Postbloom Thinning Response of ‘Bartlett’ Pears to Absciscic Acid

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Abstract. Postbloom thinning of ‘Bartlett’ pears (*Pyrus communis* L.) is required to produce fruit of commercially acceptable size. In the Pacific Northwestern United States, low temperatures during early stages of pear fruitlet development often limit the efficacy of commercial thinning compounds. Hand thinning, therefore, remains the standard crop load management practice. Chemical thinning protocols are necessary to reduce the cost and dependence on hand labor. The plant hormone absciscic acid (ABA) was evaluated over multiple years in several ‘Bartlett’ pear orchards. ABA was applied to whole canopies at variable rates (50–500 ppm) when fruit diameter was generally between 10 and 12 mm. In three of four trials, ABA thinned in a dose-dependent manner. The relative degree of thinning for a given dose, however, was inconsistent among trials. Trees treated with ABA had a higher proportion of blank and single-fruited spurs than the control. Net photosynthesis (P_n) of single leaves was reduced 75% to 90% within one day of ABA application but gradually returned to ≈80% of control levels within 7 days and fully recovered by ≈14 days. Slightly greater and longer lasting P_n inhibition occurred with increasing ABA dose. Fruit weight and return bloom generally increased with increasing ABA rate. Fruit quality, when measured, was unaffected by ABA treatments. Inconsistent thinning response with ABA may be attributed to environmental factors, biological factors, or both.

The west coast states CA, OR, and WA account for ≈97% of the U.S. fresh market ‘Bartlett’ pear crop (U.S. Department of Agriculture National Agricultural Statistics Service, 2016). About half of those pears are produced in the Pacific Northwest (PNW) where the cultural practice of hand thinning is

required to attain marketable fruit size. Over the past several decades, increasing costs and decreasing availability of labor have prioritized the development of alternative crop load management strategies (Wells et al., 1998). Both mechanical and chemical methods have shown potential to reduce or eliminate hand thinning of tree fruits. Recently, mechanical string thinner technology has been applied with varying success to peach, *Prunus persica* L. (Reighard and Henderson, 2012; Schupp et al., 2008), and apple, *Malus domestica* Borkh. (Ellis et al., 2010; Schupp and Kon, 2014). Seehuber et al. (2015) reported positive effects of mechanical thinning on crop reduction and fruit size of 0.4 × 4.0 m hedgerows of pear trees on ‘Quince A’ rootstock; however, the voluminous, three-dimensional canopies that comprise the vast acreage of pear in the PNW would likely impede machine access to blossom clusters. Furthermore, string thinning is injurious to spurs and shoots (Ngugi and Schupp, 2009) potentially predisposing pear trees to increased risk of fire blight (*Erwinia amylovora*) infection, although this

effect was not reported by Seehuber et al. (2015). Irrespective, chemical thinning approaches have been far more common for pear (Wertheim, 2000).

Thinning compounds differ with respect to their mode of action. Some chemicals applied around flowering [i.e., fish oil and lime sulfur (Yoder et al., 2009); ammonium thiosulfate (ATS) (Wertheim, 2000)] are caustic and primarily serve to damage tissues of reproductive organs. Bound and Mitchell (2002) reported significantly reduced fruit set of ‘Packham’s Triumph’ pear when ATS was applied at low concentrations (0.5% to 1.5%) at 20% and 50% of full bloom, with two applications improving the response. ATS concentrations of 3% were phytotoxic to other pear cultivars (Wertheim, 2000). Pears are generally thinned during postbloom developmental stages using chemicals that alter the source-to-sink ratio (Lakso et al., 2006) or hormonal balance (Bangerth, 2000). With the exception of ethephon, which is seldom used to thin pears, most of the hormone-like thinners are applied when fruit diameter is 10–12 mm. The cytokinin 6-benzyladenine (BA) is the most extensively used pear thinner throughout the world (Asin et al., 2009; Curetti et al., 2010; Dussi, 2011; Gimenez et al., 2009; Greene, 2012; Maas and van der Steeg, 2011; Theron et al., 2011; Wertheim, 2000). The auxin naphthalene-acetic acid (NAA) and its amide (NAD) also thin pears although results have been variable (Asin et al., 2009; Theron et al., 2011; Wertheim, 2000) and adverse effects such as induced premature ripening and reduced storage life of ‘Bartlett’ have been observed (Lombard and Grim, 1966). A critical drawback of BA and NAA/NAD is the relatively high temperature requirement for effective foliar penetration, uptake, and activity (Black et al., 1995; Edgerton and Haeseler, 1959; Luckwill and Lloyd-Jones, 1962; Wertheim, 2000). Thinning activity of BA was associated with temperatures >18 °C (Bubán, 2000). Foliar penetration of NAA was determined to increase 3-fold between 25 °C and 35 °C (Greene and Bukovac, 1971). Thus, predictable thinning outcomes can be difficult to achieve in cooler climates. Alternative thinning chemistries are needed.

