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Fruitlet Thinning Reduces Biennial Bearing in Seven High-tannin Cider Apple Cultivars

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Abstract. **Many European apple (*Malus ×domestica* Borkh.) cultivars used for making alcoholic cider have a highly biennial bearing habit. To determine target crop load recommendations, seven cider cultivars grown in a high-density orchard were hand-thinned to crop densities of 0, 3, 6, and 9 fruit/cm² trunk cross-sectional area (TCSA) or left unthinned as a control for 3 consecutive years (2016–18). Treatments were imposed on the same trees for all 3 years. Greater year-to-year yield variability, as measured by the biennial bearing index (BBI), correlated negatively with cumulative yields both within and among cultivars. Greater crop density had a negative correlation with the amount of return bloom in all years, but reducing crop density had a negligible effect on return bloom in the "off" year. When trees were left unthinned in the high-crop "on" years there was little to no return bloom in the following year. Partial budget analysis found that manually reducing crop density would result in a positive net change in 3-year profitability for Dabinett, but not the other cultivars. Over 4 years, under conservative assumptions about fruit set, chemical thinning to 9 fruit/cm² TCSA would likely result in increased cumulative profitability in all seven cultivars. Hand-thinning was projected to be less profitable than chemical thinning but would still result in increased net profitability over 4 years, for five of the seven cultivars. These findings highlight the horticultural and economic benefits of crop load management for cider apple orchards. Further, many high-tannin cider cultivars can sustain a higher crop density than what is recommended for fresh-market apple production and still have adequate return bloom and cumulative yields.**

Biennial bearing in apple (*Malus ×domestica* Borkh.) trees is a well-known phenomenon in which a tree will produce a large crop one year and then little to no crop the next. The presence of fruit—particularly seeded fruit—on a tree or branch inhibits floral bud induction, and thus return bloom the following spring (Chan and Cain 1967; Weinbaum et al. 2001). The absence of fruit in the second year often results in excessive bloom in the third year, perpetuating a cycle of dramatic yield fluctuations. This phenomenon has been recognized by orchardists, cidermakers, and horticulturists for centuries (Knight 1797; Rathvon and Harris 1877; Worlidge 1678).

Biennial bearing is largely mediated by seed-derived phytohormones known as gibberellic acids (GAs), which diffuse from developing fruitlets into adjacent vascular tissue, suppressing flower bud induction in spur and shoot meristems (Hoad 1978; Ramírez et al. 2004; Stephan et al. 1999). This suppressive effect appears to be cultivar-specific and depends on 1) the timing of peak GA diffusion relative to floral bud induction (Haberman et al. 2016; Jones et al. 1992); 2) a cultivar's complement of seed-derived GAs (Green 1987; Hedden et al. 1993)—or "gibberellome," to coin a term; and 3) the concentrations of GAs in seed diffusate. The average seed number per fruit is not solely predictive of the flowering or bearing habit (Green 1987; Hoad 1978). Rather, the vascular mobility of GAs, a function of their chemical structure and polarity, affects the degree to which seeded fruits suppress return bloom. However, the total number of seeds present on a tree does correlate negatively with return bloom (Tu 2000).

Reducing crop load through hand or chemical thinning of flowers and/or developing fruitlets in the spring is commonly practiced in commercial orchards. Thinning encourages return bloom, thereby reducing biennial bearing (Pellerin et al. 2011). Crop load management strategies have been extensively investigated in fresh-market apples, but little quantitative research has been done in high-tannin cultivars that are used for hard cider (fermented apple juice) (Milić et al. 2011; Robinson et al. 2010; Wood 1979). Many, but not all, European cider cultivars planted in the United States are reportedly prone to biennial bearing, and the few cultivar-specific assessments sometimes provide contradictory information (Copas 2001, 2013; Merwin 2015; Miles et al. 2017; Peck et al. 2021; Plotkowski and Cline 2021; Wood 1979; Zakalik 2021).

Biennial bearing is measured quantitatively using the BBI, a unitless measure ranging from 0 = completely annual to 1 = completely biennial. The BBI was first put forth by Hoblyn et al. (1937), but criteria for classifying what ranges of BBI values constitute "annual" or "biennial" bearing are either absent or inconsistent in the literature. For example, the cider cultivar 'Chisel Jersey' has been described by Merwin (2015) as "biennial," but it only had a BBI of 0.31 over 5 years in data reported by Cuthbertson and Stickley (1949), and a moderate BBI of 0.54 over 5 years in data reported by Wood (1979).

In addition, the planting of cider cultivars in North America has outpaced research into crop load management for these cultivars (Miles et al. 2020). Previous research on crop load management for cider cultivars conducted in England (Cuthbertson and Stickley 1949; Green 1987; Wood 1979) used standard-sized trees on seedling rootstocks or semi-dwarf rootstocks, which likely respond very differently from trees grown in high-density planting systems common in newer North American plantings (Peck and Knickerbocker 2018).

Cumulative yield over the lifespan of an orchard generally correlates negatively with BBI, particularly in cider cultivars (Wilcox 1944; Wood 1979; Wragg and Rendell 1977). Thus, crop load management strategies that mitigate biennial bearing can potentially increase farmgate revenue (Forshey 1986; Stover et al. 2001). The negative correlation between crop load and fruit size (Guillermin et al. 2015; Robinson and Watkins 2003; Wood 1979) affects the cost of hand-harvesting, which is currently the norm for North American cider apple orchards. Many small apples (resulting from excessive crop load) take longer to hand harvest than fewer large apples, potentially increasing harvest costs for growers who pay pickers by the hour (Cripps 1962; Davis et al. 2004; Stander and Cronjé 2016; Zhang et al. 2019). Some growers also report paying pickers a higher wage per bin to compensate for slower harvest of small-fruited cider cultivars (Zakalik and Peck 2023). The economics of crop load are understudied but important, especially given growers' uncertainty about the

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profitability of growing bitter cultivars that are only useful for processing into fermented cider (Farris et al. 2013; Peck and Knickerbocker 2018; Wragg and Rendell 1977).

The goals of this experiment were to determine the effect of crop load on return bloom (and thus, on biennial bearing), and to assess the relationship between bearing habit (as measured by BBI) and cumulative yields. We studied a diverse array of cider apple cultivars with differing reputed bearing patterns. Our hypotheses were: 1) reducing crop load would increase return bloom, 2) lower crop loads over 3 years would coincide with lower BBI, 3) cumulative yields would correlate negatively with BBI, 4) average fruit size would correlate negatively with crop load, and 5) hand-thinning would result in increased net profitability over 3 years. A companion article from this experiment describes the effects of these crop load treatments on fruit and juice quality (Zakalik et al. 2023).

Materials and Methods

Research site and orchard design. The experiment occurred at a large commercial apple orchard in Lyndonville, NY (lat. 43°19′26.4″N, long. 78°22′22.8″W) on a Galen very fine sandy loam (Soil Survey Staff 2014). 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 plant growth regulators that might affect flower bud initiation were used in any year of the experiment, which ran from May 2016 to May 2019.

In 2014, three rows each of seven high-tannin cider apple cultivars (Binet Rouge, Brown Snout, Chisel Jersey, Dabinett, Harry Masters Jersey, Michelin, and Geneva Tremlett's Bitter) were planted at 1.2 m between trees and 3.7 m between rows (~2220 trees/ha). There were ~120 trees per row. Each tree was affixed to a metal pole that was attached to a single trellis wire and trained using the tall spindle system. All trees were grafted onto 'Budagovsky 9' ('B.9') rootstock.

'Geneva Tremlett's Bitter' is classified as a bittersharp (defined as having a high tannin and high acid juice concentration) according to the Long Ashton classification system (Barker and Ettle 1910); the other six cultivars are classified as bittersweet (defined as having a high tannin and low acid juice concentration). Except for 'Binet Rouge' and 'Geneva Tremlett's Bitter', these cultivars are widely planted in England for cider production (Copas 2013; Wood 1979; Wragg and Rendell 1977). 'Dabinett', 'Harry Masters Jersey', and 'Michelin' are reputedly "annual" bearers, whereas 'Binet Rouge', 'Brown Snout', and 'Geneva Tremlett's Bitter' have reputations for being "biennial," with descriptions of 'Chisel Jersey' conflicting (Zakalik 2021).

Experimental design. On 21 Jun 2016, trees were assessed for fruit set and hand-thinned. Five groups of five trees having equivalent fruit set, for a total 25 trees per cultivar, were identified and selected (Supplemental Table 1). Each of the five treatments was assigned to one tree within a given fruit set group. Each year, the same trees were hand-thinned to the same four target crop densities or left unthinned. Target crop densities were 0, 3, 6, or 9 fruit/cm^2 TCSA. Crop density for the unthinned control varied each year based on initial fruit set. Treatments were reapplied to the same trees on 30 Jun 2017 and 15 Jun 2018. The number of days from full bloom (DAFB) to thinning (Supplemental Table 2) in each year were kept as consistent as possible given weather and time constraints and differing full bloom dates (Supplemental Table 3). Target fruitlet counts were calculated by multiplying TCSA (Supplemental Table 4) by target crop density (0, 3, 6, or 9 fruit/cm^2 TCSA) and rounding up to the nearest integer. Fruitlets were then removed by hand to achieve the appropriate number per tree, leaving only one fruitlet per cluster whenever possible. Care was also taken to distribute remaining fruit uniformly throughout the tree canopy.

