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Bloom and Postbloom Thinner Effects and Interactions on 'Gala' Fruit Growth Rate, Return Bloom, and Yield Responses at Three Locations

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Abstract. **Multistep chemical thinning programs have been widely recommended in the eastern United States; however, adoption of bloom thinners is limited. With caustic blossom thinners, narrow effective application timings and concerns related to spring frost damage are barriers for commercial use in this region. If effective and safe, use of hormonal blossom thinners for apple would be an attractive alternative. We evaluated the effects and interactions of bloom thinners [6-benzyladenine (BA) and lime sulfur (LS, or calcium polysulfide) + stylet oil (LS+SO)] and a postbloom thinner (NAA) in the context of a multistep, carbaryl-free thinning program across three locations. Experiments were conducted in 2017 and 2018 on mature 'Gala' in North Carolina, Massachusetts, and Pennsylvania, USA. In four of six studies, BA at bloom increased the efficacy of postbloom NAA and reduced crop density ($P < 0.08$). Postbloom NAA generally increased fruit relative growth rate (RGR) and reduced crop density. However, where NAA failed to reduce crop load, there was a negative influence on RGR. BA and LS+SO increased RGR in one of six studies; however, BA was generally ineffective as a blossom thinner, whereas LS+SO was more effective. Nevertheless, BA applied at bloom may have utility as part of a multistep thinning program. As a part of a multistep thinning program, BA applied at bloom may be useful in increasing efficacy of postbloom applications, particularly when use of caustic blossom thinners is not permitted.**

The intentional removal (thinning) of blossoms and/or fruitlets is a critical management practice in apple (*Malus ×domestica* L. Borkh.) production. Excessive crop load results in high yields of low-quality fruit and inadequate return bloom the following year. Application of agrichemicals to thin blossoms (blossom thinners) and/or fruitlets (postbloom thinners) is the most efficient method available to growers to reduce crop load. Chemical thinning occurs during a 3- to 4-week period in the spring, from anthesis to ~24-mm fruitlet diameter. After this period, remedial hand-thinning is the only effective method. Hand-thinning is labor-intensive, expensive, and provides decreased returns of fruit size and return bloom compared with earlier chemical thinning. Therefore, effective chemical thinning can have substantial economic impacts (Schupp et al. 2008)

Fruit are mainly heterotrophic and are a major sink for carbohydrates (Blanke and Lenz 1989). Early thinning often results in increased fruit size, as more carbohydrates are directed to persisting fruit (Dash et al. 2013; Lakso et al. 1996). Blossom thinning is the first opportunity in the season for growers to chemically thin. Currently available chemical blossom thinners can be grouped as either caustic or hormonal. In general, caustic blossom thinners are applied after a desired number of flowers have been fertilized; therefore, application timing is critical (Kon and Schupp 2018). Lime sulfur (LS, or calcium polysulfide) is one of the most consistent caustic blossom thinners available (Schmidt et al. 2011) and is often mixed with fish or petroleum-based oil to increase thinning efficacy and consistency (Schupp et al. 2005). LS thinning programs have a longer period of activity relative to other caustic bloom thinners (Schmidt and Elfving 2007). LS has multiple sites of action, including inhibition of pollen tube growth in vivo (Embree and Foster 1999; Kon et al. 2018; Yoder et al. 2009) and photosynthesis (McArtney et al. 2006). McArtney et al. (2006) found that photosynthetic capacity was decreased at least 57 d after three LS applications. While leaf function was impaired for 4 to 10 d after LS application in WA, photosynthetic recovery rates were much slower in eastern production areas (Schmidt and Elfving 2007). LS has been registered as a blossom thinner in the Pacific Northwest since 2003, and specific formulations of LS were registered in 2019 as blossom thinner in several eastern and midwestern states.

Hormonal (plant bioregulators, PBRs) blossom thinner efficacy is not dictated by flower fertilization, allowing application over a longer time during the bloom period. Synthetic auxins—1-naphthaleneacetic acid (NAA) and naphthaleneacetamide (NAD)—have thinning activity when applied before petal fall (Irving et al. 1989; Greene et al. 2015). Ethephon [(2–chloroethyl)-phosphonic acid], an ethylene inducing compound, is an inconsistent blossom thinner (Wertheim 2000) and is more effective at >18-mm fruit diameter. A recently registered PBR, 1-aminocyclopropene (ACC), can be used during bloom. However, most research with ACC has focused on postbloom thinning applications. Development of reliable hormonal blossom thinners with flexibility of application timing and limited phytotoxicity would allow more growers to gain the benefits from early thinning.

In the eastern United States, postbloom thinning is more common than blossom thinning. Postbloom thinners have efficacy from petal fall (~6 mm fruitlet diameter) until fruitlets reach ~20 mm in diameter. Synthetic auxins, 6-benzyladenine, insecticidal carbamates, and ethylene inducing compounds are among the array of PBRs with thinning efficacy during this period. NAD has mild thinning activity when applied at petal fall (Greene 2009). NAA and 6-benzyladenine (BA), a cytokinin, are widely used postbloom thinners. NAA and BA have greatest efficacy when applied at 8 to 12 mm (Greene 2009; Greene et al. 2016). Insecticidal carbamates—carbaryl (1-naphthyl methylcarbamate) and oxamyl (oximino oxamyl)—have mild thinning activity throughout the postbloom thinning period (Dennis 2000). Carbaryl is frequently used to increase the thinning activity of NAA, BA, and ethephon and is a critical component of US chemical thinning programs (Dennis 2000). However, carbaryl has been banned or restricted in several international and domestic markets due to concerns related to pollinator health. As a result, the development of new chemical thinning programs and products has been a research priority.

Several new chemical thinners are under development or recently commercialized.

Many of these products do not require supplemental use of carbaryl for sufficient thinning activity. Abscisic acid is mild thinner that is most effective in combination with other products (Cortens and Cline 2019). Metamitron is a photosynthetic inhibitor with thinning activity when applied at ~10 to 20 mm (Basak 2011; McArtney and Obermiller 2012). To date, metamitron is registered as a postbloom thinner in several countries but not the United States. Registration is anticipated for 2024. The precursor to ethylene, ACC, was registered in 2021. ACC is effective as a late postbloom thinner [>15 mm (Greene 2002; McArtney and Obermiller 2012; Schupp et al. 2012)] and can be used from late bloom to 25 mm. Unlike ethephon, ACC does not require carbaryl to enhance activity.

