Cider Apple Harvest Maturity and Preharvest Drop Can Be Effectively Managed with Aminoethoxyvinylglycine, 1-Naphthaleneacetic Acid, and Ethephon

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ABSTRACT. Certain European high-tannin cider apple (*Malus* ×*domestica* Borkh.) cultivars used for commercial production of craft hard cider (fermented apple juice) are known to have severe preharvest fruit drop, as well as asynchronous ripening. A 2-year (2018 and 2019) study at two commercial orchards in Wayne County, NY, USA, examined the effects on drop and ripeness of applying three plant growth regulators—aminoethoxyvinylglycine (AVG), ethephon (ETH), and 1-naphthaleneacetic acid (NAA)—on eight different cider apple cultivars. The treatments included i) untreated control, ii) ETH applied 1 week before harvest (WBH), iii) NAA applied 4 and 2 WBH, iv) NAA at 4 and 2 WBH plus ETH at 1 WBH, v) AVG at 4 and 2 WBH, and vi) AVG at 4 and 2 WBH plus ETH applied 1 WBH. Treatments had significant effects on fruit drop: AVG and NAA treatments significantly reduced drop, while NAA+ETH promoted drop, relative to the control. AVG delayed ripening, while NAA+ETH accelerated ripening. Cultivars that tended to have greater natural preharvest fruit drop had a greater reduction in fruit drop when treated with NAA or AVG. Our research can lead to more precise management of cider apple harvest. For example, NAA alone encouraged ripening while reducing drop, which would be advantageous for over-row machine harvest followed soon thereafter by fruit processing. NAA combined with ETH resulted in advanced ripening, reduced fruit detachment force, and fruit drop largely being condensed into the week leading up to harvest, which may be advantageous for shake-and-sweep mechanical harvest followed by short-term storage. AVG alone delayed ripeness and reduced fruit drop, while increasing flesh firmness and fruit detachment force, making this plant growth regulator (PGR) more suitable for hand harvest and long-term storage before processing.

For centuries, orchardists in Europe have grown apples and crabapples (*Malus* spp.) specifically for use in hard (alcoholic) cider. Cider apples often have unique characteristics compared with apples used for fresh consumption, such as copious sugar, malic acid, and/or tannin concentration, as well as a greater juice yield. However, many European cider apple cultivars are prone to preharvest fruit drop, whereby fruit fall from the tree before the anticipated timing of commercial harvest (Barker and Ettle 1912; Merwin 2015; Valois et al. 2006). Cider apple cultivars may have been selected for their tendency to drop more readily than fresh-market or multipurpose cultivars because they were mostly harvested from the ground and not picked from the tree. Plotkowski and Cline (2021) found that preharvest fruit drop accounted for 58% of total crop on average for English bittersharp 'Kingston Black' and 79% of total crop for French bittersweet 'Michelin', compared with only 5% of total crop for fresh-market cultivar 'Enterprise' in the same trial. Peck et al. (2021) found in a 5-year cultivar trial that on average, preharvest drops accounted for 60% to 70% of the total crop for 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', and 'Vilberie'.

PGRs alter plant growth and/or development by either stimulating the production, inhibition, or translocation of bioregulators, or by inhibiting bioregulator action (Rademacher 2015). Auxins and ethylene inhibitors can be applied to reduce preharvest drop. The action of auxin in inhibiting preharvest drop is complex; the prevailing theory is that auxin reduces tissue sensitivity to ethylene rather than slowing endogenous ethylene production (Arseneault and Cline 2016). The application of auxin to apple trees in the form of 1-naphthaleneacetic acid (NAA) inhibits stem abscission in apple fruit by retarding stem-tissue response to the ethylene-driven autocatalytic ripening cascade (Li and Yuan 2008). Yet auxins are also known to stimulate ethylene production in the fruit cortex of apples (Yu and Yang 1979). Curry (2006) reported that NAA had an "ambidextrous" effect on 'Delicious' apple fruit: in immature fruits, NAA inhibited ethylene action on the peduncle while simultaneously stimulating ethylene production, whereas the opposite was the case in mature fruits. In other words, NAA can encourage unripe fruit to ripen, while discouraging ripe fruits from dropping—when applied within a limited timeframe.

By contrast, ethylene inhibitors such as aminoethoxyvinylglycine (AVG) can limit preharvest drop by inhibiting ethylene biosynthesis and the subsequent ripening cascade (Malladi et al. 2023). There are numerous studies detailing the ability of AVG to control preharvest drop in apple (Robinson et al. 2010; Schupp and Greene 2004; Yuan and Carbaugh 2007). However, by arresting ethylene production, AVG can also maintain flesh firmness, retard peel color development, and slow starch hydrolysis (Arseneault and Cline 2016). Interestingly, it has been shown that NAA and AVG more effectively control preharvest drop in combination than either substance can alone (Robinson et al. 2010; Yuan and Carbaugh 2007; Yuan and Li 2008).

Ethephon (ETH), an ethylene precursor, has been shown to accelerate preharvest drop in 'McIntosh' apples and advance fruit maturity metrics such

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as starch hydrolysis and peel coloration, but also promotes a decrease in flesh firmness (Stover et al. 2003; Watkins 2017). These applications can be made in combination with NAA or AVG, which allows apple growers to coordinate harvest maturity with available labor and/or market demand for fruit. Ethephon is also commonly applied to tart cherry (*Prunus cerasus*) orchards to loosen fruit before mechanical harvest.

