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Summer Applications of Plant Growth Regulators, Ethephon And 1-Naphthaleneacetic Acid, Do Not Promote Return Bloom or Reduce Biennial Bearing in Seven High-Tannin Cider Apple Cultivars

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Abstract

Biennial bearing in high-tannin cider apple cultivars (*Malus ×domestica Borkh.*) exacerbates supply chain issues for cidermakers in North America. Two experiments investigated the efficacy of using the plant growth regulators (PGRs) ethephon and 1-naphthaleneacetic acid (NAA) in midsummer (i.e., not for fruitlet thinning) to promote return bloom in cider apple trees, and effects of these PGRs on yield. One experiment was conducted over three years at a commercial orchard in Lyndonville, NY, and the other over two years at a research orchard in Lansing, NY. The Lyndonville experiment compared hand-thinning against various combinations of ethephon and NAA, while the Lansing experiment compared hand-thinning and midsummer PGR applications alone against a combination of both treatments. The Lansing experiment also assessed effects on fruit maturity and juice quality. At Lyndonville, bloom and yields followed a highly "biennial" pattern for the PGR treatments and unsprayed control, while hand thinning reduced biennial bearing index (BBI) but also reduced three-year cumulative yield (kg/tree) compared to PGR treatments and control. Cumulative yield, BBI, and return bloom were not significantly different among PGR treatments and the control for any cultivar in any year. Return bloom did not differ significantly for any treatment compared to the control following the "off" year (2017). In the two-year experiment in Lansing, neither hand thinning, PGR sprays, nor a combination of the two increased return bloom relative to the control for 'Brown Snout', while for 'Chisel Jersey', hand-thinning did significantly increase return bloom in the first year, and PGRs did promote return fruit set in the second year. The inefficacy of hand thinning and PGR sprays over a single season may be attributable to extreme long-term biennial tendencies at the Lansing orchard, which had little to no crop load management in the years preceding the experiment. Further study is needed to identify ideal crop load and application rates for bloom-promoting PGRs for these and other cider cultivars.

Introduction

Biennial bearing is a phenomenon in many perennial tree crops, comprising extreme year-to-year variations in bloom and yield. Inconsistent supply of apples due to biennial bearing is a major horticultural and supply-chain challenge to growers and cidermakers, particularly those using high-tannin cider cultivars which are particularly prone to biennial bearing (Pashow 2018; Zakalik 2021). Horticultural strategies are needed to make yields of these specialty high-tannin cultivars more annually consistent (Bradshaw et al. 2020; Hoad 1978; Merwin 2015; Miles et al. 2017; Wood 1979). The inhibitory influence of seed-derived phytohormones, primarily gibberellic acids (GAs) on return bloom in apples is well-established (Dennis and Neilsen 1999; Green 1987; Hoad 1978; Wood 1979). Biennial bearing is mediated in

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large part by seed-derived GAs, though also by other bloom-suppressing and -promoting phytohormones and the putative 'florigen' (FT) protein (Elsysy and Hirst 2019; Haberman et al. 2016; Mimida et al. 2011). In particular, GA_1, GA_3, and GA_7 are considered the main inhibitors of return bloom in apples. Besides blossom and early fruitlet thinning, growers can also counteract return bloom inhibition using plant growth regulators (PGRs) such as synthetic auxins or ethylene analogs in a non-thinning capacity in midsummer (McArtney et al. 2007; Robinson et al. 2010; Schmidt et al. 2009; Wood 1979).

The interaction between crop load and summertime PGR applications is complex and depends on many factors, including genetics, long-term bearing history of a given tree or orchard (Schmidt et al. 2009), current-year crop load, and timing and rate of application. Excessive crop load can reduce or negate the efficacy of bloom-promoting PGRs, while the absence of a crop does not necessarily make bloom-promoting PGRs more effective (McArtney et al. 2007, Schmidt et al. 2009).

Crop load is often measured as "crop density", the number of fruits borne per cm^2 trunk cross-sectional area (TCSA). Crop load is widely understood to correlate negatively with various apple juice quality measures, such as soluble solids concentration (Alegre et al. 2012; Awad et al. 2001; Guillermin et al. 2015; Musacchi and Serra 2018; Stopar et al. 2002) and titratable acidity (Henriod et al. 2011; Peck et al. 2016). The effect of crop load on phenolic concentration, an important quality attribute for cider apples, is less well-studied, particularly in high-tannin cider cultivars, though Guillermin et al. (2015) and Karl et al. (2020) found increased crop loads reduced phenolic concentrations in cider cultivars by as much as 25%. The negative effect of crop load on fruit size is well-established in the literature (Guillermin et al. 2015; Henriod et al. 2011; Robinson and Watkins 2003; Wood 1979; Zakalik 2021). Though crop load exerts these effects throughout the growing season, it is often measured at-harvest, despite being treated as a predictor variable.

The ripeness-advancing effects of both exogenous ethephon (Eth) and 1-naphthaleneacetic acid (NAA) are well-known (Cline 2019; Singh et al. 2008; Stover et al. 2003; Wendt et al. 2020). Ethephon promotes preharvest fruit drop (Singh et al. 2008; Stover et al. 2003), while the opposite is the case for NAA (Cline 2019; Dal Cin et al. 2008; Stover et al. 2003). Like crop load, the effect of PGR sprays on phenolic concentration in cider apples has been under-explored. Because phenolic synthesis in apples is thought to occur within the first 40 days after full bloom (DAFB) (Renard et al. 2007), it is currently unclear how, or whether, PGR applications in midsummer (i.e., 35–80 DAFB) affect phenolic concentration at harvest.

Crop load often has a negative effect on average fruit size, resulting in a non-linear relationship between crop density (fruit count per TCSA) and yield efficiency (yield weight per TCSA) in the same season. This often results in a "diminishing returns" or "plateau" effect; conversely, even when thinning is quite drastic, increased fruit size can compensate for potential yield weight losses due to thinning (Zakalik 2021; Wood 1979).

The objectives of our experiments were to compare the effects of hand-thinning and mid-summer PGR sprays on return bloom, and to identify PGR application programs that promote return bloom in highly biennial-bearing cider apple cultivars. Our hypotheses were: (1) hand-thinning would have a significant positive effect on return bloom; (2) PGR applications would have a significant positive effect on return bloom; and (3) hand-thinning combined with PGR sprays would be more effective at promoting return bloom than either treatment alone.

Materials and Methods

Lyndonville, NY Experiment

Experimental design. In June 2016, an experiment was initiated to investigate the effectiveness of different NAA and ethephon (Eth) spray combinations at promoting return bloom in seven high-tannin European cider cultivars. This experiment was carried out at a commercial orchard in Lyndonville, NY located near the southern shores of Lake Ontario (43.324, –78.373) on a Galen very fine sandy loam soil (Soil Survey Staff 2014). The cultivars were: 'Binet Rouge', 'Brown Snout', 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', 'Michelin', and 'Geneva Tremlett's Bitter'. ('Geneva Tremlett's Bitter' is a bittersharp cultivar of unknown provenance, mistakenly propagated as the English bittersweet cultivar 'Tremlett's Bitter'.) All trees were grafted on 'Budagovsky 9' ('B.9') rootstock and planted in 2014, at 1.2 m × 3.7 m (~2,220 trees/ha) spacing in a tall-spindle training system with a single high trellis wire and a conduit on each tree. Conventional disease, insect, and weed control were used throughout the orchard (Agnello et al. 2018). There was no irrigation applied.