Apple fruit growth follows a expolinear pattern with a rapid increase shortly after fertilization to ~30 d after full bloom (DAFB) followed by a linear phase until harvest (Lakso et al. 1995). Cell division occurs from ~8 to 30 DAFB (Malladi and Johnson 2011). After this period, fruit size is mainly dictated by cell expansion rates. Increasing cell division rates increases fruit size potential. By reducing early competition, blossom thinning can enhance fruit size potential compared with postbloom thinning. As a postbloom thinner, BA increases fruit size beyond the reduction in competition by directly stimulating cell division (Wismer et al. 1995). Chemistries to increase cell division early in fruit development could increase apple fruit size potential and crop value.

Spring weather conditions and postbloom chemical thinner responses are generally erratic in the eastern United States. The risk of crop loss due to spring freezes, narrow application window, and damage to spur leaves limits widespread adoption of caustic blossom thinners. Fruitlet abscission and postbloom thinner efficacy is influenced by carbohydrate status of the tree. Additionally, abiotic factors such as solar radiation and temperature correlate to abscission rates (Lordan et al. 2019). This variability necessitates a multistep thinning approach requiring multiple chemical thinner applications during the bloom and postbloom period (Stover et al. 2002). Development of a hormonal blossom thinner would be an important step in this multistep program because it would not be dependent of flower fertilization, allowing for greater flexibility of application timing and less damage to spur leaves than caustic blossom thinners.

Limited information is available regarding use of BA as an apple blossom thinner in the eastern United States. The objective of the current study was to investigate BA as a blossom thinner in a multistep thinning program without the use of carbaryl throughout the eastern United States. Efficacy of bloom and postbloom thinners were tested across a 2-year period at three locations (North Carolina, Massachusetts, and Pennsylvania).

Materials and Methods

Plant material and treatments. Experiments were conducted in 2017 and 2018. Across all locations, trees were trained to tall spindle canopy architecture and received plant protectant sprays that adhered to local recommendations throughout the growing season. Orchards were managed with conventional pesticide and fertilizer inputs that adhered to local recommendations. Single-tree plots were separated from adjacent plots by at least one buffer tree. Treatments were assigned in a randomized complete block design with six replications, and trees were blocked by blossom cluster density. In North Carolina, mature 'Banning Gala'/M.9 trees planted at the Mountain Horticultural Crops Research and Extension Center in Mills River, NC, USA (lat. 35.428079°N, long. 82.563295°W, elevation 649 m) at 0.9 × 4.0 m spacing were used. In Pennsylvania, experiments were conducted in a mature 'Simmons Gala'/M.9 trees planted at the Fruit Research and Extension Center in Biglerville, PA, USA (lat. 35.560471°N, long. 77.151871°W, elevation 220 m) at 1.2 × 4.3 m spacing. Massachusetts experiments were conducted in a mature 'Simmons Gala'/'Budagovsky 9' planted at the UMass Cold Spring Orchard in Belchertown, MA (lat. 42.25367°N, long. 72.35981°W, 198 m) at 0.9 × 3.7 m spacing.

In 2017, the following treatments were applied: 1) an untreated control, 2) 6-BA (MaxCel®; Valent BioSciences, Libertyville, IL, USA) at 100 mg·L^{-1} applied at full bloom, 3) a postbloom (~10-mm fruit diameter) application of NAA (PoMaxa®; Valent BioSciences) at 10 mg·L^{-1}, and 4) 6-BA at 100 mg·L^{-1} applied at full bloom + NAA at 10 mg·L^{-1} (Table 1). All treatments were applied in an aqueous solution and NAA included a 0.125% (v/v) nonionic surfactant (Regulaid®; Kalo, Inc., Overland Park, KS, USA). In 2018, liquid lime sulfur [LS (Lime Sulfur Solution™; NovaSource, Phoenix, AZ, USA)] and stylet oil [SO (JMS Stylet Oil®; JMS Flower Farms Inc., Vero Beach, FL, USA)] at 2% + 2% (v/v) was added as a bloom treatment both alone and in combination with postbloom NAA in Pennsylvania and North Carolina (Table 1). The timing of LS+SO applications was dictated by a pollen tube growth model (Kon et al. 2018; Yoder et al. 2009). Treatments were applied by handgun or tractor-mounted air blast sprayers using tree row volume calibrated to apply 935 L·ha^{-1} of water to simulate a dilute spray.

Fruit relative growth rate. At petal fall, 10 uniform, well-exposed spurs on 2- to 3 year-old wood were selected and tagged. All fruit on each spur were labeled. Fruit diameter was measured with digital calipers a minimum of four times: at petal fall, ~7 d after NAA application, 14 d after NAA application, and after June drop. Fruit were measured at their widest point. Relative fruit growth rate (RGR) was determined on fruit that persisted throughout the course of the experiment using the following equation:

$$RGR = [\ln(D2) - \ln(D1)]/T2 - T1$$

D2 and D1 are fruit diameter (mm) at two time points, T2 and T1.

Yield responses and return bloom. At pink bud stage, two to three uniform limbs per tree were selected and flagged. The number of blossom clusters per limb were counted and recorded. Basal limb circumference was measured and used to determine limb cross-sectional area (LCSA). After June drop, all fruit were counted on limbs, and fruit set was calculated based on the number of fruit/cm^2 LCSA. At commercial maturity, all fruit were harvested and crop density [number of fruit/cm^2 trunk cross sectional area (TCSA)], yield, and fruit weight was determined. The following spring, return bloom was determined by counting the number of blossom clusters on two to three representative limbs and expressing the number of blossom clusters per square centimeter LCSA. Return bloom was assessed across both years in Pennsylvania and North Carolina, but not Massachusetts.

Data analysis. The statistical software R (R Core Team 2022) was used for all data analysis. For 2017 data, responses of fruit set (no. fruit/cm^2 LCSA), RGR (mm·mm^{-1}·d^{-1}), return bloom (no flower clusters/cm^2 LCSA),

Table 1. Factorial treatment structure of chemical thinner application timing (bloom and postbloom) of study conducted in 'Gala' apple (*Malus ×domestica* borkh L.). In 2017 at bloom, trees were either untreated (None) or treated with 100 mg·L^{-1} 6-benzyladenine (BA). In 2018 at bloom, a treatment of liquid lime sulfur (2%) plus stylet oil (2%)—LS+SO—was compared with None and BA. In both years, at postbloom timing (~10 mm) trees were either none or treated with 10 mg·L^{-1} naphthalene acetic acid (NAA).

