly shown for 'Blanquilla' pear (Rademacher et al., 2004) and several inherently vigorous cultivars of sweet cherry (Elfving et al., 2003a). Elfving et al. (2002) proposed different P-Ca strategies based on the unique growth habits of pear cultivars under production in the PNW of the United States. Although we limited our study to 'Anjou', trees in the cooler, upper HRV only required a single application of 250 ppm P-Ca to achieve season-long control over extension growth (Figs. 1B and 2B), whereas effects from an equivalent P-Ca application (both timing and rate) to similarly aged trees in lower HRV did not persist beyond ≈60 to 70 d from the first application (Figs. 2A and 3).

Fig. 3. Effect of 2012 prohexadione-calcium (P-Ca) and ethephon treatments applied separately or in combination on 'Anjou' pear annual shoot growth at a low-elevation site in the Hood River Valley, OR. Asterisk on the x-axis denotes time of application for 150-ppm ethephon treatments and the first application of all P-Ca treatments; the x above the x-axis denotes the second application timing for both P-Ca 250 ppm (twice) treatments. Combination treatments (P-Ca and ethephon) were tank-mixed. Dash above the x-axis denotes the application of 300 ppm ethephon for the ethephon 150 ppm + 300-ppm treatment. Vertical bars represent SE.

Table 3. The effect of 2012 prohexadione-calcium (P-Ca) and ethephon application rate and timing on vegetative and reproductive processes of 'Anjou' pear trees and scaffolds at the Mid-Columbia Agricultural Research and Extension Center (MCAREC) in the lower Hood River Valley, OR.^z

Treatments	Annual vegetative growth										Fruiting			2013 return bloom		2013 production	
	Total shoot length (cm·cm ⁻² LCA) ^y		Shoots (no./cm ² LCA)	Nodes (no./shoot)	Avg internode length (cm)	Nodes (no./cm shoot) ^x	Fruiting		Flowering spurs (%) ^w	Flowering shoots (%) ^v	Yield (kg/tree)	Avg fruit wt (g)	Yield (kg/tree)	Avg fruit wt (g)			
	cm·cm ⁻² LCA ^y	cm·cm ⁻² LCA ^y					Fruits (no./tree)	Yield (kg/tree)									
Control	76.8 a ^u	2.2	22.6 a	2.5 a	0.44 b	266.8 c	72.9	273 a	47.6 bc	52.6 a	85.4 bc	261.2 bc	85.4 bc	261.2 bc			
0 ppm + surfactant	71.3 ab	2.1	21.9 a	2.4 a	0.43 b	296.8 bc	81.0	273.9 a	54 ab	42.8 a	88.5 bc	269.8 abc	88.5 bc	269.8 abc			
Ethephon 150 ppm (1×) ^t	82.1 a	2.2	22.3 a	2.4 a	0.43 b	357.5 abc	90.8	257.3 ab	52.9 ab	45.3 a	96.7 ab	260.2 bc	96.7 ab	260.2 bc			
Ethephon (2×) (150 ppm + 300 ppm)	80.5 a	2.7	22.7 a	2.3 a	0.49 b	323 bc	72.3	228.4 d	64.9 a	47.1 a	110.3 a	255.7 c	110.3 a	255.7 c			
P-Ca 250 ppm (1×)	50 bc	3.2	16.8 b	1.7 c	0.69 a	410.3 a	97.5	243.7 cd	30.4 d	10.2 bc	74.1 cd	271.5 abc	74.1 cd	271.5 abc			
P-Ca 250 ppm (2×)	36 c	2.9	15.5 b	1.6 c	0.72 a	345.3 abc	85.6	250.2 bc	25.6 d	14.4 bc	56.9 d	285.2 a	56.9 d	285.2 a			
P-Ca 250 ppm (1×) + ethephon 150 ppm (1×)	47.7 c	2.7	15.9 b	2 b	0.63 a	352.7 ab	85.5	239.2 bcd	44.7 bc	17.9 b	63.2 d	277.3 ab	63.2 d	277.3 ab			
P-Ca 250 ppm (2×) + ethephon 150 ppm (2×)	36.3 c	2.9	15.4 b	1.6 c	0.70 a	349.2 abc	84.8	243 bcd	33.6 cd	3.5 c	56.1 d	282.8 a	56.1 d	282.8 a			
P > F	<0.0001	0.1692	<0.0001	<0.0001	<0.0001	0.0473	0.068	0.0003	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0141			

^zData are means of six replicates.