The experiment was set up in a randomized complete block design with blocking based upon location within the orchard. Treatments were randomly assigned to a tree within a block, for a total of 5 treatments × 5 blocks (25 trees per cultivar). The same treatments were applied to the same trees for three consecutive years: two high-crop "on" years (2016 and 2018) and one low-crop "off" year (2017). Rates were not adjusted in the "off" year.

All trees within a cultivar were visually assessed to have similar fruit set before treatments were implemented. Each treatment tree had a buffer tree on either side, with buffer trees not overlapping, so two buffer trees separated each experimental tree from the next. Treatments were as follows: (1) non-thin control, (2) hand thinning to 6 fruit/cm^2 trunk cross-sectional area (TCSA) in mid- to late June, (3) four applications of 5 mg·L^{-1} NAA (Fruitone-L®, AMVAC, Los Angeles, CA, USA), (4) one application of 150 mg·L^{-1} ethephon (Ethephon 2®, Arysta LifeScience North America, Cary, NC, USA) followed by three applications of 5 mg·L^{-1} NAA, and (5) two applications of 150 mg·L^{-1} ethephon followed by two applications of 5 mg·L^{-1} NAA. Applications started on 29 June 2016, 22 June 2017, and 21 June 2018, and were made on approximately two-week intervals. These rates and timings were based on recommendations for 'Honeycrisp' and 'Fuji' (Agnello et al. 2018).

Full bloom dates, and thus days after full bloom for hand-thinning and PGR application dates differed slightly among cultivars and years due to weather and time constraints (data not shown, Zakalik 2021). PGR sprays were applied using a Solo® MistBlower backpack sprayer (Newport News, VA).

Bloom assessment. All blossom clusters on trees were counted using a tally counter at the "pink" stage in May 2017 and 2019 (Chapman and Catlin 1976). In Spring 2018 fruitlet clusters were counted in late June on the day of hand-thinning (Zakalik 2021), due to scheduling and labor constraints.

Trunk measurement. Tree trunk diameter was measured 40 cm above the graft union in autumn or winter of 2016, 2017, and 2018, after growth had ceased for the season. TCSA was calculated using the formula for the area of a circle.

Harvest. Pre-harvest maturity was assessed for each cultivar using fruit from non-experimental trees via the starch pattern index (SPI) assay (Blanpied and Silsby 1992) to determine appropriate harvest dates (Zakalik 2021). For cultivars with strong tendencies to pre-harvest drop, such as 'Harry Masters Jersey', fruit was harvested before horticultural maturity for cider production (i.e., at <6 SPI). Pre-harvest drops were counted and removed immediately before the fruit remaining on trees was picked. Drops were counted within the midpoints between an experimental tree trunk and its neighbors on either side. All fruits harvested from trees were counted and weighed in the field on a platform balance (Adam CPW 75, Oxford, CT).

Calculation of biennial bearing index. Biennial bearing indices (BBI) were calculated using Equation 1 below, adapted from Hoblyn et al. (1937). BBI is a unitless measure of variation in yield among consecutive year pairs. A value of 0 indicates completely consistent yields from year to year; a value of 1 indicates complete absence of fruit borne on the tree in one year. BBI was calculated on a yield mass (kg) basis.

Equation 1. $$BBI = \frac{\sum_{i=1}^{n}\left(\frac{|yield_{i+1} - yield_i|}{yield_{i+1} + yield_i}\right)}{n-1}$$

…where n is the total number of consecutive years observed.

Lansing, NY Experiment

Experimental design. This experiment was carried out at a Cornell University research orchard in Lansing, NY to investigate the efficacy of hand-thinning and PGR sprays at promoting return bloom in two high-tannin cider cultivars, 'Binet Rouge' and 'Chisel Jersey'. The orchard, located at 42.57004°, –76.59507°, was established in 2003 and is located on a hillside of 12–20 percent slope, facing southwest, leading down to Cayuga Lake, on a Hudson Cayuga silt loam (Soil Survey Staff 2014). Experimental trees were grafted onto 'Geneva 16' ('G.16'), 'G.30', and 'Malling 9' ('M.9') rootstocks. In 2016, sixteen 'Chisel Jersey'/'M.9' and eight 'Chisel Jersey'/'G.30' trees were used, with six trees assigned to each treatment. In 2017, due to insufficient bloom and fruit set, a different set of twenty-four 'Chisel Jersey' trees (sixteen on 'M.9' and eight on 'G.30') and sixteen 'Brown Snout' trees (twelve on 'M.9' and four on 'G.16') were selected, with six 'Chisel Jersey' and four 'Brown Snout' trees assigned to each treatment group. All trees within a replicated block had the same rootstock (one of the three aforementioned).

Trees were randomly assigned to one of four treatments, as follows: (1) control, (2) PGR applications, (3) hand-thinned to one fruit per cluster throughout the tree, or (4) PGR applications combined with hand thinning to one fruit per cluster throughout the tree. In 2016, the PGR treatment consisted of one application of 150 mg·L^{-1} ethephon (Ethephon 2®, Arysta LifeScience North America, Cary, NC, USA), followed by two applications of 5 mg·L^{-1} NAA (Fruitone-L®, AMVAC Chemical Corp., Los Angeles, CA, USA). In 2017, a third NAA application was added. PGR sprays were applied using a Solo® MistBlower backpack sprayer (Newport News, VA). Hand thinning and the first applications occurred approximately 5 weeks after full bloom in both years, with subsequent spray applications made on approximately two-week intervals (Zakalik 2021). These rates and timings were based on recommendations for 'Honeycrisp' and 'Fuji' (Agnello et al. 2018).

Tree selection. Trees were visually assessed for bloom. Only trees deemed to have sufficient bloom were selected for this experiment. Subsequently, several branches from each selected tree were quantitatively assessed for initial fruit set, and branch fruit set was used as a proxy for whole-tree fruit set. Treatments were randomly assigned, with blocking by fruit set.

Harvest. Harvest dates were chosen based on previously observed harvest dates for the Lansing Orchard (Zakalik 2021). Pre-harvest drops were counted and removed from under experimental trees on multiple dates before harvest, due to a prolonged drop period and large crop size. Pre-harvest drops were also counted and removed on the day of harvest before picking fruit remaining on trees. Drop counts from all dates were summed and reported as one number per tree. In 2016, all fruit harvested from the tree were counted and weighed; average fruit weight was calculated by dividing harvest weight by harvest count. In 2017, the crop was so great that counting on-tree fruit was not feasible; instead, the first 100 fruit harvested were counted and weighed, and then the remaining on-tree fruit were weighed without counting. Total on-tree fruit count was estimated by dividing total on-tree harvest weight by the average weight of 100-fruit subsets. Total tree yield weight in 2016 was estimated by multiplying average fruit weight by the total number of drops and adding the product to on-tree fruit weight. In 2017, total tree yield weight was estimated by multiplying average fruit weight by the sum of total drop count and total on-tree count.