Bloom	Postbloom
2017	
None	None
BA	None
None	NAA
BA	NAA
2018	
None	None
BA	None
LS+SO	None
None	NAA
BA	NAA
LS+SO	NAA

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Table 2. Relative growth rate [RGR ($mm \cdot mm^{-1} \cdot d^{-1}$)] of fruitlets that ultimately persisted throughout the measurement period. Study conducted in Mills River, NC, USA; Biglerville, PA, USA; Belchertown, MA, USA. At bloom, treatments were either untreated (none), 6-benzyladenine (BA) in 2017 and 2018, or lime sulfur plus stylet oil (LS+SO) in (2018). At ~10 mm timing (postbloom), trees were either untreated or treated with naphthalene acetic acid (NAA). Mean separation conducted with Tukey's honestly significant difference (HSD). Significance determined at $P = 0.05$.

	RGR ($\times 10^{-3}$)			
	2017			
	North Carolina			
Treatment	Mean ± *SE* 18 to 25 DAFB	Mean ± *SE* 25 to 32 DAFB	Mean ± *SE* 32 to 70 DAFB	Mean ± *SE* —
Bloom				
None	65.6 ± 0.9	41.6 ± 0.6	19.6 ± 0.1 B	—
BA	67.8 ± 0.8	41.6 ± 0.5	20.0 ± 0.1 A	—
P value	0.050	0.995	0.027	—
Postbloom				
None	67.9 ± 0.7	41.5 ± 0.5	19.6 ± 0.1 B	—
NAA	65.3 ± 0.9	41.7 ± 0.6	20.1 ± 0.1 A	—
P value	0.029	0.828	<0.001	—
Bloom, postbloom				
None, none	65.6 ± 1.0 B	40.2 ± 0.7 B	19.4 ± 0.2	—
BA, none	69.9 ± 1.0 A	42.8 ± 0.6 A	19.7 ± 0.2	—
None, NAA	65.6 ± 1.5 B	43.3 ± 0.9 A	19.1 ± 0.2	—
BA, NAA	65.1 ± 1.2 B	40.1 ± 0.8 B	20.0 ± 0.2	—
P value	0.048	<0.001	0.803	—
	Massachusetts			
Treatment	Mean ± *SE* 13 to 21 DAFB	Mean ± *SE* 21 to 28 DAFB	Mean ± *SE* 28 to 35 DAFB	Mean ± *SE* 35 to 62 DAFB
Bloom				
None	58.7 ± 1.2	47.1 ± 1.5	42.6 ± 1.1	42.6 ± 1.1
BA	58.6 ± 0.6	44.8 ± 0.8	42.1 ± 0.8	42.1 ± 0.8
P value	0.828	0.077	0.759	0.033
Postbloom				
None	57.9 ± 1.1	46.3 ± 1.5	41.5 ± 0.9	41.5 ± 0.9
NAA	59.5 ± 0.5	45.5 ± 0.6	43.4 ± 1.0	43.4 ± 1.0
P value	0.211	0.583	0.181	0.227
Bloom, postbloom				
None, none	57.7 ± 2.4	47.8 ± 2.8	42.0 ± 1.3	21.6 ± 0.5A
BA, none	58.1 ± 0.7	44.9 ± 1.2	41.0 ± 1.1	19.8 ± 0.5 B
None, NAA	59.8 ± 0.6	46.4 ± 0.9	43.2 ± 1.7	21.2 ± 0.4 AB
BA, NAA	59.2 ± 0.9	44.6 ± 0.8	43.6 ± 1.0	21.3 ± 0.4 AB
P value	0.764	0.770	0.626	0.034
	RGR ($\times 10^{-3}$)			
	2017			
	Pennsylvania			
Treatment	Mean ± *SE* 17 to 24 DAFB	Mean ± *SE* 24 to 32 DAFB	Mean ± *SE* 32 to 39 DAFB	Mean ± *SE* 39 to 53 DAFB
Bloom				
None	47.2 ± 0.5	40.6 ± 1.1	16.2 ± 1.2	8.3 ± 0.9 B
BA	48.2 ± 0.5	41.9 ± 0.8	18.7 ± 1.1	11.2 ± 0.8 A
P value	0.232	0.258	0.117	0.033
Postbloom				
None	47.9 ± 0.3	40.7 ± 0.6	20.5 ± 1.1 A	11.8 ± 0.8 A
NAA	47.6 ± 0.7	41.9 ± 1.2	14.2 ± 1.2 B	7.7 ± 0.9 B
P value	0.683	0.356	<0.001	<0.001
Bloom, Postbloom				
None, none	47.7 ± 0.4	39.9 ± 0.7	18.5 ± 1.4	9.7 ± 1.1
BA, none	47.9 ± 0.5	41.4 ± 1	22.3 ± 1.6	13.7 ± 1.1
None, NAA	46.7 ± 1	41.4 ± 2.2	13.7 ± 1.9	6.8 ± 1.4
BA, NAA	48.5 ± 0.9	42.4 ± 1.1	14.6 ± 1.5	8.5 ± 1.2
P value	0.282	0.871	0.361	0.308
	2018			
	North Carolina			
Treatment	Mean ± *SE* 19 to 30 DAFB	Mean ± *SE* 30 to 35 DAFB	Mean ± *SE* 35 to 70 DAFB	Mean ± *SE* —
Bloom				
None	75.1 ± 0.6 B	42.5 ± 0.6 B	20.2 ± 0.1 B	—
BA	75.1 ± 0.8 B	43.2 ± 1.2 B	20.2 ± 0.2 B	—
LS+SO	84.1 ± 0.8 A	47.4 ± 1 A	21.6 ± 0.2 A	—
P value	<0.001	<0.001	<0.001	—

(Continued on next page)

Table 2. (*Continued*)

Treatment	2018 North Carolina Mean ± *SE* 19 to 30 DAFB	Mean ± *SE* 30 to 35 DAFB	Mean ± *SE* 35 to 70 DAFB	Mean ± *SE* —
Postbloom				
None	77.7 ± 0.6	44.6 ± 0.7	20.1 ± 0.1 B	—
NAA	77.5 ± 0.8	43.1 ± 0.1	21.4 ± 0.2 A	—
P value	0.303	0.103	<0.001	—
Bloom, postbloom				
None, none	75.5 ± 0.6 C	42.2 ± 0.7	19.9 ± 0.1	—
BA, none	73.9 ± 1.0 C	44.2 ± 1.5	19.5 ± 0.1	—
LS+SO, none	86.0 ± 0.9 A	49.2 ± 1.2	21.3 ± 0.2	—
None, NAA	74.1 ± 1.2 C	43.1 ± 1.4	20.8 ± 0.4	—
BA, NAA	77.3 ± 1.2 BC	41.4 ± 1.8	21.3 ± 0.3	—
LS+SO, NAA	81.2 ± 1.3 B	44.9 ± 1.7	22.1 ± 0.3	—
P value	<0.001	0.135	0.0538	—

