CROP LOAD MANAGEMENT OF SEVEN EUROPEAN CIDER APPLE CULTIVARS: EFFECTS ON BIENNIAL BEARING AND FRUIT QUALITY

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ABSTRACT

In the United States and Canada, rapid growth in production and sales of alcoholic or "hard" cider has brought about a rapid increase in the number of acres planted with high-tannin apple (*Malus* ×*domestica*) cultivars, mostly of English and French origin. These cultivars, valued for the "mouthfeel" they confer to alcoholic cider, are often prone to "biennial" bearing, which is largely caused by seed-derived gibberellins suppressing floral bud formation, and thus return bloom. Crop load management, via bloom or fruitlet thinning, is often used to mitigate biennial bearing, as are bloom-promoting plant growth regulator (PGR) sprays.

Four field experiments assessed the innate bearing habit, response to thinning, and response to bloom-promoting PGR sprays of seven high-tannin cider cultivars, as well as the effects of crop load on fruit maturity and juice quality. In a three-year hand-thinning experiment conducted in Lyndonville, NY (Chapter 2), biennial bearing index (BBI) correlated negatively with cumulative yield both within and among cultivars: 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey' had low BBI and high cumulative yield overall, while 'Michelin' had higher BBI and somewhat lower cumulative yield; 'Brown Snout', 'Binet Rouge', and 'Geneva Tremlett's Bitter' were highly biennial and unproductive overall. Hand-thinning reduced BBI over three years, but rarely achieved comparable or greater cumulative yields over three years. Fourth-year bloom data indicate that, had treatments been re-imposed, thinning would result in comparable or improved cumulative yield, and lower BBI, for four of seven cultivars. This experiment, and an identical experiment performed in the low-crop "off" year only on a different set of trees, indicate that thinning in the "off" year is not effective at promoting return bloom.

The same two experiments found that crop load correlated negatively with polyphenol (i.e., tannin) content, soluble solid (i.e., sugar) content, titratable acidity, and nitrogen content, of juice over three years, for all seven cultivars (Chapter 3). The relationship between maturity and crop load was cultivar-specific.

A concurrent three-year experiment (Chapter 4) found that PGRs were not effective at promoting return bloom in any of the same seven cultivars. Likewise, a two-year experiment (Chapter 4) conducted in Lansing, NY found that PGR sprays had no appreciable bloom-promoting effect either compared to or in combination with hand-thinning, in 'Chisel Jersey' or 'Brown Snout', but that crop load did have a significant negative effect on return bloom.

A survey of commercial cidermakers in the United States and Canada (Chapter 5) found that biennial bearing affects apple supply for a majority of cidermakers growing their own high-tannin fruit, but only affects a minority of non-grower cidermakers working with high-tannin cider cultivars. Thinning and other horticultural practices to promote annual bearing were not commonly performed by high-tannin cider apple growers. The most mentioned cultivars by both apple growers and cideries who only purchase fruit or juice were the reputedly annual 'Dabinett' and the notoriously biennial 'Kingston Black'. Inconsistent supply was the leading reason given by cidermakers who choose not to use high-tannin fruit in their cider.

The work presented in this thesis demonstrates: the efficacy of hand thinning in certain high-tannin cider cultivars at promoting annual bearing, improved cumulative yields, improved juice quality, and overall tannin yield; the long-term profitability of thinning in high-density cider orchards for some cultivars; and the need for further research to identify effective midsummer PGR strategies that can be used with fruit thinning to promote return bloom in biennial high-tannin cider cultivars. Thinning to 9 fruit/cm^2 TCSA can improve long-term productivity in 'Brown

Snout', 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey', and can improve long-term tannin production in all seven cultivars described in this thesis.

BIOGRAPHICAL SKETCH

David Zakalik was born to Karen and Richard Zakalik in August 1993. After attending Kadimah School until the 8th grade and graduating from Nichols School in 2011, he attended Cornell University, from which he graduated with a Bachelor's Degree in Animal Science in 2015, with minors in Horticulture and Education. After graduating he remained in Ithaca and found employment at his *alma mater* as a research technician under professors Marvin Pritts and Gregory Peck, under the latter of whom he conducted the research presented in this thesis. In June 2018, David was accepted into the Employee Degree Program, enabling him to earn a Master's Degree while continuing as an employee of the University.

To my parents, who have worked hard and sacrificed, all my life, to support my education.

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LIST OF ABBREVIATIONS

6-BA	6-Benzylaminopurine
ABA	Abscisic acid
ACA	American Cider Association
BBI	Biennial bearing index
BFI	Biennial flowering index
BS	Bourse shoot
CEPA	2-Chloroethyl phosphonic acid (ethephon)
CK	Cytokinin
DAFB	Days after full bloom
DAP	Diammonium phosphate
DAPF	Days after petal fall
FBR	Fruit:bloom cluster ratio
FC	Folin-Ciocalteu total polyphenols
FT	Flowering locus T
GA	Gibberellic acid
GAE	Gallic acid equivalent
H_2S	Hydrogen sulfide
ha	Hectare
IAA	Indole-3-acetic acid
JA	Jasmonic acid
KODA	9,10-ketol-octadecadienoic acid
MAE	Malic acid equivalent
Md	*Malus domestica*
N	Newtons
NAA	1-naphthaleneacetic acid

OPA	o-phthaldialdehyde
PAN	Primary amino nitrogen
PGR	Plant growth regulator
PPO	Polyphenol oxidase
SAM	Shoot apical meristem
SG	Specific gravity
SPI	Starch pattern index
SSC	Soluble solids concentration
T6P	Trehalose-6-phosphate
TA	Titratable acidity
TCSA	Trunk cross-sectional area
TFL-1	Terminal Flower 1 gene
TIBA	Triiodobenzoic acid
TPS	Trehalose-phosphate synthase
YAN	Yeast assimilable nitrogen
ZT	Zeatin

Chapter 1: Review of Literature

1.1 Historical Overview

Cider, also referred to as "hard cider" in the United States, is an alcoholic beverage derived from the fermented juice of apples *(Malus spp.)*. Non-fermented "apple cider" is still so ubiquitous in American culture that the qualifier "hard" must be appended to the name of this alcoholic beverage which in other countries is called simply "cider", "cidre", "sidra", or other such cognates. Cider was once the most popular drink in America, due to the predominantly Anglo-Scottish origin of European settlers on the North American continent and the adaptability of apples to difficult soil and climatic conditions (Merwin et al., 2008), as well as the difficulty of growing barley and hops in the Northeast during the colonial period. Fermented cider has also historically been distilled into brandy in America, particularly in southern states where high temperatures could cause spoilage (Fitz, 1872). The difficulty of growing European grapes in much of North America, due to the endemic pest *phylloxera*, likewise retarded the development of a wine industry in the colonial and early republic periods. As Virginian Pomologist James W. Fitz put it, "Good cider is the wine of America" (Fitz, 1872).

Long before the national prohibition of alcohol sales in the United States from 1920 until 1933, American production and consumption of cider had already undergone a retraction due to changing demographics and tastes, and urbanization (Merwin et al., 2008). In the year 1899, some 55 million gallons of cider were produced in the United States, but by 1919 that figure had dropped to only 13 million (Fabien-Ouellet and Conner, 2018). The aforementioned James Fitz (1872) remarked that "The domestic manufacture of cider is worse managed than any in our country", and at the beginning of the last century, Virginian William B. Alwood (1903) began an international study of cidermaking with these words:

"In the United States cider has been in the past too generally regarded as a product of very little importance from a commercial standpoint, and it has been too often so made that most persons of cultured taste have looked upon it with little approval when offered as a beverage."

