Comparison of Chemical Blossom Thinners Using ‘Golden Delicious’ and ‘Gala’ Pollen Tube Growth Models as Timing Aids

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Abstract. Reducing apple crop load during bloom can increase fruit size and promote annual bearing when compared with crop reduction at later timings. In this study, we compared the efficacy of chemical blossom-thinning strategies on ‘Golden Delicious’ and ‘Gala’ apple trees. Several blossom-thinning treatments were evaluated, including 1) unthinned control (control), 2) hand-thinned (HT) at bloom, 3) liquid lime sulfur + Stylet-Oil (LS + SO), 4) ammonium thiosulfate (ATS), 5) endothall (ET), and 6) naphthaleneacetamide (NAD). Chemical treatments were applied twice during bloom, using a predictive model to determine application timings. Blossom thinner effects on pollen tube growth, fruit set, and yield responses were evaluated. LS + SO and ATS reduced the number of pollen tubes that entered the style for ‘Golden Delicious’ by 75% and 63%, respectively. ET and NAD did not affect the number of pollen tubes that entered the style. In one of 2 years, LS + SO resulted in a near-ideal crop load and increased fruit weight. ATS was effective in reducing initial fruit set in ‘Golden Delicious’ and ‘Gala’, but did not reduce whole-tree crop density. ET reduced crop load in all experiments but caused excessive spur leaf injury and negatively affected fruit size of ‘Gala’ but not ‘Golden Delicious’. NAD had limited efficacy on ‘Golden Delicious’ at the concentrations and application timings used in this trial. When used as the sole method of crop load management, none of the chemistries evaluated over-thinned or increased fruit injury. However, ET caused excessive thinning when evaluated as part of a commercial crop load management program on ‘Gala’. Of the products evaluated, LS + SO provided the best overall thinning response.

The first opportunity to visually assess apple tree crop potential is at bloom. The fragile and ephemeral nature of apple blossoms presents an early opportunity for adjusting crop load. Several chemicals have been evaluated as

potential blossom thinners, with variable efficacy. One potential source of variability is the lack of precision in timing blossom thinner applications.

Application timing of apple blossom thinners is often based on arbitrary visual estimates of the percentage of open blossoms. Common timings include 20%, 60%, 80%, 100%, or all full bloom, and single or multiple applications can be applied. Inconsistent blossom-thinning responses may be attributed to application timing because pollen tubes can reach the base of the style within 48 h (Yoder et al., 2009). Increased fruit marking and russetting were attributed to blossom thinner applications that occurred at full bloom or later (Byers, 2003). The number of blossoms that are open can vary widely within a block or tree (Byers, 2003). An inherent challenge with blossom thinning is the short period of time that growers have to

apply treatments over large acreage (Moran and Southwick, 2000).

Models have been developed to estimate the rate of pollen tube growth in apple styles. Child (1966) made one of the first attempts to evaluate apple pollen tube growth rates in vivo in the cider cultivar Michelin. Detached blossoms were subjected to constant temperatures (5 to 24 °C), and pollen tube growth rates were estimated using fluorescence microscopy. Using similar techniques, Williams (1970) developed an index that estimated pollen tube growth based on temperature; however, only relatively low temperatures were evaluated (7 to 15 °C) using detached blossoms. Jefferies and Brain (1984) measured pollen tube growth rate in detached flowers at a range of controlled incubation temperatures over 24 d. A relatively complex model was produced, and the authors indicated a few shortcomings, such as the overestimation of pollen tube growth at low temperatures, and that pollen tube growth under varying temperature regimes had not been evaluated.

Efforts to model pollen tube growth rate were revisited in 2003 using attached blossoms. Mature trees on ‘M.27’ were grown in root bags and were placed in growth chambers at a range of night and day temperatures (Yoder et al., 2009), and ‘Snowdrift’ crabapple pollen was applied to emasculated king blossoms. Using this system, pollen tube growth rates of several apple cultivars were determined and modeled (Yoder et al., 2013). Maternal cultivar, temperature, and style length are inputs in the model. Although pollen genotype can influence pollen tube growth rates in vivo (Jahed and Hirst, 2017), these relationships are complex and are dependent on maternal cultivar and temperature (DeLong et al., 2016). Pollen source is not currently an input in pollen tube growth models (PTGM) and may be difficult to incorporate.

The fungicide LS was one of the first chemical constituents with recognized activity to inhibit fruit set of apple (Bagenal et al., 1925) but has only recently been used for the purpose of crop load management. LS has multiple sites of action including inhibition of pollen tube growth and reduced net photosynthesis (Pn) (McArtney et al., 2006; Yoder et al., 2009). A 2% LS + 2% fish oil (FO) application prevented pollen tubes from reaching the base of the style when applied within 24 h of the pollination event, but later applications (48 h) did not influence the number of pollen tubes that reached the base of the style (Yoder et al., 2009). Because LS inhibited growth of pollen tubes that have partly traversed the style, Schmidt and Elfving (2007) suggested that LS thinning programs may have a longer application window when compared with other products. Photosynthetic inhibition following LS + FO treatments is not considered in the PTGM.

The fertilizer ATS was shown to desiccate floral tissues of peach (Byers and Lyons, 1985) and apple (Byers, 1997). Pollen tube growth was inhibited in vitro and in vivo

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following ATS application (Embree and Foster, 1999; Myra et al., 2006). Schroder [2001, as cited in Schröder and Bangerth (2006)] suggested the mode of action of ATS is a combination of damaged floral tissue and reduced photosynthesis due to leaf injury. In some experiments, ATS caused unacceptable leaf phytotoxicity (Byers, 1997; Embree and Foster, 1999), which resulted in reduced fruit growth (Wertheim, 2000). Conversely, Schmidt and Elfving (2007) suggested that ATS primarily influences blossoms that have recently opened and have not received pollen, and applications early in the flowering period ($\approx 20\%$ bloom) increased efficacy (Bound and Wilson, 2007). However, ATS was a potent inhibitor of pollen tube growth *in vivo*, and reduced pollen tube growth when applied 12 h before (Myra et al., 2006) or 24 h after pollination (Embree and Foster, 1999). Multiple applications of ATS at low rates were more effective than a single application (Bound and Wilson, 2007). Given the assumptions of the PTGM, model-based application timing may improve the consistency of ATS applications.