Absciscic acid is a plant hormone associated with abscission and plant dormancy (Taiz and Zeiger, 2010). ABA also regulates stomatal aperture during periods of drought to prevent plant desiccation (Davies and Zhang, 1989). Exogenously applied ABA can mimic drought stress when soil moisture is nonlimiting (Correia et al., 1999). An obvious consequence of stomatal closure is reduced carbon fixation, which has been associated with improved thinner efficacy (Lakso, 2011; Lakso et al., 2006; Untiedt and Blanke, 2001). Thus, ABA may enhance fruit abscission by inducing a carbohydrate (CHO) deficit. ABA has also been associated with increased ethylene production and abscission of peach when treated at pit hardening (Giovannaz et al., 2015) and mature apples (Edgerton, 1971) but did not appear to

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explain ABA-induced pear fruitlet abscission when trees were treated 10 d after full bloom (dafb) (Einhorn and Arrington, 2017). Several researchers have sought to exploit these mechanisms to thin apple (Greene et al., 2011; McArtney et al., 2014) and pear (Greene, 2012). McArtney et al. (2014) reported reduced stomatal conductance (g_s), and by extension, P_n (Lakso, 1994), of apple leaves treated with ABA, although this was not always associated with thinning. Greene (2012) observed consistent thinning when ABA was applied to 'Bartlett' pear, both alone and in combination with BA. ABA (500 ppm) reduced control fruit set by 37%, 77%, and 99% when applied at full bloom, petal fall, and 10 mm diameter phenology stages, respectively (Greene, 2012). Because these experiments were all conducted in the Eastern United States, and may not apply to the PNW, our primary objective was to evaluate ABA performance as a postbloom thinner in a major pear-producing region of the PNW.

Materials and Methods

Planting material, treatments, and experimental design. Four experiments were carried out in three 'Bartlett' pear orchards in Hood River and Parkdale, OR, between 2012 and 2014. In all trials, concentrations of ABA (ProTone; Valent BioSciences, Walnut Creek, CA) were combined with a surfactant (Sil 100; Clariant Corp., Mount Holly, NC) at 0.1% (v:v) and applied to drip between ≈ 0600 and 1000 hr using a hydraulic, pressurized spray gun. Dilute handgun applications generally require greater spray volume per tree than

would be applied in a commercial application and may limit direct extrapolation of these results to commercial practices. Depending on the trial, ABA was applied between petal fall and 10–12 mm fruit diameter; actual dates varied according to forecasted precipitation and wind conditions. In each experiment, trees were pre-selected for uniformity of bloom and canopy size and then randomly assigned treatments. For all experiments, applications were made under calm conditions (i.e., wind speeds of <5 km·h⁻¹). All other production practices were performed according to industry standards.

Expt. 1. In 2012, an eighth-leaf 'Bartlett'/'OH × F 87' orchard (3 × 5 m; 666 trees/ha) was selected in Hood River, OR, at the Oregon State University Mid-Columbia Agricultural Research and Extension Center (MCAREC) (long. 45.68, lat. 121.51). Soil is a Van Horn fine sandy loam. Treatments were arranged in a randomized complete block design (RCBD) with four single-tree replications. Blocks comprised single rows and were separated by three guard rows. Within blocks (i.e., rows), treatment trees were separated by a minimum of one guard tree to reduce the risk of spray contamination. The following treatments were applied: 1) control, 2) deionized (DI) water + 0.1% (v:v) surfactant, 3) 125 ppm ABA, 4) 250 ppm ABA, and 5) 500 ppm ABA. Treatments were applied 21 dafb. No significant differences were observed between the control and control + surfactant for any of the measured parameters. Results, therefore, are only provided for the control. In all ensuing experiments, the water + surfactant treatment was omitted from the treatment

design. All ABA concentrations continued to be combined with 0.1% (v:v) surfactant.