Hand harvest of apples is highly time- and labor-intensive (Davis et al. 2004; Zhang et al. 2019a, 2019b), particularly from trees bearing many small fruits, as is the case in many specialty cider cultivars (Miles and King 2014; Zakalik et al. 2023b). Mechanized harvest of cider apples can take several forms: on-tree, shake-and-sweep, and ground harvest. On-tree mechanized harvest involves an over-the-row harvester knocking or "combing" fruit off the tree and then catching the fruit before they hit the ground (Miles and King 2014). Shake-and-sweep involves first shaking the base of the tree until all of the fruit fall to the ground, and then "sweeping" the fallen fruit into a windrow and finally picking up the fruit off of the orchard floor into a hopper or bin (Karl et al. 2022).

On-tree mechanized harvest reduces fruit exposure to soil, and thus soilborne pathogens and damage from insects and rodents, but can still be damaging to fruit, shortening cider apple storability before pressing (Alexander et al. 2016). Shake-and-sweep can be even more damaging because the fruit are injured first by falling to the ground and then again by being swept up off the orchard floor. Both methods can also be potentially damaging to tree trunks and branches (Alexander 2019); shake-and-sweep carries greater risk of trunk damage in high-density trellised plantings on mid- or low-vigor rootstocks. Ground harvest without shaking—that is, allowing apples to fall naturally, is far less damaging to trees but can involve cider apples sitting on the ground for a day or longer, thus raising the risk of losses due to rot (Berrie and Copas 2001), as well as damage by insects and rodents and adhesion of dirt and rocks to fruit.

A PGR program that causes apples to drop in as compact a timeframe as possible and be as uniformly ripe as possible would optimize fruit quality for cidermaking while minimizing fruit injury and contamination during mechanical harvest. With the aforementioned physiological, logistical, and economic concerns in mind, we conducted trials using several plant growth regulators to identify cider apple cultivars suitable to mechanical harvest and understand and manage harvest maturity goals for optimal harvest efficiency and juice quality. We hypothesized i) that application of NAA and AVG would reduce preharvest fruit drop and ii) that application of ETH would advance and synchronize harvest maturity in the studied cider apple cultivars.

Materials and methods

Research sites and experimental design. The experiment occurred in 2018 and 2019 at two commercial apple orchards in Williamson, Wayne County, NY, USA. Site A was located at lat. 43°14′53.5″N, long. 77°11′27.9″W and site B at lat. 43°12′51.3″N, long. 77°14′18.9″W. Arthropod, disease, and weed control followed a conventional management program typical for commercial orchards in the region (Agnello et al. 2018). No chemical thinners or other plant growth regulators besides experimental treatments were used in either year.

At site A, high-tannin cider apple cultivars were planted in 2016 at 2.7 m between trees and 5.4 m between rows (~670 trees/ha). Scion-rootstock combinations (Supplemental Table 1) were as follows: 'Brown Snout', 'Binet Rouge', 'Chisel Jersey', and 'Harry Masters Jersey' on G.11; and 'Porter's Perfection', and 'Dabinett' on 'B.9'. Trees were trained in a tall spindle training system (Robinson et al. 2006) with four wires. Soil was predominantly Elnora loamy fine sand, 0% to 6% slope (Soil Survey Staff 2014).

At site B, trees were planted in 2015 without trellising at 3 m between trees and 6.1 m between rows (~540 trees/ha). Cultivars Dabinett, Golden Russet, Kingston Black, and Porter's Perfection were all grafted onto MM.106 rootstock (Supplemental Table 1). Soil was predominantly Hilton and Ontario gravelly loam, 3% to 8% slope (Soil Survey Staff 2014).

Depending on fruit set and the number of trees available, each treatment was replicated either four times (for 24 trees total) or five times (for 30 trees total) using a randomized complete block design for each trial (Supplemental Table 1).

Treatment regimen and spray timing. The PGRs were applied at rates consistent with manufacturers' prescribed labels using a Solo 466-Master Backpack Mist Blower (Newport News, VA, USA) to the point of runoff. NAA (PoMaxa) and AVG (ReTain) were applied at rates of 0.63 $mL·L^{-1}$ (0.022 mL a.i./L) and 0.88 $g·L^{-1}$ (0.13 g a.i./L), respectively (Valent BioSciences, San Ramon, CA, USA). ReTain treatments required a surfactant and defoamer in each tank to aid proper application [0.88 $mL·L^{-1}$ LI700 and 0.08 $mL·L^{-1}$ (Unfoamer, Loveland Products, Greeley, CO, USA), respectively]. Ethephon (Motivate 2L, Fine Agrochemicals, Ltd., Walnut Creek, CA, USA) was applied at a rate of 6.26 $mL·L^{-1}$ (1.34 mL a.i./L). Application and harvest dates were estimated based on input from the farm owners.

NAA and AVG were applied twice at 4 and 2 weeks before harvest (WBH), and ethephon (ETH) was applied once at 1 WBH (Supplemental Table 2). All applications took place on the same day as drop counts were recorded, but always after drops were counted and removed from under experimental trees. Thus, the control, NAA, and AVG treatments without ETH were equivalent to those with ETH until after drops were counted at 1 WBH.

Drop and yield assessment. Beginning 4 WBH, trees were visited weekly for spraying and evaluation of drop. Before scheduled spray applications, dropped fruits were counted, collected, and removed from the tree rows under experimental trees. Preharvest fruit drop was calculated after harvest, as a percentage of cumulative yield (total no. drops + total no. harvested on-tree). At the date of first counting in each cultivar, fruitlets smaller than 3 cm in diameter were discarded as they were considered remnants of June drop.