Return bloom assessment. Bloom clusters per tree were counted in May 2017 following the first year of the experiment. Following the second year, fruit clusters per tree were counted in June 2018.

Trunk measurement. Trunk circumference was measured at 30 cm above the graft union in late autumn of 2016 and 2017 after growth had ceased for the season. Circumference was converted to TCSA using the formulae for the circumference and area of a circle.

Fruit analysis. Subsets of ten tree-harvested fruit per tree were randomly sampled and taken to Cornell University for analysis. Subsets were refrigerated at 4 °C for no more than three days until it was possible to analyze fruit maturity. Ten fruit per experimental unit were first weighed, and then visually assessed for whole-fruit peel background color or percent blush. For 'Brown Snout', which has a predominantly green-to-yellow peel, the background color was scored on a 1–5 scale where 1=yellow and 5=dark green (Evans et al. 2012). For 'Chisel Jersey', the percent surface area covered by red blush was visually estimated from 0–100%. Fruits were then assessed for flesh firmness using a penetrometer (GSFruit Texture Analyzer; Güss, Strand, South Africa) fitted with an 11.1-mm tip. Peel was removed at two opposite locations at the equator of each apple and fruit were probed once at each location. Subsequently, starch pattern index (SPI) was determined by removing equatorial wedges 5-10 mm thick and wetting with a 0.22% w/v iodine and 0.88% w/v potassium iodide (EMD Millipore Corp., Billerica, MA, USA) solution (Blanpied and Silsby 1992).

Juice extraction. The remaining fruit was diced and then ground on a Norwalk 290 (Bentonville, AR) hydraulic tabletop juicer into Good Nature filter bags (Buffalo, NY, USA), which were then pressed on the Norwalk 290 until the stream of juice became discontinuous.

Juice chemical analysis. Soluble solids concentration (SSC) was measured as ºBrix on a PAL-1 BLT digital refractometer (Omaeda, Saitama, Japan). Titratable acidity was measured on a Metrohm 809 Titrando autotitrator (Herisau, Switzerland) by titrating 5 mL juice aliquot in 40 mL ultrapure Milli-Q water (Darmstadt, Germany) against a standardized 0.1 M NaOH solution to an endpoint of pH 8.1. Acidity was reported as $g \cdot L^{-1}$ malic acid equivalent (MAE) and initial pH. Samples for these analyses, stored at –20 °C, were thawed to room temperature and homogenized via VWR Analog Vortex Mixer (Radnor, PA, USA).

Total polyphenol concentration was measured using the Folin-Ciocalteu method (Singleton et al. 1999) on a Spectramax 384 Plus microplate spectrophotometer and SoftMax Pro 7 Microplate Data Acquisition & Analysis Software (Molecular Devices, San Jose, CA). 1.5-mL vials frozen at –80 °C were thawed, vortexed, and then centrifuged at 500 g for 8 minutes. Reaction mixtures consisted of 1.5 µL of sample or standard, 34.9 µL of water and 90.9 µL of 0.2 N Folin-Ciocalteu reagent (Sigma Aldrich, Darmstadt, Germany); 72.7 µL of 7% w/v sodium carbonate buffer was added six minutes after Folin-Ciocalteu reagent. Reaction mixtures were incubated at room temperature in the dark. Reactions were carried out in Cellistar 96-well microplates (Greiner Bio-One, Monroe, NC, USA). Standards were generated using an eight-point standard curve with 0 to 3 $g \cdot L^{-1}$ gallic acid. Samples were measured at 765 nm and total polyphenol content was determined by linear regression from the standard curve plot. Results were reported as $g \cdot L^{-1}$ gallic acid equivalent (GAE).

Statistical analysis. All statistical analysis was conducted in R statistical software (R

Core Team 2014). For the Lyndonville, NY experiment, treatment averages were compared against the non-thinned control using Dunnett's Test (Dunnett and Tamhane 1992), performed via the 'DunnettTest' function in the *DescTools* package in R (Signorelli 2021). Each cultivar and each year was analyzed as a separate experiment. The Lansing, NY data were analyzed as mixed model regressions with a random block term, using the *lmer* function from the *lme4* package in R (Bates et al. 2021). Because thinning resulted in a wide range of crop densities, regression analysis of a mixed linear model was performed. Treatment averages were reported but not compared statistically. Return bloom density was regressed against the previous fall's crop density (total fruits per cm^2 TCSA). Fruit and juice quality variables, as well as yield, were regressed against the same year's crop density, treating at-harvest crop density as equivalent to crop density throughout the growing season. Yield weight was regressed against crop density to assess the nature of the relationship (linear vs. nonlinear). Regression analyses were conducted separately for each cultivar for each year of the experiment.

Results

Return bloom, Lyndonville and Lansing. At Lyndonville, hand-thinned treatment had the greatest return bloom following both high crop "on" years, 2016 and 2018, for all cultivars, and no PGR treatment had significantly different return bloom or return fruit set from the control for any cultivar in any year (data not presented, Zakalik 2021). No treatment significantly influenced return fruit set compared to the control in June 2018 (following the "off" year, 2017). Cultivars 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', and 'Michelin' had some return bloom in Spring 2017 (following the "on" year) regardless of treatment, while cultivars 'Brown Snout', 'Binet Rouge', and 'Geneva Tremlett's Bitter' had little to no return bloom in Spring 2017 unless hand-thinned in the previous "on" year. Nevertheless, 2017 bloom for the four former cultivars was low (0.9 to 8.6 clusters/cm^2 TCSA) except for the hand-thinned treatment (3.5 to 16.6 clusters/cm^2 TCSA). In Spring 2019 (following the second "on" year), 'Harry Masters Jersey' was the only cultivar that had substantial return bloom (>3 clusters/cm^2 TCSA) regardless of treatment. All other cultivars had low return bloom in Spring 2019 unless hand-thinned the previous year. Return bloom generally had a significant negative correlation with the previous harvest's crop density (Zakalik 2021).

For the Lansing experiment, Fall 2016 crop density (fruits/cm^2 TCSA) had a significant ($P=0.026$) negative linear effect on return bloom for 'Chisel Jersey' (y=14.5–1.7x), but Fall 2017 crop density had no significant effect on return fruit set for either 'Brown Snout' ($P=0.218$) or 'Chisel Jersey' ($P=0.063$) (Table 1). The PGR applications had a significant ($P=0.016$) positive effect on return fruit set for 'Chisel Jersey' in 2017, reflected in the greater return fruit set for the two PGR treatments compared to control and thin-only treatment. Return bloom and return fruit set were greater overall for 'Chisel Jersey' than for 'Brown Snout'.