After the end of Prohibition, national production and consumption did not recover even as other alcoholic drinks—many of which were being sold illegally all along—quickly rebounded. Though sweet (non-alcoholic) cider production persisted through Prohibition and, indeed, became a ubiquitous part of American popular culture, the practice of fermenting sweet cider into hard cider faded into obscurity over the course of the 20th century. This phenomenon still awaits a full historical explanation.

The modern American hard cider industry has grown rapidly in the last decade, both in the volume of cider sold, as well as in the number of cider producers and the variety of products for sale (Cyder Market, 2019; NBWA, 2016; Thériault, 2019). From 2008 to 2019, the number of producers nationwide increased from 94 to more than 900; off-premise sales have increased ten-fold from ~$50 million in 2009 to ~$500 million in 2018 (Brager, 2020). Parallel with production, cider culture, among both producers and consumers, has evolved in a very short time, unrestrained by the conventions of Europe or even the traditions of pre-Prohibition America. Or perhaps it is more accurate to say that cider culture is in the process of evolving (Fabien-Ouellet and Conner, 2018).

Style and Flavor Profile in North America and Europe

In British and French ciders, tannin tends to be central to the flavor profile of cider, while in North America, acidity is more often dominant (Jolicoeur, 2011), though these generalizations are changing. The cultivation of high-tannin cider apples has occurred at an industrial scale for much of the twentieth century in England and France, but in North America commercial cultivation of these apples—and thus supply—is still somewhat nascent, with far greater demand than supply. A few commercial orchards, such as Poverty Lane Orchards in New Hampshire, DeFisher Farms in New York, and Harmony Orchards in Washington are among the few that grow high-tannin cider apples at a large scale to sell to other cideries. Some American cidermakers are developing partnerships with established orchards to plant high-tannin cider apples to secure a reliable supply, but typically on a case-by-case basis. Most cidermakers, if they grow high-tannin apples, have established small plantings of one or a few acres, using all the high-tannin fruit they grow for their own cidermaking rather than selling it to other cideries. The glut of cosmetically imperfect "cull" apples from the North American fresh-market apple industry, and moreover, apple concentrate from apple-producing giants like China or Poland—means that supply of low-tannin apples, juice, and concentrate vastly exceeds the supply of high-tannin cider fruit.

The author of these lines has of course enjoyed many a fine American or Canadian cider made from low-tannin apple cultivars, with hardly any bitterness or astringency. Yet excessive acidity and sweetness unbalanced by tannin is very common in American cider, particularly in mass-produced products. Many ciders produced and sold in the United States today are heavily back sweetened with apple juice or concentrate, or else, even if low in residual sugar, are often supplemented with high levels of exogenous malic acid. This style, sometimes referred to derisively as "alcopop", is in part due to the relative novelty of modern cidermaking and cider consumption, and also due to the nature of the apple supply available to cidermakers (Pashow and Mahr, 2018; Valois et al., 2006).

Consumer preference for less sweet, more tannic cider (Tozer et al., 2015) has led Angry Orchard, by far the nation's largest and top-selling cider company, to produce two new lines of hard cider, called “Unfiltered” and “Stone Dry”. The former is advertised as having “fuller mouthfeel, hazy appearance” and being “less sweet…made with bittersweet apples”; the latter is advertised as “the driest cider in Angry Orchard’s core collection…” balancing acidity “with the tannins of traditional cider making apples” (Angry Orchard, 2021a, 2021b). Consumer perception of “dryness” depends both on residual sugar as well as phenolic (tannin) content (Dawson et al., 2019; Lea and Arnold, 1978). The New York Cider Association has developed a “MerLyn Dryness Scale” (NYCA, 2018), similar to the International Riesling Foundation’s dryness scale, with the added modification of adjusting the rating “dryer” if the cider’s phenolic content is above a certain threshold, enabling consumers to seek out ciders that they will perceive as “dryer” or “sweeter” according to their own preference and taste.

The supply of dessert and culinary cull apples vastly exceeds the small but growing supply of heirloom cider-specific high-tannin apples. Fresh-market apples derive their complexity and interest from the texture of their flesh—which current tastes dictate should be crisp—and from juiciness, sweetness, and acidity. Yet these qualities can often render a cider insipid, in both senses of the word, just as viscosity, bitterness, or astringency would make an apple unpalatable for fresh consumption. Though many fresh-market apples are rich in aromatic compounds in their flesh and juice, aroma is only one of the qualities that make a cider interesting. The oversupply of fresh-market cull apples destined for processing has also led many commercial cider producers to view cider as a blank canvas, and to flavor cider with non-apple juices or other adjuncts such as jalapeno peppers, guava, prickly pear, hibiscus, blueberry, raspberry, blackcurrant, etc. For many cidermakers, particularly in non-apple growing regions, this stylistic choice is not merely born of necessity but may be stylistic. Even in England cider has been flavored with non-apple fruit adjuncts for centuries (Austen, 1657; Ellis, 1754).

Previous researchers, however, have found that the non-use of high-tannin cider apples is much more often due to lack of supply than a matter of taste or style (Becot et al., 2016; Pashow and Mahr, 2018; Raboin, 2017). Nonetheless, most cidermakers have reported to the author of these lines that if they do use high-tannin varieties, these represent a minority of the fruit used in a blend rather than a majority (Chapter 5), and previous research has found the same (Pashow and Mahr, 2018). Single-varietal ciders made from high-tannin cultivars can sometimes be perceived negatively by American consumers as excessively bitter or astringent (Dawson et al., 2019), though many commercial cideries now offer single-varietal ciders made from ‘Kingston Black’, ‘Redfield’, and other high-tannin cultivars.

Some very fine ciders are made with fresh-market or dual-purpose apples, whose interest and complexity come from barrel aging, secondary fermentations, or even dry-hopping, the latter practice being attested since at least the 19th century (Thacher, 1825). Still, the author of these lines is not alone in the opinion that nothing beats the body and complexity of a cider made with tannin-rich apples. Though it is not a truth universally acknowledged in the United States, it has been widely held for centuries by connoisseurs, artisans, and researchers that some amount of tannin is necessary for a full-bodied, well-rounded cider. In his treatise on cider and perry, Englishman Thomas A. Knight (1797) wrote:

> *“[Sugar] only is known to be capable of producing ardent spirit, and it might thence be inferred that the strongest ciders would be afforded by the sweetest fruits: but the juice of these generally remains defective in what is termed “Body” in liquors […] I suspect that the body of the liquor is strengthened, and it’s* [sic] *flavour improved, by the astringent juice […] The strongest ciders (and I believe the strongest wines) are made from fruits which possess some degree of astringency.”*

B.T.P. Barker (1911), Director of the National Fruit and Cider Institute at Long Ashton, England, wrote:

> *"…if the market apples alone are used for cider making, the type of drink which is produced…is a thin, sharp drink, lacking in body, and generally […] of a comparatively coarse flavour."*

Knight's and Barker's countrywoman Rosemary J. Green (1987) reaffirmed this sentiment when she wrote:

> *"Excess dessert fruit or apple concentrate can provide the "bulk filler" for cider production, but there is no substitute for good bittersweet cultivars; it is these that are in demand by cider makers."*

These high-tannin cultivars to which Green refers have for centuries been grown in England and France, and to a lesser degree in Spain, exclusively for use in cidermaking. Some are centuries old, while others have recently been selected or bred (Bore and Fleckinger, 1997; Dapena and Blázquez, 2004; Merwin et al., 2008; Ramírez-Ambrosi et al., 2015).