Expt. 2. In 2013, an 18-year-old 'Bartlett'/'OH × F 97' pear orchard (2.5 × 5.5 m; 727 trees/ha) was selected in Hood River, OR, at the MCAREC. Soil is a Van Horn fine sandy loam. Treatments were arranged in an RCBD with four single-tree replications. Blocks comprised single rows and were separated by five guard rows. Within blocks (i.e., rows), treatment trees were separated by a minimum of one guard tree to reduce the risk of spray contamination. Treatments consisted of a control, 50, 100, 150, and 200 ppm ABA. Applications were made 22 dafb.

Expt. 3. In 2013, a 10th-leaf commercial 'Bartlett'/'OH × F 97' pear orchard (3 × 6 m; 556 trees/ha) was selected in Parkdale, OR (long. 45.29, lat. 121.34). Soil is a Hutson fine sandy loam. Treatment trees were confined to three rows and were arranged in a complete randomized design (CRD) with four replications, each comprising two trees. A minimum of one guard tree was maintained in all directions. The following treatments were applied: 1) control, 2) 50 ppm ABA, 3) 100 ppm ABA, 4) 200 ppm ABA, and 5) 400 ppm ABA. Applications were made 20 dafb.

Expt. 4. In 2014, a trial was established in the orchard described in Expt. 2 using trees not previously treated with thinning compounds. Treatments were arranged in an RCBD with four replications each comprising two trees. Blocks comprised single rows and were separated by five guard rows. Within blocks (i.e., rows), treatment trees were separated by a minimum of one guard tree to reduce the risk of spray contamination. The following treatments were applied: 1)

Table 1. Expt. 1. Effect of 2012 abscisic acid (ABA) applications (21 d after full bloom) on fruit set, number of fruit hand thinned, number of fruit harvested, yield, average fruit weight, and return bloom of eighth-leaf 'Bartlett'/'OH × F 97' pear trees (3 × 5 m; 666 trees/ha) at the Oregon State University Mid-Columbia Agricultural Research and Extension Center in Hood River, OR. Data are means of four single-tree replications.

ABA treatment (ppm)	Fruit set before hand thinning (no./tree)	Hand-thinned fruit (no./tree)	Fruit no. (fruit/tree)	Yield (kg/tree)	Mean fruit wt. (g)	Return bloom (% of control)
0	212 (100) ^z	88	158	69.1	213.7	100
125	135.5 (64)	30	128	59.1	218.6	95
250	19 (9)	1	17	8.2	230.3	103
500	0.3 (0)	0	0	0	n.d. ^y	122
Significance						
Linear	0.0113	0.0375	<0.001	<0.001	0.0481	0.0418
Quadratic	0.0459	0.0138	<0.001	<0.001	0.0204	NS ^x

^zPercent of control.

^yn.d. = no data because of no fruit at harvest.

^xNS = nonsignificant.

Table 2. Expt. 2. Effect of 2013 abscisic acid (ABA) applications (22 d after full bloom) on fruit set, number of fruit hand thinned, number of fruit harvested, yield, average fruit weight, and return bloom of 18-year-old 'Bartlett'/'OH × F 97' pear trees (2.5 × 5.5 m; 727 trees/ha) at the Oregon State University Mid-Columbia Agricultural Research and Extension Center in Hood River, OR. Data are means of four two-tree replications.

ABA treatment (ppm)	Fruit set (no. fruit/cluster)	Hand-thinned fruit (no./tree)	Fruit no. (fruit/tree)	Yield (kg/tree)	Mean fruit wt (g)	Return bloom (% of control)
0	0.56	32	254	54.1	212.5	100
50	0.74	72	277	64.3	231	81
100	0.61	51	227	50.2	220.2	102
150	0.55	30	240	58.1	241.6	87
200	0.72	69	257	59.5	229.5	97
Significance						
Linear	NS ^z	NS	NS	NS	0.0206	NS
Quadratic	NS	NS	NS	NS	NS	NS

^zNS = nonsignificant.

Table 3. Expt. 3. Effect of 2013 abscisic acid (ABA) applications (20 d after full bloom) on fruit set, number of fruit hand thinned, number of fruit harvested, yield, fruit weight, and return bloom of 10th leaf 'Bartlett'/'OH × F 97' pear trees (3 × 6 m; 556 trees/ha) at a commercial orchard in Parkdale, OR. Data are means of four two-tree replications.