Fruit was harvested from experimental trees, counted, and weighed (Adam CPW 75 balance, Oxford, CT, USA). Total fruit count was calculated by adding total preharvest drops + total fruit harvested on-tree. Total yield (kg/tree) was estimated by multiplying the average weight of fruits harvested on-tree by total fruit count.

Crop density and yield efficiency were calculated by dividing total fruit count and total yield (kg) by trunk cross-sectional area (TCSA), cm^2, respectively.

TCSA was measured after harvest at the end of the growing season, when trees had defoliated and gone dormant. Two trunk diameter measurements were taken 30 cm above the graft union, perpendicular to one another. The two measurements were averaged and converted to TCSA using the area formula for a circle.

Fruit detachment force measurement. Ten fruit per tree were harvested using an Imada DS2-11 (Northbrook, IL, USA) digital force gauge. In 2018, fruits were harvested with the hook end of the force gauge, at the peduncle. In 2019, a basket was manufactured that allowed the fruit to be pulled without falling to the ground once removed from the tree. Pulling force was applied by hand in a direction transverse to the peduncle, although sometimes fruit or branches obstructed the preferred direction.

Fruit analysis. Subsets of 10 tree-harvested fruit per tree were randomly sampled and brought back to Cornell University for analyses. Where fewer than 10 fruit remained on a tree, drops were included in the subsets. For trees with fewer than 10 total fruit, all fruits were used. Subsets were refrigerated at 4 °C for up to 3 d until it was possible to analyze fruit maturity.

Subset fruits were first assessed for weight, diameter, and peel color or percent blush depending on cultivar. For ‘Brown Snout’, which has a predominantly green-to-yellow peel, the background color was scored on a 1 to 5 scale where 1 = yellow and 5 = dark green (Evans et al. 2012). For other cultivars, the percentage of total peel surface covered by red was visually estimated. Chlorophyll degradation was measured by Δ absorbance (DA) using a Turoni (Forlí, Italy) DA Meter. The internal ethylene concentration (IEC) of each fruit was measured on 1-mL samples of internal gas from the core cavity using a Hewlett-Packard 5890 series II gas chromatograph (Hewlett-Packard, Wilmington, DE, USA) equipped with a flame ionization detector and a Hewlett-Packard 3394A integrator. Temperatures were 230 °C and 245 °C for the injector and detector, respectively, with the oven run isothermally at 160 °C. The stainless-steel column (2 m × 3 mm id) was packed with 60/80 mesh Alumina F-1. Flow rates were 30 $mL\cdot min^{-1}$ for the nitrogen carrier gas, while the detector was supplied with 30 $mL\cdot min^{-1}$ hydrogen and 230 $mL\cdot min^{-1}$ compressed air. Flesh firmness was assessed using a GÜSS penetrometer fitted with an 11.1-mm probe (Jennings, Strand, South Africa). Peel was removed at two opposite locations at the equator of each apple (the sun-exposed and shaded sides) and then probed once at each location. Starch pattern index (SPI) was determined by removing equatorial slices 5 to 10 mm thick and saturating the surface with a 2.2 $g\cdot L^{-1}$ iodine, 8.8 $g\cdot L^{-1}$ potassium iodide (EMD Millipore Corp., Billerica, MA, USA) solution. SPI was rated on a 1- to 8-point scale, with 1 = 0% starch degradation and 8 = 100% starch degradation (Blanpied and Silsby 1992).

Juice extraction. The remaining fruit was diced and then milled in a Norwalk 290 (Bentonville, AR, USA) hydraulic tabletop juicer into Good Nature (Buffalo, NY, USA) filter bags, which were then pressed on the Norwalk 290 until the stream of juice discontinued. This method closely mimics a typical “rack and cloth” cider press. Juice samples were then aliquoted into sample tubes and frozen at −20 °C or –80 °C.

Juice chemical analysis. Soluble solids concentration was measured on a PAL-1 BLT digital refractometer (Omaeda, Saitama, Japan). Titratable acidity was measured on a Metrohm 809 Titrando auto-titrator (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 a 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 and Analysis Software (Molecular Devices, San Jose, CA, USA). Frozen (−80 °C) samples were thawed, vortexed, and then centrifuged at 500 g_n for 8 minutes. Reaction mixtures consisted of 34.9 μL of water, 1.5 μL of sample or standard, and 90.9 μL of 0.2 N Folin-Ciocalteu reagent (Sigma-Aldrich, Darmstadt, Germany). Solutions were mixed in the plate cell via aspiration by a pipet tip; 72.7 μL of 70 $g\cdot L^{-1}$ sodium carbonate buffer was added 6 minutes after the Folin-Ciocalteu reagent. Reaction mixtures were then incubated at room temperature in the dark for 1 hour. 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 gallic acid in a range of zero to 3 $g\cdot L^{-1}$. Samples were measured at 765 nm and total polyphenol concentration was determined by using the linear equations from the standard curve plot.