An aquatic herbicide, ET [7, oxybicyclo (2,2,2)heptane-2-3 dicarboxylic acid] has been evaluated as an apple blossom thinner since 1993. The mode of action of ET was assumed to be as a desiccant (Williams et al., 1995) and it reduced the number of pollen tubes that reached the style base when applied 24 h after pollination (Embree and Foster, 1999). Two applications of ET during bloom reduced fruit set and improved fruit size when compared with a single application (Bound and Wilson, 2007; Greene, 2004; Williams et al., 1995), although this relationship was not consistent (Byers, 1997). Because the proposed mode of action of ET is similar to ATS, model-based application timing may be of benefit.

Naphthaleneacetamide is a hormonal thinner developed in the 1930s. NAD was developed as a milder analog of 1-naphthaleneacetic acid thinner for use on summer ripening cultivars and has efficacy at bloom (Greene, 2002). Although NAD use has been limited in recent years, there is renewed interest in the use of NAD as a bloom thinner in the eastern United States (Greene et al., 2015). Greene et al. (2015) observed thinning activity at bloom and petal fall, with no observed dose response. Because activity of hormonal thinners is not linked to desiccation of stylar tissues, PTGM may not be suitable for timing NAD sprays.

The objective of these studies was to evaluate the efficacy of several blossom-thinning chemistries, using predictive models developed for 'Golden Delicious' and 'Gala' to determine application timing. Blossom-thinning treatments were evaluated as the sole method of 'Golden Delicious' crop load management, and as part of a 'Gala' crop load management program in a commercial orchard.

Materials and Methods

'Golden Delicious'. Experiments were conducted in 2014 and 2015 at Pennsylvania

State University's Fruit Research and Extension Center in Biglerville, PA. Uniform 'Golden Delicious'/'Budagovsky 9' trees were selected at the pink bud stage. Trees were planted in 2004 at 1.5×4.6 m spacing and trained to vertical axis. Treatments were randomly assigned to single tree plots, with buffer trees between each treatment. Two to three uniform limbs were selected and flagged on each tree. Limb circumference was measured, and blossom clusters were counted on uniform limbs.

At the late balloon stage, 50 king blossoms from adjacent trees were collected, and the length of the longest style in each bloom was measured with digital calipers. The average length of the longest styles was calculated and used as an input in the model. Flagged limbs were used to determine the timing of model initiation. A handheld gauge was used to measure limb diameter and provide target crop densities (Equilfruit; INRA, Montpellier, France, described in Kon and Schupp, 2013). Once the number of blossoms that were open matched the F value [≈ 6 fruit per cm^2 branch cross-sectional area (BCSA)], the 'Golden Delicious' PTGM was initiated. In the Spring of 2014, freeze injury was observed in flower buds and was documented. Bud mortality of all flowers on 10 randomly selected limbs was evaluated. About 30% of flower buds were visibly injured, but sufficient viable blossoms remained to conduct the experiment. To account for this injury, the initiation of the model was delayed until ≈ 12 blossoms per cm^2 BCSA were open on selected limbs in 2014. Because cold injury was not observed in 2015, six fruit per cm^2 BCSA was set as the target crop density.

Hourly temperature data from a local weather station (located <1.6 km from all plots) was used as an input in the model. Two blossom thinner applications were applied in accordance with current recommendations for use of the PTGM (Yoder et al., 2013). After the model-estimated pollen tube length was equivalent to the mean style length, the first application of the thinning treatments occurred (Fig. 1). After the initial application, the model clock was reset to track the growth of pollen tubes in unopened flowers. The second application occurred at or before the model estimate of pollen tube length was 70% of the mean style length.

The following treatments were applied in both years: 1) unthinned control (control), 2) HT, 3) 2% (v:v) LS (Miller Chemical and Fertilizer, LLC, Hanover, PA) and 2% (v:v) SO (JMS Flower Farms, Inc., Vero Beach, FL), 4) 2% (v:v) ATS, and 5) $1.5 \text{ mL} \cdot \text{L}^{-1}$ ET (ThinRite; 5.37% a.i.; United Phosphorus, Inc., King of Prussia, PA). In 2015, $50 \text{ mg} \cdot \text{L}^{-1}$ NAD (Amid-Thin; AMVAC, Los Angeles, CA) was also evaluated.

The experiment was a completely randomized design with five replications. All chemical thinning treatments were applied with a CO_2 sprayer at 276 kPa (Bellspray, Inc., Opelousas, LA) to single-tree plots. Caustic products were applied until the canopy was thoroughly wetted and NAD was

applied until runoff. HT was conducted during bloom, and crop load was manually adjusted using scissors. Using the aforementioned hand-thinning gauge, crop load was manually adjusted to ≈ 12 or six blossoms per cm^2 BCSA to reflect the targeted crop load in 2014 and 2015, respectively. Open king blossoms were retained preferentially.

One week after treatment, spur leaf phytotoxicity was visually rated on 10 spurs on the east and west side of each tree (1 to 5 scale: 1 = no visible damage; 2 = trace to 10% damage; 3 = 11% to 24% damage; 4 = 25% to 49% damage; 5 = $\geq 50\%$ damage). Fruit were counted on selected limbs at ≈ 9 mm fruit diameter and after June drop. Crop density (fruit no. per cm^2 BCSA) and fruit set were calculated at both timings.

Fruit were harvested from entire trees at a commercially acceptable level of maturity, and fruit number, yield, and average fruit weight were determined using an electronic fruit sizer (Durand-Wayland, LaGrange, GA). A 20-fruit sample was collected and russet was evaluated using digital image analysis adapted from Winzeler and Schupp (2011). Seeds were extracted from the 20-fruit sample and were counted and recorded. During dormancy, trunks were measured 30 cm above the graft union and number of fruit per cm^2 trunk cross-sectional area (TCSA) was calculated. The following Spring, return bloom density was determined by counting the number of blossom clusters on two or three representative limbs on each tree and expressing the number of blossom clusters per cm^2 BCSA.