Fruitlets were counted using handheld tally counters before thinning treatments were imposed in June 2016 (Year 1) and 2017 (Year 2, Supplemental Table 5). In 2016, all trees had far greater initial crop densities than the target number needed for each treatment. Fruit set on control trees was also counted and recorded in 2017. In 2017, the "off" year for the whole planting, return bloom and fruit set were often insufficient to achieve target crop load in 'Binet Rouge', 'Brown Snout', and 'Geneva Tremlett's Bitter'. Where this was the case, trees were not hand-thinned. Where there was sufficient fruit set, achieving target crop load was prioritized over thinning to single fruit per cluster. Initial fruit set in 2018 was deemed too great to count in a timely manner on all 200 experimental trees, so clusters were thinned to single fruitlets, and then further hand-thinning was used to achieve the target crop densities. Workers self-reported post-thin fruitlet counts, which were generally within one to two fruitlets of the calculated target.

Harvest. Preharvest maturity was assessed for each cultivar using fruit from nonexperimental trees based on the starch pattern index (SPI) assay to determine appropriate harvest dates, at SPI of 6 or greater where possible (Blanpied and Silsby 1992). For cultivars that are prone to preharvest fruit drop, such as Harry Masters Jersey, fruit were harvested before 6 SPI. Harvest dates for each cultivar (Supplemental Table 6) were similar year-to-year but occasionally had to be shifted due to weather or time constraints, sometimes by 1 week or more. Preharvest fruit drops were counted and removed before remaining fruit were picked. Fruit drops were counted within the midpoints between an experimental tree trunk and the neighboring trunk on either side. All fruits picked on-tree were counted and weighed (Adam CPW 75 balance, Oxford, CT, USA) in the field. Average fruit mass was calculated by dividing total on-tree mass by total on-tree fruit count. Total estimated yield weight was calculated by multiplying average fruit mass by drop count and adding to total on-tree weight.

Trunk size. Two trunk diameter measurements were taken about perpendicular to each other 40 cm above the graft union, averaged, and converted to TCSA using the area formula for a circle. After initial measurements in June 2016, tree trunk diameter was again measured after growth had ceased for the season and leaves had fallen off trees, and before bud swell had begun the following spring of 2016, 2017, and 2018 at 40 cm above the graft union. Yearly and cumulative trunk growth were calculated over the length of the experiment as percent change. Because the experiment began after fruit set in 2016, percent change values for that year do not reflect total trunk growth in 2016, but rather trunk growth from the day of treatment application (21 Jun) until growth ceased in late autumn. Crop density was calculated by dividing total fruit count (on-tree + drops) by TCSA. Yield efficiency was calculated by dividing estimated total yield (on-tree + drops, kg) by TCSA.

Return bloom assessment. Bloom clusters were counted on all experimental trees in May 2017, 2018, and 2019 at the "pink" stage using a tally counter (Chapman and Catlin 1976).

Off-year experiment, 2017 only. Because of low bloom and fruit set in Spring 2017, the same experimental design was replicated in 2017 on a different set of previously unthinned trees of 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', and 'Michelin' that had sufficient bloom. This experiment was designed to examine the efficacy of off-year crop load management. Initial fruit set in these four cultivars (both experiments) was significantly lower in 2017 than in 2016 but was more than sufficient to re-impose the same target crop loads as in the 3-year experiment (Supplemental Table 7). Spring TCSA for this experiment was measured on the day of thinning (Supplemental Table 8). Thinning treatments for the off-year experiment were only imposed in 2017. Fruit was harvested and analyzed as described previously in Fall 2017; on-tree yield weight, on-tree fruit counts, and drop counts were also recorded in Fall 2018 even though treatments had not been re-imposed in Spring 2018. Return bloom from this experiment was assessed in Spring 2018 only.

Excluded experimental units, original experiment. Of a total 525 observations (175 trees × 3 years), 37 were excluded from the final dataset because of lack of confidence in the accuracy of drop counts. This occurred for plots where there were far more drops on the ground than fruit left on the tree and when adjacent nonexperimental trees had high drop rates, especially in 2018 due to universally high fruit set and crop load in the entire orchard. Trees were excluded based on a combination of location, percent drop, and by comparison of final fruit count to initial fruit set. In 2017 ("off" year), nonexperimental trees had little or no fruit set; for this reason, confidence was greater for fruit counts in both experiments in 2017. Two trees from the 0 fruit/cm^2 treatment were excluded from the dataset because they were erroneously not thinned in 2018.

Fruit analysis. External and internal fruit maturity and quality, and juice quality measures, are described in a separate paper (Zakalik et al. 2023). Analyses were performed on subsets of 10 fruit per experimental tree, or fewer if yield was insufficient on a tree. Seeds per fruit were counted in 2018 only. Estimated seed density was calculated by multiplying average seed count per fruit by total at-harvest crop density (on-tree + drops, fruit/cm^2 TCSA).

Calculation of BBI. BBIs were calculated using Eq. [1], adapted from Hoblyn et al. (1937). BBI is a measure of variation in yield among consecutive year pairs: a value of 0 indicates completely annual bearing (no difference in yields from year to year), and a value of 1 indicates completely biennial bearing (no yield in at least one "off" year). BBI was calculated on a yield mass (kg/tree) basis. BBI calculated on a yield efficiency (kg/cm^2 TCSA) basis was highly similar to BBI calculated on yield mass basis (data not shown). Yield mass was chosen over fruit count because mass is a more important metric for cider production.

$$BBI = \frac{\sum_{i=1}^{n}\left(\frac{|yield_{i+1} - yield_i|}{yield_{i+1} + yield_i}\right)}{n-1}, \qquad [1]$$

where n is the total number of consecutive years observed.

Modifying the formula for BBI by substituting bloom density for yield mass, the degree of year-to-year fluctuation in return bloom density from 2017–19 is described as the "biennial flower index."

Partial budget calculation. Recorded total yields (kg) per tree (on-tree + drops) were extrapolated to estimate total yield (kg) per hectare, given a planting density of 2220 trees/ha (the approximate planting density of the orchard where the experiment was conducted). All fruit were assumed to be sold at the farmgate for \$0.77/kg (Peck and Knickerbocker 2018). An average picking rate of \$0.044/kg for apples above 90 g weight, and of \$0.073/kg for apples below 90 g weight, was used to estimate average harvest cost per acre. Fruit weight of 90 g corresponded to ~64 mm diameter (data not shown), the cutoff cited by growers (Anonymous, private communication) for paying pickers a higher rate to harvest "small" fruit or the lower rate for "normal-sized" fruit.

Annual material cost for two thinning PGR applications was assumed to be \$346/ha, with a variable machinery cost of \$75.40/ha (Farris et al. 2013), totaling \$421.40/ha per year. No costs were associated with the unthinned control. Annual hand-thinning cost was estimated based on communication with a business management extension specialist (Mark Wiltberger, personal communication), as well as an estimate of 123.3 labor hours per hectare (Robinson et al. 2014b), assuming a \$15/h adverse effect wage rate for New York State (Employment and Training Administration 2021). Hand-thinning cost for 1 hectare at 2220 trees/ha planting density was estimated to be \$1850/ha per year. This estimate does not account for reduced thinning cost in the "off" year due to lower overall fruit set. Profit was calculated as return above variable costs; all fixed costs were taken to be constant and thus excluded from partial budgets.

Statistical analysis. This experiment was conducted as a complete, randomized block design. Statistical analysis was conducted in R (R Core Team 2014). All relationships were analyzed as mixed model regressions with a random block term, using the *lmer* function from the *lme4* package (Bates et al. 2021). At-harvest crop density was regressed against at-harvest yield efficiency and against the following spring's return bloom. Cumulative yield per tree was regressed against BBI. Modeling methods (linear, quadratic, logarithmic, etc.) were chosen after visualizing data; model assumptions were checked by assessing R^2 values and examining residuals. Each cultivar was analyzed separately. 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). When analyzing correlations between return bloom and the previous season's crop density, maximum crop densities before total inhibition of return bloom were identified by calculating the x-intercept of the line of best fit for each cultivar. This method was adapted from similar analysis by Wood (1979). These lines of best fit were determined from intercept and slope estimates generated by the *lmer* function in R. No statistical analysis was performed for partial budgets.