ABA treatment (ppm)	Fruit set (no. fruit/cluster)	Hand-thinned fruit (no./tree)	Fruit no. (fruit/tree)	Yield (kg/tree)	Mean fruit wt (g)	Return bloom (% of control)
0	1.36	416.5	510	95.5	196.1	100
50	1.01	309.3	439	82.9	193.8	92
100	0.77	186.9	349	76.7	212.5	89
200	0.25	111.3	244	51.5	238.3	106
400	0.03	109.4	172	37.6	232.1	118
Significance						
Linear	0.0476	<0.001	<0.001	<0.001	<0.001	0.0437
Quadratic	NS ²	<0.001	<0.001	<0.001	<0.001	NS

²NS = nonsignificant.

Table 4. Expt. 4. Effect of 2014 abscisic acid (ABA) applications (8 d after full bloom) on fruit set, number of fruit at harvest, yield, average fruit weight, and return bloom of 19-year-old 'Bartlett'/'OH × F 97' pear trees (2.5 × 5.5 m; 727 trees/ha) at the Oregon State University Mid-Columbia Agricultural Research and Extension Center in Hood River, OR. Data are means of four two-tree replications.

ABA treatment (ppm)	Fruit set (no. fruit/cluster)	Fruit no. (fruit/tree)	Yield (kg/tree)	Mean fruit wt (g)	Return bloom (% of control)
0	0.75	494	96.8	199.2	100
50	0.7	458	91	198.5	144
100	0.64	450	85	188.6	136
200	0.59	480	92.5	192.4	181
400	0.41	379	78.6	208.8	168
Significance					
Linear	<0.001	0.0308	0.0342	NS ²	0.0468
Quadratic	<0.001	NS	NS	NS	NS

²NS = nonsignificant.

Table 5. The effect of 2014 abscisic acid applications on harvest and postharvest 'Bartlett' pear fruit quality. Postharvest analyses were performed after 60 d of regular air (RA) cold storage at -1 °C, >95% relative humidity and after a ripening period of 5 d at 20 °C. Data are means of four replications.

ABA treatment (ppm)	Harvest			60 d RA storage			60 d RA storage plus 5 d ripening		
	FF (kg)	SSC (%)	TA (%)	FF (kg)	SSC (%)	TA (%)	FF (kg)	SSC (%)	TA (%)
0	8.2	12.7	0.31	7.1	13.3	0.26	1.6	13.5	0.27
50	8.1	12.5	0.33	7.7	13.4	0.3	1.6	13.8	0.24
100	8.3	12.8	0.32	7.7	13.6	0.27	1.6	14.3	0.26
200	8	13.1	0.31	7.6	14.2	0.28	1.6	13.7	0.26
400	8.3	13.9	0.28	7.9	14.1	0.28	1.5	13.5	0.26
Significance									
Linear	NS ²	NS	NS	NS	NS	NS	NS	NS	NS
Quadratic	NS	NS	NS	NS	NS	NS	NS	NS	NS

FF = fruit firmness; SSC = soluble solids concentration; TA = titratable acidity.

²NS = nonsignificant.

Fig. 1. The effect of abscisic acid rate (0, 50, 100, 200, and 400 ppm) on the number of fruit retained per spur on 'Bartlett' pear limbs in Expt. 3. Measurements were taken 40 d after full bloom following natural fruit drop but before hand thinning. Data are means of four replications ($n = 4$ limbs, each with ≈ 40 spurs). Vertical bars are ± 1 SE.

control, 2) 50 ppm ABA, 3) 100 ppm ABA, 4) 200 ppm ABA, and 5) 400 ppm ABA. Applications were made 8 dafb.