In 2015, king blossoms and lateral blossoms on five spurs were selected and tagged on each tree immediately after the model was initiated. The spurs were selected with king bloom at anthesis, king blossoms were labeled, and the furthest developed side blossom (generally at the balloon stage) was labeled. Similar methods to those of Embree and Foster (1999) were used to visualize pollen tube growth. Blossoms were harvested 48 h after the first application timing, placed in labeled vials containing 5% sodium sulfite, and stored at 4°C . Samples were autoclaved at 121°C for 10 min to soften tissues for slide preparation. Before microscopic examination, blossoms were rinsed with distilled-deionized water and styles were removed with a scalpel at the junction with the hypanthium. Remaining floral tissues were discarded. Styles were rinsed, separated, and soaked in a water-soluble fluorescence solution of 0.01% aniline blue stain in $0.067 \text{ M K}_2\text{HPO}_4$ on a microscope slide. Styles were squashed between two microscopic slides. The samples were incubated overnight and observed via a fluorescence microscope at $100\times$ (Olympus BX51; Tokyo, Japan), equipped with a ultraviolet/DAPI long-pass filter cube (19000-AT-ultraviolet/DAPI; Chroma Technology Corporation, Bellows Falls, VT). Pollen density on the stigmatic surface was visually rated using a 0 to 10 scale, described in Yoder et al. (2009). Pollen tubes that entered the style and those that reached the style base were counted. Longest pollen tube

Fig. 1. Graphical representation of 'Golden Delicious' pollen tube growth model application timings (indicated by arrows), estimates of pollen tube growth rates, and temperature in 2014 and 2015 (A and B, respectively). The model was initiated at 0900 HR on 4 May 2014 and 1400 HR on 29 Apr. 2015. The model was initiated when ≈ 12 open blossoms per cm^2 BCSA and ≈ 6 open blossoms per cm^2 BCSA were observed (A and B, respectively).

length and style length were measured with an ocular micrometer. Pollen tube length was standardized by style length to estimate pollen tube growth [pollen tube growth = (pollen tube length/style length) $\times$ 100].

'Gala'. In 2015, a trial was conducted in a commercial orchard of mature 'Buckeye Gala'/'M.9 RN 29'. Trees were trained to tall spindle at 1.5 $\times$ 4.6 m spacing. Twenty-four uniform 'Gala' trees were selected and flagged. Treatments were randomly assigned to single-tree plots, with buffer trees between each treatment. Model initiation and application timing of the 'Gala' PTGM were conducted as previously described. The target crop load was ≈ 6 fruit per cm^2 BCSA.

Using the 'Gala' PTGM (Fig. 2), the following blossom-thinning treatments were applied to whole trees with a CO_2 sprayer at 276 kPa until thoroughly wetted: 1) control, 2) LS + SO, 3) ATS, and 4) ET. Rates used were identical to those of the previous experiment. All trees received the following post-bloom-thinning application via an airblast sprayer: 100 $\text{mg}\cdot\text{L}^{-1}$ 6-benzyladenine (6-BA, Exilis Plus; Fine Americas, Inc., Walnut Creek, CA) + 1 pint 1-naphthyl methylcarbamate (carbaryl) + 1 pint adjuvant (Level 7; Winfield

Solutions, LLC, St. Paul, MN). Post-bloom thinner was applied via an airblast sprayer calibrated to apply 843 L water per hectare on 14 May 2015 (fruit diameter was ≈ 10 mm). The experiment was a completely randomized design and was replicated six times.

With a few exceptions, all response variables described in the previous experiment were documented and evaluated. A 20-fruit sample was collected and the percentage of apple peel exhibiting russet was quantified by visual estimations, rather than digital image analysis. In addition, fruit shape appeared to differ among treatments. The length and diameter of the 20-fruit sample were measured and recorded. Fruit length:diameter ratio was calculated to characterize fruit shape. In the Spring of 2016, a series of cold weather events resulted in some flower bud mortality. To determine if blossom-thinning treatments influenced frost tolerance, flower bud mortality on three limbs per tree was evaluated. The number of flowers was counted, then each individual flower was dissected, and the pistil was rated as dead or alive. The percentage of viable flowers was calculated.

Statistical analysis. Data were analyzed using the personal computer version of SAS

(SAS 9.3; SAS Institute, Cary, NC). Analysis of variance was performed using PROC MIXED. Tukey's honest significance test was used to compare treatment means at $P = 0.05$.

Results and Discussion

'Golden Delicious'. Several potential blossom-thinning chemistries were evaluated using the PTGM as a timing aid. The number of blossom-thinning applications was restricted to two, because most blossoms were open at the time the second blossom-thinning spray was applied. In some years or geographical areas, the bloom period may be protracted due to environmental conditions, requiring additional blossom thinner applications (Moran and Southwick, 2000).

Pollen tube growth metrics for king blossoms were not significantly influenced by any treatment, suggesting that selected open king blossoms were not susceptible to blossom thinners (Table 1). LS + FO was a potent inhibitor of pollen tube growth when applied at 4 and 24 h after pollination, but was ineffective 48 h after pollination (Yoder et al., 2009). Similarly, ATS and ET reduced the number of

Fig. 2. Graphical representation of 'Gala' pollen tube growth model application timings (indicated by arrows), estimates of pollen tube growth rates, and temperature in 2015. The model was initiated at 1500 HR on 30 Apr. 2015. The model was initiated when ≈ 6 open blossoms per cm^2 BCSA was observed.

Table 1. Comparison of blossom-thinning treatments on pollen density rating, number of pollen tubes that entered the style, number of pollen tubes that reached the style base, and pollen tube growth in king and side bloom of 'Golden Delicious'/'Budagovsky 9' apple trees in 2015.^z

Thinning treatment ^{yx}	Pollen tube density on stigma (0 to 10 rating) ^w	Pollen tubes entering style (no. visible/flower)	Pollen tubes at style base (no. visible/flower)	Pollen tube growth (%) ^v
<i>King blossom</i>				
Control	3.2 a ^u	124 a	8.7 a	86 a
HT	2.4 a	100 a	7.4 a	79 a
LS + SO	3.0 a	130 a	6.0 a	75 a
ATS	3.3 a	119 a	5.3 a	73 a
ET	3.3 a	131 a	9.0 a	87 a
NAD	2.8 a	123 a	7.7 a	82 a
<i>Side blossom</i>				
Control	2.8 ab	141 b	7.8 a	78 a
HT	3.5 a	188 a	6.1 ab	76 a
LS + SO	2.1 b	35 c	0.5 b	24 b
ATS	2.0 b	52 c	2.8 ab	37 b
ET	3.5 a	154 ab	9.2 a	80 a
NAD	2.8 ab	135 b	4.4 ab	65 a

^zMeans of four observations. Blossoms were harvested 48 h after the first application timing.

^yTiming of chemical treatments were determined with the 'Golden Delicious' pollen tube growth model. In 2015, the model was initiated at 1400 HR on 29 Apr. Chemical treatments were applied at 1000 HR on 3 May 2015 and 1600 HR 4 May 2015. The hand-thinned control treatment was applied on 3 May 2015.