^yThe data are expressed as the total growth in cm per cross-sectional area (LCA) of scaffold. LCA was calculated from the circumference of the scaffold, 10 cm from its point of origin to the trunk.

^xThe number of nodes per centimeter of current-season shoot growth. Data are taken from the 12-shoot population graphed in Figure 3.

^wThe total population of spurs from each scaffold treated in 2012 was observed for the presence or absence of flower clusters in Spring 2013. The data are expressed as the percentage of apical flower clusters in Spring 2013 (i.e., 1-year-old shoots). The data are expressed as the percentage of 1-year-old shoots with flower clusters.

^vThe total population of shoots on primary scaffolds with measurable extension growth during 2012 was observed for the presence or absence of apical flower clusters in Spring 2013 (i.e., 1-year-old shoots). The data are expressed as the percentage of 1-year-old shoots with flower clusters.

^uMeans were separated within columns by Fisher's protected least significant difference ($P < 0.05$), whereby means associated with different letters are significantly different.

^tAll treatments received their first application "to drip" to entire scaffolds on 20 d after full bloom when new shoots had ≈ 5 cm of new growth; P-Ca as Apogee® and ethephon as Ethrel®. For treatments P-Ca 250 ppm + ethephon 150 ppm and P-Ca 250 ppm (2×) + ethephon 150 ppm (2×), products were applied together. Ethephon at 300 ppm was applied 57 d after full bloom. The second application for both P-Ca 250 ppm (2×) treatments was applied on 87 d after full bloom.

Unrath (1999) observed dissimilar growth responses to P-Ca for 'Red Delicious' apple growing in either warm or cool climates; the cooler climate was associated with an early, enduring cessation of growth. These results underscore the importance of evaluating cultivars in the environments where they are produced.

In addition to exhibiting less extension growth, shoots treated with P-Ca had fewer nodes and shorter internodes compared with untreated shoots, mostly as a result of the inhibitory P-Ca effect over growth-active GA₁ (Evans et al., 1999), which is responsible for internode elongation (Owens and Stover, 1999). This modification to the development of shoots resulted in limbs with more nodes per centimeter shoot length, implicating a potential for increased future fruiting efficiency on a shoot basis. Shoot initiation, as a process, was unaffected by P-Ca in any of the trials.

P-Ca did not significantly alter fruit set of 'Anjou' in any of the seasons that it was applied (data not shown), as similarly demonstrated with other pear cultivars (Asin et al., 2007; Costa et al., 2001; Rademacher et al., 2004; Sugar et al., 2004), with the exception of a few cases in which a positive effect on fruit set was observed (i.e., 2012; Costa et al., 2004; Smit et al., 2005). 'D'Anjou' is a cultivar that would benefit from practices that increase fruit set. The potential for P-Ca to improve fruit set may be attributed to its interfering action on ethylene metabolism (Rademacher, 2000). A large body of literature implicates an essential role of ethylene in fruit abscission (see reviews by Baird Morrison and Webster, 1979; Bangerth, 2000). Retention of pear fruitlets after applications of aminoethoxyvinylglycine, an ethylene inhibitor, was markedly higher for 'Comice' (Lombard and Richardson, 1982), 'Abate Fetel', and 'Packham's Triumph' (Sanchez et al., 2011) and 'Anjou' (Einhorn, unpublished data) when timed between anthesis and 14 DAFB. The fact that fruit set is not unequivocally augmented in response to P-Ca treatment indicates the complexity of the process and the multiple factors that modulate it such as genotypic response/sensitivity to ethylene, hormonal balance, the preceding season's cropload, timing of P-Ca application, and environmental conditions before, during, and after applications (Stover and Greene, 2005).

Yield components (number and size of fruits) were affected by P-Ca in only 1 of 3 years (i.e., 2012). For this particular trial, P-Ca applied to whole canopies led to numerically higher and, in some treatments, statistically higher fruit numbers relative to untreated trees (Table 3). A negative relationship between cropload (fruit number/cm² trunk cross-sectional area) and final fruit size in 2012 ($R^2 = 0.37$; $P < 0.0001$) suggests that reduced fruit size and a lower percentage of fruit in large size classes (data not shown) were indirect consequences of a source:sink imbalance. In 'Rosemarie', increased fruit set induced by P-Ca, in part, led to decreased

Table 4. The effect of 2012 prohexadione-calcium (P-Ca) and ethephon application rate and timing on post-harvest “Anjou” pear fruit quality (FF = fruit firmness; EJ = extractable juice; SS = soluble solids concentration; TA = titratable acidity) immediately after 3 and 4.5 months of regular air cold storage (RACS) at -1°C and after a ripening period (RT) of 7 d at 20°C .^z