Statistical analysis. The experiment was conducted 12 times over 2 years, at two locations, on eight cultivars. Drops were counted weekly at 4, 3, 2, and 1 WBH and at harvest. NAA and AVG applications occurred at 4 and 2 WBH, and ETH at 1 WBH, after drops were counted and removed at each timepoint (Supplemental Table 2). Thus, the response to each PGR was observed in the week(s) following application: treatment differences at 2 WBH should be understood as a response to the initial application of NAA and AVG at 4 WBH, and differences at 1 WBH should be understood as a response to the second NAA and AVG applications, which occurred at 2 WBH. Differences in drop rate at harvest should be thought of as a response to all applications, but especially to the ETH sprays at 1 WBH.

Mean cumulative drop per treatment group was calculated for each cultivar. For cultivars used in multiple trials, data from all trials were pooled. A single mixed model was fitted per cultivar, with response variables regressed against a fixed treatment effect, with random trial and block-within-trial effects. Mixed models were fitted in R using the *lmer* function (*lme4* package). Mean separation for a family of estimates (estimated marginal means, *emmeans* package), using the Tukey method (Lenth 2021), was performed using the *cld* function (*multcomp* package) (Hothorn et al. 2021).

Results

Cumulative preharvest drop. When all 12 trials were combined into a single statistical model, ETH and

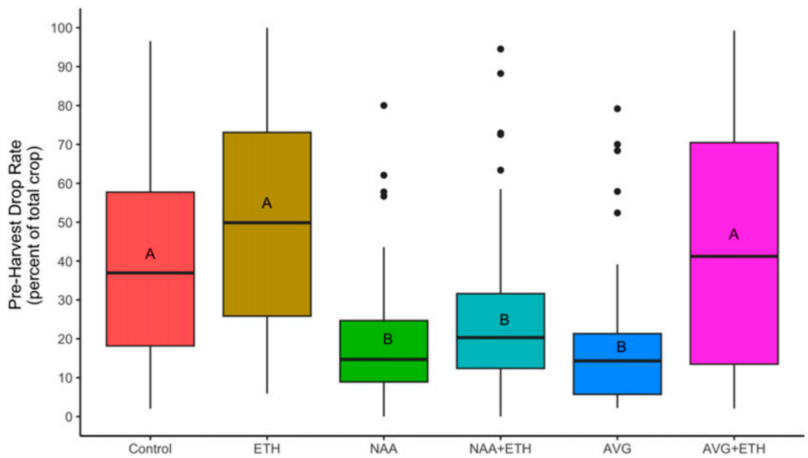

Fig. 1. Cumulative drop rate by treatment from a 2-year study applying three plant growth regulators—aminoethoxyvinylglycine (AVG), ethephon (ETH), and 1-naphthaleneacetic acid (NAA)—on eight different cider apple cultivars in Wayne County, NY, USA. Data pooled by year, trial, timepoint, block, and cultivar. Mean separation via Tukey's honestly significant difference test ($P \leq 0.05$).

ETH+AVG treatments had equivalent cumulative drop to the control, whereas NAA, NAA+ETH, and AVG treatments significantly ($P < 0.001$) reduced cumulative drop relative to the control and other treatments (Fig. 1).

Although there were cultivar-specific responses to the treatments (Table 1), the following trends were observed: the ETH treatment had cumulative drop rate statistically equivalent to the control (all eight cultivars), but significantly greater than NAA treatment (five of eight cultivars). For five of eight cultivars, the AVG treatment had significantly lower cumulative drop rate than the control.

Nevertheless, there were notable cultivar differences to the PGRs treatments, and overall drop regardless of treatment. 'Harry Masters Jersey' and 'Brown Snout' were both highly drop-prone (~79% and ~82% of total crop for control), but also very responsive to NAA and AVG treatments, with drop rate reducing by at least half (Table 1). 'Golden Russet' and 'Porter's Perfection' were least drop-prone (~10% to 15% of total crop on average, ~18% and 12% for control, respectively) and also not highly responsive to the PGR treatments. Other cultivars were somewhere in-between (~28% to 43% of total crop on average, ~35% to 45% for control).

Sensitivity to ETH, in particular, also differed by cultivar (Fig. 1, Table 1). For 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey', NAA or AVG in combination with ETH significantly increased cumulative drop relative to NAA or AVG alone, but for the other five cultivars, NAA+ETH and AVG+ETH had cumulative drop rate similar or equivalent to NAA or AVG alone, respectively.

Drop by timepoint. The PGR treatments strongly affected not only overall preharvest drop, but also the timing of drop (Fig. 2). The control treatment had a gradual increase in drop from 4 WBH until harvest, whereas NAA and AVG treatments had consistently low drop through harvest. Treatments containing ETH saw a sharp increase in drop at harvest (that is, the week following ETH application). The control and ETH treatment can be thought of as equivalent up until harvest, because the single ethephon application happened after drops were counted at 1 WBH. As expected from 4 until 1 WBH, control and ETH treatment had roughly equivalent drop rate, and the other four treatments had equivalent and significantly lower drop rates. ETH treatment diverged from the control in the final week, from ETH application to harvest.

The PGR treatments had no significant effect on preharvest drop at 4 or 3 WBH (Fig. 2). At 2 WBH, drop was still low overall, but treatments containing NAA and AVG had significantly lower drop than the control. Thus, the initial NAA and AVG applications at 4 WBH had an effect on drop, but this effect was observed 2 weeks later, at 2 WBH. At harvest (i.e., following the ETH spray at 1 WBH), ETH and AVG+ETH treatments had the greatest drop rate,

Table 1. Mean cumulative preharvest drop observed from a 2-year study applying three plant growth regulators—aminoethoxyvinylglycine (AVG), ethephon (ETH), and 1-naphthaleneacetic acid (NAA)—on eight different cider apple cultivars in Wayne County, NY, USA.