RGR ($\times 10^{-3}$)

Treatment	2018 Massachusetts Mean ± *SE* 11 to 17 DAFB	Mean ± *SE* 17 to 24 DAFB	Mean ± *SE* 24 to 43 DAFB	Mean ± *SE* —
Bloom				
None	85.0 ± 1.7	62.5 ± 1.7	31.1 ± 0.3	—
BA	86.9 ± 1.9	62.3 ± 1.8	30.3 ± 1.0	—
LS+SO	—	—	—	—
P value	0.557	0.945	0.353	—
Postbloom				
None	87.4 ± 0.8	58.7 ± 0.7 B	30.2 ± 0.4	—
NAA	82.9 ± 0.3	67.3 ± 2.8 A	31.8 ± 0.6	—
P value	0.123	0.001	0.012	—
Bloom, postbloom				
None, none	87.7 ± 0.7	58.1 ± 0.7	29.9 ± 0.4 B	—
BA, none	86.5 ± 2	60.4 ± 1.8	30.9 ± 0.7 AB	—
LS+SO, none	—	—	—	—
None, NAA	81.7 ± 3.7	67.7 ± 3.4	32.4 ± 0.4 A	—
BA, NAA	87.5 ± 3.8	65.5 ± 3.8	29.4 ± 2.3 B	—
LS+SO, NAA	—	—	—	—
P value	0.283	0.486	0.008	—

Treatment	Pennsylvania Mean ± *SE* 10 to 24 DAFB	Mean ± *SE* 24 to 31 DAFB	Mean ± *SE* 31 to 41 DAFB	Mean ± *SE* 41 to 45 DAFB
Bloom				
None	70.2 ± 1.3	25.0 ± 1.6	23.9 ± 1.1	20.4 ± 1.1
BA	72.1 ± 1.5	24.2 ± 1.5	20.0 ± 1.7	21.2 ± 1.8
LS+SO	71.3 ± 0.3	26.5 ± 3.4	20.7 ± 3.0	25.4 ± 3.1
P value	0.648	0.736	0.183	0.213
Postbloom				
None	69.2 ± 1.0	21.8 ± 1.2	20.6 ± 1.4	20.8 ± 1.8
NAA	73.1 ± 1.6	28.0 ± 1.7	22.9 ± 1.4	22.3 ± 1.0
P value	0.043	0.003	0.408	0.642
Bloom, postbloom				
None, none	67.3 ± 1.4	20.9 ± 2.0	24.1 ± 0.8	20.1 ± 1.3
BA, none	70.6 ± 1.3	22.1 ± 1.5	18.3 ± 2.2	19.5 ± 2.4
LS+SO, none	67.2 ± 4.8	23.9 ± 5.7	22.1 ± 4.7	33.4 ± 13.5
None, NAA	72.1 ± 1.9	27.9 ± 2.2	23.7 ± 1.9	20.5 ± 1.7
BA, NAA	75.6 ± 3.8	29.0 ± 3.0	23.9 ± 1.8	25.4 ± 1.5
LS+SO, NAA	72.6 ± 3.7	27.4 ± 4.2	20.3 ± 3.7	23.0 ± 1.3
P value	0.994	0.865	0.347	0.055

DAFB = days after first bloom; *SE* = standard error. Treatments within a column with differing letters are statistically different according to Tukey's HSD at $P < 0.05$.

and harvest parameters [no. fruit/cm^2 TCSA, fruit weight (g), total yield (kg/tree)] were analyzed as a location (3) × blossom thinner (2) × postbloom thinner (2) factorial. For 2018, when LS+SO was added to blossom thinner timing, this treatment structure was 3 × 3 × 2. In all cases, the main effect of location was significant, and data were analyzed within each location (Massachusetts, North Carolina, and Pennsylvania). Within each location, the interaction and main effects of bloom and postbloom thinner were tested with ANOVA. Tukey's honest significant difference was performed to separate treatments. All significance was tested at a level of $P = 0.05$.

Results

Fruit relative growth rate. RGR responses varied by year, location, and measurement interval during early fruit development. In 2017, the interaction between bloom and postbloom thinner was significant for RGR in North Carolina (Table 2) from 18 to 25 DAFB [RGR_1 ($P < 0.05$)] and 25 to 32 DAFB [RGR_2 ($P < 0.001$)], but not 32 to 70 DAFB [RGR_3 ($P = 0.803$)]. Faster growth rates were observed at RGR_1 with BA alone when compared with all other treatments (7% increase relative to the control). At RGR_2, BA alone and NAA alone increased RGR relative to the control and BA + NAA ($P < 0.05$). For RGR_3,

BA and NAA increased RGR independently (~2% increase).

The effect of bloom, postbloom, and the interaction between bloom and postbloom thinner did not influence RGR in Massachusetts across three of four intervals. From 35 to 62 DAFB (RGR_4), the interaction of bloom and postbloom thinner was significant ($P < 0.05$). There, BA reduced RGR relative to all other treatments by ~7%.

In Pennsylvania, the main effects of bloom and postbloom thinner and the interaction did not influence RGR from 17 to 24 DAFB (RGR_1) and 24 to 32 DAFB (RGR_2). From 32 to 39 DAFB (RGR_3), the main effect of postbloom thinner was significant, and NAA reduced RGR by 31%. A 35% reduction in RGR with NAA was also observed during RGR_4 (39 to 53 DAFB), whereas BA increased RGR by 26%.

In 2018, the interaction between bloom and postbloom thinner was significant for RGR in North Carolina from 19 to 30 DAFB [RGR_1 ($P < 0.001$)]. For RGR_1, LS+SO alone resulted in the highest RGR (12% increase relative to the control), followed by LS+SO + NAA (7% increase). All other treatments did not differ from the control. From 30 to 35 DAFB (RGR_2), only the main effect of bloom thinner influenced RGR ($P = 0.001$). For RGR_2, trees treated with LS+SO at bloom had a higher growth rate than untreated and BA treated (>10% increase). Both main effects influenced RGR 35 to 70 DAFB [RGR_3 ($P < 0.05$)] and LS+SO and NAA independently increased RGR by 6%.

In Massachusetts, the main effects of bloom and postbloom thinner and their interaction were not significant in 2018 from 11 to 17 DAFB (RGR_1). From 17 to 24 DAFB (RGR_2), NAA increased RGR by 13% ($P < 0.01$). The interaction between bloom and postbloom thinner had a significant effect on RGR from 24 to 43 DAFB [RGR_3 ($P < 0.01$)]. Postbloom NAA increased RGR relative to BA + NAA (11%) and the control (8%), but not BA alone.