Results

Yield and biennial bearing, 2016–18. Cumulative yield (on-tree + drops, kg/tree) over 3 years correlated negatively with BBI; this relationship obtained across, but not always within, cultivars (Supplemental Figure 1). The four more reputedly "annual" cultivars in this study, Chisel Jersey, Dabinett, Harry Masters Jersey, and Michelin, had higher cumulative yield on average than Binet Rouge, Brown Snout, and Geneva Tremlett's Bitter (Table 1), which are reputedly biennial (Zakalik 2021). Although the unthinned control had greater 3-year cumulative yields on average, the control was not always the most cumulatively productive. When thinned to 9 fruit/cm^2, 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey' had equivalent or greater cumulative yields (27.5, 19.5, and 19.6 kg/tree, respectively) compared with unthinned 'Binet Rouge', 'Brown Snout', 'Michelin', and 'Geneva Tremlett's Bitter' (16.0, 14.1, 19.4, and 12.9 kg/tree, respectively). The latter four cultivars also had much greater BBI when unthinned (1.00, 0.99, 0.95, and 1.00, respectively) than the former three when unthinned (0.49, 0.87, and 0.58, respectively). The latter four cultivars also exhibited a wider range of BBI values when thinned, whereas BBI was relatively low for 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey'.

In 2016 and 2018, the "on" years throughout the planting, unthinned controls had the greatest yields in terms of fruit number and mass (Zakalik 2021). 'Dabinett' was the one exception, achieving the greatest yields in 2016 and 2017 when thinned to a target of 6 fruit/cm^2 TCSA. In 2017, the "off" year for the whole planting, the unthinned control was the least productive for all cultivars except Chisel Jersey. In 2017, unthinned 'Binet Rouge', 'Brown Snout', 'Michelin', and 'Geneva Tremlett's Bitter' had negligible yields. By contrast, unthinned 'Chisel Jersey' had similar yields in 2016 and 2017. Yields were greatest in 2018 across all cultivars and treatments.

Crop load, yield weight, and fruit size. Crop density had a negative, nonlinear correlation with average fruit mass: fruit on lowest-crop trees were twice or three times as large as fruit on highest-crop trees (Fig. 1). This in turn caused a "diminishing returns" relationship between crop density and yield efficiency (kg/cm^2 TCSA) for all seven cultivars (Fig. 2). For example, yield efficiency in 'Dabinett' and 'Harry

Table 1. Average cumulative yield (on-tree + drops, kg/tree) and biennial bearing index (BBI) of seven cider apple cultivars during a 3-year hand-thinning experiment at a commercial high-density orchard in Lyndonville, NY, USA.

Target crop load (fruits/cm^2 TCSA)[i]	Binet Rouge		Brown Snout		Chisel Jersey		Dabinett		Harry Masters Jersey		Michelin		Geneva Tremlett's Bitter	
	Cumulative yield (kg/tree)	BBI[ii]	Cumulative yield (kg/tree)	BBI	Cumulative yield (kg/tree)	BBI	Cumulative yield (kg/tree)	BBI	Cumulative yield (kg/tree)	BBI	Cumulative yield (kg/tree)	BBI	Cumulative yield (kg/tree)	BBI
0	0.5 d	—	1.6 d	—	3.0 c	—	3.4 b	—	3.2 c	—	0.3 c	—	1.4 c	—
3	7.7 c	0.45 b	7.9 c	0.33 b	15.2 bc	0.28	21.8 a	0.36 b	11.3 b	0.25	7.2 b	0.33 b	6.6 bc	0.25 b
6	10.4 bc	0.82 ab	8.6 bc	0.79 a	27.4 ab	0.27	32.4 a	0.26 b	18.0 ab	0.24	9.7 b	0.33 b	9.4 ab	0.30 b
9	11.7 ab	0.97 a	12.4 ab	0.29 b	27.5 ab	0.17	19.5 a	0.19 b	19.6 a	0.19	15.9 a	0.36 b	10.7 ab	0.74 a
Control	16.0 a	1.00 a	14.1 a	0.99 a	36.8 a	0.49	22.1 a	0.87 a	20.5 a	0.58	19.4 a	0.95 a	12.9 a	1.00 a

[i] Trunk cross-sectional area (TCSA) was measured 40 cm above the graft union.

[ii] BBI was calculated on a yield mass (kg/tree) basis. A value of 0 = completely annual and 1 = completely biennial.

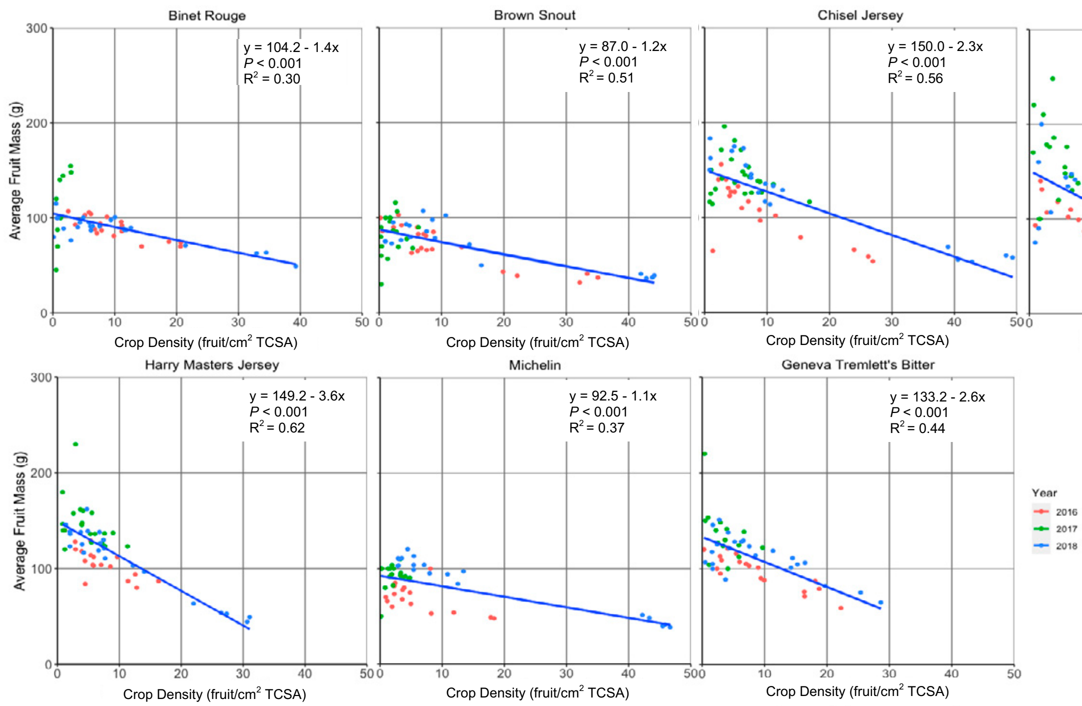

Fig. 1. The relationship between crop density and average fruit mass of seven cider apple cultivars during a 3-year hand-thinning experiment at a commercial high-density orchard in Lyndonville, NY, USA. Each datapoint represents data from a single tree in a given year. Trunk cross-sectional area (TCSA) was measured 40 cm above the graft union.

Masters Jersey' plateaued at a crop density of ~15 fruit/cm^2 TCSA. The other five cultivars did not exhibit such inflection points but yield efficiency did increase to a lesser degree as crop density increased.

Return bloom, Spring 2017–19. There were highly significant negative linear relationships between fall crop density and return bloom density (clusters/cm^2 TCSA) in all cultivars (Fig. 3). Each cultivar had a crop density value above which all return bloom was inhibited (indicated in gold text on Fig. 3). The slope and x-intercept of these relationships was cultivar dependent. The reputedly annual cultivars Chisel Jersey and Dabinett had the lowest slopes (i.e., weakest crop load effect on return bloom) and greatest x-intercepts, meaning that they were able to support the largest crop load and still bloom the following spring.

Return bloom in Spring 2017 was affected differently by 2016 at-harvest crop density for each cultivar (Supplemental Table 9). When unthinned in 2016 (the "on" year), all seven cultivars produced significantly less bloom in Spring 2017 ("off" year) compared with all of the target crop load treatments.