High-Tannin Apples in Pre-Revival American Cidermaking

There has been some recorded cultivation of high-tannin cider cultivars in the United States dating back to the late 18th century, and American cidermakers have had a taste for such apples for centuries. Horticulturist Bernard MacMahon of Philadelphia remarked that the widely recognized principle in winemaking that table grapes are "the worst for making wine," was similarly:

"…agreeable to the practice of cider makers, who always prefer the rough, juicy, and austere kinds of apples, to those that are considered best for the table" (Macmahon, 1819).

Nurseryman and pomologist Charles Downing (1802-1885) of Newburgh, New York echoed this sentiment in an updated edition of 'Fruit and Fruit Trees of America', originally co-written with his brother Andrew (1815-1852):

"Cider apples are varieties frequently useless for any other purpose. The best for this purpose are rather tough, piquant, and astringent; their juice has a high specific quality, and they are usually great bearers, as the Harrison, the Red Streak, and the Virginia Crab" (Downing and Downing, 1872).

In the first years of the American Republic, there was some interest in the cider apples of England. Abraham Crocker of Somerset, England wrote to his newly independent correspondents at the American Academy of Arts and Sciences to recommend a number of highly esteemed British high-tannin cultivars, including "Hagley's [Hagloe] Crab", 'Coccagee', 'Redstreak', and one called simply 'Bittersweet', for making cider *"fit for the best citizens of 'the free and independent states of America' to regale themselves with"* (Crocker, 1793). Americans' regard for cider, and for high-tannin cider apples, must have been quite high indeed for some of their most accomplished scientists to be in such brotherly correspondence with an Englishman about the best English cider apple varieties, a mere decade after the end of the Revolutionary War. However, the historical record—namely, nursery catalogues and pomology texts—indicates that few if any English high-tannin cultivars gained wide popularity in America prior to the cider revival of the last few decades. Mentions of French cider cultivars are even rarer in American catalogues or pomological texts.

In the first half-century or so of the Republic some nurseries in America offered English high-tannin cider cultivars such as 'Bittersweet', 'Coccagee', 'Foxwhelp', 'Redstreak', 'Royal

Wilding', 'Styre', and 'Hagloe Crab' (Booth, 1810; Mills, 1824; Pierce, 1824; Prince, 1793). Also of note is 'Siberian Bittersweet' (Kenrick, 1832), a cross between 'Yellow Siberian Crab' and English cider cultivar 'Golden Harvey' made by famed pomologist and cidermaker Thomas Andrew Knight (Thompson, 1904). Early recommendations of English bittersweet and bittersharp cultivars gradually gave way, over the course of the 19^{th} century, mostly to crabapples of American origin, though the English 'Hagloe Crab' remained popular. Reasons for this shift are complex. Perhaps growers found English cultivars were less suited to the mid-Atlantic and southern climate; nurserymen and orchardists may have simply lost interest in cider apples from abroad, instead looking inward to beloved American cultivars like 'Hewes Virginia Crab'. Perhaps the cost of importing and propagating high-tannin cider cultivars from Europe was not worth it for cidermakers.

Of the American high-tannin crabs and crab hybrids recommended by nurserymen and pomologists for cider, the most common by far was 'Hewes Virginia Crab', as well as 'Roane's White Crab', a seedling of the aforementioned 'Hewes' (Coxe, 1817; Pierce, 1824), 'Waugh's Crab' of Virginia origin (Berckmans, 1858; Downer, 1870; Downing and Downing, 1872; Saul, 1870; Warder, 1867), and 'Transcendent Crab', an American seedling of the Siberian *Malus baccata* (Greening, 1894, 1923, 1914; Harman, 1915; Stuart, 1895). 'Hyslop Crab', thought to have originated in Massachusetts, also warranted recommendation (Greening, 1923; Harman, 1915; Stuart, 1895). 'Martha' (Harman, 1915; Stuart, 1895), developed by Peter Gideon of Minnesota (Duin, 1974), was frequently mentioned for cider, as was 'Whitney Crab', developed by A.R. Whitney of Illinois (Harman, 1915; Locke, 1894; Stuart, 1895).

American nurserymen also recommended crabapples of regional or local origin to their customers, some of which now lie in obscurity: Peter Gideon's 'Mathilda' from Minnesota

(Unknown, 1890), 'Dartmouth Crab' from New Hampshire (Manning, 1875), 'North Carolina Crab' and 'Hughs Cider*' (Kelly, 1890), 'Yates Crab' from Georgia (Locke, 1894), and others. In *The Apples of New York* (Beach et al., 1905), several cultivated hybrids between "*P. iowensis"* (i.e., *Malus ioensis*) and the domesticated apple are described as "fit only for culinary uses or for cider", namely the 'Soulard' (i.e., *M. ×soulardii)*, 'Howard', 'Mercer', and 'Kentucky Mammoth (Mathews)' crabs. Several of these survive in the USDA *Malus* germplasm collection; they possess both high tannins and acidity (unpublished data).

As late as 1923 (i.e., during national Prohibition), the Greening Nursery Company in Monroe, Michigan was advertising 'Hyslop', 'Transcendent', and 'Whitney' crab apples as "valuable for preserving, jelly, cider, ornament, and some […] for eating" (Greening, 1923). But this was a far cry from the same nursery's advertisement in its 1894 catalogue, commending "Crab Apple Wine" to readers as "A Most Delicious Drink", which "resembles the finest of Madeira Wine", even offering to send a free guide to any patron who would plant a crab orchard "for wine purposes" (Greening, 1894). This catalogue praised bittersharp 'Transcendent Crab' as being "[t]he best of its class for cider" and "[t]he best for wine". A 1914 catalogue from the same nursery likewise commended 'Transcendent Crab' for cider but made no mention of "Crab Apple Wine" (Greening, 1914).

The case of Greening Nursery illustrates a broader shift across America in the relationship of apple orcharding to cider, wherein utility in cider became increasingly sidelined by culinary use. As the Temperance and Improvement movements gained force, as lager beer gained popularity, and as demographics shifted in the latter half of the nineteenth century, nurseries across America similarly became less likely to classify apple cultivars solely as "cider apples", tending

*Likely distinct from 'Hewes Virginia Crab' to list cidermaking as one of many uses for these cultivars, along with ornament, preserving, canning, baking, etc. Just as English cider apples gave way to American crabapples and crab-hybrids over the first century of independence from Britain, the concept of a "cider apple" gave way to what we would now call the "multipurpose" apple.

Though a handful of high-tannin apples have originated, been grown, and used for cidermaking in the United States prior to the recent revival of cidermaking in this country, most notably the aforementioned 'Hewes Virginia Crab' (Alwood, 1903; Thacher, 1825; Warder, 1867) and the hybrid *Malus ×soulardii* or 'Soulard Crab' (Alwood et al., 1904; Latham, 1873), the number of high-tannin cider cultivars in America, and even multipurpose cultivars, recommended and sold for cider, appears from the literature to have paled in comparison to the diversity of high-tannin cider cultivars grown and originating in the cider regions of England and France. However, this apparent lack of diversity may be an artifact of how high-tannin apples were propagated.

It is likely that a vast diversity of high-tannin cider apples existed in early America, but that these were not widely cultivated asexually by grafting. James Fitz, in *The Southern Apple and Peach Culturist*, quotes a treatise by one P.C. Reynolds of Rochester, New York:

> *"There are but few old orchards in the country that do not contain some trees which are decidedly unprofitable. Some bear small, sour, natural fruit, only fit for cider or swine*",

…and Fitz himself noted that "in a wild state", apple seeds produce "the small and bitter crab", and that:

> *"the fruit of the wild crab tree of our woods and forest is flatish [sic], about one inch in diameter, yellow when ripe, or of the color of polished brass, and possesses an agreeable fragrancy"* (Fitz, 1872).