	Preharvest drop rate (% of total crop)							
Treatment	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Golden Russet	Harry Masters Jersey	Kingston Black	Porter's Perfection
Control	40.8 ab[i]	82.4 a	42.3 ab	34.5 bc	18.2 ab	79.2 a	45.8 a	11.7
ETH	62.0 a	63.1 ab	63.0 a	53.1 ab	21.7 a	90.4 a	49.2 a	11.4
NAA	22.4 b	39.9 bc	5.6 c	21.0 cd	14.6 abc	34.0 b	16.3 b	9.2
NAA+ETH	34.3 ab	34.2 c	21.6 bc	24.3 cd	14.1 abc	70.9 a	18.8 b	9.4
AVG	36.2 ab	17.7 c	14.0 c	11.1 d	11.9 bc	34.4 b	18.3 b	7.1
AVG+ETH	59.9 a	16.0 c	48.5 a	73.2 a	8.2 c	73.1 a	21.9 b	12.7
No. of trials[ii]	2	1	2	2	1	1	1	2
P value	<0.001	<0.001	<0.001	<0.001	0.003	<0.001	<0.001	0.489

[i] *P* values calculated after controlling for block effects. Mean separation within column by Tukey's honestly significant difference test.

[ii] No random trial effect included in mixed models for 'Brown Snout', 'Golden Russet', or 'Harry Masters Jersey', and 'Kingston Black' because only one trial was performed for these cultivars.

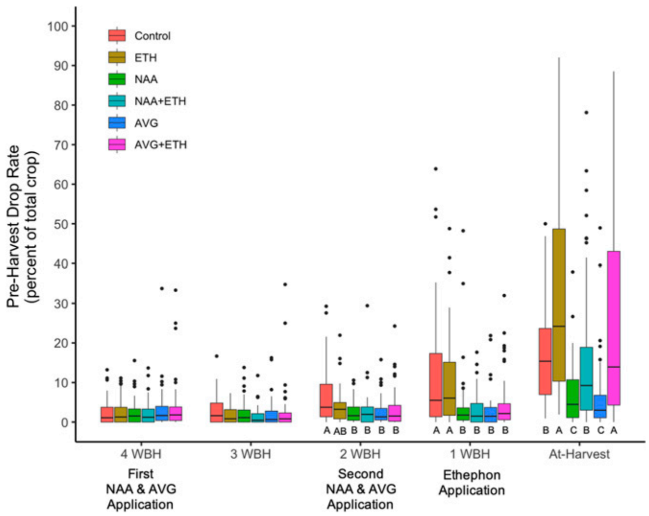

Fig. 2. Drop rate by treatment at five timepoints from a 2-year study applying three plant growth regulators—aminoethoxyvinylglycine (AVG), ethephon (ETH), and 1-naphthaleneacetic acid (NAA)—on eight different cider apple cultivars in Wayne County, NY, USA. Data pooled by year, trial, block, and cultivar. Mean separation within sample week via Tukey's honestly significant difference test ($P \leq 0.05$).

control and NAA+ETH had a moderate drop rate, and NAA and AVG had the lowest drop rate.

Drop rate was also less variable following NAA and AVG sprays, and more variable following ETH sprays (Fig. 2). The untreated control and ETH treatments had more variable drop at 1 WBH, and treatments containing ETH had much more variable drop at harvest than control, NAA, and AVG treatments, which were functionally the same as ETH, NAA+ETH, and AVG+ETH, respectively, until ETH was applied after drops were counted at 1 WBH. Ethephon application not only increased drop but also made drop rate much more variable among treated trees.

Crop load effects on drop. There was no significant correlation between crop density and cumulative drop ($P = 0.412$), or cultivar-crop density interaction ($P = 0.142$), although cultivar did have a significant effect on cumulative drop ($P < 0.001$, data not shown).

Fruit detachment force. Treatment had a highly significant ($P < 0.001$) effect on fruit detachment force (FDF) (Table 2). AVG and NAA treatments had the greatest FDF (in absolute terms) and treatments containing ETH had the least, with the control being in-between the treatments with and without ETH. Treatment effects were significant for seven of eight cultivars, with 'Golden Russet' being the exception ($P = 0.135$); there was a significant treatment effect overall, but not among individual treatments, for 'Harry Masters Jersey' and 'Porter's Perfection' (Supplemental Table 3). ETH and AVG+ETH had the lowest (in absolute terms) FDF for 'Binet Rouge', 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', 'Kingston Black', and 'Porter's Perfection'.

Maturity and ripeness. When all trials were analyzed in one statistical model, the PGR treatments had a significant effect on ripening (Table 3). The AVG and AVG+ETH treatments had delayed ripening as measured by DA, SPI, and IEC. The NAA+ETH treatment had similar SPI and IEC to NAA, but significantly greater than ETH treatment; NAA appeared to contribute more to ripening than ETH. Peel chlorophyll, as measured by DA, was significantly higher (i.e., chlorophyll degradation was delayed) for AVG and AVG+ETH treatments (1.3), with other treatments and the control being equivalent (1.0–1.1). Similarly, SPI was lowest (i.e., starch hydrolysis was delayed) for AVG and AVG+ETH (3.6 and 3.8, respectively) compared with the control and other treatments (4.2–4.7). Likewise, AVG and AVG+ETH treatments had equivalently low IEC (1.2 and 14.7 ppm, respectively); NAA+ETH had highest IEC (80.6 ppm); ETH had significantly lower IEC (49.9 ppm) than NAA+ETH; and control and NAA (56.3 and 61.9 ppm, respectively) were similar to NAA+ETH and ETH. Overall treatment differences in SPI and IEC also were largely obtained within each individual cultivar (Supplemental Tables 4 and 5), although in 'Binet Rouge' and 'Porter's Perfection', treatment had no significant effect on SPI. The PGR treatments had no significant effect on DA for 'Chisel Jersey' or 'Kingston Black', but for the other cultivars, the treatments containing ETH and NAA had the lowest DA—that is, chlorophyll degradation was greatest (Supplemental Table 6).