Cumulative yield 2016–2018, Lyndonville. For all seven cultivars, thinning to 6 fruit/cm^2 TCSA significantly ($P<0.05$) reduced cumulative yield over three years compared to the control (Table 2). PGR treatments had equivalent cumulative yield to the control over three years. 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey' were the most productive (~21–36 kg/tree for control and PGR treatments); 'Binet Rouge' and 'Michelin' were less productive (~16–20 kg/tree for control and PGR treatments); 'Brown Snout' and 'Geneva Tremlett's Bitter' were least productive (~10–15 kg/tree for control and PGR treatments). For the Lyndonville experiment, average fruit mass was not significantly different between the control and any PGR treatment, while hand-thinned treatment increased fruit mass compared to

Table 1. Return bloom density of trees at a research orchard in Lansing, NY following Year 1 (2016), and return fruit set following Year 2 (2017) of a hand-thinning and summer plant-growth regulator (PGR) experiment. Hand thinning (Thin) consisted of reducing all fruitlet clusters to single fruitlets. The PGR treatment consisted of 150 mg·L^{-1} ethephon followed by two (2016) or three (2017) applications of 5 mg·L^{-1} 1-napthaleneacetic acid. Hand thinning and the first PGR applications occurred approximately 5 weeks after full bloom in both years, with subsequent PGR applications made on approximately two-week intervals.

	Spring 2017 Bloom Density (clusters/cm^2 TCSA)	Spring 2018 Fruitlet Density (clusters/cm^2 TCSA)	
Treatment	'Chisel Jersey'[z]	'Chisel Jersey'	'Brown Snout'
Control	2.70	4.90	0.00
Thin only	2.67	4.89	0.01
PGR Only	0.43	8.52	0.00
Thin + PGR	2.45	5.98	0.12
Crop Density	*P=0.026*[y]	*P=0.063*	*P=0.218*
PGR	*P=0.498*	*P=0.016*	*P=0.177*
Crop Density:PGR	*P=0.783*	*P=0.105*	*P=0.252*

[z] n=6 trees per treatment for 'Chisel Jersey' in both years; n=4 trees per treatment for 'Brown Snout'.
[y] P-values generated from analysis of a linear mixed effects model of return bloom or return fruit set, where previous fall's crop density (fruits/cm^2 TCSA) is a covariate and PGR is an indicator variable. Each cultivar and year analyzed separately.

Table 2. Cumulative yield (2016-2018) of seven cultivars from a three-year experiment at Lyndonville, NY. Hand thinning and the first plant growth regulator applications occurred approximately 4-6 weeks after full bloom in both years, with subsequent applications made on approximately two-week intervals. 1-napthaleneacetic acid (NAA) was applied at 5 mg·L^{-1} and ethephon (Eth) at 150 mg·L^{-1}.

	2016-2018 cumulative yield (kg/tree)						
Treatment	'Binet Rouge'	'Brown Snout'	'Chisel Jersey'	'Dabinett'	'Harry Masters Jersey'	'Michelin'	'Geneva Tremlett's Bitter'
Control	17.4[z,y]	11.5	24.0	30.9	21.1	18.0	14.6
Hand-thin (6 fruit/cm^2)	11.7*	6.1*	17.6*	17.3*	13.5*	10.9*	8.8*
NAA, NAA, NAA, NAA	17.6	14.5	24.4	24.5	17.1	19.2	10.2
Eth, NAA, NAA, NAA	18.3	12.6	27.4	23.5	23.1	19.9	12.3
Eth, Eth, NAA, NAA	17.6	10.2	29.2	36.4	24.0	16.2	14.9

[z] Significance in columns compared each treatment to the control using Dunnett's test. * *indicates significance at $P \leq 0.05$.*
[y] n=5 trees per treatment (25 trees per cultivar)

Table 3. Biennial bearing index (BBI) on a yield weight basis from a three-year experiment at Lyndonville, NY. Hand thinning and the first plant growth regulator applications occurred approximately 4-6 weeks after full bloom in both years, with subsequent applications made on approximately two-week intervals. 1-napthaleneacetic acid (NAA) was applied at 5 $mg \cdot L^{-1}$ and ethephon (Eth) at 150 $mg \cdot L^{-1}$.

	Biennial bearing index (BBI)						
Treatment	'Binet Rouge'	'Brown Snout'	'Chisel Jersey'	'Dabinett'	'Harry Masters Jersey'	'Michelin'	'Geneva Tremlett's Bitter'
Control	1.00[z,y,x]	1.00	0.65	0.65	0.47	0.98	1.00
Hand-thin (6 fruit/cm^2)	0.34***	0.31***	0.12***	0.35***	0.20***	0.44***	0.42***
NAA, NAA, NAA, NAA	0.93	1.00	0.40	0.77	0.34	0.86	1.00
Eth, NAA, NAA, NAA	0.98	1.00	0.42	0.68	0.18	0.70	1.00
Eth, Eth, NAA, NAA	0.88	1.00	0.54	0.25	0.35	0.98	1.00

[z] Significance in columns compared each treatment to the control using Dunnett's test. *** *indicates significance at $P \leq 0.001$.*
[y] n=5 trees per treatment (25 trees per cultivar).
[x] BBI (unitless) ranges from 0 to 1, with a value 0 indicating completely consistent yields, and a value of 1 indicating complete absence of a crop in at least one year.

the control for all seven cultivars in 2018, and for six of seven cultivars in 2016, with 'Harry Masters Jersey' being the exception (data not presented, Zakalik 2021).

Projected yield, 2019, Lyndonville
Though thinning increased return bloom in Spring 2019 relative to control and PGR treatments, the recorded increase was insufficient to compensate for reduced yields due to thinning in 2016–2018. Even if a crop density of 6 fruit/cm^2 TCSA had been imposed for a fourth season, cumulative yields for the thinned treatment would have been lower than for control and PGR treatments (data not presented, Zakalik 2021).

Biennial bearing, Lyndonville. Of the seven cultivars used in this experiment, 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey' bore fruit fairly regularly (BBI was relatively low) when untreated; 'Binet Rouge', 'Brown Snout', 'Michelin', and 'Geneva Tremlett's Bitter', were mostly or entirely biennial (BBI of ~1.00) (Table 3). 'Michelin' was somewhat less biennial than 'Binet Rouge', 'Brown Snout', or 'Geneva Tremlett's Bitter' for two of the three PGR treatments. Yield (kg/tree) was least overall in 2017, and greatest overall in 2018, for all seven cultivars (data not presented, Zakalik, 2021). Reputedly "annual" cultivars 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey' had horticulturally meaningful (>2 kg/tree) yields in 2017, while the other four cultivars bore little to no fruit (0–2 kg/tree) in 2017, the "off" year for the whole orchard.