Of high-tannin pears, Fitz, giving no thought to their potential use in perry, similarly remarks:

"nearly every old orchard or fruit yard has a number of worthless old pear trees, producing […] *bitter, astringent, natural fruit".*

And yet, Fitz subsequently recommends 'Hewes Virginia Crab', 'Hagloe Crab', and 'Redstreak', as well as "French Crab", along with better-known American multipurpose cultivars, to be grown for use in cidermaking. In *The Apples of New York* Beach, Booth, and Taylor (1905) noted: "The fruit from the seedling trees would now be called 'natural' or 'seedling' fruit…Such apples were then used chiefly for feeding to stock and for cider-making, being on that account often called cider apples." These texts illustrate the ambivalence of American pomologists and farmers toward growing apples for cider as the 19th century drew to a close and the 20th began.

Regardless of cider's retreat in the American diet and the American orchard, we can nonetheless infer that high-tannin cider apples in the American context, many originating as chance seedlings planted by settlers or by artisan nurserymen, might have represented as great a diversity as that of England or France, but with few varieties gaining popularity beyond the farmstead on which a given seedling sprouted and grew. These seedlings would rarely be described in pomological texts, in comparison to historically well-attested crabapples, or low-tannin multipurpose cider varieties like 'Yellow Newtown Pippin' or 'Harrison', which were widely propagated throughout the United States via grafting. Most of these "seedling" trees were gradually grafted over to tried-and-true multipurpose cultivars, surviving only as rootstocks.

Despite the long history of both crabapples and high-tannin *Malus ×domestica* cultivars being used in cider, even these apples' cultivation was not highly industrialized in the United States as it has begun to be in the early 21st century. As William B. Alwood (1903) noted:

…we have not at present in the United States a distinct industry in the growing of cider fruits. Yet it is true that some of our crab apples, and some varieties of apples also, have

> *been cultivated to a limited extent for cider and are considered valuable for this purpose, but it is seldom that they are grown to any large extent.*

Alwood wrote those words at a time when cider production and consumption in America, though less ubiquitous than in preceding centuries, was still much more widespread than it would be in this country prior to the recent cider revival. Today's dedicated—if small—industry of growing high-tannin cider cultivars for commercial production can thus be considered a novelty in the United States.

High-Tannin Apples in Contemporary American Cidermaking

Recent literature describing high-tannin cultivars thus deals almost exclusively with heirloom European cultivars (Alexander et al., 2016, 2016; Karl et al., 2020a; Merwin, 2015; Merwin et al., 2008; Miles et al., 2017; Peck and Knickerbocker, 2018; Plotkowski and Cline, 2021; Valois et al., 2006). Though high-tannin crab apples such as 'Dolgo' currently enjoy some popularity among North American growers as a source of tannins, in part due to their ubiquity as ornamental trees and orchard pollinizers, many were developed for jelly making or ornamental purposes (Alwood et al., 1904; Hansen, 1940), and given their small size, firmness, and dryness, have understandably received little attention from only a few cider-focused researchers (Valois et al., 2006; Wojtyna, 2018). My own survey of grower-cidermakers (Chapter 5) found that of the dozen most-mentioned high-tannin cider cultivars, only 'Hewes Virginia Crab' originated in the United States; nine originated in England and two in France. For these reasons, it is the English and French high-tannin cultivars that have been most widely researched and cultivated in both the Old World and the New.

1.2 Phenolic Content and Other Juice Quality Characteristics

The current renaissance of "sophistication" in American tastes for cider (Jamir et al., 2020) and growing consumer preference for less sweet, more tannic ciders (Tozer et al., 2015) has brought about an increase in the number of North American acres planted with specialty bittersweet and bittersharp cider apple cultivars (Merwin et al., 2008; Miles et al., 2015; Pashow and Mahr, 2018; Raboin, 2017; Valois et al., 2006). These cultivars are particularly rich in certain classes of phenolic compounds. Polyphenols, also referred to as "tannins" or "phenolics", impart bitterness and astringency to a cider (Lea and Arnold, 1978). Astringency is the velvety or drying sensation, experienced on the tongue and palate, when highly polymerized phenolics bind proteins in saliva and fall out of solution. Bitterness is the sometimes-unpleasant flavor one may experience when consuming very dark chocolate or raw cacao nibs, green potatoes, escarole, tea, or coffee. The proportions or ratios of different classes of compounds, with differing degrees of polymerization, determine whether a cultivar contributes bitterness or astringency, or a combination of the two, to cider.

Phenolic compounds are extracted from the flesh of apples during the pressing process, unlike grapes, in which tannins are primarily skin-derived. Apple cultivars rich in phenolics (>0.2% w/v[†]) are classified as bitter according to a commonly used scheme first put forth by the National Fruit and Cider Institute in England; depending on their acid content, these high-tannin cultivars are designated either "bittersweet" or "bittersharp", (Barker and Ettle, 1903; Lea and Drilleau, 2003). Specifically, the flesh and juice of these cultivars are rich in monomeric (+)-

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[†]As calculated by the Lowenthal Permanganate assay. Equivalent to 1.2 g/L GAE, measured using the Folin-Ciocalteu assay

catechins and (–)-epicatechins and their oligomeric forms procyanidins (Devic et al., 2010; Guyot et al., 2003; Lea and Arnold, 1978; Lea and Beech, 1978). In certain cider cultivars such as ‘Guillevic’ and ‘Avrolles’, these more bitter monomeric compounds may be virtually absent. In the juice of other cider cultivars, such as ‘Marie Menard’, monomeric catechins may comprise as much as 11% of total phenolic compounds.

The proportions of different phenolic classes also determine the tendency of a cultivar’s juice toward oxidation by the polyphenol oxidase (PPO) enzyme: monomeric catechins are a preferential substrate for PPO, as is chlorogenic acid, a compound in the hydroxycinnamic acid family (Devic et al., 2010). Oxidation affects both the color of cider and the perception of bitterness and astringency. Some high-tannin cultivars may yield very clear, pale juice and cider, while most are likely to yield golden, orange, bronze, or brown color, and even red (Bars-Cortina et al., 2017; Février et al., 2017). The color of unfermented juice, and of finished cider, depends on both the cultivar’s specific phenolic profile and the overall concentration of tannins in juice, as well as PPO activity and pressing conditions. Orchard practices affecting the phenolic content of fruit can thus be expected to have some effect on juice color in high-tannin cultivars.

Acidity, perceived as “sourness”, “sharpness”, or “tartness”, is largely attributable to malic acid content in apples, as measured by g/L malic acid equivalent (MAE) (Jolicoeur, 2011). A cultivar with TA of 4.5 g/L MAE or greater is classified as “sharp” or “bittersharp” (Barker and Ettle, 1903). Though acidity need not be a predominant sensory attribute in all ciders, some amount of acid is required to maintain microbial stability. A pH of 3.7 or lower has been found necessary to prevent “framboise” spoilage by *Zymomonas mobilis pomacea* (Coton and Coton, 2003), and a pH of 3.8 or lower is recommended for overall microbial stability and the predomination of *Saccharomyces* yeast species in initial alcoholic fermentation (Lea and Drilleau, 2003), though secondary fermentation by other microbes may impart enjoyable attributes to a cider. There are cider apple cultivars with virtually no malic acid content, such as ‘Sweet Alford’, which can have a TA as low as 0.013 g/L and a corresponding pH of 4.48 (Haynes, 1925). There are also cider cultivars with quite high acid content such as ‘Cap of Liberty’ (13.3 g/L MAE) and a corresponding pH of 3.14 (Valois et al., 2006). In extreme cases the pH of a cultivar’s juice can be 2.75 or even lower (Wojtyna, 2018). Blending of different cultivars to achieve a balance of flavors is often key in cidermaking.