Flowering and fruiting. For Expts. 2–4, four scaffold limbs per replication were selected at bloom. Scaffolds possessed a minimum of

40 clusters and provided ≈ 200 flower clusters for fruit set estimates per replication. After June drop (≈ 40 dafb), the number of fruit on each scaffold limb was counted and fruit set was expressed as the number of fruit per flower cluster. For Expt. 3, all spurs on selected scaffolds were further classified based on the number of fruit remaining at 40 dafb. In Expt. 1, flower clusters were not counted at bloom and fruit set was expressed as the number of total fruit per tree after June drop, but before hand thinning, relative to the control fruit set. For all experiments, trees were hand thinned, if necessary, between 40 and 50 dafb according to industry standards by reducing the number of fruit per flower cluster to one or two. In cases where thinning was excessive, hand thinning was still performed if greater than two fruit per cluster remained after June drop. The number of fruit removed by hand was recorded. Trees in Expt. 4 were not hand thinned. Tree yield was determined by weighing the total number of fruit harvested per tree in a single harvest when fruit reached commercial maturity [i.e., fruit firmness (FF) between 8.6 and 7.6 kg].

Average fruit weight was determined by weighing individual fruit from a random 50-fruit sample per replication. Return bloom was determined the year after treatment applications from the same limbs used to estimate fruit set by dividing the number of flower clusters counted per limb by the total number of spurs present on each limb. Because 'Bartlett' also fruits on terminal positions of 1-year shoots, the number of clusters per 1-year-old shoot was also determined, but these data were not included in the analysis because a limited number of shoots were observed per scaffold and their presence was inconsistent from limb to limb. Fruit set data were expressed as a percentage of control return bloom.

Fruit quality. Fruit quality attributes were measured in Expt. 4 only. Twenty fruit per replication were sampled at harvest and 30 fruit per replication were stored in regular air (RA) [-1 °C (± 0.5 °C), >95% relative humidity (RH)] for 60 d before postharvest evaluations. At all sample dates, FF was measured on two sites per fruit (opposite one another) using an automated penetrometer

(Fruit Texture Analyzer; Güss Manufacturing, Strand, South Africa) after removing a $\approx 5 \text{ cm}^2$ area of skin. Soluble solids concentration was determined using a digital refractometer (Model PR-101; ATAGO Co., LTD., Bellevue, WA). Titratable acidity (TA) was quantified using an automated titration system (Model DL15; Mettler-Toledo, LLC., Columbus, OH) by titrating a 10-mL juice sample in 10 mL of DI water to an endpoint pH of 8.1 with 0.1 N NaOH. For the postharvest evaluations, half of the fruit (15/rep) were assessed when fruit had warmed to room temperature after removal from RA. The remaining 15 fruit were ripened for 5 d at 20°C ($\pm 1^\circ\text{C}$) before evaluation.

Leaf gas exchange. Gas exchange [P_n ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$); g_s ($\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)] was quantified using a PP systems Ciras-2 gas analyzer (PP systems, Amesbury, MA) on fully expanded leaves in basal to mid positions of current season, extension shoots in Expts. 2 and 3. For each replication and sampling date, four randomly selected leaves from exterior positions of the canopy at a height of $\approx 1.5 \text{ m}$ were measured between 1200 and 1400 HR. Measurements occurred at ≈ 3 - to 4-d intervals. CO_2 was supplied to the cuvette at 385 ppm and measurements were recorded when leaf gas exchange reached steady state in the cuvette ($\approx 60 \text{ s}$). All measurements were made under near-saturated light levels (i.e., photosynthetically active radiation $> 1000 \mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$).

Solar radiation and temperature. Daily temperature and total incoming solar radiation ($\text{W}\cdot\text{m}^{-2}$) data were recorded at 15-min intervals and downloaded from the nearest weather stations to their respective orchard sites: For Expts. 1, 2, and 4, a meteorological station was located within 1 km of the trial sites (IFPNet); for the commercial orchard in Expt. 3, data were collected from a U.S. Bureau of Reclamation weather station (AgriMet) located $\approx 20 \text{ km}$ from the site. Diurnal curves were generated between -5 and $+10 \text{ d}$ from ABA application (dfa).

Statistical analyses. All statistical analyses were carried out in R-studio statistical platform. A mixed model (lm4 package) was used and blocking was assigned as a random effect. Both linear [lm() function] and quadratic [poly() function] models were tested and significance was reported at $P \leq 0.05$. Arccosine transformations for percent data were performed using Microsoft Excel (Microsoft Corporation, Bothell, WA) and back transformed for presentation.