Treatment	EJ				EJ			
	FF (N)	(mL/100 g FW)	SS ($^{\circ}\text{Brix}$)	TA (%)	FF (N)	(mL/100 g FW)	SS ($^{\circ}\text{Brix}$)	TA (%)
3 months RACS								
Control	54.7	70.8 a ^y	13.9 bc	0.26 b	22.9	58.1	14.3 b	0.26 b
0 ppm + surfactant	53.5	70.3 ab	13.9 b	0.26 b	22.4	58.4	14.3 b	0.25 bc
Ethephon 150 ppm (1 $\times$) ^x	54.6	70.1 ab	13.6 bcd	0.26 bc	25.8	58.8	14.0 bc	0.25 bc
Ethephon (2 $\times$) (150 ppm + 300 ppm)	56.3	68.3 cd	14.6 a	0.30 a	23.2	56.8	15.0 a	0.30 a
P-Ca 250 ppm (1 $\times$)	55.0	68.8 c	13.3 cd	0.20 d	23.6	58.5	13.8 c	0.21 e
P-Ca 250 ppm (2 $\times$)	56.8	68.3 cd	13.3 d	0.23 cd	29.9	59.8	13.9 bc	0.24 bcd
P-Ca 250 ppm (1 $\times$) + ethephon 150 ppm (1 $\times$)	55.3	67.4 d	13.9 b	0.22 d	26.0	58.3	14.1 bc	0.23 cde
P-Ca 250 ppm (2 $\times$) + ethephon 150 ppm (2 $\times$)	55.5	69.0 bc	13.9 bc	0.22 d	21.3	57.9	14.1 bc	0.22 de
<i>P</i> > <i>F</i>	0.31	<0.0001	0.0006	<0.0001	0.2784	0.8646	<0.0001	<0.0001
4.5 months RACS								
Control	52.2	72.3 a	13.8 b	0.20 abc	12.2	56.6 a	13.8 bc	0.20 b
0 ppm + surfactant	51.2	71.8 ab	13.6 bc	0.19 bcd	12.6	56.0 ab	13.8 bc	0.21 ab
Ethephon 150 ppm (1 $\times$)	51.3	71.6 abc	13.4 bc	0.22 ab	12.0	53.5 abc	13.9 bc	0.19 bc
Ethephon (2 $\times$) (150 ppm + 300 ppm)	50.0	70.2 c	14.5 a	0.23 a	13.0	52.3 c	14.4 a	0.22 a
P-Ca 250 ppm (1 $\times$)	51.2	70.3 bc	13.4 bc	0.17 d	10.7	54.3 abc	13.4 c	0.17 d
P-Ca 250 ppm (2 $\times$)	54.2	70.4 bc	13.1 bc	0.20 abcd	13.4	54.2 abc	13.4 c	0.17 cd
P-Ca 250 ppm (1 $\times$) + ethephon 150 ppm (1 $\times$)	51.9	70.2 c	13.6 bc	0.17 cd	10.7	51.6 c	13.9 bc	0.18 cd
P-Ca 250 ppm (2 $\times$) + ethephon 150 ppm (2 $\times$)	51.3	71.0 abc	13.5 bc	0.20 abc	11.6	53.2 bc	13.9 b	0.17 d
<i>P</i> > <i>F</i>	0.1675	0.0514	0.0025	0.0123	0.0779	0.0326	0.0041	<0.0001

^zTreatments were applied at the Mid-Columbia Agricultural Research and Extension Center in the lower Hood River Valley, OR. Data are means of six replicates.

^yMeans were separated within columns by Fisher's protected least significant difference ($P < 0.05$), whereby means associated with different letters are significantly different.

^xAll treatments received their first application “to drip” to entire scaffolds on 20 d after full bloom when new shoots had ≈ 5 cm of new growth; P-Ca as Apogee[®] and ethephon as Ethrel[®]. For treatments P-Ca 250 ppm + ethephon 150 ppm and P-Ca 250 ppm (2 $\times$) + ethephon 150 ppm (2 $\times$), products were applied together. Ethephon at 300 ppm was applied 57 d after full bloom. The second application for both P-Ca 250 ppm (2 $\times$) treatments was applied on 87 d after full bloom. FW = fresh weight.