In Pennsylvania, neither the interaction nor the main effect of bloom thinner influenced RGR across any measurement date in 2018. Postbloom NAA increased growth rate during RGR1 and RGR_2 (5% and 22%, respectively).

Crop density. Crop density responses were variable across year and location (Table 3). The interaction between bloom and postbloom thinner on crop density was not significant at $\alpha = 0.05$ at any location in both years. However, P values were <0.08 across all locations in 2017 [$P = 0.073$ (North Carolina), $P = 0.075$ (Pennsylvania), and $P = 0.079$ (Massachusetts)]. In 2017, crop density was influenced by postbloom thinner (North Carolina, 29% reduction), bloom thinner (Pennsylvania, 19% reduction), or there was no relationship (Massachusetts).

Relatively low crop densities were reported in Pennsylvania, as a hailstorm on 10 May 2018 reduced fruit set across all treatments. In 2018, the interaction between bloom and postbloom thinner in North Carolina and Pennsylvania did not influence crop density but was nearly significant in Massachusetts at ($P = 0.056$). For Massachusetts, mean separation was performed for the interaction between bloom and postbloom thinner (not presented). There, trees receiving BA + NAA resulted in the lowest crop load at 3.23 fruit/TCSA, which was numerically less than NAA alone at 6.35 fruit/cm^2 TCSA ($P = 0.088$). Trees receiving postbloom thinner had significantly lower crop density than BA alone and the control. In North Carolina, the postbloom NAA reduced crop density by 34%. At bloom, trees receiving LS+SO resulted in 11.1 fruit/cm^2 TCSA, which was numerically less than trees untreated [15.3 fruit/TCSA ($P = 0.0520$)] and BA [13.5 fruit/TCSA ($P = 0.337$)] (Table 3). In Pennsylvania, LS+SO reduced crop density when compared with untreated (53%, $P < 0.01$) and BA (44%, $P < 0.05$). Postbloom NAA reduced crop density by 34%.

Fruit weight. In general, fruit weight at harvest was increased with treatments that reduced crop load (Table 4). In North Carolina, the interaction between bloom and postbloom thinner influenced fruit weight in both years. In 2017, BA + NAA increased fruit weight in North Carolina (139.3 g) relative to BA alone (113.7 g) and the control (115.9 g). BA + NAA did not increase fruit weight relative to NAA alone (121.8 g; $P = 0.082$). In Massachusetts, neither bloom ($P = 0.243$) or postbloom thinner ($P = 0.077$), nor their interaction ($P = 0.119$), influenced fruit weight. However, trees receiving NAA at postbloom timing were numerically larger than untreated (10.0 g; $P = 0.077$). In Pennsylvania, the interaction between bloom and postbloom thinner was not significant ($P = 0.343$), but the main effect of postbloom thinner was significant ($P < 0.05$). BA treated fruit were 12.0 g larger than untreated at bloom ($P = 0.055$). NAA treated fruit were 13.3 g larger than untreated fruit during postbloom ($P < 0.05$).

In 2018, treatments that included a bloom and postbloom thinners generally increased

Table 3. Summary statistics of crop density [no. fruit/cm^2 (TCSA)] at harvest in 2017 and 2018. Main effects and interaction of bloom and postbloom thinner tested with analysis of variance. At bloom treatments were either untreated (none), 6-benzyladenine (BA) in 2017 and 2018, or lime sulfur plus stylet oil (LS+SO) in 2018. At 10-mm fruit diameter, trees were either untreated or treated with naphthalene acetic acid (NAA). Mean separation conducted with Tukey's honestly significant difference (HSD). Significance determined at $P = 0.05$. Study conducted in Mills River, NC, USA (NC); Biglerville, PA, USA (PA); and Belchertown, MA, USA (MA).

	No. fruit/cm^2 TCSA		
	2017		
Treatment	NC Mean ± *SE*	MA Mean ± *SE*	PA Mean ± *SE*
Bloom			
None	12.5 ± 0.6	22.1 ± 1.32	7.3 ± 0.48 A
BA	11.6 ± 1.1	23.4 ± 0.88	5.9 ± 0.43 B
P value	0.343	0.429	0.044
Postbloom			
None	14.0 ± 0.8 A	23.2 ± 1.03	6.9 ± 0.44
NAA	10.0 ± 0.6 B	22.3 ± 1.22	6.2 ± 0.53
P value	<0.001	0.564	0.248
Bloom, Postbloom			
None, none	13.6 ± 1.0	21.2 ± 1.38	7.1 ± 0.83
BA, none	14.4 ± 1.2	25.2 ± 1.04	6.8 ± 0.37
None, NAA	11.4 ± 0.5	23.1 ± 2.33	7.5 ± 0.54
BA, NAA	8.7 ± 0.8	21.5 ± 0.95	5.0 ± 0.58
P value	0.073	0.079	0.075
	2018		
Treatment	NC Mean ± *SE*	MA Mean ± *SE*	PA Mean ± *SE*
Bloom			
None	15.3 ± 1.1	9 ± 1.1	1.9 ± 0.2 A
BA	13.5 ± 1.2	7.67 ± 1.4	1.6 ± 0.2 A
LS+SO	11.1 ± 1.3	-	0.9 ± 0.2 B
P value	0.065	0.143	0.005
Postbloom			
None	16.2 ± 0.8 A	11.88 ± 0.7 A	1.8 ± 0.2 A
NAA	10.7 ± 0.7 B	4.79 ± 0.7 B	1.2 ± 0.1 B
P value	<0.001	<0.001	0.013
Bloom, postbloom			
None, none	17.4 ± 1.5	11.7 ± 1.2	2.2 ± 0.4
BA, none	16.7 ± 1.0	12.1 ± 0.7	2.0 ± 0.2
LS+SO, none	14.6 ± 1.8	—	1.2 ± 0.3
None, NAA	13.5 ± 1.2	6.4 ± 1.0	1.5 ± 0.2
BA, NAA	10.3 ± 0.9	3.2 ± 0.5	1.3 ± 0.1
LS+SO, NAA	8.2 ± 0.7	—	0.7 ± 0.2
P value	0.488	0.055	0.868

SE = standard error. Treatments within a column with differing letters are statistically different according to Tukey's HSD at $P < 0.05$.