A two-way analysis of variance was used to compare the correlation of cumulative drop to both SPI and IEC. There was a significant ($P = 0.028$) IEC effect, and a significant IEC-SPI interaction ($P = 0.020$), but SPI alone did not significantly correlate with cumulative drop ($P = 0.196$).

Average fruit weight and diameter were unaffected by treatment (Table 3), whereas peel color development, as measured by percent blush and yellow/green color (1–5 scale), was significantly delayed for treatments containing AVG relative to other treatments. The incidence of watercore was greatest (~33%) for NAA treatment and lowest (~16%) for AVG.

Flesh firmness was lowest for NAA+ETH treatment, and greatest for AVG and AVG+ETH treatments, with control firmness somewhere in-between (statistically similar to) PGR treatments (Table 3, Supplemental Table 7).

Juice quality. Juice quality measures were largely unaffected by

Table 2. Mean fruit detachment force observed from a two-year study applying three plant growth regulators—aminoethoxyvinylglycine (AVG), ethephon (ETH), and 1-naphthaleneacetic acid (NAA)—on eight different cider apple cultivars in Wayne County, NY, USA.

Treatment	Fruit detachment force (N)
Control	−13.0 bc[i]
ETH	−10.9 a
NAA	−14.2 c
NAA+ETH	−12.2 ab
AVG	−14.5 c
AVG+ETH	−10.9 a

[i] P values calculated after controlling for block effects. Mean separation within column by Tukey's honestly significant difference test ($P \leq 0.001$).

Table 3. Pooled values fruit quality and maturity metrics from a plant growth regulator trial of eight cider apple cultivars in Wayne County, NY, USA, 2018–19.

Treatment	Avg fruit wt (g)	Fruit diam (mm)	Peel blush (% of total surface)	Peel green color (1–5)	Delta absorbance	Starch pattern index (1–8)	Flesh firmness (N)	Incidence of watercore (0–1)	IEC (ppm)	SSC (Brix)	pH	Titratable acidity ($g{\cdot}L^{-1}$ MAE)	Total phenolics ($g{\cdot}L^{-1}$ GAE)
Control	87.6[i]	60.2	78.8 a	2.5 ab	1.1 b	4.2 bc	100.8 b	0.26 abc	56.3 ab	15.0	4.0	4.6	2.1
ETH	85.4	60.0	80.5 a	2.2 c	1.1 b	4.2 bc	98.3 bc	0.23 abc	49.9 b	15.2	4.1	4.6	2.0
NAA	86.1	60.5	80.4 a	2.2 bc	1.0 b	4.6 ab	96.9 bc	0.33 a	61.9 ab	15.2	4.1	4.5	2.0
NAA+ETH	85.4	60.3	82.6 a	2.1 c	1.0 b	4.7 a	95.6 c	0.30 ab	80.6 a	15.3	4.1	4.5	2.1
AVG	81.1	59.0	71.3 b	2.6 a	1.3 a	3.6 cd	109.1 a	0.16 c	1.2 c	14.8	4.1	4.7	2.1
AVG+ETH	82.8	59.3	72.7 b	2.6 a	1.3 a	3.8 d	108.9 a	0.19 bc	14.7 c	15.2	4.1	4.5	2.2
P value	0.143	0.088	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001	0.563	0.079	0.539	0.041

[i] *P* values calculated after controlling for block effects. Mean separation within column by Tukey's honestly significant difference test.
AVG = aminoethoxyvinylglycine; ETH = ethephon; GAE = gallic acid equivalent; IEC = internal ethylene concentration; MAE = malic acid equivalent; NAA = 1-naphthaleneacetic acid.

treatment (Table 3). Although there was a significant ($P = 0.041$) treatment effect on phenolic concentration, differences among individual treatments (~0.1 $g{\cdot}L^{-1}$ gallic acid equivalent) were not statistically significant and would be minimally impactful from an organoleptic perspective.

Yield and productivity. Total yield (kg/tree) was unaffected by treatment for any cultivar (Supplemental Table 8). Crop density was unaffected by treatment for seven of eight cultivars; an apparent treatment effect on crop density for 'Chisel Jersey' (Supplemental Table 9) did not translate into significant differences in yield.

Discussion

Cumulative preharvest drop. For the cider cultivars in our study, the NAA and AVG treatments significantly reduced drop relative to the control, agreeing with the general understanding of these PGRs when used for fresh-market cultivars (Schultz et al. 2023; Stover et al. 2003).