fruit size at harvest (Smit et al., 2005). Sugar et al. (2004), on the other hand, observed smaller fruit size in ‘Bartlett’, but not ‘Bosc’ or ‘Anjou’, the season of treatment, the effects of which appeared to be direct because ‘Bartlett’ fruit set was not simultaneously improved (i.e., no apparent carbohydrate deficits). Elfving et al. (2003b) suggested that high concentrations of P-Ca applied to ‘Bartlett’ trees during the fruit cell division period led to smaller fruit at harvest. It is unclear as to why ‘Bartlett’ fruit size would be more sensitive than other cultivars to P-Ca. Potentially the relatively short growing season of ‘Bartlett’ amplifies the early-season growth limitations associated with P-Ca. Fruit size is a function of both the number and size of cells, and despite limited evidence positively relating cell number to final fruit size in apple (Goffinet et al., 1995), late-season cultivars have a distinct advantage over early-season cultivars for compensatory growth through a markedly longer period of cellular expansion. Cumulative, seasonal fruit growth curves would be helpful to determine precisely when and to what degree fruit growth is compromised under these conditions. Reductions in the final fruit size of ‘Rosemarie’, an early-season cultivar, corroborate this argument but the lack of effects of P-Ca on fruit size of two other early-season cultivars, Early Bon Chretien and Flamingo, does not (Smit et al., 2005).

Return bloom of ‘Anjou’ was consistently, adversely impacted by P-Ca in all years, albeit not always significantly. These results contradict those of a previous report that evaluated the flowering response of ‘Anjou’ to P-Ca (Sugar et al., 2004) over multiple years and sites. Importantly, in 2012, the percent reduction of return bloom was similar to the decrease in return yield (relative to untreated trees) posing a potential barrier to the reconsideration of P-Ca for use on ‘Anjou’. Rademacher et al. (2004) showed that reduced return bloom of ‘Conference’ pear, induced by P-Ca, did not translate to lower yields. Indeed, remaining spurs of ‘Passe Crassane’ had higher fruit setting efficiency when pruning treatments reduced the number of spurs (flower clusters) per branch (Sansavini, 2002). The marked reduction of flowers borne on 1-year-old shoots would not be expected to substantially limit the production of ‘Anjou’ given the cultivar’s “type 2” spur-bearing habit (Sansavini, 2002), but the data were intriguing nonetheless. P-Ca may have more serious consequences on yield in the next season for cultivars that produce a significant proportion of their yield from tip bloom.

Ethephon, applied on its own, increased return bloom and return yield, especially when applied at 57 DAFB, a treatment timing meant to coincide with floral bud initiation of ‘Anjou’ (Westwood, 1993). Ethephon did

not, however, offset the adverse effects of P-Ca on return bloom, or yield, the year after combination treatments. These results may have been attributed to asynchrony in floral bud initiation and application timing (ethephon when used in P-Ca/ethephon combinations was either applied in early spring or both early spring and 87 DAFB) or a non-efficacious dose (both of the P-Ca/ethephon combination treatments comprised 150 ppm ethephon). Unfortunately, we were not able to combine a 57-DAFB ethephon application with P-Ca as a result of a limited number of trees. Such a combination should be evaluated to determine if ethephon can counteract the negative effects of P-Ca on return bloom and fruit set of ‘Anjou’. Improved vigor control from combinations of P-Ca and ethephon previously documented for apple (Byers et al., 2004; Duyvelshoff and Cline, 2013) and sweet cherry (Elfving et al., 2003a) was not observed for ‘Anjou’ (Fig. 3; Table 3).

Fruit quality of ‘Anjou’ after cold storage was unaffected by P-Ca. Costa et al. (2004) and Elfving et al. (2003b) found similar results for P-Ca-treated ‘Bartlett’ and ‘Abate Fetel’, respectively. Interestingly, fruit treated with 300 ppm ethephon at 57 DAFB had the highest SS and TA before and after ripening. Although this positive influence on key quality attributes may be of low priority to commercial producers, these fruit were likely of higher quality and may be more appealing

to consumers; however, we did not collect sensory evaluation data to support this.

Conclusion

Control of ‘Anjou’ tree vigor is a fundamental prerequisite for the development of moderate- to high-density orchard systems. P-Ca was effective at markedly reducing shoot elongation at multiple sites over several growing seasons. In one case, the added benefits of increased fruit set and yield were also observed. However, the consistent reduction in return bloom and its translation to lower return yields, not previously documented for ‘Anjou’, counteracts these benefits. The potential for ethephon to ameliorate the activity of P-Ca on return bloom and production requires further investigation. Optimization of these combinations could provide consistent cropping potential on small-statured trees.

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