Table 4. Summary statistics of fruit weight (g) at harvest in 2017 and 2018. Main effects and interaction of bloom and postbloom thinner tested with analysis of variance. At bloom, treatments were either untreated (none), 6-benzyladenine (BA) in 2017 and 2018, or lime sulfur plus stylet oil (LS+SO) in 2018. At 10-mm fruit diameter, trees were either untreated or treated with naphthalene acetic acid (NAA). Mean separation conducted with Tukey's honestly significant difference (HSD). Significance determined at $P = 0.05$. Study conducted in Mills River, NC, USA (NC); Biglerville, PA, USA (PA); and Belchertown, MA, USA (MA).

	Fruit wt (g)		
	2017		
Treatment	NC Mean ± *SE*	MA Mean ± *SE*	PA Mean ± *SE*
Bloom			
None	122.0 ± 2.7	89.2 ± 4.4	112.3 ± 3.4
BA	126.5 ± 4.4	95.4 ± 3.6	124.4 ± 4.9
P value	0.166	0.243	0.055
Postbloom			
None	114.8 ± 1.9 B	87.3 ± 2.4	111.7 ± 4.2 B
NAA	133.7 ± 2.8 A	97.3 ± 4.8	125.0 ± 4.0 A
P value	<0.001	0.077	0.033
Bloom, Postbloom			
None, none	115.9 ± 2.9 BC	88.4 ± 3.4	108.3 ± 6
BA, none	113.7 ± 2.6 C	86.2 ± 3.6	115.1 ± 6.1
None, NAA	128.1 ± 3.1 AB	90.0 ± 8.5	116.3 ± 2.9
BA, NAA	139.3 ± 3.6 A	104.6 ± 3.1	133.6 ± 5.7
P value	0.043	0.119	0.343
	2018		
Treatment	NC Mean ± *SE*	MA Mean ± *SE*	PA Mean ± *SE*
Bloom			
None	118.3 ± 3.0	136.0 ± 7.7	149.9 ± 4.7
BA	122.8 ± 5.9	131.1 ± 6.0	155.6 ± 4.2
LS+SO	132.5 ± 5.4	—	156.8 ± 3.3
P value	0.146	0.431	0.453
Postbloom			
None	111.7 ± 2.7	115.3 ± 4.8 B	142.9 ± 2.1
NAA	135.8 ± 3.2	151.8 ± 3.5 A	165.3 ± 2.0
P value	<0.001	<0.001	<0.001
Bloom, postbloom			
None, none	113.9 ± 4.13 C	116.4 ± 9.1	134.8 ± 1.5 C
BA, none	106.5 ± 4.7 C	114.2 ± 4.3	143.0 ± 3.0 C
LS+SO, none	116.0 ± 5.1 C	—	151.0 ± 2.5 BC
None, NAA	121.9 ± 3.9 BC	155.6 ± 5.0	165.6 ± 1.5 A
BA, NAA	139.2 ± 4.7 AB	147.9 ± 4.9	168.2 ± 2.6 A
LS+SO, NAA	146.2 ± 2.9 A	—	162.7 ± 5.3 AB
P value	0.014	0.667	0.013

Treatments within a column with differing letters are statistically different according to Tukey's HSD at $P < 0.05$.

fruit weight relative to the other treatments in North Carolina and Pennsylvania. In North Carolina, NAA alone (121.9 g) had lower fruit weight than LS+SO + NAA treated fruit ($P < 0.01$), but not fruit from BA followed by NAA treatment ($P = 0.063$). In Pennsylvania, BA followed by NAA and NAA alone were significantly larger than LS+SO alone, BA alone, and the control. LS+SO followed by NAA fruit were significantly larger than BA ($P < 0.001$) and the control ($P < 0.001$). LS+SO alone resulted in fruit significantly larger than untreated fruit (134.8 g; $P < 0.01$). In Massachusetts in 2018, only the effect of postbloom thinner was significant ($P < 0.001$). There, NAA treated fruit were 36.5 g larger than untreated ($P < 0.001$). The interaction between bloom and postbloom thinner was significant in both North Carolina ($P < 0.05$) and Pennsylvania ($P < 0.05$).

Yield. In North Carolina, only the main effect of postbloom thinner was significant across both years. NAA reduced yield by 18% and 12% (2017 and 2018, respectively) (Table 5). In 2017 in Massachusetts, neither the interaction ($P = 0.454$) nor the main effects of bloom ($P = 0.796$) and postbloom ($P = 0.59$) influenced yield. In 2018, NAA reduced yield by 50% in Massachusetts and BA had no effect. In Pennsylvania, the interaction between bloom and postbloom thinner was significant ($P < 0.05$) in 2017. NAA alone resulted in 42.7 kg/tree compared with BAA + NAA at 32.1 kg/tree ($P = 0.061$). In 2018, the main effect of bloom thinner was influential and LS+SO significantly reduced yield relative to the control (52%) and BA (47%).

Return bloom. Return bloom data were not collected in Massachusetts. The interaction between bloom and postbloom thinner was not significant for return bloom in either North Carolina or Pennsylvania in 2018 or 2019 (Table 6). In North Carolina, only the main effect of postbloom thinner was significant in 2018 and trees treated with NAA increased blossom cluster density by 56%. In Pennsylvania in 2018, following treatments from 2017, the main effect of blossom thinner was significant ($P < 0.001$). There, BA treatment resulted in 52% greater blossom density than the control.

In 2019, the main effect of bloom ($P < 0.001$) and postbloom ($P < 0.01$) influenced return bloom in North Carolina. Trees treated with LS+SO resulted in 6.6 more clusters/cm^2 LCSA than BA treated ($P < 0.001$) and 7.3 more clusters/cm^2 LCSA than untreated ($P < 0.001$) trees. Trees treated with NAA at postbloom timing increased return bloom by 3.4 clusters/cm^2 LCSA [$P < 0.05$ (Table 4)]. In Pennsylvania, the interaction ($P = 0.557$) and main effects of bloom ($P = 0.226$) and postbloom ($P = 0.270$) thinner were not significant.

Discussion

The results of this study do not support previous findings that BA increases fruit size directly (Wismer et al. 1995). BA was applied during full bloom and failed to increase RGR in four of six studies (Table 2). However, this lack of response may be attributed, in part, to the application timing of BA. Wismer et al. (1995) observed increased fruit cell layer number and subsequent fruit size with 50 or 100 mg·L^{-1} BA when treatments were applied at >10-mm fruit diameter. Apple fruit cell production is arrested ~7 d before anthesis and is reactivated between 8 to 11 d after full bloom (Malladi and Johnson 2011). Additionally, sufficient temperatures for BA activity during the bloom period may be challenging in some production regions. Yuan and Greene (2000) observed reduced Pn and increased mitochondrial respiration rates at 30 °C with increasing BA concentration but observed no effect at 20 °C. Because BA activity is temperature dependent, application during suboptimal temperatures may have limited effects on RGR and thinning activity.