Results

Flowering and fruiting. Application of ABA significantly reduced fruit set in three of the four trials (Tables 1–4). When ABA thinned, the effect was rate responsive. The severe thinning observed in Expt. 1 was explained better by a quadratic model, but generally thinning cropping responses were more strongly explained by the linear regression model. The degree of magnitude in thinning, however, was inconsistent

among trials for a given dose. For example, fruit set of 200 ppm ABA-treated trees after June drop differed markedly between trials producing drastic thinning in Expt. 3 but only slight thinning in Expt. 4 (Tables 3 and 4). The relatively light fruit set of control trees in Expt. 2 and Expt. 4 (roughly half that of Expt. 3) may have rendered chemical thinning more difficult. ABA rates $\geq 200 \text{ ppm}$ severely over-thinned, but in only two of the four trials (Expts. 1 and 3; Tables 1 and 3), resulting in fewer harvested fruit and lower yields despite hand thinning of control trees (Tables 1 and 3). At the spur level, ABA significantly increased the percentage of spurs with 0 or 1 fruit and decreased the proportion of spurs having ≥ 2 fruit compared with the control (Fig. 1). ABA did not thin fruit in Expt. 2, irrespective of rate. Subsequently, all treatment trees were minimally hand thinned and yield differences were not detectable at harvest (Table 2). When thinning was observed, fruit weight increased with increasing ABA rate (Tables 1 and 3), except in Expt. 4 (Table 4). In Expt. 2, fruit weight, like fruit set, was unaffected by ABA treatments (Table 2). ABA-induced thinning was generally associated with an increase in return bloom; however, significantly greater

return bloom tended to only occur when high ABA concentrations caused excessive thinning.

Fruit quality. Commercial harvest maturity of fruit was unaffected by ABA (determined by FF; data not shown). Fruit quality attributes at harvest and after 2 months of RA storage were not significantly affected by ABA, irrespective of rate (Table 5). ABA had no effect on fruit quality attributes after ripening, and all fruit were considered of fine eating quality (juicy and buttery texture), although a formal sensory evaluation was not performed.

Leaf gas exchange. ABA significantly lowered leaf P_n rate in Expt. 3 (Fig. 2A). Within hours from application, P_n was reduced 75% to 90% of control levels irrespective of concentration (Fig. 2A). Leaves treated with 50 and 100 ppm ABA recovered to $\approx 75\%$ of control levels by 4 d from application (dfa) and fully by 8 dfa. Conversely, trees treated with higher rates of ABA (i.e., 200 and 400 ppm) required 15–20 dfa to recover to control levels. In Expt. 2, P_n measurements were not recorded between 1 and 6 dfa because of instrument malfunction; however, on 6 dfa, P_n of leaves treated with 200 ppm ABA was significantly reduced from control levels by $\approx 20\%$ (Fig. 2B). By

Fig. 2. The effect of abscisic acid rate on photosynthesis (P_n) of 'Bartlett' pear leaves in Expt. 3 (A) and Expt. 2 (B). Measurements were taken at solar noon ($\pm 1 \text{ h}$). Data are means of four replications ($n = 4$). Vertical bars are $\pm 1 \text{ se}$.

day 13, P_n rates of all ABA treatments were $\geq 90\%$ of controls.

Solar radiation and temperature. Diurnal solar radiation patterns before and after ABA treatments differed drastically among trials (Fig. 3). Expt. 3 had the most days with reduced light compared with other experiments. Average daytime solar radiation was 40% to 50% of clear-sky conditions ($\approx 900 \text{ W}\cdot\text{m}^{-2}$) five of the 10 d following ABA applications, with the exception of a few sunbreaks. Expts. 1 and 4 had a similar number of cloudy days within the 10-d period following treatments but differed with respect to their occurrence relative to treatment timings. In contrast, 10 consecutive cloud-free days followed ABA treatments in Expt. 2 (Fig. 3B). Daytime temperatures tended to track well with solar radiation; cloudy days had much lower average and minimum temperatures than sunny days (Fig. 4). Minimum nighttime temperatures within the 10-d period after applications ranged from 5 to 10 °C for Expts. 1, 3, and 4 but exceeded 10 °C for most of the nights in Expt. 2.