Yield, Lansing. Thinning reduced total yield weight (kg) per tree compared to the control, while PGRs did not significantly affect yield weight in either year of the Lansing experiment (Table 4). Thinning significantly reduced crop density compared to the control, while PGRs had no effect on crop density at harvest in either year (Table 5). Thin and Thin+PGR treatments both had lower crop density than PGR-only and control in both years, though apparent differences were not significant for 'Chisel Jersey' in 2017. Crop density was lower overall for 'Chisel Jersey' compared with 'Brown Snout' yet yield weight per tree was often greater.

Trunk growth. There was no difference in TCSA or TCSA growth among treatments for six of seven cultivars in the Lyndonville experiment. For 'Geneva Tremlett's Bitter',

Table 4. Fruit yield of a hand-thinning and summer plant-growth regulator (PGR) experiment in Lansing, NY. Hand thinning (Thin) consisted of reducing all fruitlet clusters to single fruitlets. The PGR treatment consisted of 150 mg·L^{-1} ethephon followed by two (2016) or three (2017) applications of 5 mg·L^{-1} 1-napthaleneacetic acid. Hand thinning and the first PGR applications occurred approximately 5 weeks after full bloom in both years, with subsequent PGR applications made on approximately two-week intervals.

Treatment	Total Yield (kg/tree)		
	2016 'Chisel Jersey'	2017 'Chisel Jersey'	2017 'Brown Snout'
Control	42.4[z]	71.7	38.5
Thin only	30.1	22.9	23.4
PGR Only	48.8	17.8	30.9
Thin + PGR	33.1	26.8	22.4
Crop Density	*P<0.001*[y]	*P<0.001*	*P<0.001*
PGR	*P=0.111*	*P=0.732*	*P=0.141*
Crop Density:PGR	*P=0.072*	*P=0.603*	*P=0.043*

[z] n=6 trees per treatment for 'Chisel Jersey' in both years; n=4 trees per treatment for 'Brown Snout'
[y] P-values generated from analysis of a linear mixed effects model, where yield is the response variable, same-year fall crop density (total fruits/cm^2 TCSA) is the covariate, and PGR is the indicator variable. Each cultivar and year analyzed separately.

TCSA only differed among treatments at the end of the 2016 growing season. By 2017, there were no TCSA differences among treatments (data not presented, Zakalik 2021). Differences in TCSA growth among cultivars from Fall 2016 to Fall 2018 were not significant. There were no treatment differences in TCSA in the Lansing experiment (Zakalik 2021).

Pre-harvest fruit drop. At Lyndonville, hand thinning effects on pre-harvest drop differed by cultivar and year (data not presented, Zakalik 2021). Hand-thinned treatment had less drop than the control for 'Binet Rouge', 'Dabinett', and 'Geneva Tremlett's Bitter', but greater drop for 'Brown Snout', 'Chisel Jersey', and 'Michelin'. Fruit drop was quite high for 'Harry Masters Jersey', though drop in this cultivar decreased as the number of NAA applications increased. NAA also significantly reduced drop for 'Binet Rouge' in 2017. 'Geneva Tremlett's Bitter' generally had least pre-harvest drop, while 'Harry Masters Jersey' and 'Michelin' generally had greatest pre-harvest drop.

Table 5. Crop density from a hand-thinning and plant-growth regulator (PGR) experiment at a research orchard in Lansing, NY. Hand thinning (Thin) consisted of reducing all fruitlet clusters to single fruitlets. The PGR treatment consisted of 150 mg·L^{-1} ethephon followed by two (2016) or three (2017) applications of 5 mg·L^{-1} 1-napthaleneacetic acid. Hand thinning and the first PGR applications were made approximately 5 weeks after full bloom in both years, with subsequent PGR applications make on approximately two-week intervals.

Treatment	Crop Density (fruit/cm^2 TCSA)[z]		
	2016 'Chisel Jersey'	2017 'Chisel Jersey'	2017 'Brown Snout'
Control	12.3[y]	8.8	26.7
Thin only	6.7	3.0	11.6
PGR Only	19.5	1.7	24.9
Thin + PGR	6.6	3.8	9.6
Thinning	*P<0.001*[x]	*P=0.308*	*P<0.001*
PGR	*P=0.080*	*P=0.097*	*P=0.449*
Thinning:PGR	*P=0.064*	*P=0.056*	*P=0.984*

[z] Fall crop density was calculated by dividing total fruit count per tree by trunk cross sectional area (TCSA) after growth ended in autumn
[y] n=6 trees per treatment for 'Chisel Jersey' in both years; n=4 trees per treatment for 'Brown Snout'.
[x] P-values for thinning and PGR effects generated from two-way ANOVA, with presence of thinning and PGR sprays as factors.

Table 6. Pre-harvest fruit drop (percent of total crop) from a hand-thinning and plant-growth regulator (PGR) experiment at the Cornell University research orchard in Lansing, NY. Hand thinning (Thin) consisted of reducing all fruitlet clusters to single fruitlets. The PGR treatment consisted of 150 mg·L^{-1} ethephon followed by two (2016) or three (2017) applications of 5 mg·L^{-1} 1-napthaleneacetic acid. Hand thinning and the first PGR applications were made approximately 5 weeks after full bloom in both years, with subsequent PGR applications make on approximately two-week intervals.

	Pre-harvest fruit drop (percent of total crop)		
	2016	2017	2017
Treatment	'Chisel Jersey'	'Chisel Jersey'	'Brown Snout'
Control	45.7[z]	27.2	74.0
Thin only	55.8	19.0	48.3
PGR Only	21.0	27.1	47.2
Thin + PGR	28.0	12.7	26.4
Crop Density	*P=0.124*[y]	*P=0.418*	*P=0.009*
PGR	*P=0.009*	*P=0.479*	*P=0.148*
Crop Density:PGR	*P=0.362*	*P=0.567*	*P=0.176*

[z] n=6 trees per treatment for 'Chisel Jersey' in both years; n=4 trees per treatment for 'Brown Snout'.
[y] P-values generated from analysis of a linear mixed effects model of pre-harvest drop, where fall crop density (fruits/cm^2 TCSA) is a covariate and PGR is an indicator variable. Each cultivar and year analyzed separately.

For the Lansing experiment, pre-harvest drop in 'Brown Snout' showed a slight positive correlation with crop density (*P=0.009*) (Table 6). Pre-harvest fruit drop in 'Chisel Jersey' was lower overall in both years, compared to 'Brown Snout' and in 2016, there was a significant negative PGR effect (*P=0.009*) on drop. Drop was low overall for 'Chisel Jersey' in 2017, a lower-crop year for that cultivar, and was not significantly affected by either crop density or PGRs.