LS+SO had inconsistent effects on RGR. In North Carolina, LS+SO applied at bloom increased RGR from 19 to 70 DAFB compared with BA. This increase in RGR was likely due to reduced crop density with LS+SO compared with BA. LS+SO did not influence RGR in Pennsylvania, however, hail damage may have influenced results.

Postbloom NAA increased RGR during at least one measurement interval in four of six studies. Crop density was reduced with NAA in these cases (Table 3). However, NAA reduced RGR in some situations. The most profound reduction in RGR was observed in 2017 in Pennsylvania (up to 35%). In 2017 in North Carolina, BA had a higher RGR than BA + NAA from 18 to 32 DAFB. This was after the application of NAA at 17 DAFB. In 2018, fruit treated with LS+SO alone had greater RGR than LS+SO + NAA for the measurement period directly following NAA application. These findings align with previous reports of reduced fruit growth

Table 5. Summary statistics of yield (kg/tree) following fruitlet abscission period in 2017 and 2018. Main effects and interaction of bloom and postbloom thinner tested with analysis of variance. At bloom treatments were either untreated (none), 6-benzyladenine (BA) in 2017 and 2018, or lime sulfur plus stylet oil (LS+SO) in 2018. At 10-mm fruit diameter trees were either untreated or treated with naphthalene acetic acid (NAA). Mean separation conducted with Tukey's honest significant difference (HSD). Significance determined at $P = 0.05$. Study conducted in Mills River, NC, USA (NC); Biglerville, PA, USA (PA); and Belchertown, MA, USA (MA).

	Yield (kg/tree)		
	2017		
Treatment	NC Mean ± *SE*	MA Mean ± *SE*	PA Mean ± *SE*
Bloom			
None	15.0 ± 1.0	25.6 ± 1.8	39.7 ± 2.2
BA	14.9 ± 1.0	26.2 ± 1.5	35.3 ± 2.0
P value	0.950	0.796	0.124
Postbloom			
None	16.4 ± 1.1 A	26.6 ± 1.7	37.6 ± 1.9
NAA	13.5 ± 0.6 B	25.3 ± 1.6	37.4 ± 2.4
P value	0.035	0.590	0.954
Bloom, postbloom			
None, none	15.9 ± 1.8	27.2 ± 2.9	36.8 ± 3.2 A
BA, none	16.9 ± 1.5	26.0 ± 1.9	38.4 ± 2.4 A
None, NAA	14.1 ± 1.0	24.0 ± 2.1	42.7 ± 2.7 A
BA, NAA	12.9 ± 0.8	26.5 ± 2.5	32.1 ± 2.7 A
P value	0.399	0.454	<0.039
	2018		
Treatment	NC Mean ± *SE*	MA Mean ± *SE*	PA Mean ± *SE*
Bloom			
None	24.3 ± 1.3	13.9 ± 1.2	15.1 ± 1.1 A
BA	22.6 ± 0.8	10.5 ± 1.7	13.7 ± 1.3 A
LS+SO	21.0 ± 1.0	—	7.3 ± 1.0 B
P value	0.094	0.120	<0.001
Postbloom			
None	24.2 ± 1.0 A	16.3 ± 0.7 A	13.3 ± 1.2
NAA	21.2 ± 0.6 B	8.1 ± 1.1 B	10.8 ± 1.1
P value	0.013	<0.001	0.156
Bloom, postbloom			
None, none	27.5 ± 1.1	16.9 ± 1.1	15.9 ± 1.5
BA, none	24.3 ± 1.0	15.6 ± 0.7	15.2 ± 2.1
LS+SO, none	21.0 ± 2.1	—	8.8 ± 1.7
None, NAA	21.7 ± 1.4	10.8 ± 1.2	14.4 ± 1.6
BA, NAA	20.9 ± 0.9	5.5 ± 1.2	12.2 ± 1.4
LS+SO, NAA	21.0 ± 0.9	—	5.9 ± 0.8
P value	0.092	0.089	0.858

Treatments within a column with differing letters are statistically different according to Tukey's HSD at $P < 0.05$.

rates following NAA application (Greene and Lakso 2013; Lakso et al. 2001). Understanding the interaction between environmental conditions and NAA concentration that reduce fruit RGR could have multiple applications and/or implications. NAA is used in commercial apple production as a chemical thinner, to promote return bloom, and to reduce apple preharvest drop. Additionally, NAA has been demonstrated to promote vascular function and reduce bitter pit incidence (Griffith et al. 2022). On large-fruited cultivars, reduced fruit growth rates observed with NAA may be advantageous to avoid excessive fruit size. If reduced fruit growth rates of practical significance is observed with NAA, then there is a disincentive for use as a thinner on small-fruited cultivars. However, stem-end splitting (SES) of 'Fuji' was associated with an imbalance of cell enlargement rates in the mesocarp and pericarp (Kasai et al. 2008). At present, it is unclear whether plant bioregulators can be used to modulate fruit and/or tissue growth rates to minimize stem-end splitting. Given the number of potential commercial applications of NAA on apple at multiple stages of fruit development within the course of a season, we feel that future efforts to determine effects on fruit growth rate, cell division and expansion, and gene expression of different fruit tissues with each of these NAA use patterns would be of great value.

In the current study, there is limited evidence to suggest that BA is an effective blossom thinner. Only in 2017, in Pennsylvania, did BA applied at bloom reduce crop density (Table 3). The thinning activity of BA when applied postbloom (~8 to 12 mm) has been reported extensively (Bound et al. 1991; Dennis 2000; Greene and Autio 1994; Greene et al. 1990; Yuan and Greene 2000). Timing studies have found that 14 to 20 DAFB was found to be the most effective timing of BA (Bound et al. 1991; Greene and Autio 1989). Yuan and Greene (2000) hypothesized that the mode of thinning action of BA is due to decreased carbohydrate availability attributable to increased dark respiration. This increase in dark respiration is likely due to increased shoot initiation following BA application (Greene and Autio 1990). Applications of BA at 20 DAFB had greater total shoot growth than when applied at bloom over a range of rates [50 to 400 $mg \cdot L^{-1}$ (Bound et al. 1991)].