Fermentable sugars, primarily fructose, along with sucrose and glucose, are the metabolic fuel for yeasts during fermentation, and are the essential precursors to ethanol, the alcohol that differentiates apple juice or sweet cider from true, alcoholic, cider. The total concentration of these sugars in raw apple juice is often measured as soluble solids concentration (SSC), though specific gravity (SG) is sometimes used in the cidermaking context. Sorbitol, a sugar alcohol generally not fermented by *Saccharomyces cerevisiae* yeast, is present in apples generally, and quite prevalent in certain cider cultivars while virtually absent in others (Wojtyna, 2018). Sorbitol lends residual sweetness to a cider in which other sugars have been fermented to ethanol.

Nitrogen, and particularly organic forms of nitrogen, is another essential nutrient for a vigorous fermentation and a cider free of hydrogen sulfide (H_2S) off-flavors and smells (Karl et al., 2020a, 2020b; Song et al., 2020). Nitrogen is one of the building blocks of cellular life, being a principal component of proteins, but nitrogen content of raw apple juice used in cidermaking is generally much lower than that of grape musts used in winemaking; the levels typically observed in apple juice are considered deficient by cidermaking and winemaking standards (Karl et al., 2020a; Valois et al., 2006). As a result, cider makers often supplement nitrogen to achieve minimum concentrations to ensure yeast vitality in the fermentative environment (Lea and Drilleau, 2003).

Elevated amino acid concentration in juice has also been found to correlate with increased metabolic evolution of esters (Santos et al., 2016, 2015), which confer desirable aromas to cider (Xu et al., 2007). Nitrogen deficiency has been found to correlate with higher evolution of undesirable higher alcohols such as isobutyl and isoamyl (Ough and Bell, 1980). However, within certain parameters, lower nitrogen content resulting in slower fermentation can achieve greater yeast production of desirable aromatic esters (Villière et al., 2015). The relationship between nitrogen status and aromatic evolution by yeasts is complicated. Any horticultural practices that affect the nitrogen content of raw juice are thus of great practical importance to cidermakers.

Though the planted acreage of high-tannin cider apple cultivars has increased in North America over the last decade or so (Miles et al., 2015; Pashow and Mahr, 2018; Raboin, 2017), research on crop load management for these cultivars is lacking, not only as pertains to bearing habit and yields, but as pertains to the relationship between crop load and juice quality parameters. Despite some research on the effect of crop load on the bearing patterns of many of these highly irregular cultivars (Green, 1987; Hedden et al., 1993; Hoad, 1978; Wood, 1979), almost no experimental research has considered the effect of crop load on juice quality specific to cider, such as soluble solids, acid, nitrogen, and phenolic content. Recent research has focused on the effects of other practices on these cultivars' juice quality (Alexander et al., 2016; Karl et al., 2020a; Miles and King, 2014), or else on the effect of crop load on phenolic content in low-tannin multipurpose cultivars (Peck et al., 2016; Stopar et al., 2002; Unuk et al., 2006).

1.3 Research Questions

The experiments described in this thesis address a wide array of questions. In Chapter 2, I describe and analyze a three-year crop load experiment at a commercial orchard in Western New York, examining how crop load affects bearing patterns and cumulative yields in seven European cider cultivars, and what crop load(s), if any, are appropriate to promote consistent bearing in these cultivars in a modern high-density system. In Chapter 3, I analyze more data from the same three-year experiment to assess the effect of crop load on phenolic content and other juice quality characteristics, as well as maturity and ripeness. In Chapter 4, I analyze a concurrent three-year study at the same orchard, as well as a two-year study at a research orchard in Lansing, NY, to quantify the response—in terms of return bloom and yield—of the same seven European cider cultivars to midsummer PGR applications. In the two-year study at Lansing, NY, I also analyze the interaction of crop load and midsummer PGR sprays in promoting return bloom. All three experiments described in this thesis also characterize the innate bearing habits (annual vs. biennial) of seven European cider cultivars when crop load is unmanaged. In Chapter 5, I describe the findings of a survey of cidermakers across North America, including cider apple supply chain, cider cultivars being grown in the U.S. and Canada, the effects of biennial bearing on cidermaking, strategies to counteract or adapt to biennial bearing, and the effect of apple supply on cider style.

1.4 Previous Research

<u>Biennial Bearing in Cider Cultivars</u>

Many polyphenol-rich cultivars, besides lending complexity and mouthfeel to a cider, also present unique horticultural challenges to growers. One such challenge is the tendency of many cider cultivars toward alternate or biennial bearing: a tree will bear high fruit yields one year, and little or no fruit the next year (Hoblyn et al. 1937, Huff, 2001; Wood, 1979; Merwin, 2015; Green, 1987). This phenomenon, particularly as it pertains to cidermaking, has been recognized for centuries. In his treatise on cider and other fruit wines, noted English agriculturist John Worlidge (1678) praised the widely grown cider cultivar 'Redstreak' as being "a constant bearer". A century later, English botanist Thomas Andrew Knight noted the following about cider apples and perry pears:

> "*It must be admitted that the produce of different years is extremely unequal, and that a great year of fruit introduces much excess and irregularity…"* (Knight, 1797).

An 1877 entry in *The Lancaster Farmer* noted that:

> "*In view of the fact that a year of excess and low prices, is followed by scarcity and high prices, inquiries have come to us in such numbers as to show that many are considering the practicability of changing this state of affairs*",

and that the tendency toward alternate bearing

> "*is a character to which little attention has been given by our pomologists; they state if a tree comes into bearing early, or if it is an abundant or shy bearer, but its tendency to annual or biennial bearing is rarely recorded, while it is one of the most important qualities*" (Rathvon and Harris, 1877).

To this day, inconsistency of yields, and thus of potential economic returns, remains a serious challenge to apple growers, as does the unpredictability of labor and storage needs concomitant with widely varying yields.

Cider cultivars have differing proclivities for this bearing habit: popular bittersweet cultivar 'Brown Snout' and bittersharp cultivar 'Geneva Tremlett's Bitter', among many others, are said to have a very strong biennial tendency (Merwin, 2015). Yet quantitative descriptions of cider cultivars' multi-year bearing habits and responsiveness to crop load management are lacking. The Biennial Bearing Index (BBI), a metric of yield variation first put forth by Hoblyn et al. (1937), is calculated as follows:

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

…where n is the total number of consecutive years observed, and i is a given year. Reporting yield as total fruit weight, as opposed to number of fruits, is more useful from a processing or cidermaking standpoint, and may be more appropriate when assessing the effect of manipulating crop load (number of fruits) on bearing pattern. A value of 0 represents completely consistent yields, while a value of 1 represents completely biennial bearing (no crop in the "off" year).

There is a dearth of recent multi-year studies on cider-specific cultivars. A recent genetic study of the USDA's *Malus* collection found that cider cultivars "derive more ancestry from *M. sylvestris* while dessert apples derive more ancestry from *M. sieversii*" (Migicovsky et al., 2021), though it is unknown whether this genetic difference may explain the highly biennial tendencies of cider cultivars. Many cider cultivars are notoriously prone to biennial bearing and have been reported anecdotally to be less responsive to crop load-reducing PGR sprays than even 'Honeycrisp' or 'Fuji', both dessert apples with a strong tendency toward biennial bearing. Most recent research in cider cultivars has not included BBI data for either managed or unmanaged trees. Because calculation of these indices requires at least two consecutive pairs of years (i.e., at least three years, though ideally four or more), studies that only examine return bloom and yields after one year of treatment cannot reflect the effect of crop load management on the long-term bearing patterns of these cultivars. Likewise, long-term variety trials of these cultivars need to include quantitative assessment of cider cultivars' natural bearing patterns.