Maturity, ripeness, and juice chemistry, Lansing. Neither hand thinning nor summer PGR applications affected SPI for 'Chisel Jersey' in either year, while in 'Brown Snout', there were significant positive crop density (*P<0.001*) and PGR (*P=0.005*) effects on SPI, as well as a significant positive crop density-PGR interaction (*P<0.001*) (Table 7). Juice pH was high (>4.6) and TA was low (<3.5 g·L^{-1} MAE) regardless of treatment and year (Table 8) for both cultivars, which are classified as low-acid "bittersweets" according to the Long Ashton Research Station

Table 7. Starch pattern index of 10-fruit subsets from a hand-thinning and plant-growth regulator (PGR) experiment at a research orchard in Lansing, NY. Hand thinning (Thin) consisted of reducing all fruitlet clusters to single fruitlets. The PGR treatment consisted of 150 mg·L^{-1} ethephon followed by two (2016) or three (2017) applications of 5 mg·L^{-1} 1-napthaleneacetic acid. Hand thinning and the first PGR applications were made approximately 5 weeks after full bloom in both years, with subsequent PGR applications make on approximately two-week intervals.

	Starch pattern index		
	2016	2017	2017
Treatment	'Chisel Jersey'	'Chisel Jersey'	'Brown Snout'
Control	4.7[z]	4.8	5.0
Thin only	3.9	6.9	4.1
PGR Only	4.2	5.4	7.0
Thin + PGR	3.9	5.6	3.3
Crop Density	*P=0.890*[y]	*P=0.968*	*P<0.001*
PGR	*P=0.351*	*P=0.892*	*P=0.005*
Crop Density:PGR	*P=0.546*	*P=0.865*	*P<0.001*

[z] n=6 trees per treatment for 'Chisel Jersey' in both years; n=4 trees per treatment for 'Brown Snout'.
[y] P-values generated from analysis of a linear mixed effects model of starch pattern index, where fall crop density (fruits/cm^2 TCSA) is a covariate and PGR is an indicator variable. Each cultivar and year analyzed separately.

Table 8. Juice quality measures from a hand-thinning and plant-growth regulator (PGR) experiment at a research orchard in Lansing, NY. Hand thinning (Thin) consisted of reducing all fruitlet clusters to single fruitlets. The PGR treatment consisted of 150 $mg \cdot L^{-1}$ ethephon followed by two (2016) or three (2017) applications of 5 $mg \cdot L^{-1}$ 1-napthaleneacetic acid. Hand thinning and the first PGR applications were made approximately 5 weeks after full bloom in both years, with subsequent PGR applications make on approximately two-week intervals.

	Soluble Solids Concentration (°Brix)			Folin-Ciocalteu Total Phenolics ($g \cdot L^{-1}$ GAE)			pH			Titratable Acidity ($g \cdot L^{-1}$ MAE)		
Treatment	2016 'Chisel Jersey'	2017 'Chisel Jersey'	2017 'Brown Snout'	2016 'Chisel Jersey'	2017 'Chisel Jersey'	2017 'Brown Snout'	2016 'Chisel Jersey'	2017 'Chisel Jersey'	2017 'Brown Snout'	2016 'Chisel Jersey'	2017 'Chisel Jersey'	2017 'Brown Snout'
Control	12.1[z]	15.1	9.7	2.20	3.26	1.13	4.52	4.52	4.18	2.4	2.39	2.75
Thin only	13.1	16.9	9.9	1.85	3.73	1.25	4.47	4.48	4.25	2.8	2.89	3.15
PGR Only	11.1	17.6	9.5	1.67	4.04	1.33	4.47	4.47	4.15	2.4	2.43	2.55
Thin + PGR	12.9	16.2	9.9	2.09	3.50	1.23	4.51	4.49	4.22	2.7	2.57	3.15
Crop Density	$P=0.037$[y]	$P=0.839$	$P=0.421$	$P=0.015$	$P<0.001$	$P=0.774$	$P=0.556$	$P=0.574$	$P=0.182$	$P=0.013$	$P=0.453$	$P=0.114$
PGR	$P=0.380$	$P=0.328$	$P=0.834$	$P=0.108$	$P=0.486$	$P=0.188$	$P=0.225$	$P=0.645$	$P=0.339$	$P=0.933$	$P=0.076$	$P=0.396$
Crop Density:PGR	$P=0.478$	$P=0.092$	$P=0.816$	$P=0.181$	$P=0.354$	$P=0.055$	$P=0.237$	$P=0.802$	$P=0.243$	$P=0.714$	$P=0.243$	$P=0.237$

[z] n=6 trees per treatment for 'Chisel Jersey' in both years; n=4 trees per treatment for 'Brown Snout'.
[y] P-values generated from analysis of a linear mixed effects model of each juice quality variable, where fall crop density (fruits/cm^2 TCSA) is a covariate and PGR is an indicator variable. Each variable (soluble solids, total phenolics, pH, and titratable acidity) was analyzed separately for each cultivar and year.

classification system (Barker and Ettle 1903). Crop density had a significant (*P=0.007*), but likely of negligible sensory impact, negative effect on TA for 'Chisel Jersey' in 2016. Crop density did not correlate with pH. Crop density had a significant negative effect on SSC for 'Chisel Jersey' in 2016 (*P=0.037*) but had no significant effect on SSC in 'Brown Snout'. Likewise, crop density correlated negatively with total polyphenols for 'Chisel Jersey' in both years but did not affect total polyphenols in 'Brown Snout'. The PGR treatments did not affect juice chemistry.

Discussion

Return bloom. At Lyndonville, the lack of any significant hand-thinning effect on return bloom following 2017, the "off" year for the whole planting, may in part be attributable to the later timing of hand-thinning that year. Yet even in the total absence of fruit in the cultivars 'Brown Snout' and 'Geneva Tremlett's Bitter' in 2017, no combination of NAA or Eth had any additional promoting effect on return bloom. This finding suggests that absence of a crop is already so dis-inhibitory to return bloom, that exogenous ethephon application for other purposes, such as control of tree growth, does not risk exacerbating excessive "snowball" bloom on highly biennial trees following an "off" year. This conflicts with the finding of Schmidt et al. (2009) who reported that ethephon at 300, 600, or 900 $mg \cdot L^{-1}$ application rates in combination with total de-fruiting substantially increased return bloom, compared to total de-fruiting alone, for 'Cameo' apple trees.

Our finding that 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', and 'Michelin' had substantial return bloom following the first "on" year, 2016, agrees with previous descriptions of these cultivars as being "annual", or "less biennial" than other cider cultivars (Copas 2013; Copas 2001; Green 1987; Merwin 2015; Wood 1979). Likewise, the absence of return bloom in 'Brown Snout', 'Binet Rouge', and 'Geneva Tremlett's Bitter' following the first "on" year agrees with previous descriptions of these cultivars as "biennial" (Merwin 2015). The fact that only 'Harry Masters Jersey' had substantial return bloom in Spring 2019, following the second "on" year 2018, is likely attributable to this cultivar's genetically predisposed "annual" tendencies, and to the relatively low crop load borne by 'Harry Masters Jersey' in 2018 compared to the other three similarly "annual" cultivars, 'Chisel Jersey', 'Dabinett', and 'Michelin' (Zakalik 2021). Crop density and yield efficiency were greatest across treatments and cultivars in 2018, the final year of the experiment, when trees first entered "full production".