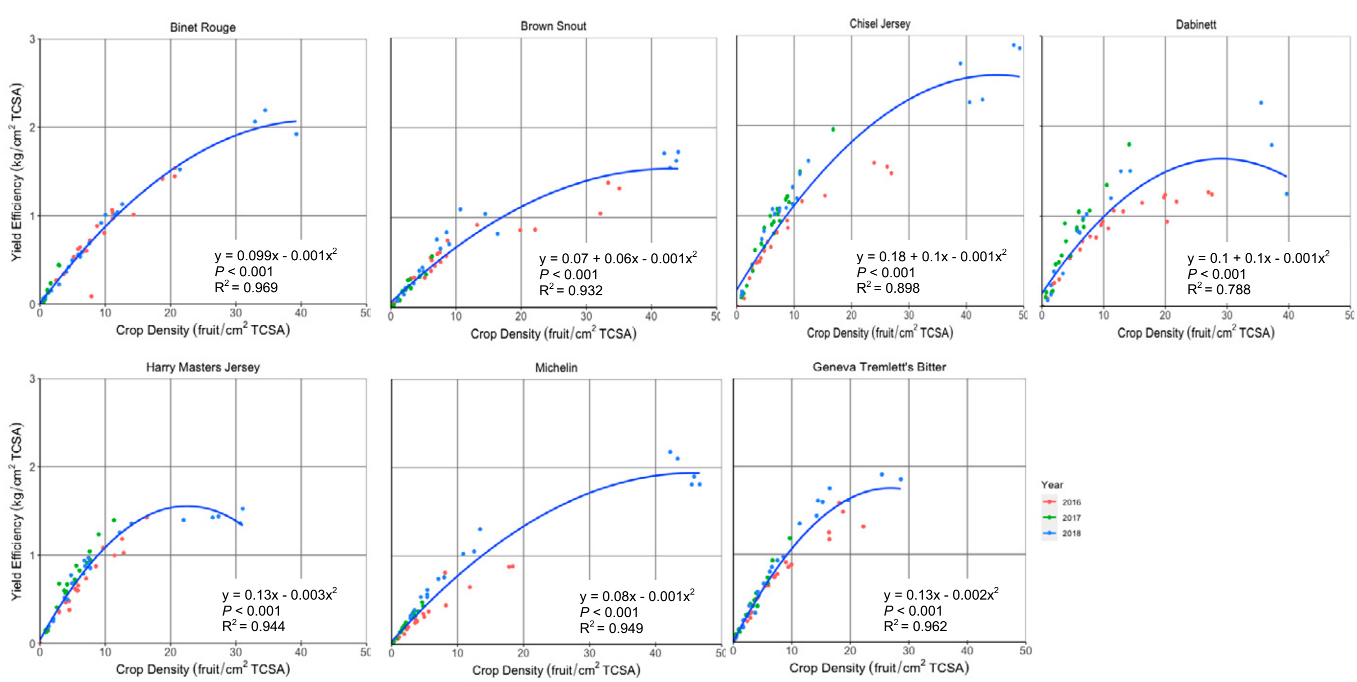

Fig. 2. The relationship between crop density and yield efficiency of seven cider apple cultivars during a 3-year hand-thinning experiment at a commercial high-density orchard in Lyndonville, NY, USA. Each datapoint represents data from a single tree in a given year. Trunk cross-sectional area (TCSA) was measured 40 cm above the graft union.

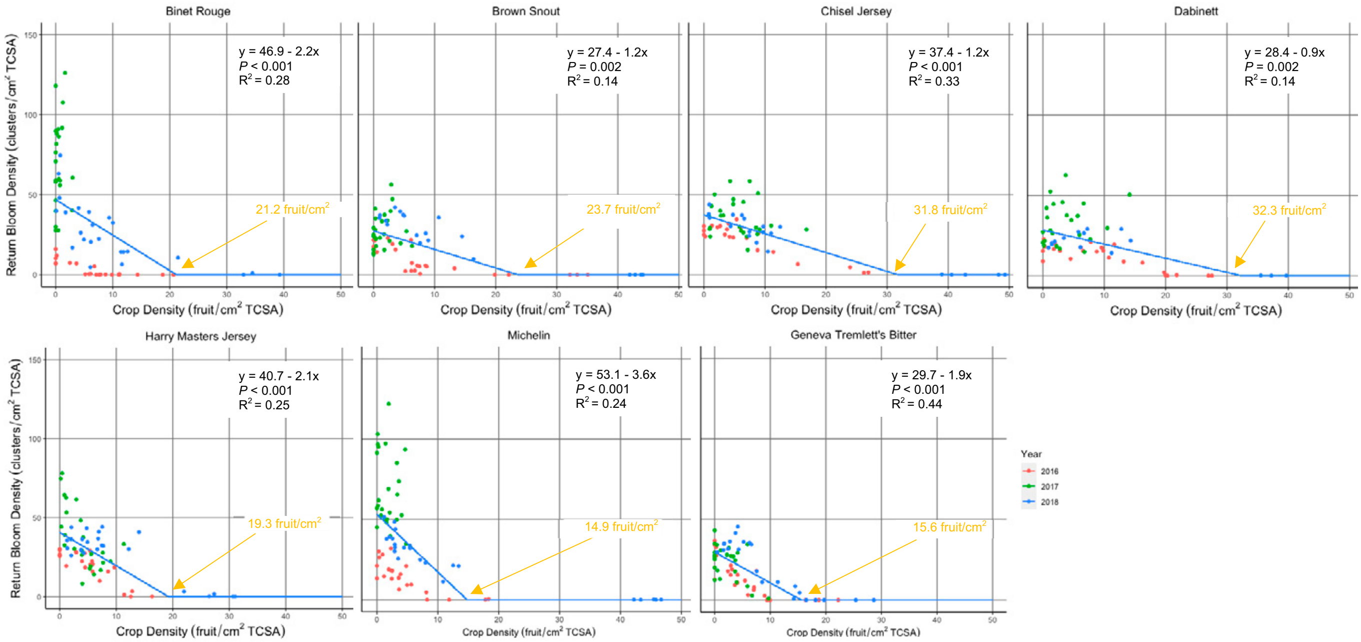

Fig. 3. The relationship between crop density and return bloom the following spring of seven cider apple cultivars during a 3-year hand-thinning experiment at a commercial high-density orchard in Lyndonville, NY. Each datapoint represents data from a single tree in a given year. Trunk cross-sectional area (TCSA) was measured 40 cm above the graft union. The gold-colored text and arrow indicate the crop density above which no return bloom is likely to occur the following spring.

The unthinned control for 'Binet Rouge', 'Brown Snout', and 'Geneva Tremlett's Bitter' did not flower in 2017, whereas for 'Chisel Jersey' and 'Harry Masters Jersey', unthinned trees had horticulturally significant return bloom in 2017 (21.8 and 5.4 clusters/cm^2 TCSA, respectively), although still much lower than when thinned to any target crop load. Likewise, for all seven cultivars, the unthinned control had little or no return bloom in Spring 2019 (following the "on" year 2018), while the thinned treatments showed greater bloom density (Supplemental Table 9). However, following the "off" year 2017, the unthinned control did not have the highest Spring 2018 bloom density of any treatment group, despite bearing little or no crop in 2017.

The average spring bloom density of the 0 fruit/cm^2 treatment (i.e., all fruit removed) differed among years (Supplemental Table 9). Although a few cultivars had comparable spring bloom density in 2018 and 2019 when thinned to 0 fruit/cm^2 TCSA, the general trend for this treatment was that bloom density in 2017 (following the first "on" year) was much lower than in 2018 (following the "off" year). In other words, the developing fruitlets exerted some inhibitory effect on return bloom in the period before the hand-thinning treatment was imposed. Biennial flower index was usually lowest for 0 fruit/cm^2 treatment but was still greater than zero (Table 2).

2017-only experiment. Mean total yield weight (on-tree + drops, kg/tree) and yield efficiency were greatest for unthinned trees in all four cultivars in the 2017-only experiment, and both yield and yield efficiency decreased as target crop density decreased (Supplemental Table 10). In the 2017-only experiment, crop density had a significant negative effect on return bloom in 'Chisel Jersey' ($P < 0.001$) and 'Harry Masters Jersey' ($P < 0.001$), and no significant effect for 'Dabinett' or 'Michelin' (data not shown). The general trend across both experiments was that fruitlet thinning in the "off" year did not significantly promote return bloom the following spring relative to the unthinned control. No tree in either experiment had a return bloom density of zero clusters/cm^2 TCSA in Spring 2018 ("on" year for the whole orchard). In the 2017-only experiment, differences in Spring 2018 bloom for 'Chisel Jersey' translated to small but significant treatment differences in 2018 at-harvest crop density, but differences in yield efficiency were not significant (Supplemental Table 11). Significant differences in Spring 2018 bloom density for 'Harry Masters Jersey' did not translate into significant differences in crop density or yield efficiency at harvest that autumn ($P = 0.09$).

Tree trunk growth 2016–18. In 2016, the first "on" year, trunk growth was greatest on trees with the lowest crop load (Supplemental Tables 12 and 13). In 2017, the "off" year, all cultivars except for 'Binet Rouge' and 'Brown Snout' followed this trend. Crop density had a significant ($P < 0.001$) negative logarithmic correlation with TCSA growth overall (data not shown). There was no significant interaction between crop density and cultivar, but 'Geneva Tremlett's Bitter' had a significantly ($P = 0.011$) lower average TCSA growth than the other six cultivars. Crop density had the strongest negative effect on tree growth in 2016, the first year of the study.

2017 fruit set. Bloom density correlated negatively with fruit-to-bloom cluster ratio in 2017 (data not shown). That is, more flowers on a tree resulted in less efficient fruit set, with more flowers aborting and not forming fruit.

Table 2. Biennial flower index (bloom density basis) of seven cider apple cultivars during a 3-year hand-thinning experiment at a commercial high-density orchard in Lyndonville, NY, USA.