^xControl = unthinned control; HT = hand-thinned at bloom; LS + SO = 2% (v:v) LS (Miller Chemical and Fertilizer, LLC) and 2% (v:v) Stylet-Oil (JMS Flower Farms, Inc.); ATS = 2% (v:v) ammonium thiosulfate; ET = 1.5 mL·L⁻¹ (5.37% a.i.; United Phosphorus, Inc.); NAD = 50 mg·L⁻¹ Amid-Thin (AMVAC).

^wA visual rating scale was used to quantify pollen tube density on the stigma: 0 = no pollen tubes visible on the surface; 1 = 1% to 10% area covered; 2 = 11% to 20%; 3 = 21% to 30%; 4 = 31% to 40%; 5 = 41% to 50%; 6 = 51% to 60%; 7 = 61% to 70%; 8 = 71% to 80%; 9 = 81% to 90%; 10 = 91% to 100% of surface covered by pollen tubes.

^vPollen tube growth = (the length of the longest pollen tube/style length) $\times$ 100.

^uMean separation within columns for king and side blossoms by Tukey's honest significance test at $P = 0.05$.

NAD = naphthaleneacetamide; ET = endothall; ATS = ammonium thiosulfate; LS = liquid lime sulfur; SO = Stylet-Oil.

pollen tubes that reached the style base when applied 24 h after pollination (Embree and Foster, 1999). Based on the assumptions of the PTGM, open king blossoms received pollen at

the initiation of the model. Model estimates of pollen tube growth rates are based on hourly temperature data. In theory, pollen tubes in king blossoms should reach the hypanthium

before the first application of thinner. Pollen tube growth occurs at the tip, and the cytoplasm is physically separated from the rest of the pollen tube by callose plugs. After reaching the hypanthium, it is assumed that pollen tubes are unlikely to be influenced by chemical thinning treatments. Therefore, limited influence on pollen tube growth of selected king blossoms was a desirable outcome and our data suggest that the model was successful in preventing premature application of blossom-thinning chemicals.

Significant differences among treatments were observed in measured responses of pollen tube growth in side blossoms. When compared with the control, LS + SO and ATS reduced the number of pollen tubes that entered the style of side blossoms by 75% and 63%, respectively. LS + SO significantly reduced the number of pollen tubes that reached the style base, but ATS did not. Several experiments demonstrated that LS + oil and ATS were effective in reducing pollen tube growth in vivo (Embree and Foster, 1999; McCartney et al., 2006; Myra et al., 2006; Yoder et al., 2009). Pollen tube growth was unaffected by ET or NAD. The lack of effects observed on pollen tube growth with ET was unexpected because ET had previously been shown to reduce the number of pollen tubes that reach the style base when applied 24 h after pollination (Embree and Foster, 1999). Williams et al. (1995) suggested that ET acts as a desiccant of floral tissue, thereby preventing fertilization. However, our data show that inhibition of pollen tube growth is an improbable mechanism for ET and NAD because responses to these treatments did not differ from that of the control.

PTGM were developed using king blossoms as the principal experimental unit. Differences in pollen tube growth rates existed when comparing king and side blossoms in 'Golden Delicious' (Losada and Herrero, 2013). Additional research is needed to determine if this relationship is true across commercially important cultivars. In addition, there were significant differences in the average style length between king and side blossoms. The current heuristic for the timing of secondary or tertiary applications using the PTGM is to wait until the estimated cumulative pollen tube growth is 60% to 70% of the average style length. If positional differences in pollen tube growth rates exist, perhaps modeling of pollen tube growth in side, lateral, or both blossoms would increase the accuracy and precision of the model.

Although ET did not influence pollen tube growth in 2015, ET increased damage to spur leaf tissue in both years of this trial (Table 2). Symptoms included marginal leaf injury, leaf curling, and round necrotic lesions. Spur leaf injury was rated 7 d after treatment. Shortly after evaluation, some of the spur leaves exhibiting injury abscised. Any reduction in spur leaf area or leaf function was not formally quantified. Williams et al. (1995) suggested that some cultivars, particularly 'Golden Delicious', were sensitive to ET.

They observed bud and leaf damage at 1.0 and 1.5 mL·L⁻¹ on ‘Golden Delicious’; however, fruit size and quality were unaffected (Williams et al., 1995). In this study, similar injury to ‘Golden Delicious’ was observed at 1.5 mL·L⁻¹. In 2014, but not in 2015, ATS slightly increased leaf phytotoxicity when compared with the control (trace to 10% leaf damage). ATS injured apple foliage at lower concentrations than were used in this study (Balkhoven-Baart and Wertheim, 1997). Because environmental effects, such as temperature and relative humidity, can influence drying conditions, incidents of ATS phytotoxicity can be unpredictable (Wertheim, 2000). When compared with the control, HT, LS + SO, and NAD did not significantly increase visible leaf phytotoxicity in either year.

Unfertilized blossoms abscise shortly after petal fall (Greene et al., 2013). Therefore, initial fruit set is a good indicator of blossom-thinning treatment efficacy. When compared with the control, LS + SO, ATS, and ET reduced initial fruit set by 37% to 57% in 2014. In 2015, LS + SO and ATS reduced initial fruit set (51% and 35%, respectively), but ET did not differ from the control. The observed reduction in pollen tube growth metrics was consistent with the initial fruit set. HT resulted in the lowest initial fruit set in both years because blossom number was reduced manually to 49% or 24% fruit set (2014 and 2015, respectively). In HT treatments, very few fruit abscised between measurements of initial and final fruit set, suggesting that HT reduced competition among fruitlets and limited June drop.