As the number of acres planted with European cider cultivars increases in North America, the need for strategies to counteract the biennial bearing tendencies for these cultivars is becoming more critical (Bradshaw et al. 2020; Miles et al. 2020; Peck et al. 2021). A greater understanding of the interaction between crop load and the efficacy of midsummer PGRs cannot be derived from our findings in the three-year Lyndonville experiment, as we did not manipulate crop load for any of the midsummer PGR treatments.

The lack of a significant relationship between crop density and return bloom in 'Brown Snout' in the Lansing experiment may be an artifact of the relatively high range of crop densities, and very low range of return crop the following spring. Crop densities observed in 'Brown Snout' for each treatment in 2017 were greater than those observed for 'Chisel Jersey' in either year at Lansing. In a concurrent three-year hand-thinning experiment at Lyndonville (Zakalik 2021), we found that 'Brown Snout' would not produce any return bloom at a crop density greater than ~24 fruit/cm^2 TCSA. 'Brown Snout' in the Lansing experiment also had greater average crop density than any thinning treatment (0, 3, 6, or 9 fruit/cm^2) in the three-year hand-thinning experiment at Lyndonville (Zakalik 2021) or the 6 fruit/cm^2 crop load imposed in the three-year PGR experiment at Lyndonville (present paper). Thus, the lack of significant return crop for 'Brown Snout' at Lansing, even when thinned the previous year, is explainable: overall crop load in 2017 was likely too great for hand-thinning, summer PGR applications, or a combination thereof, to have any significant effect on return bloom or return crop. Our finding that the suppressive effect of crop load overwhelmed any return bloom-promoting effect of NAA or ethephon resembles the findings of several experiments in 'Honeycrisp', which like the cultivars in the present study is prone to biennialism (Schmidt et al. 2009; Robinson et al. 2010).

Wood (1979) found that triiodobenzoic acid (TIBA), an inhibitor of polar auxin and GA transport, was not very effective in the "on" year at counteracting GA-mediated inhibition of floral initiation when used alone, but that in combination with chemical thinning, TIBA was highly effective at promoting return bloom. Even with chemical thinning alone, Wood reported, "Virtually no flower initiation occurred…until [fruit] set was reduced to about 50 to 60 fruits per 100 blossom clusters, or if cropping was much above 0.4 kg/cm^2."

In contrast to 'Brown Snout', 'Chisel Jersey' can produce some return bloom even with crop density up to ~32 fruit/cm^2 TCSA (Zakalik 2021), well above the range of crop densities observed for that cultivar in either year of the Lansing experiment. This explains, at least partly, the much greater return bloom for 'Chisel Jersey' in both years of the Lansing experiment compared to 'Brown Snout', which had little to none. Though we do not have multiple years' data from the same trees from Lansing, we can infer that 'Chisel Jersey' was on a less extreme flowering and bearing pattern than 'Brown Snout'. Because initial fruit set was already so low in 2017 for 'Chisel Jersey' at Lansing, thinning did not result in significantly different crop densities among treatments (Table 5). Thus, the lack of a crop load effect on Spring 2018 return fruit-set is unsurprising. Similarly, low overall crop load in 2017 likely contributed to the strong positive effect of PGRs on return fruit set the following spring (Table 1).

Cumulative yield, Lyndonville. The differences in productivity among cultivars agree with findings by other authors and with non-quantitative descriptions of these cultivars. Czynczyk et al. (2008) found that in a study from 1998–2003, on multiple rootstocks, 'Chisel Jersey' and 'Dabinett' had the highest cumulative yields, with 'Harry Masters Jersey' somewhat lower, and 'Michelin' lower still.

Our findings at Lyndonville should not be taken to demonstrate that crop load management, in general, does not result in greater cumulative yields. Rather, thinning these European cider cultivars to 6 fruit/cm^2 TCSA, a common recommendation for fresh-market fruit (Anthony et al. 2019; Kon and Schupp 2013; Robinson 2008), may simply be excessive, causing greater losses from thinning than gains from enhanced return bloom.

Moreover, cumulative yields over three years do not necessarily give a full understanding of this relationship, because we are assessing two high-crop "on" years and only one low-crop "off" year. Ideally, any study on the effect of horticultural practices on bearing habits, particularly in highly biennial cultivars, should observe two high-crop "on" years and two low-crop "off" years. To get a better understanding, the return bloom data from 2019 were examined and theoretical yield was projected imagining that the treatments had been imposed for a fourth year.

Projected yield, 2019, Lyndonville. Though non-thinned control and treatments containing PGRs mostly had little return bloom (<2 clusters/cm^2 TCSA) in 2019, and thus little to no potential crop, thinning to 6 fruit/cm^2 TCSA would still result in lower cumulative yields compared to the control and PGR treatments (data not presented, Zakalik 2021). In a concurrent three-year hand-thinning experiment at the same orchard (Zakalik 2021), we found that thinning to 9 fruit/cm^2 resulted in sufficient return bloom to achieve equivalent or greater cumulative yields compared to the un-thinned control, had target crop loads been imposed for a fourth year, for four of these seven cultivars. This indicates that 6 fruit/cm^2 TCSA may be an excessively low recommendation for crop load in cider apples.

Bearing habit, Lyndonville. It is useful but difficult to compare findings in this experiment with other descriptions of the bearing habits for cider cultivars because of the differences in regional observations and reporting metrics. 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey' had the lowest BBI when left un-thinned of the seven cultivars (0.65, 0.65, and 0.47, respectively) and had the highest cumulative yield (24.0, 30.9, and 21.1 kg/tree, respectively). Merwin (2015) described 'Chisel Jersey' as "biennial but productive", 'Dabinett' as "annual", and 'Harry Masters Jersey' as "annual and productive". 'Chisel Jersey' and 'Dabinett' had identical mean BBI when un-thinned at Lyndonville, disagreeing with results reported by Wood (1979) and the descriptions of bearing habit by Merwin (2015). The low overall BBI for 'Chisel Jersey' and low BBI in hand-thinned 'Geneva Tremlett's Bitter' (0.42) likewise agrees with Miles et al. (2017), while the extremely high BBI of control and un-thinned PGR treatments comports with Merwin's (2015) description of the latter cultivar as being very biennial.

'Brown Snout', 'Binet Rouge', 'Michelin', and 'Geneva Tremlett's Bitter' all had extremely high BBI when left un-thinned (1.00, 1.00, 0.98, and 1.00, respectively), and relatively low three-year cumulative yield (17.4, 11.5, 18.0, and 14.6 kg/tree, respectively), contradicting Wood (1979), who reported that over twelve years, 'Michelin' had the lowest BBI (0.42) and the greatest cumulative yield (506 kg/tree) of twenty cider cultivars. Though Wood reported that 'Brown Snout' had a somewhat high BBI of 0.68 over twelve years, he also found that it had a greater average cumulative yield (321 kg/tree) than either 'Dabinett' or 'Chisel Jersey'. It should be noted that Wood (1979) was reporting data from trees on seedling rootstocks, rather than trees on a dwarfing rootstock such as 'B.9' used in the Lyndonville experiment.