One notable exception is the work of David E.S. Wood (1979) on biennial bearing in several English and French cider cultivars. Although Wood's work deals with trees in training systems not generally used in modern North American plantings, it is nonetheless very useful. Wood reported biennial bearing indices of both unmanaged and managed trees of multiple cider-specific cultivars. Ideally, any research or extension publication dealing with the subject of biennial bearing should include numerical quantification of bearing patterns in both unmanaged and managed trees of the same cultivar, so that growers can have a standardized, accurate idea of

Figure 1-1. 'Binet Rouge' trees at the Cornell University Orchard in opposite phases of biennial flowering.

not only a cider cultivar's innate tendency toward biennial bearing, but also its responsiveness to crop load management over more than two bearing years.

Plotkowski and Cline (2021) published three-year cumulative yield and BBI data from a cider variety trial in Ontario, Canada, but only on hand-thinned trees. Miles et al. (2017) likewise published data from a multi-year cider variety trial at Mount Vernon, Washington, but employed standard fruit thinning practices throughout the study. These authors' data are more useful for comparing cultivars' response to crop load management than for comparing innate bearing tendencies. However, yield data collected by Miles et al. (2018) from a separate subset of trees, reproduced in Table A1-3 in the Appendix, do not seem to show any clear relationship between BBI and cumulative yield.

"Biennial" or "alternate" bearing patterns, and crop load management strategies to manage these patterns, are fairly well studied in fresh-market cultivars. For instance, the popular fresh-market cultivar 'Honeycrisp' is well-known to have biennial bearing tendencies, with BBI ranging from 0.4 to 0.6 depending on rootstock (Robinson et al., 2014a). By contrast, the cider cultivars 'Dabinett' and 'Porter's Perfection', generally regarded as being "annual-bearing" (Merwin, 2015), have been reported to have equivalently calculated BBI of 0.69 and 0.87, respectively, over twelve years (Wood, 1979); whereas 'Michelin', reported by Wood to have an index of 0.42, was described by Green (1987) as "fairly regular". 'Chisel Jersey', a bittersweet cider cultivar described by Merwin as "biennial", has been reported by Wood to have BBIs of 0.54 and 0.70 at different locations over five and twelve years, respectively, and Copas (2001) said that 'Chisel Jersey' "crop[s] annually". French bittersweet 'Reine des Hâtives' has been reported by Wood to have an index of 1.00 (i.e., no bloom or crop in the 'off' year) when left unmanaged for four years, while with an effective thinning regime the same cultivar can have BBI as low as 0.21. Yet another cider cultivar, ‘Somerset Redstreak’, can have a BBI as high as 0.95 when left unmanaged, but as low as 0.14 with application of GA to mitigate excessive off-year flower bud initiation (Wood, 1979). Descriptions of cultivars’ multi-year bearing habits differ among sources: a comparison of five authors’ descriptions of the same cultivars is presented in Table A1-6 in the Appendix.

Cuthbertson and Stickley (1949) reported three years of yield data (tons per acre) from a cider variety trial coordinated by the National Fruit and Cider Institute at Long Ashton, England. I have calculated BBI from the three years’ worth of data reported by Cuthbertson and Stickley, recorded from 1947-1949 at farms in Faversham (Kent) and Kings Acres (Hereford). The data from these two farms, reproduced in Table A1-1 in the Appendix, show ‘Michelin’ to be one of the most productive (40.6 tons/acre and 27.9 tons/acre, respectively), but also one of the more biennial (calculated BBI of 0.85 and 0.72, respectively) cultivars over the three years observed. ‘Dabinett’, also planted at both Faversham and Kings Acres, was reported to be moderately productive (12.2 and 22 tons/acre, respectively) and somewhat annual (0.53 and 0.69, respectively). A separate trial at Long Ashton, Bristol, also reported by Cuthbertson and Stickley (1949) similarly found ‘Dabinett’ to be fairly productive (13.9 tons/acre) and moderately annual (calculated BBI of 0.58) over the years 1945-1949. ‘Chisel Jersey’ was reported to be both productive (27.9 tons/acre) and quite annual (calculated BBI of 0.31) at Faversham, Kent. There was no clear relationship, in the data reported by these authors, between bearing habit (BBI) and cumulative yield, though given that data were reported over a short time span, and that data were not reported for individual trees, it is difficult to assess the nature of such a relationship. By contrast, Wood (1979) has reported a tendency of cumulative yields to decrease over time as bearing becomes more “biennial” or “alternate”.

Economic Impacts of Excessive Crop Load and Alternate Bearing

The economic impacts of biennial bearing in cider apples are manifold but difficult to quantify. Opportunity cost, inconsistent supply, inconsistent and inferior juice quality, and unstable labor costs and needs at harvest are all potential negative consequences. Williams and Edgerton (1975) cite reduced storage costs and more predictable labor needs as economic incentives to control or minimize biennial bearing. With less risk of a crop failure in alternating years, cider makers can reduce the length of time they store fruit, juice, or fermented cider, and can have a stable product ready for market sooner. In a survey of cidermakers and growers of high-tannin cider fruit (Chapter 5), many respondents said they do not perform chemical or hand thinning, with others having attempted to thin in the past and stopped. Far more reported either fermenting what they have and using it in that year's blend, or less frequently, storing fermented cider to use in a subsequent year's blend.

Reduced cumulative yields due to biennial bearing are another economic incentive to manage biennial bearing: Wood (1979) and Wilcox (1944) reported lower cumulative yields over multiple years associated with alternate bearing patterns. For orchards selling their specialty bittersweet and bittersharp fruit to cideries, more reliable yields from year to year, as well as higher cumulative yields, would ostensibly be an economic benefit, in terms of higher and more reliable revenue, and a more reliable relationship with purchasers. For farm-cideries growing specialty high-tannin cider apples for their own use, the incentives for managing alternate bearing are less easy to quantify, though if the assertions of Wood (1979) and Wilcox (1944) hold for most apple cultivars, higher yields associated with more annual bearing would still certainly be a benefit. More even yields from year to year can make labor needs less extreme in the "on" year, and orchard laborers can have greater assurance that they will have employment at the same orchard the following harvest season.

Biennial bearing tendencies also have the potential to impact the larger cider industry, in addition to individual orchards and orchard-cideries: a recent survey of the US cider industry found that 58% of cider producers did not own or lease orchard land, and hence rely on independent orchard businesses for their supply of fruit and raw juice (Cyder Market, 2019). For wineries, breweries, and meaderies that also produce cider, the proportion of producers not owning or leasing orchard land is even higher. The same survey found that as of January 2019, nationwide, approximately one-fourth of cideries, and ~13% of wineries, report using “heirloom” cider apples in their hard cider. While “heirloom” does not necessarily signify ‘bittersweet’ or ‘bittersharp’, one can assume that some significant proportion of cider producers do, or seek to, use high-tannin cider apples, nearly all of which can be classified as “heirloom”. A survey of New York State cideries reported that 19% of fruit used by respondents fell under ‘bittersweet’ or ‘bittersharp’ classification, and 20% of respondents reported having difficulty sourcing bitter fruit or juice (Pashow and Mahr, 2018). In my own survey of commercial cideries across North America (Chapter 5) a majority of respondents reported they use high-tannin fruit, with a sizeable portion of those not using high-tannin fruit reporting that they plan to in the future. Lack of supply was the leading reason reported why a cidermaker does not use high-tannin fruit.