Final crop density is an estimate of whole-tree crop density cm² TCSA. There were some differences in final crop density among treatments, but our discussion will focus on whole-tree crop density. Although whole-tree crop density was reduced by HT and ET in 2014, it was unaffected by LS + SO or ATS (Table 3). This may be partly explained by the delay in initiation of the model to a target crop load of 12 fruit per cm² BCSA. A spring frost resulted in 30% flower bud mortality in 2014. To account for the loss of viable flower buds, the model was delayed until ≈12 blossoms per cm² BCSA were open. Despite a reduction in crop density by HT and ET in 2014, yield was not influenced by either treatment. This is likely explained by the observed increase in fruit weight as a result of HT and ET. In 2015, LS + SO and ET reduced crop density by 39% and HT by 68% when compared with the control. Both LS + SO and ET resulted in near-optimal crop loads for ‘Golden Delicious’ (six to eight fruit per cm² TCSA), whereas HT overthinned. HT trees were thinned to ≈6 fruit per per cm² BCSA, but had a whole-tree crop load of 3.9 fruit per cm² TCSA. This difference may be due to tree BCSA, as final crop load of trees thinned with the hand-thinning gauge is a function of the total BCSA per tree (Kon and Schupp, 2013). PTGMs were developed for LS blossom-thinning programs,

Table 2. Comparison of blossom-thinning treatments on phytotoxicity, fruit set, and crop density of ‘Golden Delicious’/‘Budagovsky 9’ apple trees in 2014 and 2015.^z

Thinning treatment ^{yxw}	Leaf phytotoxicity (1 to 5) ^v	Initial		Final	
		Crop density (no. fruit/cm ² BCSA) ^u	Fruit set (%) ^t	Crop density (no. fruit/cm ² BCSA)	Fruit set (%)
2014					
Control	1.0 c ^s	99.3 a	287 a	18.5 a	55 a
HT	1.0 c	15.8 c	49 c	14.1 ab	44 a
LS + SO	1.2 c	65.8 ab	178 b	17.6 a	54 a
ATS	2.0 b	39.9 bc	124 b	15.5 ab	49 a
ET	2.6 a	49.1 bc	181 b	9.7 b	37 a
2015					
Control	1.0 b	122.7 a	389 a	19.1 a	59 a
HT	1.0 b	8.3 c	24 c	7.0 b	20 c
LS + SO	1.6 b	60.4 b	186 b	12.6 ab	39 abc
ATS	1.6 b	79.8 b	235 b	13.4 ab	40 abc
ET	2.6 a	129.6 a	344 a	16.5 a	43 ab
NAD	1.0 b	136.3 a	352 a	14.9 a	38 bc

^zMeans of five observations.

^yTiming of chemical treatments were determined with the ‘Golden Delicious’ pollen tube growth model. Model was initiated at 0900 HR on 4 May 2014. Treatments were applied at 1800 HR on 8 May 2014 and 1100 HR on 10 May 2014. The hand-thinned control was applied on 8 May 2014.

^xTiming of chemical treatments were determined with the ‘Golden Delicious’ pollen tube growth model. Model was initiated at 1400 HR on 29 Apr. Treatments were applied at 1000 HR on 3 May 2015 and 1600 HR 4 May 2015. The hand-thinned control treatment was applied on 3 May 2015.

^wControl = unthinned control; HT = hand-thinned at bloom; LS + SO = 2% (v:v) LS (Miller Chemical and Fertilizer, LLC) and 2% (v:v) Stylet-Oil (JMS Flower Farms, Inc.); ATS = 2% (v:v) ammonium thiosulfate; ET = 1.5 mL·L⁻¹ (5.37% a.i.; United Phosphorus, Inc.); NAD = 50 mg·L⁻¹ Amid-Thin (AMVAC).

^vThe following visual rating scale was used to quantify leaf phytotoxicity: 1 = no visible damage; 2 = trace to 10% damage; 3 = 11 to 24% damage; 4 = 25% to 49 damage; 5 = 50% damage or greater.

^uBCSA = branch cross-sectional area.

^tFruit set = (no. fruit / no. flower clusters) × 100.

^sMean separation within columns for 2014 and 2015 by Tukey’s honest significance test at *P* = 0.05.

NAD = naphthaleneacetamide; ET = endothall; ATS = ammonium thiosulfate; LS = liquid lime sulfur; SO = Stylet-Oil.

Table 3. Comparison of blossom-thinning treatments on fruit number, crop density, yield, and fruit weight of ‘Golden Delicious’/‘Budagovsky 9’ apple trees in 2014 and 2015.^z

Thinning treatment ^{y,xw}	Crop density			
	Fruit (no./tree)	(no. fruit/cm ² TCSA) ^y	Yield (kg/tree)	Fruit wt (g)
2014				
Control	545 a ^u	14.7 a	53.3 a	98 c
HT	318 b	9.5 b	46.3 a	146 a
LS + SO	438 ab	11.4 ab	49.1 a	114 bc
ATS	393 b	11.6 ab	44.7 a	113 bc
ET	371 b	7.8 b	48.2 a	132 ab
2015				
Control	500 a	12.2 a	55.9 a	113 c
HT	166 c	3.9 c	37.7 b	228 a
LS + SO	333 abc	7.5 b	53.2 ab	160 b
ATS	390 ab	9.1 ab	55.3 a	141 bc
ET	318 bc	7.5 b	47.4 ab	156 b
NAD	454 ab	10.5 ab	61.2 a	135 bc

^zMeans of four observations.

^yAll chemical treatments were applied in accordance with the ‘Golden Delicious’ pollen tube growth model. Model was initiated at 0900 HR on 4 May 2014. Treatments were applied at 1800 HR on 8 May 2014 and 1100 HR on 10 May 2014. The hand-thinned control was applied on 8 May 2014.

^xTiming of chemical treatments were determined with the ‘Golden Delicious’ pollen tube growth model. Model was initiated at 1400 HR on 29 Apr. Treatments were applied at 1000 HR on 3 May 2015 and 1600 HR 4 May 2015. The hand-thinned control treatment was applied on 3 May 2015.

^wControl = unthinned control; HT = hand-thinned at bloom; LS + SO = 2% (v:v) LS (Miller Chemical and Fertilizer, LLC) and 2% (v:v) Stylet-Oil (JMS Flower Farms, Inc.); ATS = 2% (v:v) ammonium thiosulfate; ET = 1.5 mL·L⁻¹ (5.37% a.i.; United Phosphorus, Inc.); NAD = 50 mg·L⁻¹ Amid-Thin (AMVAC).

^vTCSA = trunk cross-sectional area.

^uMean separation within columns for 2014 and 2015 by Tukey’s honest significance test at *P* = 0.05.

NAD = naphthaleneacetamide; ET = endothall; ATS = ammonium thiosulfate; LS = liquid lime sulfur; SO = Stylet-Oil.

and Pn is not a factor in the model. Reduced Pn as a result of a LS program has been confirmed in partial leaf (McArtney et al., 2006; Noordijk and Schupp, 2003), leaf

(Hoffman, 1935), and whole-tree experiments (Lombardini et al., 2003; Whiting, 2007). In the Pacific Northwest, this stress was reported to last between 4 and 10 d

(Schmidt and Elfving, 2007), but spur leaf Pn was reduced for more than 57 d in New Zealand (McArtney et al., 2006). The reduction in crop density observed with ET was apparently not related to desiccation of stylar tissues because it did not reduce pollen tube growth or initial fruit set in 2015. However, the observed damage and subsequent abscission of leaf tissue may explain the reduction in crop density.