PGR sprays and biennial bearing index, Lyndonville. Higher BBI was associated with greater three-year cumulative yields in all seven cultivars, and none of the PGR treatments had any significant effect on BBI or three-year cumulative yields. Treatments containing ethephon did significantly increase 2017 yield weight compared to the control in 'Dabinett' and 'Michelin', but these differences did not translate into significantly lower three-year BBI or greater cumulative yield compared to the control in those cultivars. NAA or ethephon applications alone, at the rates and timings used in this study, were not effective at counteracting the bloom-inhibiting effect of crop load.

Yield and crop density, Lansing. Despite 'Chisel Jersey' in both years having lesser overall crop density than 'Brown Snout', the former cultivar frequently had equivalent or greater total yield weight per tree. This contradiction can be explained both by the innately larger average fruit size of 'Chisel Jersey' compared to 'Brown Snout' (Valois et al. 2006) and by the negative effect of crop density on fruit size generally (Awad et al. 2001; Kelner et al. 1999; Robinson and Watkins 2003; Stopar et al. 2002). A "diminishing returns" effect of excessive crop load is supported by this finding. Conversely, even though thinning reduced crop density (fruits/cm^2 TCSA) by more than half compared to the control (Table 5), yield weight at harvest (kg) was not reduced nearly as much (Table 4). Thus, increased fruit size partly compensated for yield losses due to thinning, similar to the observations of Wood (1979).

Comparing experiments. The lack of any meaningful PGR effect on return bloom or bearing habit should not be taken to show definitively that these seven cultivars are unresponsive to midsummer NAA or ethephon treatments, but rather that the rates applied in these experiments may simply have been insufficient, and timed too late, even when crop load was reduced as in the Lansing experiment. Future studies should compare hand thinning and midsummer PGRs at higher rates, following the same trees over multiple years.

Rootstock effects. The combination of low-vigor rootstock 'B.9' with a low-vigor and strongly spur-type scion, namely 'Geneva Tremlett's Bitter' (Merwin 2015; Peck et al. 2021), may explain the extreme biennial bearing observed in this cultivar, while heavily tip-bearing cultivar 'Harry Masters Jersey' on the same low-vigor rootstock may explain this cultivar's much lower overall BBI, as hypothesized by Barritt et al. (1997). At Lansing, there was no significant rootstock effect on return bloom or yield for either 'Chisel Jersey' or 'Brown Snout' (data not shown).

Maturity and ripeness, Lansing. Our finding that SPI was unaffected by crop density in 'Chisel Jersey' is likely due to a low range of crop densities in that cultivar compared with 'Brown Snout' (Table 1). Our finding that crop density had a positive effect on SPI for 'Brown Snout' is difficult to compare with other research in apples, which has conflicted on the effects of crop load on maturity (Awad et al. 2001; Stopar et al., 2002). The positive effect of our PGR treatments on SPI in 'Brown Snout' should not be surprising: the ripeness-advancing effects of NAA and ethephon are well established (Cline 2019; Singh et al. 2008; Stover et al. 2003; Wendt et al. 2020).

Pre-harvest fruit drop in 'Brown Snout' was lesser than for 'Chisel Jersey' in the Lansing experiment, while the opposite was the case at Lyndonville. The drop-reducing effect of NAA observed in the case of 'Brown Snout' and 'Harry Masters Jersey' at Lyndonville in low-crop year 2017, and for 'Chisel Jersey' at Lansing in 2016, agrees with the general understanding of the effect of NAA and similar PGRs on pre-harvest drop, including in drop-prone cider cultivars (Byers 1997; Cline 2019; Dal Cin et al. 2008; Peck et al. 2020; Stover et al. 2003). However, the interaction of crop load with PGRs in relation to both SPI and pre-harvest drop is less well understood; further study is needed.

Juice chemistry, Lansing. Crop load's negative effect on SSC and total polyphenol concentration in 'Chisel Jersey' agrees with our findings in a concurrent hand-thinning experiment at Lyndonville (Zakalik 2021), as well as with Guillermin et al. (2015). The greater phenolic content and SSC of 'Chisel Jersey' in 2017 compared to 2016, corresponding with lower overall crop density in 2017 than in 2016, agrees with Karl et al. (2020), who reported that phenolic content was lower overall in French bittersweet cultivar 'Medaille d'Or' in the lower-crop load first year of their experiment than the higher-crop second year. Likewise, low overall total polyphenol concentration for 'Brown Snout' corresponded to greater overall crop density in this cultivar compared to 'Chisel Jersey'. The lack of a PGR effect on juice quality variables, such as SSC, FC, or TA, agrees with the findings of Peck et al. (2020).

Conclusion

The results of these two experiments confirm the findings of previous researchers that midsummer PGR sprays alone are insufficient to increase return bloom in biennial cider cultivars. A lack of PGR effect on return bloom in the Lyndonville experiment indicates that crop load management is likely necessary to make PGR sprays effective, as are greater application rates. The lack of a PGR effect on return bloom for 'Brown Snout' in the Lansing experiment indicates that the rates for PGRs to be effective in 'Brown Snout' are likely greater than those applied in our experiments. Thinning to 6 fruit/cm^2 alone may be excessive, resulting in greater cumulative yield losses due to fruit removal than gains due to improved return bloom in the "off" year. Further multi-year research, comparing different crop loads, greater rates of NAA and ethephon, and combinations thereof, is needed. The negative correlation between crop load and juice quality, as measured by SSC, TA, and total phenolics, agrees with previous research. Growers will need to perform crop thinning quite early in the season, and perhaps experiment with greater rates of PGR application, to encourage return bloom in these cultivars.

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About The Cover:

Mamey sapote (*Pouteria sapota*) belongs to the Sapotaceae family and is sometimes called Red Mamey, Sapote, Zapote Colorado, and Mammeee. The slow-growing fruit tree is native to Mexico, Central and South America and it is also cultivated in the Caribbean, and was introduced into Florida in 1887, possibly from Cuba. In Florida, trees bloom in summer, fall or winter depending on the cultivar, so different cultivars are harvested from March to November. Mature trees may be 15 to 45 m tall. To maintain genetic identity, trees are propagated by grafting. There are at least 13 cultivars and fruits are typically 8 to 25 cm long and 6 to 10 cm in diameter. Mamey sapote is produced on a small scale in Australia, Florida, Indonesia, Malaysia, and the Philippines, and sold fresh or frozen by local vendors. Fruits are also used to flavor beverages and deserts. The fruit is a berry and is oval to ellipsoid in shape. The skin is thick, light to dark brown with a texture that feels like sandpaper. Flesh color ranges from orange, red, to salmon and is soft, creamy, with a fine, smooth texture and a sweet, almond-like flavor. In the center of the fruit are 1 to 4 elliptical glossy, black-brown seeds. The seeds are toxic and inedible when raw, but they can be treated to remove toxins for culinary use. *Photo by Jonathan Crane, University of Florida.*