Discussion

With the exception of one trial, ABA significantly thinned ‘Bartlett’ pears. For a given ABA dose, however, the rate of thinning varied among years. Greene (2012) reported consistent thinning when applying

ABA to single limbs of mature ‘Bartlett’ pear trees at similar concentrations to those reported herein. Generally, efficacy of a given dose of ABA was markedly higher in that study, which may be attributed to differences between the two climates. Although ‘Bartlett’ is not regarded as a biennial bearer, return bloom was generally improved by ABA, commensurate with the level of thinning, as previously documented (Greene, 2012). In addition to fruit abscission, Greene (2012) reported irreversible leaf yellowing and abscission at high ABA rates ($\geq 250 \text{ ppm}$) despite the addition of BA, which was previously demonstrated to counteract ABA-induced yellowing of apple leaves (Greene et al., 2011). We did not include BA in our trials. We did observe severe defoliation at 400 and 500 ppm ABA (Expts. 1 and 3, an estimated one-third of the leaf population though leaf abscission data were not recorded) and slight defoliation at 250 ppm (Expt. 1; $\approx 10\%$ of leaves); however, appreciable leaf abscission was not observed in Expt. 4, despite treatment with 400 ppm ABA. These results indicate a potential interaction between ABA and environmental factors on leaf senescence processes. Middelberg et al. (2014) demonstrated increased ABA penetration following rewetting of ABA-treated leaves. Precipitation did accompany low solar radiation (i.e., cloudy conditions) the week after ABA applications

in Expts. 1 and 3 and may have enhanced ABA uptake. Leaf abscission would have certainly contributed to the excessive thinning observed in Expt. 1 and Expt. 3.

ABA-induced stomatal regulation of pear (Einhorn and Arrington, 2017) and apple (McArtney et al., 2014) was similar in magnitude and duration, with the main exception of a much stronger inhibition of pear leaf gas exchange immediately after application (Fig. 2; Einhorn and Arrington, 2017). Despite a pronounced reduction of apple leaf g_s , ABA did not cause thinning of ‘Morganspur Delicious’ fruit (McArtney et al., 2014). We also observed disparity between P_n inhibition and thinning response of trees treated with 200 ppm ABA in Expt. 2. Although P_n data for that experiment are lacking between 1 and 6 dfa, the significantly reduced P_n on 6 dfa is evidence that ABA was effectively taken up by the leaf. We can extrapolate from the proportionately similar P_n reduction of 200 ppm ABA-treated trees in Expt. 3, from their controls, that much greater photosynthetic inhibition occurred immediately after ABA application in Expt. 2. Given the putative relationship between CHO deficit and fruitlet thinning (Lakso, 2011; Lakso et al., 2006; Untiedt and Blanke, 2001), sufficient CHO was clearly available to meet fruit demand in Expt. 2, withstanding the transient supply deficit imposed by ABA.

Studies on the transport, availability, and relative dependence of reserve CHO and current-season photosynthate by rapidly growing apples (Corelli Grappadelli et al., 1994; Hansen, 1971; Quinlan and Preston, 1971; Stopar et al., 2001; Yuan and Greene, 2000) generally agree that current-season photosynthate disproportionately supports fruit soon after flowering. Sink strength of newly expanding leaves for assimilates was greater than developing Japanese pears (*Pyrus pyrifolia* Nakai) within 30 dafb (Zhang et al., 2005). Apple leaves similarly compete with developing fruit. Hansen (1971) determined that $\approx 50\%$ of the total CHO of the first five to six extension shoot leaves was from reserve CHO pools. Moreover, export of CHO from extension shoots did not occur until 10–12 leaves had emerged (Johnson and Lakso, 1986). Developing fruitlets, therefore, rely heavily on spur leaf P_n (Wünsche et al., 1996). Leaf emergence of European pear does not occur until post-bloom, which is considerably later than that of apple. In the present study, ABA was applied between 10 and 20 dafb, when extension shoots are typically 10–20 cm long and possess ≈ 3 –6 leaves (Einhorn, unpublished data), potentially providing longer lasting reserves to support early fruitlet development. Furthermore, the vast difference in tree size among our trials and, potentially CHO reserves, was noteworthy: ≈ 10 -year-old trees (i.e., Expts. 1 and 3) seemed easier to thin than ≈ 20 -year-old trees, which were either insensitive to ABA (Expt. 2) or required markedly higher ABA rates to induce moderate thinning (Expt. 4). However, the strong ABA thinning response of mature

Fig. 3. Daily solar radiation ($\text{W}\cdot\text{m}^{-2}$) for Expt. 1 (A), Expt. 2 (B), Expt. 3 (C), and Expt. 4 (D). Meteorological stations were located within 1 km (A, B, and D) and 20 km (C) from the trial sites.