Despite reducing initial fruit set in both years, ATS did not reduce crop density, yield, or increase fruit weight. In sweet cherry, several physiological measurements demonstrated that ATS had a minor impact on leaf function (Lenahan and Whiting, 2006) and ethylene-induced abscission was not likely a causal factor (Janoudi and Flore, 2005). ATS reduced pollen tube growth when applied 12 h before (Myra et al., 2006) or 24 h after pollination (Embree and Foster, 1999). These studies suggest that the primary mode of action of ATS can be attributed to the desiccation of floral tissues and subsequent inhibition of pollen tube growth in vivo. Although the scorching of leaf tissue may affect leaf function, apple leaves can tolerate a minor reduction in functional leaf area without reducing Pn. Physical removal of up to 10% of spur leaves did not reduce Pn (Hall and Ferree, 1976). In this experiment, visual estimates of leaf injury by ATS did not exceed a rating of two (trace to 10% damage).

The hormonal thinner NAD reduced final limb crop density by 35% but did not reduce whole-tree crop density. NAD was an effective thinner while using the PTGM as a timing aid on 'Honeycrisp' (G.M. Peck et al., unpublished data). Although the maximum legal rate of NAD was used on 'Golden Delicious' in this experiment, thinning activity was limited. The lack of efficacy may be partly explained by cultivar, as 'Golden Delicious' is considered a difficult-to-thin variety and requires high rates of NAA to effect thinning (Anonymous, 2018). The model estimates the rate of pollen tube growth based on hourly temperature, but temperatures proximal to application timing are not an important factor. Conversely, the efficacy of hormonal thinning products, particularly products that induce generation of ethylene, is influenced by temperatures proximal to application timing (Greene, 2002). Evaluation of NAD bloom application in combination with adjuvants or other thinners on hard-to-thin cultivars should be considered in future work.

Fruit russet was greater on fruit from HT trees in 2014 (Table 4). The reason for this increase was unknown, but it was inconsequential and would not reduce the grade of the fruit. There were no differences in fruit russet in 2015 and none of the treatment means exceeded 10% russet. Fast drying conditions occurred during both years of the experiment at the time of application, which was suggested to reduce russet incidents (Byers, 2003). Although seed number can be reduced by caustic products (Bound and Jones, 1997; Bound and Wilson, 2007), seed

number was not influenced by any treatment in either year.

When compared with the control, HT increased return bloom in both years. Despite the early reduction in initial fruit set for LS + SO, ATS, and ET, return bloom did not differ

from the control for any of these treatments. In 2014, HT reduced crop density to ≈ 14 fruit per cm^2 BCSA. The resulting return bloom in the Spring of 2015 was 4.9 blossom clusters per cm^2 BCSA. This blossom density would be adequate to set a commercial crop.

Table 4. Comparison of blossom-thinning treatments on fruit russet, seed number, and return bloom of 'Golden Delicious'/'Budagovsky 9' apple trees in 2014 and 2015.^z

Thinning treatment ^{xw}	Fruit russet (%) ^y	Seeds (no./fruit)	Return bloom (no. blossom clusters/ cm^2 BCSA) ^u
<i>2014</i>			
Control	1.8 b [†]	8.3 a	0.0 b
HT	6.2 a	7.3 a	4.9 a
LS + SO	4.2 ab	7.9 a	3.0 ab
ATS	1.8 ab	8.2 a	0.8 ab
ET	2.8 ab	7.5 a	0.4 b
<i>2015</i>			
Control	6.2 a	7.0 a	0.8 b
HT	5.7 a	5.9 a	26.2 a
LS + SO	7.1 a	6.4 a	5.0 b
ATS	5.3 a	5.5 a	5.3 b
ET	6.1 a	7.2 a	3.6 b
NAD	3.2 a	6.8 a	2.3 b

^zMeans of three observations.

^yTiming of chemical treatments were determined with the 'Golden Delicious' pollen tube growth model. Model was initiated at 0900 HR on 4 May 2014. Treatments were applied at 1800 HR on 8 May 2014 and 1100 HR on 10 May 2014. The hand-thinned control treatment was applied on 8 May 2014.

^xTiming of chemical treatments were determined with the 'Golden Delicious' pollen tube growth model. Model was initiated at 1400 HR on 29 Apr. Treatments were applied at 1000 HR on 3 May 2015 and 1600 HR 4 May 2015. The hand-thinned control treatment was applied on 3 May 2015.

^wControl = unthinned control; HT = hand-thinned at bloom; LS + SO = 2% (v:v) LS (Miller Chemical and Fertilizer, LLC) and 2% (v:v) Stylet-Oil (JMS Flower Farms, Inc.); ATS = 2% (v:v) ammonium thiosulfate; ET = 1.5 mL·L⁻¹ (5.37% a.i.; United Phosphorus, Inc.); NAD = 50 mg·L⁻¹ Amid-Thin (AMVAC).

^uA 20-fruit sample was collected and the russeted portion of the peel was estimated using digital image analysis.

^uBCSA = branch cross-sectional area.

[†]Mean separation within columns for 2014 and 2015 by Tukey's honest significance test at $P = 0.05$.

NAD = naphthaleneacetamide; ET = endothall; ATS = ammonium thiosulfate; LS = liquid lime sulfur; SO = Stylet-Oil.

Table 5. Comparison of blossom-thinning treatments on pollen density rating, number of pollen tubes that entered the style, number of pollen tubes that reached the style base, and pollen tube growth in king and side bloom of seventh leaf 'Buckeye Gala'/'M.9 RN-29' apple trees in 2015.^z

Thinning treatment ^{xw}	Pollen tube density on stigma (0 to 10 rating) ^y	Pollen tubes entering style (no. visible/flower)	Pollen tubes at style base (no. visible/flower)	Pollen tube growth (%) ^u
<i>King blossom</i>				
Control	2.1 a [†]	71 ab	1.7 a	58 a
LS + SO	2.1 a	44 b	1.4 a	45 a
ATS	2.7 a	63 ab	3.4 a	51 a
ET	2.9 a	79 a	2.2 a	59 a
<i>Side blossom</i>				
Control	4.0 a	180 a	2.8 a	58 a
LS + SO	1.9 bc	15 c	0.0 b	5 b
ATS	1.2 c	19 c	0.0 b	6 b
ET	2.8 ab	120 b	1.4 ab	47 a

^zMeans of four observations. Blossoms were harvested 48 h after the first application timing.