Estimates of carbon balance have been found to correlate with fruitlet abscission rates (Lordan et al. 2019). Stored carbohydrates that support early season growth are exhausted shortly after bloom (Breen et al. 2020; Lakso and Goffinet 2017). After this point, fruitlet growth is dependent on current season photoassimilates (Lakso and Goffinet 2017). A significant carbon deficit (–59 g carbon/d) was estimated for Pennsylvania in 2017 on the day of application (data not presented). Comparatively, in North Carolina in 2017, where BA did not have an effect at bloom, estimated carbon balance was –5 g carbon/d on the day of application (data not presented). This aligns with trends of natural fruitlet abscission in 'Gala' that was correlated with carbon balance at two periods: 1) bloom to petal fall and 2) 18-mm fruitlet diameter (Lordan et al. 2019). BA may only have thinning efficacy at bloom when trees are experiencing substantial carbohydrate stress.

LS+SO reduced crop load more consistently than BA. In both instances that LS+SO was tested at bloom, North Carolina and Pennsylvania in 2018, fruit set was reduced compared with BA and untreated. LS+SO is one of the most consistent blossom-thinning chemistries available (Kon and Schupp 2018). Hormonal blossom thinners create a transient stress that induces a thinning response (Larson et al. 2022), while LS+SO has multiple sites of action (McArtney et al. 2006). The results of this study indicate that BA is not a reliable stand-alone blossom thinner compared with available options.

However, there is evidence that BA applied at bloom increased the efficacy of NAA applied postbloom. In four of six trials, BA at bloom increased the efficacy of postbloom NAA and reduced crop density if $\alpha = 0.08$ was used as a threshold. We determined that $\alpha = 0.05$ would be used in our analysis during the development of this project. However, Marini (2022) suggested that a *P* value of 0.08 is adequate evidence to reject the null hypothesis for interaction terms in the analysis of experiments with factorial treatment structures. In each location and year combination, there is a numerical decrease in crop density (7% to 50%) on trees that were treated with BA and NAA compared with just NAA alone. This decrease is present even in years and locations where BA alone resulted in numerically higher crop load than the control. For example, in Massachusetts in 2018, the control and BA alone resulted in 11.65 and 12.1 fruit/cm^2 TCSA at harvest, respectively. Trees that received NAA resulted in 6.35 and 3.23 fruit/cm^2 TCSA at harvest (NAA alone and BA+NAA, respectively). This increased efficacy of NAA after BA is

Table 6. Summary statistics of return bloom [no. blossoms/cm^2 limb cross-sectional area (LCSA)] in 2018 and 2019 following treatments in 2017 and 2018, respectively. In 2017, whole trees were either untreated (none) or treated with 6-benzyladenine (BA) at bloom. Then at about 10-mm fruit diameter, either none or treated with NAA. In 2018, the bloom timing included lime sulfur plus stylet oil (LS+SO). Significance of main effects and the interaction of bloom and postbloom thinner tested with analysis of variance. Mean separation of treatments conducted with Tukey's honestly significant difference (HSD). Significance determined at $P = 0.05$.

	No. blossom clusters/cm^2 LCSA	
	2018	
Treatment	NC Mean ± *SE*	PA Mean ± *SE*
Bloom		
None	1.5 ± 0.3	7.8 ± 0.7 B
BA	1.5 ± 0.2	15.1 ± 1.6 A
P value	0.929	<0.001
Postbloom		
None	0.9 ± 0.2 B	11.9 ± 1.35
NAA	2.1 ± 0.2 A	11.1 ± 1.9
P value	<0.001	0.650
Bloom, Postbloom		
None, none	0.9 ± 0.3	8.3 ± 1.0
BA, none	1.0 ± 0.2	15.5 ± 1.3
None, NAA	2.1 ± 0.4	7.4 ± 0.9
BA, NAA	2.1 ± 0.3	14.7 ± 3.1
P value	0.921	0.989
	2019	
Treatment	NC Mean ± *SE*	PA Mean ± *SE*
Bloom		
None	9.6 ± 1.0 B	11.8 ± 1.6
BA	10.2 ± 1.1 B	13.0 ± 1.5
LS+SO	16.9 ± 1.2 A	15.7 ± 1.7
P value	<0.001	0.226
Postbloom		
None	10.4 ± 1.2 B	12.4 ± 1.2
NAA	13.8 ± 1.0 A	14.5 ± 1.6
P value	<0.05	0.270
Bloom, postbloom		
None, none	8.2 ± 1.1	11.6 ± 2.5
BA, none	7.6 ± 0.9	12.4 ± 2.1
LS+SO, none	14.1 ± 1.5	13.2 ± 1.9
None, NAA	9.2 ± 1.0	11.9 ± 2.4
BA, NAA	14.6 ± 1.9	13.5 ± 2.3
LS+SO, NAA	19.1 ± 2.3	18.2 ± 2.5
P value	0.305	0.557

Treatments within a column with differing letters are statistically different according to Tukey's HSD at $P < 0.05$.

likely due to decreased carbohydrate availability. Again, a likely increase in dark respiration following application of BA leads to increased fruitlet abscission susceptibility of trees treated with NAA at postbloom (Greene et al. 1990).

At harvest, treatments that resulted in the lowest crop density had the greatest fruit weight (Table 4). This relationship is well established (Dash et al. 2013; Jing and Malladi 2020; Serra et al. 2016). It is notable, however, that in instances where RGR was negatively influenced during early fruit development by NAA, that fruit weight at harvest was increased. Yield was reduced by NAA in three of six studies, and by LS+SO in one of two studies (Table 5). A moderate reduction in yield is acceptable if fruit size and quality is enhanced. Although fruit quality effects were not characterized, increased fruit size was observed in all cases where yield was reduced.

The effect of crop load on return bloom has been well documented and is one of the primary benefits of thinning fruit trees (Dennis 2000; Elsysy and Hirst 2017; Serra et al. 2016). Return bloom was inversely related to crop load the previous year (Table 6). Treatments that reduced crop load resulted in increased return bloom. 'Gala' is considered annual bearing—that is, not subjected to large variations in fruiting from year to year—compared with biennial-bearing cultivars, such as Honeycrisp (Elsysy and Hirst 2017). The results of our study underscore the importance of thinning to promote return bloom, even in annual-bearing cultivars.

Conclusions

The findings of this study indicate that BA is not a potent blossom thinner. There was not a consistent decrease in crop load with BA. LS+SO was more effective at reducing crop density than BA at bloom. When BA did not have a thinning effect, there were no positive benefits of fruit size at harvest. However, as part of a multistep thinning program BA applied at bloom may have utility. There is evidence that BA at bloom can increase the efficacy of NAA applied postbloom. Bloom-applied BA may be useful for growers who are reluctant to adopt caustic blossom thinners. Further research should examine the use of BA and other PBRs at bloom to increase efficacy of postbloom thinners, with a focus on an economic analysis of these programs.

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