Fig. 4. Daily temperature for Expt. 1 (A), Expt. 2 (B), Expt. 3 (C), and Expt. 4 (D). Meteorological stations were located within 1 km (A, B, and D) and 20 km (C) from the trial sites.

'Bartlett' pear trees on seedling rootstock (Greene, 2012) with, presumably, high CHO reserves does not support this contention. In addition, less-severe thinning in Expt. 4 may have been due to the earlier application timing (8 dafb as opposed to ≈ 20 dafb in all other trials). Indeed, Greene (2012) demonstrated greater ABA efficacy at 10 mm 'Bartlett' fruit diameter compared with petal fall applications. A change in environmental factors from year to year after thinning applications may have additionally modulated the response to ABA as observed with other chemical compounds (Greene, 2002; Stover and Greene, 2005).

Ten consecutive days of high solar radiation following ABA sprays in Expt. 2 suggests that a surplus in CHO supply may have increased the difficulty to chemically thin pears. In contrast, reduced light in the week after ABA applications in Expts. 1, 3, and 4 may have resulted in CHO deficits, increasing the thinning activity of ABA. Cloudy conditions favor enhanced chemical thinning (Stover and Greene, 2005) owed, in part, to reduced CHO supply and altered CHO partitioning (Corelli Grappadelli et al., 1994). A strong correlation between P_n inhibition and fruit abscission was observed for 'Bartlett' pear trees treated with either ABA or shade (Einhorn and Arrington, 2017). Fifteen days of moderate shade (44%

reduced light) enhanced ABA thinning slightly, albeit nonsignificantly, but not 15 d of severe shade (77%) because light reactions inhibited P_n far greater than the stomatal effect of ABA (Einhorn and Arrington, 2017). Additive thinning effects of shade and chemical thinners were observed when the thinner's mode of action was not P_n inhibition, such as carbaryl (Byers et al., 1990, 1991; Lehman et al., 1987) and ethephon (Lehman et al., 1987). Elucidation of the complex interactions among environmental and genetic factors and their effect on chemical thinner efficacy will require controlled environment studies.

Temperature affects CHO metabolism and growth potential of fruits. Optimum net canopy assimilation and dry matter production of apple trees occur around 20 to 25 °C and 10 to 15 °C for day and night, respectively (Lakso, 2011). Higher temperatures, especially at night, were associated with increased thinning of apples (Byers, 2002) likely because of higher respiration. P_n response to temperature was similar for leaves of apple and asian pear (*Pyrus serotina* L.) (Higgins et al., 1992). Comparable data are not available for european pear. It is not unreasonable, however, to expect similar P_n :temperature thresholds between apple and pear because *Pyrus communis* L. and the major species hybridized to develop

M. ×domestica Borkh. have similar centers of origin (Westwood, 1993), nearly equivalent photosynthetic light response behavior (Einhorn et al., 2012; Lakso, 1994), and early-season fruit growth and development patterns (Westwood, 1993). Based on data from apple and the previous assumptions, maximum daytime temperatures during Expt. 2 of 25 to 32 °C and nighttime temperatures between 5 and 9 dfa (i.e., >15 °C) would have reduced available CHO because of increased respiratory costs. Conversely, low day and night temperatures following ABA sprays in Expts. 1 and 3 would not have been expected to increase fruit growth or respiratory demand. These conditions contrast those in the Eastern United States where cloudy days are often accompanied by high temperatures during early fruit development (D. Greene, personal communication). Notwithstanding extreme temperature fluctuations, pear fruit set may be more sensitive to light than temperature. Indeed, fruit set and light interception of mature Anjou pear trees were markedly improved when reflective fabrics were applied at full bloom (Einhorn et al., 2012).

ABA likely thinned 'Bartlett' pear by inducing a short-term carbon stress. However, the effect on carbon balance seems to be relatively short lived and it is unclear whether ABA thins solely by reducing P_n . Biotic and abiotic factors (light and carbon reserves) may additionally alter the thinning response. In high-light environments, ABA might not provide sufficient P_n inhibition to effectively thin fruit. Because ≥ 250 ppm ABA induced significant phytotoxicity and excessive leaf abscission, increasing ABA rates when conditions are less conducive to thinning (i.e., high light) is not an effective option. In these regions, alternative thinning compounds should be used, or, potentially, successive applications of 200 ppm ABA.

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