^yTiming of chemical treatments were determined with the 'Gala' pollen tube growth model. Model was initiated at 1500 HR on 30 Apr. 2015. Treatments were applied at 0600 HR on 3 May 2015 and 1100 HR on 4 May 2015.

^xLS + SO = 2% (v:v) LS (Miller Chemical and Fertilizer, LLC) and 2% (v:v) Stylet-Oil (JMS Flower Farms, Inc.); ATS = 2% (v:v) ammonium thiosulfate; ET = 1.5 mL·L⁻¹ (5.37% a.i.; United Phosphorus, Inc.).

^wOn 14 May 2015, all trees received a post bloom-thinning application: 100 mg·L⁻¹ 6-benzyladenine (6-BA, Exilis Plus, Fine Americas, Inc.) + 1 pint 1-naphthyl methylcarbamate (carbaryl) + 1 pint adjuvant (Level 7; Winfield Solutions, LLC).

^uThe following visual rating scale was used to quantify pollen tube density on the stigma: 0 = no pollen tubes visible on the surface; 1 = 1% to 10% area covered; 2 = 11% to 20%; 3 = 21% to 30%; 4 = 31% to 40%; 5 = 41% to 50%; 6 = 51% to 60%; 7 = 61% to 70%; 8 = 71% to 80%; 9 = 81% to 90%; 10 = 91% to 100% of surface covered by pollen tubes.

^uPollen tube growth = (length of the longest pollen tube / style length) $\times$ 100.

[†]Mean separation within columns for king and side blossoms by Tukey's honest significance test at $P = 0.05$.

ET = endothall; ATS = ammonium thiosulfate; LS = liquid lime sulfur; SO = Stylet-Oil.

Schmidt et al. (2009) suggested that blossom densities between two and six blossom clusters per cm² TCSA were acceptable. Reducing crop load early in the season has potential to increase return bloom; however, in some strongly biennial cultivars, summer bloom promoting sprays are required to ensure consistent cropping potential (Ferree and Schmid, 2000; McCartney et al., 2007). Although not evaluated in this trial, research is needed to understand the interaction between blossom thinners and products that promote return bloom.

'Gala'. Effects on pollen tube growth were similar to observed responses on *'Golden Delicious'*, as LS + SO and ATS were potent inhibitors of pollen tube growth in side blossoms (Table 5). In general, pollen tube growth responses in king blossoms were not influenced by any treatment. LS + SO reduced the number of visible pollen tubes that entered the style but did not affect the number of tubes that reached the style base. In side blossoms, LS + SO and ATS were effective inhibitors of pollen germination and growth in the style. Compared with the control, pollen tube density on the stigmatic surface was reduced with all blossom thinners. This is likely due to the desiccation of floral tissues, direct effects on pollen viability, pollen tube mortality, or all of these (Embree and Foster, 1999; Myra et al., 2006). ET application resulted in a minor reduction in the number of pollen tubes that entered the style (33%), but did not reduce the number of pollen tubes that reached the style base or pollen tube growth percentage.

ATS and ET caused leaf phytotoxicity (Table 6) and visible ATS injury primarily occurred at the leaf margin. Leaf phytotoxicity may be reduced by using multiple applications of low ATS rates (0.8% to 1.5%), with similar thinning outcomes to a single application at higher rates (Bound and Wilson, 2007). Leaf phytotoxicity symptoms of ET were similar to the damage observed in the trial on *'Golden Delicious'*. Bound and Jones (1997) observed increased phytotoxicity with increasing concentration of ET on *'Delicious'*, and rates of 1.25–1.5 mL·L⁻¹ were suggested to reduce crop load without excessive damage. Our treatments were within this range, and it is unclear why phytotoxicity was increased with ET. The authors are unaware of evidence suggesting that *'Gala'* is sensitive to ET, and drying conditions after treatments were ideal.

Initial and final crop densities were unaffected by treatment (Table 6). Because initial fruit set and whole-tree crop load were not different, these estimates may not have been sensitive enough to detect differences. Initial fruit set was significantly reduced by ATS and ET (42% and 35%, respectively). Because pollen tube growth was not reduced with ET, the reduction in initial fruit set may be due to other factors, such as carbohydrate limitations. Loss of photosynthetic spur leaf

area during bloom negatively affected fruit set (Ferree and Palmer, 1982).

All treatments reduced crop density below the optimal for *'Gala'* (six to eight fruit per cm² TCSA; Table 7). All treatments, including the control, received a post-bloom thinner application. This treatment resulted in over-thinning. LS + SO and ATS did not reduce crop density when compared with the control, suggesting that chronic effects of the blossom thinner application did not cause additional over-thinning. However, ET reduced the number of fruit per tree, crop density, and yield. Research was conducted on interactions between ET and post-bloom compounds in multistep thinning programs (Bound and Wilson, 2007; Stover et al., 2002). While assessing a multistep thinning program, Stover et al. (2002) observed that the addition of a petal fall thinning application was beneficial in a 2-year trial, but the addition of a blossom-thinning spray with

ET was not. Despite a significant reduction in crop load, ET reduced fruit weight when compared with the control. At high rates of ET (3.0 mL·L⁻¹), Bound and Jones (1997) suggested that spur leaf damage had negative consequences on fruit weight.

Fruit russet increased slightly with ATS and ET, but treatments resulted in less than 1% of the fruit surface covered with russet (Table 7). Seed number was not influenced by any treatment (data not presented). Some reports document that ET can result in the flattening of apple fruit (Bound and Jones, 1997), whereas others found no effects on fruit shape (Greene, 2004). In this trial, ET reduced the L:D ratio when compared with LS + SO and ATS, but was not different from the control (data not presented). Therefore, although statistically significant, the minor effect on fruit flattening may not be of practical significance. In

Table 6. Comparison of blossom-thinning treatments on phytotoxicity, crop density, and fruit set of seventh leaf 'Buckeye Gala'/'M.9 RN-29' apple trees in 2015.^z

Thinning treatment ^{xw}	Leaf phytotoxicity (1 to 5) ^v	Initial		Final	
		Crop density (no. fruit/cm ² BCSA) ^u	Fruit set (%) ^t	Crop density (no. fruit/cm ² BCSA)	Fruit set (%)
Control	1.0 c ^s	76.2 a	306 a	4.2 a	15 a
LS + SO	1.5 bc	61.5 a	242 ab	2.2 a	9.5 a
ATS	2.3 a	53.9 a	176 b	2.3 a	9.2 a
ET	2.2 ab	54.7 a	200 b	2.3 a	7.8 a

^zMeans of five observations.