Target crop load (fruits/cm^2 TCSA)[i]	Biennial flower index (0–1)[iii]						
	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
0	0.45 b[ii]	0.18 c	0.15 b	0.31 b	0.23 b	0.37 b	0.17 b
3	0.68 ab	0.23 bc	0.12 b	0.25 b	0.18 b	0.45 b	0.26 b
6	0.75 a	0.46 bc	0.13 b	0.50 ab	0.19 b	0.41 b	0.47 b
9	0.80 a	0.35 b	0.20 b	0.13 b	0.22 b	0.61 b	0.79 a
Control	0.92 a	1.00 a	0.91 a	0.99 a	0.95 a	1.00 a	1.00 a

[i] Trunk cross-sectional area (TCSA) was measured 40 cm above the graft union.
[ii] Mean separation (in columns within each cultivar) by Tukey's honestly significant difference test at $P \leq 0.05$.
[iii] A value of 0 = completely annual and 1 = completely biennial.

Seed number. Estimated seed density (seed number/cm^2 TCSA) in Fall 2018 had a significant ($P < 0.001$) negative logarithmic correlation with Spring 2019 bloom density (data not shown). However, the average seed number *per fruit* did not correlate with return bloom, within or among cultivars. In fact, the most "annual" cultivars (Chisel Jersey, Dabinett, and Harry Masters Jersey) had the greatest seed number per fruit.

Thinning accuracy. Workers' self-reported post-thin fruitlet counts were often lower than the final fruit counts at harvest—that is, on some trees, more fruit was counted at harvest than expected based on post-thin fruitlet counts. Even on trees assigned the "0" target crop load treatment, final numbers of drops and fruit picked on-tree were often greater than zero. Some trees also had fewer total fruit at harvest than their target crop number, due to overthinning. However, the discrepancy (as a percent) between target crop number and at-harvest fruit count did not correlate with target crop load ($P = 0.13$, $R^2 = 0.003$, data not shown). Thus, the inaccuracy of hand-thinning was not greater for any one treatment. A small number of fruit drops from adjacent nonexperimental trees were likely misattributed to experimental trees in high-crop years 2016 and 2018.

Discussion

In this study, 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey' were found to be less biennial than 'Binet Rouge', 'Brown Snout', 'Michelin', and 'Geneva Tremlett's Bitter', largely agreeing with previous descriptions of these cultivars (Copas 2001, 2013; Merwin 2015). However, 'Michelin' did not match its description as an annual-bearing or "less biennial" cultivar, and bloom in Spring 2019 (Supplemental Table 9) was sufficient for hand-thinned 'Brown Snout' to bear more annually than described by others (Copas 2013; Green 1987). In addition, the more annual cultivars (per previous descriptions and as observed in this study) bore the greatest cumulative yields. Our finding, that the more biennial cultivars (previous descriptions and observed here) were more productive when unthinned over 3 years and a projected fourth year than when thinned to any target crop load, suggests that crop thinning may not be worthwhile for all cider cultivars, at least from a productivity standpoint. 'Chisel Jersey' was so naturally annual and productive that the costs of thinning were not compensated by improvements in cumulative yield.

Yield and biennial bearing. The relationship between BBI and cumulative yield was affected by both crop load and cultivar. The overall negative correlation between BBI and cumulative yield concurs with our hypothesis, and with the findings of Wood (1979), Crassweller et al. (2005), and Czynczyk et al. (2008). Although Czynczyk et al. (2008) did not publish BBI values, in a 7-year trial on three different rootstocks they found that 'Chisel Jersey' and 'Dabinett' had the greatest cumulative yields, 'Harry Masters Jersey' was intermediate, and 'Michelin' was the least productive. Plotkowski and Cline (2021) reported that hand-thinned 'Dabinett' trees had significantly lower BBI and significantly higher cumulative yield over 3 years than hand-thinned 'Binet Rouge', 'Brown Snout', and 'Michelin', although they did not include unthinned trees in their study. Apparent negative relationships between BBI and cumulative yield (Supplemental Fig. 1) were not significant for 'Chisel Jersey' and 'Harry Masters Jersey', possibly due to lack of statistical power from dropped data points.

A standardized quantitative framework for describing the bearing habits of apple cultivars, particularly cider cultivars, is lacking in the literature. Reported differences on the "annual" or "biennial" nature of apple cultivars are due to the wide range of tree planting densities, rootstocks, and orchard management practices, such as tree and branch training, that are used in apple orchards. There are also few reports about how specific cultivars respond to crop load management. A more comprehensive and quantitative framework that accounts for both a cultivar's natural tendency and its response to crop load management is needed to further our understanding of how to manage biennial bearing in commercial orchards.

For instance, the BBI observed in this experiment for unthinned 'Dabinett', which is called "annual-bearing" by Merwin (2015), was comparable to BBI values observed on unthinned trees of 'Binet Rouge' and 'Geneva Tremlett's Bitter'—cultivars often described as being highly "biennial." Yet when thinned to any target crop load, 'Dabinett' trees bore much more evenly (BBI was lower) than 'Binet Rouge' trees thinned to the same respective target crop loads. Thus, we propose a system of classifying cultivars by both unthinned bearing habit and bearing habit when thinned (Table 3). A BBI of less than 0.50 should be considered "very annual," a BBI of 0.50–0.65 considered as "annual," 0.66–0.80 as "biennial," and 0.81–1.00 as "very biennial." These categories apply to both a cultivar's unthinned bearing habit and its bearing habit in response to thinning.

Because of the lack of data from other authors at different sites using different rootstocks and tree types, our descriptions should be taken as preliminary, and more research efforts should investigate this premise further. It is important to remember that the trees used in this experiment were still in their first bearing years, and that this experiment was conducted for 3 years, with a projected fourth year of yield data based on spring flower density. To determine the inherent bearing habits of cider apple cultivars, future studies should be conducted for 4 or more years.

In 2016, unthinned trees typically had fewer fruit at harvest than they were expected to have based on initial fruit set counts. This strongly suggests that unthinned trees underwent significant fruitlet drop (i.e., self-thinning) early in that growing season, a phenomenon colloquially called "June drop." This phenomenon, attributable to nutrient competition among developing fruitlets (Abruzzese et al. 1995), underscores the importance of thinning for overall tree health, even when thinning may not result in greater cumulative yields.

Return bloom. The negative effect of the previous season's crop load on return bloom, in all seven cultivars, concurs with the consensus in the literature (Chan and Cain 1967; Embree et al. 2007; Pellerin et al. 2011; Robinson and Watkins 2003; Wood 1979). However, neither the maximum fall crop density before complete suppression of return bloom, nor the slope of a line of best fit alone (Fig. 3) were robust, accurate predictors of bearing habits when trees were left unthinned. For example, 'Dabinett' had a much higher threshold for total return bloom suppression than did 'Harry Masters Jersey', and yet unthinned 'Dabinett' had much higher average BBI than did unthinned 'Harry Masters Jersey'.

The equivalent or higher Spring 2018 bloom density on trees that had set fruit in 2017, compared with unthinned trees that set little to no fruit in 2017, is counter to our hypothesis, and suggests a multiyear bloom-suppressing effect of excessive crop load in young trees. The year-to-year differences in return bloom density on trees thinned to 0 fruit/cm^2 (Supplemental Table 9) indicate that significant suppression of return bloom occurs within 20 to 45 DAFB when fruitlets undergo cell division (Smith 1950). For maximum return bloom, thinning should be timed earlier in the growing season than the hand-thinning done in this study. The time window in which crop thinning can affect return bloom has been found to differ among apple cultivars, so future studies comparing the effects of thinning at different developmental stages may be useful (Haberman et al. 2016; Iwanami et al. 2018; Jones et al. 1992).

The small or nonexistent effect of 2017 at-harvest crop density on Spring 2018 bloom in both experiments indicates that crop load management in the "off" year may not be necessary for cider apples, where fruit size is a less important quality attribute. It is possible that adequate thinning in the first "on" year would be sufficient to set trees on a 2-year cycle of regular bearing.

Table 3. Proposed schematic for categorizing cider cultivars by bearing habit.

Cultivar	Innate tendency	Thinning response
Binet Rouge	Very biennial	Biennial and reduced yields at 9 fruit/cm^2
Brown Snout	Very biennial	Biennial and equivalent yields at 9 fruit/cm^2
Chisel Jersey	Biennial	Annual and increased yields at 9 fruit/cm^2
Dabinett	Biennial	Annual and increased yields at 9 fruit/cm^2
Harry Masters Jersey	Annual	Annual and increased yields at 9 fruit/cm^2
Michelin	Very biennial	Annual but reduced yields at 9 fruit/cm^2
Geneva Tremlett's Bitter	Very biennial	Biennial and reduced yields at 9 fruit/cm^2

Table 4. Projected yields per tree extrapolated from 2019 bloom cluster counts of seven cider apple cultivars during a 3-year hand-thinning experiment at a commercial high-density orchard in Lyndonville, NY, USA. No statistical analysis performed.

Target crop load	2019 projected avg yield (kg/tree)[ii]						
(fruits/cm² TCSA)[i]	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	3.9	2.6	5.2	5.9	4.1	3.9	2.1
6	3.5	4.2	9.0	11.1	8.2	5.1	3.3
9	7.3	6.3	13.2	9.7	11.4	8.3	3.6
Control	0.4	0.0	0.0	0.0	0.2	0.0	0.0

[i] Trunk cross-sectional area (TCSA) was measured 40 cm above the graft union.