Physiological Mechanisms of Biennial Bearing

The relationship of plant hormones and other signals to flower bud formation in apples is complex and somewhat contested in the literature (Dennis and Neilsen, 1999; Iwanami et al., 2018; Pellerin et al., 2011; Weinbaum et al., 2001). A relationship between tree growth habit and biennial bearing tendency has been put forth (Lauri and Laurens, 2005), and the genetic basis of flowering and biennial bearing is beginning to be understood (Gottschalk, 2020; Guitton et al., 2012; Hanke et al., 2007), but this review will focus on the hormone-mediated physiological effects of flowers and fruit on biennial bearing, with a limited discussion of the underlying molecular and histological mechanisms. Because research into the effects of flowers and fruit on return bloom has involved blossom or fruitlet thinning, an exploration of the mechanisms of biennial bearing will necessarily involve a discussion of horticultural practices to control it.

Flower bud induction and initiation

Many perennial fruit crop species, including the apple, form flower buds in the growing season previous to when they flower. The process of flower bud formation in apples is generally divided into the following stages: induction, initiation, and differentiation (Milyaev et al., 2018). Induction is sometimes characterized as a change in hormonal balance and carbon assimilate distribution (Xing et al., 2019). Essentially, induction is the reversible process by which an undifferentiated bud becomes susceptible to becoming a floral bud. Initiation is a stage of rapid mitotic activity and change in histological structure, in which the central meristem unfolds. Following histological change, the transition from vegetative to floral is considered irreversible (Koutinas et al., 2010). Differentiation is said to begin with the formation of bract and lateral flower primordia, followed by the formation of the apical (king) flower primordium.

Flower buds in apples generally form from the terminal bud of a growing shoot, be it a short spur, a bourse shoot, or a longer vegetative shoot (see Figure 1-2, reproduced from Alaphilippe et al., 2008). Terminal bud-set is considered necessary for flower bud formation. Spurs generally cease growth 2-4 weeks after full bloom, whereas bourse and branch shoots continue growth further into the season (Buban and Faust, 2011; Jonkers, 1979). Floral initiation on the terminal buds of long shoots occurs approximately one month after initiation in spur and axillary buds. The following spring, the flowering site on a spur becomes enlarged and is called a bourse. A bourse shoot grows from this site and in turn sets a terminal bud later in the season. Flowering on the tips of long shoots is less common in commercially grown apple cultivars, although some such as 'Golden Russet' and 'Northern Spy' are anecdotally reported to produce significant bloom on the tips of longer branch and bourse shoots.

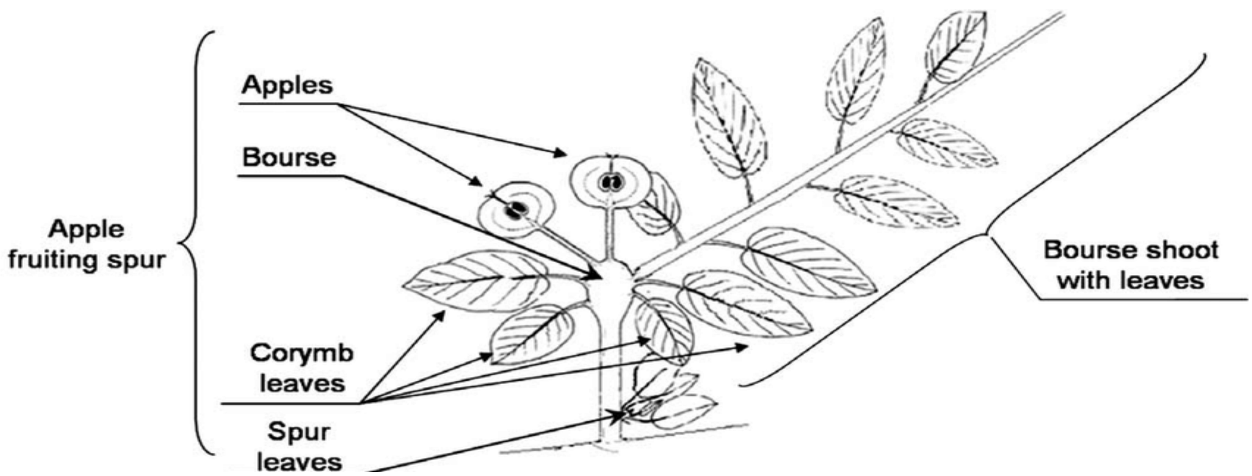

Figure 1-2. Apple fruiting spur with location of different sites and leaf types. Reproduced from Alaphillipe et al. 2008.

The effect of seed-derived gibberellins on flower bud formation

The relationship of seed-derived gibberellic acids (GAs) to flower bud initiation is incompletely understood but established. GAs exuded by seeds and flowers, particularly $GA_{1,3,7}$, have been identified as the main hormonal suppressants of flower bud formation in biennial-bearing apple cultivars (Dennis and Neilsen, 1999; Hoad, 1978). GA_4 has been found in some cases to promote flowering in apple (Tu, 2000), and may not always be seed-derived, unlike other GAs. GA_4 will be discussed separately. The effect of crop load on a cultivar's flowering and bearing habit is dependent both on a cultivar's complement of GAs (or "gibberellome", to coin a term) and on its tendency to transport seed-derived GAs out of developing fruitlets, via vascular tissue, into shoot apical meristems (SAMs). Mobility of GAs differs by cultivar, due in part to the differences in polarity of individual gibberellin-family compounds (Ramírez et al., 2001; Stephan et al., 2001). The timing of GA peaks and diffusion, relative to the timing of floral induction, further mediates the effect of crop load on a given cultivar's return bloom (Green, 1987).

Chan and Cain (1967), in a classic study on the subject, reported that return bloom in 'Spencer Seedless' apple and 'Bartlett' pear, both of which are facultatively parthenocarpic, was unaffected by crop load. Weinbaum et al. (2001) reported that although spurs bearing un-pollinated 'Bartlett' fruit had significantly higher return bloom than those with pollinated fruit, the presence of seedless fruit also had an inhibitory effect on return bloom, albeit a smaller one than seeded fruits, suggesting that nutrient allocation likely plays a role alongside phytohormonal signals. Belhassine et al. (2019) found that the presence of fruit on a given shoot had a reversible inhibitory effect on flower induction in 'Golden Delicious' up until 70 days after full bloom (DAFB), after which point the inhibition of flower induction was irreversible. Haberman et al. (2016) found that complete removal of fruitlets could still partially disinhibit flower bud induction at 80 DAFB, but they did not determine a window of time after which the inhibitory effect of fruit on flower induction was completely irreversible. Marino and Greene (1981) reported higher GA-like activity in flowering shoots than in vegetative shoots of biennial-bearing 'Early Macintosh', and Luckwill et al. (1969) found that GA-like compounds are present in higher concentrations in fruit-bearing spurs than in de-fruited spurs, in the more annual cultivar 'Cox's Orange Pippin'.

Belhassine et al. (2019) reported further, that levels of GA_8, the degraded form of GA_1 (the latter being hypothesized by these authors to inhibit floral induction) were higher in SAMs of fruiting than of non-fruiting branches. Defoliation was not found to have an effect on the concentration of any GA compounds quantified in their experiment, which conforms to current understandings of GAs as originating in seeds in apples. However, these authors did not establish a direct connection between GA presence and flower induction. Zhang et al. (2016) found that exogenous application of GA_3 suppressed MdSPL[‡] and MdFT1/2[§] expression, and moreover inhibited flower bud induction. They found that increased levels of GA_3 in turn set off accelerated formation of $GA_{1,4,7}$. They also found that elevated GA_3 suppressed production of cytokinins (CK) and of the oxidase enzyme, MdGA20ox, which catalyzes production of GAs. The role of CKs in promoting flower bud induction will be explored subsequently. Zuo et al. (2018) also found elevated levels of GA and MdGA20ox in "on" year (heavily blooming/bearing) trees of cv. 'Nagafu No. 2', and low levels thereof in "off" year trees of the same cultivar.