One of the goals of this experiment was to assess the utility of a preharvest ETH spray to loosen fruit just before harvest, which in combination with drop-suppressing AVG or NAA applications in the preceding weeks, would condense the period of preharvest drop into the week leading up to harvest. We found that this strategy was highly successful: drop rate at harvest, for the three treatments containing ETH, was usually far greater than the previous 4 weeks combined (Fig. 2). As expected, the ETH treatment did not have significantly greater drop than the control except at harvest (the week after ETH was applied). The combination of NAA or AVG at 4 and 2 WBH, with ETH at 1 WBH, could be a highly effective spray program for preventing preharvest drop before mechanical harvest, and also for encouraging drop in the week immediately before machine harvest.

Treatment effects on detachment force were cultivar-dependent, but often statistically significant. The increased (in absolute terms) detachment force observed for AVG treatment for 'Dabinett', 'Kingston Black', and 'Porter's Perfection' agrees with the findings of Ozkan et al. (2016) for 'Red Chief'. The observed reduction (in absolute terms) of detachment force for treatments containing ETH, especially in drop-prone cultivars Chisel Jersey, Dabinett, and Harry Masters Jersey, further suggests that, in addition to the aforementioned chronological concentration of drop into the week leading up to harvest, a late ETH application could facilitate faster mechanical harvest via the "shake-and-sweep" method, possibly reducing damage to trees incurred by mechanical shaking. For growers using ground-harvesting machinery without tree-shaking, though, detachment force might not even be a consideration (Karl et al. 2022).

Although mechanical harvest was not part of this experiment, and our methodology for measuring detachment force is somewhat novel—more closely mimicking hand harvest of individual fruits than large-scale harvest by shaking—our finding that detachment force was significantly reduced by ethephon application indicates that the effects of PGRs on peduncle abscission are ripe for further study, in fresh-market, as well as cider apple production.

Both the natural propensity for preharvest drop and the sensitivity to different PGRs are known to be cultivar specific (Arseneault and Cline 2016; Sun et al. 2009). 'Harry Masters Jersey' is notoriously drop-prone (Copas 2013; Peck et al. 2021; Zakalik et al. 2023b), as are 'Chisel Jersey' and 'Dabinett'. The lower cumulative drop observed in the present study for 'Porter's Perfection' compared with 'Binet Rouge' and 'Brown Snout' differs from our findings in a 5-year cultivar trial, although drop rates can differ as much as 4-fold year-to-year for the same cultivar depending on crop load, weather, and possibly other factors (Peck et al. 2021).

Cultivar-specific responses to the PGRs applied in this study were also notable and agree with previous research (Arseneault and Cline 2016; Byers 1997). 'Harry Masters Jersey' was most prone to drop overall, but also had a significant reduction in cumulative drop in response to NAA and AVG treatments, relative to the control. This was also the case for fairly drop-prone 'Chisel Jersey' and 'Kingston Black'.

'Harry Masters Jersey' has been found to drop fruit from the tree when little to no starch has hydrolyzed to sugar, with the drop period lasting for a month or longer before on-tree fruit reaching an SPI of 7 or 8 (Cook et al. 2024). By contrast, 'Porter's Perfection' had low drop overall in our experiment, and no significant difference in drop for any treatment relative to the control.

In a prior study on the return-bloom effects of midsummer NAA applications in 'Brown Snout' and 'Chisel Jersey', we found that NAA, applied much earlier in the season than in the present study, had a significant drop-reducing effect on 'Chisel Jersey', but no significant effect in 'Brown Snout' (Zakalik et al. 2023a). For cultivars not prone to preharvest drop, such as Golden Russet or Porter's Perfection, NAA and AVG treatments may be both ineffective and unnecessary; a higher rate of ETH just before harvest may be appropriate if the goal is to maximize drop around harvest time.

Effects on fruit physiology. Drop rate was not always correlated with fruit ripeness, as also reported in a review article by Arseneault and Cline (2016). The AVG treatment had significantly lower SPI and IEC overall (Table 2), as well as significantly lower drop, compared with the control (Fig. 1, Table 1); whereas NAA had lower drop, but equivalent or advanced ripeness (as measured by SPI and IEC), compared with the control. In other words, AVG delayed ripening and prevented drop, whereas NAA sometimes encouraged fruit to ripen on the tree and not drop before the anticipated harvest date. ETH alone rarely advanced starch degradation or ethylene biosynthesis relative to the control, possibly because of the short interval (1 week) between application and harvest. However, the combination of NAA+ETH had SPI and IEC similar to but greater than NAA, and significantly greater than ETH (Table 3). NAA+ETH and AVG+ETH also condensed drop in the week before harvest (Fig. 2).

When data were pooled by cultivar, IEC and the IEC×SPI interaction correlated significantly with cumulative drop, but SPI alone did not. When the correlation of cumulative drop with SPI and IEC was examined at the cultivar level, five of eight cultivars showed no significant relationship (data not shown). IEC correlated with cumulative drop for 'Brown Snout' and 'Harry Masters Jersey', whereas SPI correlated with cumulative drop for 'Porter's Perfection' only. It is worth noting that the former two cultivars were found to be most drop-prone in this experiment, whereas the latter was one of the least. However, IEC was higher across all treatments for low-drop 'Porter's Perfection' than for high-drop 'Brown Snout', but generally comparable between 'Porter's Perfection' and 'Harry Masters Jersey' (Supplemental Table 5). IEC and SPI were also strongly correlated across and within all cultivars regardless of drop rate or responsivity to PGR treatments (data not shown). Clearly, endogenous ethylene production is not the only factor influencing drop date. Besides seed-derived phytohormones, a "tree factor" also may be involved.