[ii] Projected yields were calculated using formula estimates from regressions of crop density against average fruit mass (2016–18), substituting in target crop densities for a fourth season.

In the 2017-only experiment, treatment differences in Spring 2018 bloom density for 'Chisel Jersey' and 'Harry Masters Jersey' did not translate to significant differences in Fall 2018 yield (Supplemental Table 11). This can be explained by the negative relationship between crop density and fruit size, as well as the phenomenon of trees with less bloom having greater fruit set efficiency as measured by a fruit-to-bloom cluster ratio (Wood 1979; Zakalik 2021). Differences in Spring 2018 bloom for this experiment were also smaller than for the main 3-year experiment. Even in the main 3-year experiment, bloom density in Spring 2018 (following the "off" year 2017) did not differ significantly among treatments, except in 'Binet Rouge' and 'Harry Masters Jersey'.

2017 fruit set. Our finding that bloom density correlated negatively with fruit set efficiency concurs with Wood (1979), who observed that in trees with lower bloom density, fruit set per 100 blossom clusters was often significantly greater than on trees with greater bloom density. Wood (1979) attributed increased relative fruit set to reduced competition among fruitlets on branches. Greater bloom density is not a guarantee of high fruit set; therefore, maximizing return bloom may be less important than achieving moderate but consistent bloom over multiple years, particularly where freeze or frost damage are not a major concern.

Spring 2019 bloom and projected yield. Yields for a 2019 harvest were projected using the bloom cluster counts collected in Spring 2019 and coefficient estimates from the regressions between crop load and fruit size data recorded from 2016 to 2018. Projected crop density was used to calculate expected fruit size, which was then multiplied by expected crop number, based on either spring bloom density (for unthinned trees) or target fruit numbers if target crop loads were imposed for a fourth year. Flower clusters were assumed to set one fruit each, which in a low-bloom "off" year is a conservative assumption (Wood 1979; Zakalik 2021). Cumulative 4-year projected yield and projected 4-year BBI were then calculated by adding projected 2019 yield to recorded yields from 2016 to 2018.

Unthinned control for all seven cultivars had little to no potential crop in Fall 2019 because of low bloom that spring (Table 4). The tendency of more "annual" cultivars Chisel Jersey, Dabinett, and Harry Masters Jersey to bear greater cumulative yields than the other four cultivars in this experiment was projected to be even more pronounced had crop load treatments been reapplied for a fourth year (Table 5, Supplemental Fig. 2). In 'Brown Snout', 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey', 2019 bloom was sufficient for the 9 fruit/cm² TCSA treatment to achieve cumulative 4-year yields equivalent to or greater than the unthinned control, had treatments been reapplied. The tendency of 'Dabinett' to bear the greatest cumulative yields when thinned to 6 fruit/cm² target crop load was projected to persist in 2019. For the more biennial cultivars Binet Rouge and Geneva Tremlett's Bitter, and for Michelin, cumulative yields were projected to remain higher if left unthinned than if thinned in 2019.

Partial budget analysis. The profitability (return above variable costs) of chemical thinning differed by cultivar, crop load, and timespan (Table 6). Over 3 years, chemical thinning was only profitable for 'Dabinett' thinned to 6 or 9 fruit/cm² target crop load. However, by the fourth year, under conservative assumptions about fruit set based on 2019 bloom data, chemical thinning was projected to be profitable for all seven cultivars when thinned to 9 fruit/cm², due both to increased revenues and reduced harvest costs. Thinning to a target crop density of 6 fruit/cm² was also projected to be profitable over 4 years for 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', and 'Geneva Tremlett's Bitter'. Similar to the horticultural assessment of biennial bearing, the economic assessment is most informative when long-term trends can be assessed and an equal number of "on" and "off" years can be assessed.

Hand-thinning was projected to be far less profitable compared with chemical thinning, highlighting the need for further research to determine ideal thinning spray formulations, rates, and timing of application for these cultivars. Over 3 years, hand-thinning would only result in a net increase in profitability for 'Dabinett' when hand-thinned to 6 fruit/cm² TCSA target crop load; no other cultivar under any crop load treatment would result in a net increase in profitability over 3 years. Over 4 years, hand-thinning was projected to increase profitability relative to no thinning for 'Binet Rouge', 'Brown Snout', 'Dabinett', 'Harry Masters Jersey', and 'Michelin' when thinned to 9 fruit/cm², and for 'Dabinett' and 'Harry Masters Jersey' when thinned to 6 fruit/cm². Hand-thinning would not be profitable over 4 years for 'Chisel Jersey' or 'Geneva Tremlett's Bitter' under any crop load treatment in this experiment.

The lack of a bloom-promoting effect for hand-thinning in the "off" year indicates that thinning may be unnecessary in a low-crop year, so our cumulative cost estimates for chemical- and hand-thinning may be excessive. The partial budget analysis performed here relies on specifications and assumptions that may not apply to all situations. For instance, the effect of a massive crop failure because of a frost event, which can cause reversion to extreme biennial bearing (Peifer et al. 2018; Wood 1979), cannot be quantified using these models. Because of the influence

Table 5. Projected 4-year cumulative yields per tree extrapolated from 2019 bloom cluster counts of seven cider apple cultivars during a 3-year hand-thinning experiment at a commercial high-density orchard in Lyndonville, NY, USA. No statistical analysis performed.

Target crop load	Projected 4-yr cumulative yield (kg/tree)[ii]						
(fruits/cm² TCSA)[i]	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
0	—	—	—	—	—	—	—
3	9.6	9.0	22.1	33.4	16.5	9.4	7.9
6	10.8	9.1	43.1	54.6	26.7	11.5	11.1
9	11.9	14.1	39.5	28.0	27.7	18.3	11.7
Control	17.5	14.1	36.1	22.1	20.8	19.4	12.9

[i] Trunk cross-sectional area (TCSA) was measured 40 cm above the graft union.

[ii] Four-year cumulative yields were calculated by adding observed yield values (2016–18) to projected 2019 yield.

Table 6. Potential revenues and costs of a model hectare when chemically thinned to 3, 6, or 9 fruit/cm^2 trunk cross-sectional area (TCSA), compared with the same model hectare with no thinning, based on yield data of seven cider apple cultivars during a 3-year hand-thinning experiment at a commercial high-density orchard in Lyndonville, NY, USA. Three-year estimates based on observed data; 4-year estimates incorporate yield projections based on Spring 2019 bloom data.

		Revenue (compared with unthinned)[i]		Costs (compared with unthinned)[ii]		Net change in profitability ($/ha)			
Cultivar	Target crop load (fruits/cm^2 TCSA)[i]	3-yr revenue ($/ha)[ii]	Projected 4-yr revenue ($/ha)	3-yr harvest cost ($/ha)	Projected 4-yr harvest cost ($/ha)	Spray-thinning, 3 yr	Spray-thinning, 4 yr	Hand-thinning, 3 yr	Hand-thinning, 4 yr
Binet Rouge	3	−14,835	−11,723	−1,688	−1,510	−14,411	−11,899	−18,697	−17,613
	6	−10,012	−6,318	−1,303	−1,092	−9,973	−6,912	−14,259	−12,626
	9	−5,386	+7,918	−898	−138	−5,752	+6,370	−10,038	+656
Brown Snout	3	−9,965	−5,850	−1,377	−1,141	−9,853	−6,394	−14,139	−12,109
	6	−8,749	−1,741	−833	−166	−9,180	−3,261	13,466	−8,975
	9	−2,457	+8,172	−517	+495	−3,204	+5,991	−7,490	+277
Chisel Jersey	3	−36,094	−27,881	−2,675	−2,206	−34,683	−27,361	−38,969	−33,075
	6	−13,857	+1,826	−1,140	−244	−13,981	+384	−18,266	−5,330
	9	−18,599	+4,507	−1,280	+40	−18,582	+2,783	−22,868	−2,931
Dabinett	3	−14,740	−6,179	−1,010	−521	−13,094	−5,709	−17,379	−11,424
	6	+12,415	+32,260	+949	+2,083	+5,889	+21,469	+1,604	+15,754
	9	+352	+19,065	+91	+1,161	−1,003	+16,249	−5,289	+10,504
Harry Masters Jersey	3	−16,658	−10,490	−1,368	−1,016	−16,554	−11,160	−20,840	−16,874
	6	−2,174	+12,057	−278	+535	−3,160	+9,836	−7,446	+4,122
	9	−1,117	+17,848	−248	+836	−2,133	+15,327	−6,419	+9,612
Michelin	3	−20,186	−13,201	−2,228	−1,831	−19,223	−13,055	−23,508	−18,780
	6	−17,818	−8,907	−2,089	−1,583	−16,993	−9,010	−21,279	−14,724
	9	−3,835	+11,709	−668	+219	−4,431	+9,805	−8,717	+4,091
Geneva Tremlett's Bitter	3	−10,650	−7,004	−1,335	−1,127	−10,579	−7,563	−14,865	−13,277
	6	−5,212	+1,817	−943	−541	−5,533	+673	−9,819	−5,042
	9	−3,680	+5,896	−700	−153	−4,244	+4364	−8,530	−1,350

[i] All fruit were assumed to be sold by the grower at the farm gate for $0.77/kg.