^xTiming of chemical treatments were determined with the *'Gala'* pollen tube growth model. Model was initiated at 1500 HR on 30 Apr. 2015. Treatments were applied at 0600 HR on 3 May 2015 and 1100 HR on 4 May 2015.

^yLS + SO = 2% (v:v) LS (Miller Chemical and Fertilizer, LLC) and 2% (v:v) Stylet-Oil (JMS Flower Farms, Inc.); ATS = 2% (v:v) ammonium thiosulfate; ET = 1.5 mL·L⁻¹ (5.37% a.i.; United Phosphorus, Inc.).

^wOn 14 May 2015, all trees received a post bloom-thinning application: 100 mg·L⁻¹ 6-benzyladenine (6-BA, Exilis Plus, Fine Americas, Inc.) + 1 pint 1-naphthyl methylcarbamate (carbaryl) + 1 pint adjuvant (Level 7; Winfield Solutions, LLC).

^v1 = no visible damage; 2 = trace to 10% damage; 3 = 11 to 24% damage; 4 = 25% to 49 damage; 5 = 50% damage or greater.

^uBCSA = branch cross-sectional area.

^tFruit set = (no. fruit / no. flower clusters) × 100.

^sMean separation within columns by Tukey's honest significance test at *P* = 0.05.

ET = endothall; ATS = ammonium thiosulfate; LS = liquid lime sulfur; SO = Stylet-Oil.

Table 7. Comparison of blossom-thinning treatments on fruit number, crop density, yield, and fruit weight of seventh leaf 'Buckeye Gala'/'M.9 RN-29' apple trees in 2015.^z

Thinning treatment ^{xw}	Fruit (no./tree)	Crop density		Yield (kg/tree)	Fruit wt (g)	Fruit russet (%) ^u
		(no. fruit/cm ² TCSA) ^v				
Control	110 A ^t	4.5 a		18.6 a	170 ab	0.21 b
LS + SO	70 ab	2.7 ab		12.7 ab	180 a	0.33 ab
ATS	80 ab	3.0 ab		14.3 ab	181 a	0.62 a
ET	44 b	2.1 b		7.1 b	161 b	0.64 a

^zMeans of four observations.

^xTiming of chemical treatments were determined with the *'Gala'* pollen tube growth model. Model was initiated at 1500 HR on 30 Apr. 2015. Treatments were applied at 0600 HR on 3 May 2015 and 1100 HR on 4 May 2015.

^yLS + SO = 2% (v:v) LS (Miller Chemical and Fertilizer, LLC) and 2% (v:v) Stylet-Oil (JMS Flower Farms, Inc.); ATS = 2% (v:v) ammonium thiosulfate; ET = 1.5 mL·L⁻¹ (5.37% a.i.; United Phosphorus, Inc.).

^wOn 14 May 2015, all trees received a post bloom-thinning application: 100 mg·L⁻¹ 6-benzyladenine (6-BA, Exilis Plus, Fine Americas, Inc.) + 1 pint 1-naphthyl methylcarbamate (carbaryl) + 1 pint adjuvant (Level 7; Winfield Solutions, LLC).

^vTCSA = trunk cross-sectional area.

^uFruit russet = visual estimate of apple peel that exhibited russet. A 20-fruit sample was evaluated from each tree.

^tMean separation within columns by Tukey's honest significance test at *P* = 0.05.

ET = endothall; ATS = ammonium thiosulfate; LS = liquid lime sulfur; SO = Stylet-Oil.

general, higher ET concentrations increased the effect of fruit flattening (Bound and Jones, 1997).

Return bloom was not influenced by any treatment (data not presented). ‘Gala’ is an annual bearing cultivar and all treatments had suboptimal crop loads in 2014. Blossom-thinning treatments did not influence flower bud mortality in the year after treatment (data not presented). Blossom-thinning treatments improved freeze tolerance of peach flower buds in the following year (Byers and Marini, 1994; Edgerton, 1948), but no such evidence exists for apple.

Conclusions

When compared with later crop load management strategies, blossom thinning has the greatest potential to increase fruit size (Lakso et al., 1996), and can promote return bloom in the following season (Batjer, 1965; Bobb and Blake, 1938). In our opinion, if blossom thinning is to be adopted in the eastern United States, partial crop load reduction is the desired outcome. Unpredictable weather conditions during apple bloom, particularly the risk of spring frosts, are possible in the east. While using the PTGM as a timing aid, none of the chemistries evaluated over-thinned or increased fruit injury to commercially unacceptable levels. Also, initial fruit set was reduced by compounds that were proven to inhibit pollen tube growth *in vivo*, which is a desirable outcome. Limited fruit injury was attributed to favorable drying conditions, which minimized the amount of time that spray solutions rested on the fruit surface.

Although a significant thinning response was observed with HT in consecutive years, this practice would be labor intensive, time sensitive, and could increase risk of mechanical transfer of the fire blight pathogen, *Erwinia amylovora*. Chemical thinners with potential multisite action had the greatest thinning effects in this trial. LS + SO, an Organic Materials Review Institute approved combination, was a promising thinning treatment and resulted in a near ideal crop load and increased fruit weight in one of 2 years. In addition to inhibiting pollen tube growth *in vivo*, LS can reduce Pn, and multiple applications can prolong the duration of Pn reduction (McArtney et al., 2006). ET reduced crop load in all experiments, and negatively affected fruit size of ‘Gala’, but not ‘Golden Delicious’. The documented leaf injury and subsequent leaf abscission observed with ET likely had a negative effect on Pn. Pn was not measured in this experiment, but the limited influence of ET on pollen tube growth and initial fruit set suggest that an additional stress was imposed. Perhaps the partial reduction in primary spur leaf area reduced fruit set (Ferree and Palmer, 1982). ATS was effective in reducing pollen tube growth and initial fruit set in ‘Golden Delicious’ and ‘Gala’, but did not reduce whole-tree crop density. NAD had limited efficacy on ‘Golden Delicious’ at the concentration and application timings used in this trial.

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