The interplay between self-catalyzing ethylene biosynthesis, drop, and starch hydrolysis was complicated and cultivar-dependent in this study, agreeing with previous work. For instance, Thammawon and Arakawa (2007, 2009) found that a rapid increase in ethylene evolution coincided with rapid starch degradation in 'Tsugaru' apples but that starch degradation was slower and ethylene remained low during ripening in 'Fuji'. Lau et al. (1986), by contrast, reported that starch degradation preceded endogenous ethylene buildup in 'Golden Delicious'.

The noncorrelation between IEC, SPI, and drop rate observed in some cultivars also may be a product of sampling bias: fruits analyzed in the laboratory were harvested from on the tree, not from the ground. Greene et al. (2014) reported that dropped fruit had higher IEC and SPI than tree-harvested fruit in 'McIntosh' and 'Delicious', and that dropped fruit had fewer seeds than tree-harvested fruit in 'McIntosh'. Ward (2004) similarly reported that dropped fruit had higher SPI (advanced starch degradation) compared with tree-harvested fruit on the same dates for 'Red Chief Delicious' and 'Commander York'. Had dropped fruits also been analyzed in the present study, it is possible that a different trend between IEC, SPI, and drop rate might have been apparent in some cultivars.

Implications for preharvest drop management. The PGR combinations explored in this study differ in their effects on overall preharvest drop and on the chronology of drop, as well as maturity. The lack of a significant treatment effect on yield is expected and advantageous: growers need not be concerned that use of these PGRs in the month leading up to harvest will involve any sacrifice in productivity. No single treatment combination can be said to be superior to any other; the merits of each depend on the specific harvest methods, labor pool, storage capacity, and cider production schedule of a given orchard and/or cidery.

For instance, a grower using "shake-and-sweep" mechanical harvest, who plans to press fruit within the following week, may find a regimen of two NAA sprays useful, in that this combination and timing would hold most fruit on the tree until the week of mechanical harvest, while also resulting in fruit being ripe enough to be processed soon thereafter. Loosening of fruit, or encouraging drop in the final week leading up to harvest (as seen with the addition of an ETH spray after NAA sprays), might be counterproductive if over-row harvesters are being used: encouraging fruit to drop before harvest would obstruct the path of the machinery, requiring ground harvest before over-row machinery, or else resulting in fruit being crushed under the wheels of the harvester.

For growers employing pickers to harvest fruit by hand, the FDF-reducing effects of ETH, either alone or in combination with AVG or NAA, might facilitate faster and more efficient harvest.

Our findings also have cultivar-specific implications, especially for the extremely drop-prone English bittersweet cultivar Harry Masters Jersey. For this and other cider cultivars that drop much of their fruit at low SPI, fruit can often rot in storage before becoming suitably ripe for pressing. By keeping fruit on the tree and encouraging ripening, with several NAA applications in the month leading up to harvest, growers can minimize losses and maximize juice yield of this particularly dry-fleshed, mucilaginous (or "chewy") specialty cultivar.

By contrast, a grower intending to store mechanically harvested fruit for several weeks before pressing might find a regimen like the AVG+ETH treatment more useful: drop would be concentrated into the week leading up to harvest, and FDF would be somewhat reduced. The reduced IEC and SPI observed for AVG and AVG+ETH treatments (Table 3), and the concomitant increase in flesh firmness, would in turn be advantageous for cidermakers who plan to store fruit for several weeks before processing. The increased flesh firmness is particularly advantageous for mechanical harvest, as fruit may be less prone to damage during the process, and thus less likely to decay or undergo phenolic oxidation in storage. However, AVG alone might be better suited than AVG+ETH to a situation in which fruit will be stored for more than a week or two: although both treatment combinations had low IEC compared with other treatments and the control, AVG+ETH often had similar but higher IEC compared with AVG alone.

Although a major reason for this study was to assess the suitability of different spray programs for mechanical harvest of cider apples, actual test runs of different harvest machinery were not part of these field trials. As North American growers of specialty cider cultivars shift away from hand harvest (currently the norm) toward more economically advantageous mechanized harvest (Karl et al. 2022), it will be even more important to minimize preharvest drop until fruit are physiologically suitable for cidermaking.

Conclusion

The implications of our findings for harvest management in cider cultivars are complex and dependent on the contingencies of farm scale, harvest strategy, postharvest storage needs, and cider production style. For cidermakers seeking to emulate the oxidized tannic structure of many English or French ciders, a spray regimen combining NAA followed by ethephon to encourage fruit to fall and be bruised during harvest may be advantageous. Larger-scale operations harvesting fruit to sell to a cidermaker client may prefer an AVG spray program to minimize damage, extend storage life, and delay ripening until fruit are ready to be shipped. The lack of a treatment effect on juice quality means that orchardists and cidermakers using apples sprayed with these PGRs will not be sacrificing the quality of their cider with these applications. Future research should assess the relative efficiency of machine harvest, as well as the short- and long-term storage quality of machine-harvested fruit from trees treated with different combinations of the PGRs used in this study. A labor and economic analysis of these orchard practices is also needed. Although our results are preliminary, we have characterized the innate preharvest drop tendencies, and responsivities to PGRs commonly used for managing drop, of eight of the most widely grown cider apple cultivars in North America. The efficacy of several treatment combinations in this study at suppressing or condensing drop, and delaying or advancing ripening, shows promise for taming the often-unruly harvest phenology of these challenging cultivars.

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