[ii] Thinning spray costs: $1264 and $1685/ha over 3 and 4 years, respectively. Hand-thinning costs were specified as $5550 and $7400/ha.

of rootstock on bearing patterns (Barritt et al. 1997; Green 1987; Lordan et al. 2017; Robinson et al. 2014a), and the highly disparate productivity and profitability of cider apple production in different training systems (Peck and Knickerbocker 2018), the results of this analysis should not be assumed to pertain to a vastly different training system.

2018 Average seed counts. The more biennial cultivars Binet Rouge and Geneva Tremlett's Bitter had lower average seed count (7.6 and 8.3 seeds per fruit, respectively) than did annual cultivar Harry Masters Jersey (11.1), agreeing with the findings of Hoad (1978), Wood (1979), and Green (1987). The rate and timing of GA diffusion from seeds to vascular tissue is thought to be more predictive of bearing habit than average seed number per fruit, or even the rate of GA synthesis per seed (Green 1987). Although the average number of seeds per fruit is not a robust predictor of a cultivar's bearing habit, the total number of seeds on a tree did correlate with return bloom the following spring, similarly to how crop density correlated with return bloom. Thus, crop density serves as a proxy for the total seed number per tree. Average fruit size, which is influenced by GAs, was not predictive of bearing habit or productivity: large-fruited 'Chisel Jersey' was annual and highly productive, whereas large-fruited 'Geneva Tremlett's Bitter' was biennial and unproductive. The negative effect of crop density on fruit size means that average total yield mass per tree is not as predictive (although still a robust predictor) of return bloom as is crop density (Wood 1979).

Study limitations. The use of hand-thinning, as opposed to chemical thinning, makes our findings and crop load recommendations somewhat idealized. Having quantified seven cider cultivars' responsivities—or lack thereof—to thinning over multiple years and having identified a target crop load (9 fruit/cm^2 TCSA), future research is needed to determine effective chemical thinning formulations, timings, and rates for bloom or fruitlet thinning these and other widely grown cider cultivars. Ideally, such research would assess thinning over at least 4 years (2 "on" and 2 "off" years), because BBI becomes more robust with each successive bearing season.

In addition, future studies should be either initiated or continued on trees after they enter "full production," which in our study only occurred in 2018, the final year of treatment. Trees were planted in 2014, and there was a notable increase in bloom and yield from 2017 to 2018 regardless of treatment. The magnitude and universality of this increase skewed biennial bearing indices upward, even when calculated on a yield efficiency basis (i.e., adjusting for tree size). Nonetheless, our finding that crop thinning is effective in the first bearing years (2016–18) highlights the importance of crop load management in the orchard establishment period to encourage long-term regular cropping.

Conclusion

In these experiments, we found that thinning in the "on" year moderated biennial bearing and, in some cultivars, resulted in greater cumulative yields. A negative relationship between crop density and fruit size, combined with the inhibitory effect of crop load on return bloom, led to a 3-year trend of more biennial bearing trees and cultivars achieving lower cumulative yields than less biennial bearing trees and cultivars. Spring bloom density also correlated negatively with a fruit-to-bloom cluster ratio, meaning that maximizing return bloom may not be a goal in and of itself, but that spring bloom density is one consideration in the complicated puzzle of crop load management. Despite the young age of the trees and the short span of the study, the trends we observed over 3 years—and a projected fourth year—agree with previous findings from longer-term studies. Partial budget analysis found that by the fourth year, chemical thinning to a target of 9 fruit/cm^2 TCSA would result in increased revenues and decreased harvest costs, leading to an overall increase in profitability compared with leaving trees unthinned. Given that hand-thinning was less profitable, effective chemical thinning formulations, timings, and rates, or other more affordable nonchemical methods, are needed, as are research-based recommendations to growers, and targeted breeding for reliably annual-bearing cider cultivars.

References Cited

Abruzzese A, Mignani I, Cocucci SM. 1995. Nutritional status in apples and June drop. J Am Soc Hortic Sci. 120(1):71–74. https://doi.org/10.21273/JASHS.120.1.71.

Agnello A, Brown B, Carroll J, Cheng L, Cox K, Curtis P, Helms M, Kain D, Robinson T. 2018. Cornell pest management guidelines for commercial tree fruit production. Cornell Coop. Ext., Ithaca, NY.

Barker BTP, Ettle J. 1910. Report for the years 1903–1910. National Fruit and Cider Institute, Long Ashton, England. https://hdl.handle.net/2027/uc1.$b227173.

Barritt BH, Konishi BS, Dilley MA. 1997. Tree size, yield and biennial bearing relationships with 40 apple rootstocks and three scion cultivars. Acta Hortic. 451:105–112. https://doi.org/10.17660/ActaHortic.1997.451.8.

Bates D, Maechler M, Bolker B, Walker S. 2021. Package "lme4." University of Wisconsin, Madison, Madison, WI. https://cran.r-project.org/web/packages/lme4/lme4.pdf.

Blanpied GD, Silsby KJ. 1992. Predicting harvest date windows for apples. Cornell Cooperative Extension, Ithaca, NY.

Chan BG, Cain JC. 1967. The effect of seed formation on subsequent flowering in apple. Proc Am Soc Hortic Sci. 91:63–68.

Chapman PJ, Catlin GA. 1976. Growth stages in fruit trees—from dormant to fruit set. New York's food and life sciences bulletin. Cornell University, Geneva, NY, Bulletin No. 58.

Copas L. 2013. Cider apples: The new pomona. Short Run Press Ltd., Exeter, UK.

Copas L. 2001. A Somerset pomona: The cider apples of Somerset. Dovecote Press, Stanbridge, Wimborne, Dorset, England.

Crassweller R, McNew R, Azarenko A, Barritt B, Belding R, Berkett L, Brown S, Clemens J. 2005. Performance of apple cultivars in the 1995 NE 183 regional project planting I. Growth and Yield Characteristics. J Am Pomol Soc. 51(1):18–27.

Cripps JEL. 1962. Research report: Chemical thinning of apples. Journal of the Department of Agriculture, Western Australia. 3(8):583–593. http://researchlibrary.agric.wa.gov.au/ journal_agriculture4/vol3/iss8/4.

Cuthbertson JD, Stickley RM. 1949. The production of cider fruit on bush trees. Observations on yields, 1945–1949, p 25–30. In: Annual Report of the Agricultural and Horticultural Research Station (The National Fruit and Cider Institute) Long Ashton, Bristol, England.

Czynczyk A, Chlebowska D, Epps T. 2008. Growth, yielding and susceptibility to fire blight of cider apples in the climatic conditions of Central Poland. Folia Hortic. 20(1):3–14. https://doi.org/10.2478/fhort-2013-0101.

Davis K, Stover E, Wirth F. 2004. Economics of fruit thinning: A review focusing on apple and citrus. HortTechnology 14(2):282–289. https://doi.org/10.21273/HORTTECH.14.2. 0282.

Embree CG, Myra MTD, Nichols DS, Wright AH. 2007. Effect of blossom density and crop load on growth, fruit quality, and return bloom in 'Honeycrisp' apple. HortScience. 42(7):1622–1625. https://doi.org/10.21273/HORTSCI.42.7.1622.

Employment & Training Administration. 2021. Adverse effect wage rates [WWW Document]. US Dep. Labor. https://www.dol.gov/agencies/eta/foreign-labor/wages/adverse-effect-wage-rates. [accessed 1 Jul 2021].

Farris J, Peck G, Groover G. 2013. Assessing the economic feasibility of growing specialized apple cultivars for sale to commercial hard cider producers (Extension Bulletin No. AREC-46P). Virginia Polytechnic Institute and State University. https://vtechworks.lib.vt.edu/bitstream/handle/10919/47428/AREC-46_pdf.pdf?sequence=1&isAllowed=y. [accessed 25 Apr 2021].

Forshey CG. 1986. Chemical fruit thinning of apples (Bulletin No. 116). New York's Food and Life Sciences Bulletin. New York State Agricultural Experiment Station, Cornell University.

Green JR. 1987. The hormonal control of biennial bearing in cider apples (PhD Diss). University of Bristol, Long Ashton, England.

Guillermin P, Piffard B, Primault J, Dupont N, Gilles Y. 2015. Fruit quality prediction on cider apple: Effect of annual fruit load, soil and climate. Acta Hortic. 1099:851–858. https://doi.org/10.17660/ActaHortic.2015.1099.108.

Haberman A, Ackerman M, Crane O, Kelner J-J, Costes E, Samach A. 2016. Different flowering response to various fruit loads in apple cultivars correlates with degree of transcript reaccumulation of a TFL1-encoding gene. Plant J. 87(2):161–173. https://doi.org/10.1111/tpj.13190.

Hedden P, Hoad GV, Gaskin P, Lewis MJ, Green JR, Furber M, Mander LN. 1993. Kaurenoids and gibberellins, including the newly characterized gibberellin A88, in developing apple seeds. Phytochemistry. 32(2):231–237. https://doi.org/10.1016/S0031-9422(00)94973-2.

Hoad GV. 1978. The role of seed derived hormones in the control of flowering in apple. Acta Hortic. 80:93–104. https://doi.org/10.17660/ActaHortic.1978.80.14.

Hoblyn TN, Grubb NH, Painter AC, Wates BL. 1937. Studies in biennial bearing.—I. J Pom Hort Sci. 14(1):39–76. https://doi.org/10.1080/03683621.1937.11513464.

Hothorn T, Bretz F, Westfall P. 2021. Package "multcomp." https://cran.r-project.org/web/packages/multcomp/multcomp.pdf. [accessed 9 Jul 2021].

Iwanami H, Moriya-Tanaka Y, Honda C, Hanada T, Wada M. 2018. A model for representing the relationships among crop load, timing of thinning, flower bud formation, and fruit weight in apples. Sci Hortic. 242:181–187. https://doi.org/10.1016/j.scienta. 2018.08.001.

Jones K, Bound S, Koen T, Oakford M. 1992. Effect of timing of hand thinning on the cropping potential of Red Fuji apple trees. Aust J Expt Agr. 32(2):417–420. https://doi.org/10.1071/EA9920417.

Knight TA. 1797. A treatise on the culture of the apple & pear, and on the manufacture of cider and perry. H. Procter, Ludlow, Shropshire, England.

Lenth RV. 2021. emmeans: Estimated marginal means. https://rdocumentation.org/packages/emmeans/versions/1.7.2.

Lordan J, Fazio G, Francescatto P, Robinson T. 2017. Effects of apple (*Malus ×domestica*) rootstocks on scion performance and hormone concentration. Scientia Hortic. 225:96–105. https://doi.org/10.1016/j.scienta.2017.06.050.

Merwin IA. 2015. Growing apples for craft cider. N.Y. Fruit Q. 23(1):5–9. https://nyshs.org/wp-content/uploads/2015/03/NYFQ-Book-Spring-2015-compressed.pdf#page=5.

Miles CA, Alexander TR, Peck GM, Galinato S, Gottschalk C, van Nocker S. 2020. Growing apples for hard cider production in the United States—trends and research opportunities. HortTechnology. 30(2):148–155. https://doi.org/10.21273/HORTTECH04488-19.

Miles CA, King J, Alexander TR, Scheenstra E. 2017. Evaluation of flower, fruit, and juice characteristics of a multinational collection of cider apple cultivars grown in the U.S. Pacific Northwest. HortTechnology. 27(3):431–439. https://doi.org/10.21273/HORTTECH03659-17.

Milić B, Magazin N, Keserović Z, Dorić M. 2011. Flower thinning of apple cultivar Braeburn using ammonium and potassium thiosulfate: Short communication. Hortic Sci. 38(3):120–124. https://doi.org/10.17221/57/2011-HORTSCI.

Peck G, Knickerbocker W. 2018. Economic case studies of cider apple orchards in New York State. Fruit Q. 26(3):5–10. https://nyshs.org/fall-2018/.

Peck G, Zakalik D, Brown M. 2021. Hard cider apple cultivars for New York. Fruit Q. 29(1): 30–35. https://www.researchgate.net/publication/354339299_Hard_Cider_Apple_Cultivars_for_New_York.

Peifer L, Ottnad S, Kunz A, Damerow L, Blanke M. 2018. Effect of non-chemical crop load regulation on apple fruit quality, assessed by the DA-meter. Scientia Hortic. 233:526–531. https://doi.org/10.1016/j.scienta.2017.11.011.

Pellerin BP, Buszard D, Iron D, Embree CG, Marini RP, Nichols DS, Neilsen GH, Neilsen D. 2011. A theory of blossom thinning to consider maximum annual flower bud numbers on biennial apple trees. HortScience. 46(1):40–42. https://doi.org/10.21273/HORTSCI. 46.1.40.

Plotkowski D, Cline JA. 2021. Evaluation of selected cider apple (*Malus domestica* Borkh.) cultivars grown in Ontario. I. Horticultural attributes. Can J Plant Sci. 101(6):818–835. https://doi.org/10.1139/cjps-2021-0009.

R Core Team. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/.

Ramírez H, Torres J, Benavides A, Hernández J, Robledo V. 2004. Fruit bud initiation in apple cv. Red Delicious linked to gibberellins and cytokinins. Revista de la Sociedad Química de Mexico 48:7–10. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.573.1870&rep=rep1&type=pdf.

Rathvon SS, Harris A. 1877. Changing the bearing year. The Lancaster Farmer: A Monthly Journal 9(6):93.

Robinson T, Lopez S, Iungerman K. 2010. Chemical thinning and summer PGRs for consistent return cropping of 'Honeycrisp' apples. Acta Hortic. 884:635–642. https://doi.org/10.17660/ActaHortic.2010.884.84.

Robinson TL, Fazio G, Aldwinckle HS. 2014a. Characteristics and performance of four new apple rootstocks from the Cornell-USDA apple rootstock breeding program. Acta Hortic. 1058: 651–656. https://doi.org/10.17660/ActaHortic.2014.1058.85.

Robinson TL, Hoying SA, Miranda Sazo M, Dominguez LI, Fachinello JC. 2014b. Yield, fruit quality and mechanization of the tall spindle apple production system. Acta Hortic. 1058:95–103. https://doi.org/10.17660/ActaHortic.2014.1058.9.

Robinson TL, Watkins CB. 2003. Cropload of Honeycrisp affects not only fruit size but many quality attributes. N.Y. Fruit Q. 11(3):7–10. https://nyshs.org/wp-content/uploads/2003/01/Cropload-of-Honeycrisp-Affects-Not-Only-Fruit-Size-but-Many-Quality-Attributes.pdf.

Smith WH. 1950. Cell-multiplication and cell-enlargement in the development of the flesh of the apple fruit. Ann Bot. 14(1):23–38. https://doi.org/10.1093/oxfordjournals.aob. a083232.

Soil Survey Staff. 2014. Keys to soil taxonomy. 12th ed. USDA-Natural Resources Conservation Service, Washington, DC.

Stander OPJ, Cronjé PJR. 2016. Reviewing the commercial potential of hand thinning in citrus with a cost-benefit analysis of summer hand thinning of 'Nadorcott' mandarin. HortTechnology. 26(2): 206–212. https://doi.org/10.21273/HORTTECH.26.2.206.

Stephan M, Bangerth F, Schneider G. 1999. Quantification of endogenous gibberellins in exudates from fruits of *Malus domestica.* Plant Growth

Regulat. 28:55–58. https://doi.org/10.1023/A:1006211309707.

Stover E, Wirth F, Robinson T. 2001. A method for assessing the relationship between cropload and crop value following fruit thinning. HortScience. 36(1):157–161. https://doi.org/10.21273/HORTSCI.36.1.157.

Tu Y. 2000. Endogenous gibberellins in developing apple seeds in relation to alternate bearing (MS Thesis). Purdue University, West Lafayette, Indiana, USA.

Weinbaum SA, DeJong TM, Maki J. 2001. Reassessment of seed influence on return bloom and fruit growth in 'Bartlett' Pear. HortScience. 36(2):295–297. https://doi.org/10.21273/HORTSCI.36.2.295.

Wilcox JC. 1944. Some factors affecting apple yields in the Okanagan Valley: I. Tree Size, tree vigour, biennial bearing, and distance of planting. Sci Agric. 25(4):189–213. https://doi.org/10.4141/sa-1944-0064.

Wood DES. 1979. The control of biennial bearing in cider apple cultivars: An experimental investigation using chemical sprays (PhD Diss). University of Bath, Bath, England.

Worlidge J. 1678. Section II. Of the nursery of all sorts of fruits, p 36–49. In: Worlidge J. Vinetum Britannicum or, a treatise of cider and other wines and drinks extracted from fruits growing in the Kingdom. Thomas Dring and Thomas Burrel, London, England. https://doi.org/10.5962/bhl.title.144920.

Wragg SR, Rendell J. 1977. The economics of cider apple production, agricultural enterprise studies in England and Wales. Economic Report, University of Bristol Agricultural Economics Research Unit.

Zakalik D. 2021. Crop load management of seven European cider apple cultivars: Effects on biennial bearing and fruit quality (MS Thesis). Cornell University, Ithaca, NY, USA. https://doi.org/10.7298/van0-xz83.

Zakalik D, Brown M, Peck GM. 2023. Fruitlet thinning improves juice quality in seven high-tannin cider cultivars. HortScience. 58(10):1119–1128. https://doi.org/10.21273/HORTSCI17096-23.

Zakalik D, Peck GM. 2023. High-tannin apple supply and demand in North America: Results from a 2021 cider industry survey. Fruit Quarterly. 29(1):30–34. https://nyshs.org/fruit-quarterly/.

Zhang Z, Wang Y, Zhang Z-h, Li D, Wu Z, Bai R, Meng G. 2019. Ergonomic and efficiency analysis of conventional apple harvest process. Int J Agric Biol Eng. 12:210–217. https://doi.org/10.25165/j.ijabe.20191202.4567.