In a comparison of cider apple cultivars with differing biennial tendencies, Hoad (1978) found the highest levels of GA diffusate in fruitlet pedicels of the notoriously biennial bittersweet cultivar 'Tremlett's Bitter', while at an equivalent number of days after full bloom (DAFB), lowest levels of total GA were found in pedicels of annually-blooming cv. 'Worcester Pearmain'. However, differences were not found in GA-like activity in the seeds, supporting the hypothesis that GA mobility, rather than rate of GA production per seed, is a determining factor in bearing tendencies of apple cultivars. In the facultatively parthenocarpic cultivar 'Spencer's Seedless', Hoad (1978) found that fruit from hand-pollinated trees had higher seed counts and higher levels of GA in pedicel diffusates than did fruit from non-pollinated trees.

A cultivar's average seed number per fruit does not, however, determine its bearing habit. Hoad (1978) reported that annual-flowering 'Laxton's Epicure' had an average seed number per

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[‡] *Malus domestica* SQUAMOSE-PROMOTER BINDING-LIKE
[§] *Malus domestica* Flowering locus T

fruit of 9.1, while biennial-flowering ‘Tremlett’s Bitter’ had an average seed number of 4.9. Green (1987) found that the more annual ‘Dabinett’ and the highly biennial ‘Tremlett’s Bitter’ had roughly equivalent numbers of seeds per fruit (~7), also finding comparable levels of GA_4 and GA_7 in the seeds of both cultivars (~14.5 ng/seed). Green failed to detect these gibberellins in pedicel diffusates or in developing buds via reverse-phase HPLC and GC-MS, speculating that a co-eluting compound of similar size and polarity may have created significant ‘noise’ interfering with detection.

Green did nonetheless find, using a radiocarbon-label assay, that more presumptive-GA_4 moved from fruit to leaves and bourse shoots in biennial ‘Tremlett’s Bitter’ (2.3%) than in more regular ‘Dabinett’ (0.4%). More radiolabeled presumptive-GA_4 in pedicels, leaves, and bourse shoots occurred at 77 days after full bloom (DAFB) than at 63 DAFB, but a period of peak GA_4 movement was not identified because the assay was only performed on two dates. The data do, however, indicate a trend of rising GA_4 mobility approaching the date of bud differentiation in ‘Tremlett’s Bitter’ (83 DAFB). Nonetheless as Green noted, injection of radiolabeled hormone into developing fruit is highly invasive, and these data, though statistically significant, are suggestive rather than conclusive. The putative roles of GA_4 as both suppressor and promoter of return bloom in different circumstances further complicates Green’s and other authors’ findings. Green concluded that differences in GA diffusion between these two cultivars, rather than levels of GA production in seeds, explained their differing bearing habits.

Hedden et al. (1993) reported that at equivalent sampling time (10 weeks after anthesis), different complements of GAs were extracted from developing seeds of ‘Dabinett’ compared with

‘Tremlett’s Bitter’[**]. While GAs 4, 7, 17, 45, and 63 were identified in developing seeds for both cultivars, other GAs were only identified in seeds of one or the other. GAs 1, 20, 62, and 80 were identified in ‘Dabinett’ only, and GAs 9, 25, 35, 54, 68, and 84 were identified in ‘Tremlett’s Bitter’ only. GAs 3, 12, 15, 19, 34, 44, 53, and 61 were not identified in either of these cider cultivars but were identified in ‘Sunset’ and/or ‘Cox’s Orange Pippin’. These authors’ findings strongly underscore the point that each cultivar has its own “gibberellome”, with considerable influence on a cultivar’s multi-year “annual” or “biennial” bearing habit. The idiosyncratic nature of each cultivar’s blossoming and bearing tendencies, and the differing “gibberellomes” and rates of GA diffusion from seed to meristematic tissue, highlight the need for research further research into the role of GAs in biennial bearing of apples, especially in cider cultivars.

Bloom-promoting hormones: Cytokinin, GA_4, jasmonic acid, KODA, IAA, and the hormone-balance hypothesis

The role of flower-promoting hormones in apple is not as clearly understood as the role of bloom-inhibiting GAs. The idea of a “critical ratio” or ratios of bloom-inhibiting and -promoting hormones in apples has been put forth by multiple authors (McLaughlin and Greene, 1991; Pellerin et al., 2012; Ramirez et al., 2014). The hormone-balance hypothesis assumes that leaf and/or meristem tissue exudes flower-promoting hormones—be they JA, KODA, auxin, ‘florigen’, etc., but it is unclear to what extent levels of endogenous production of these promoter hormones is affected by the presence of fruit and seeds, or if the effects of these promoter hormones are simply counteracted by gibberellins, particularly $GA_{1,3,7}$, from seeds. The work of Kittikorn et al. (2010)

[**] This is the true English bittersweet cultivar ‘Tremlett’s Bitter’, not to be confused with the bittersharp ‘Geneva Tremlett’s Bitter’, widely grown in North America and also highly biennial, but of unknown provenance.

indicates that the former may be true. Those authors found somewhat higher levels of Jasmonic acid (JA) and much higher levels of 9,10-ketol-octadecadienoic acid (KODA) in trees with all flowers removed than in trees with high fruit set, at various lengths of time after full bloom.

The role of cytokinin in flowering and growth has become better understood in apples in recent years. Li et al. (2016) characterized the effect of exogenous 6-BA on endogenous hormone levels and on the growth and flowering of 'Fuji' trees. These authors found that concentrations of zeatin (ZT), a cytokinin, greatly increased after 6-BA application while indole-3-acetic acid (IAA, an endogenous auxin) greatly decreased. The following spring, the proportion of spurs was much higher, indicating that shoot growth was greatly reduced, while flower bud density was also significantly higher, compared with untreated trees. Cytokinin (CK) was later found to suppress GA signaling by down-regulating GA20ox (GA-catalyzing enzyme) transcription and up-regulating GA2ox (GA-degrading enzyme) transcription. CK has also been found to promote floral transition (Li et al., 2018). Lower GA signaling was posited to reduce shoot growth, while accelerated bud growth was attributed to elevated CK and IAA, as well as elevated sucrose and T6P signaling. Ramírez et al. (2014) reported that injection of ZT into spurs resulted in increased flower bud formation both in the presence and absence of fruit and speculated that CK:GA ratio in developing seeds has an effect on return bloom, in 'Golden Delicious'.

GA_4 was found by Stephan et al. (1997) to be the predominant GA in exudate of facultatively parthenocarpic cultivar 'Spencer Seedless' and noted a higher GA_3:GA_4 ratio of 8:1 in biennial 'Elstar', compared to 1:5 in more regular 'Spencer Seedless'. They noted, however, that other authors had not found the same trend in 'Golden Delicious'. McArtney et al. (2007) found that application of exogenous GA_{4+7}, in combination with ethephon, had a bloom-promoting effect in 'Cameo' but not in 'Mutsu' or 'Golden Delicious'. Belhassine et al. (2019) found that the gibberellic acid GA_9, the inactive precursor of bioactive GA_4 (Figure 1-3), was much more abundant in shoot apical meristems (SAMs) of non-fruiting branches and trees than in SAMs on fruiting branches and trees. They reported further that floral induction was promoted in the absence of fruit. However, levels of active GA_4 itself were not significantly different between SAMs of fruiting and non-fruiting branches. These findings partially conflict with Tu's (2000) finding that GA_4 promotes floral bud formation, though the latter author analyzed GA levels in 'Gala' and 'Fuji', but not in 'Golden Delicious'. Ramírez et al. (2001) speculated that GA_9 was unable to diffuse from seed into vascular tissue in 'Golden Delicious' due to lack of hydroxylation.

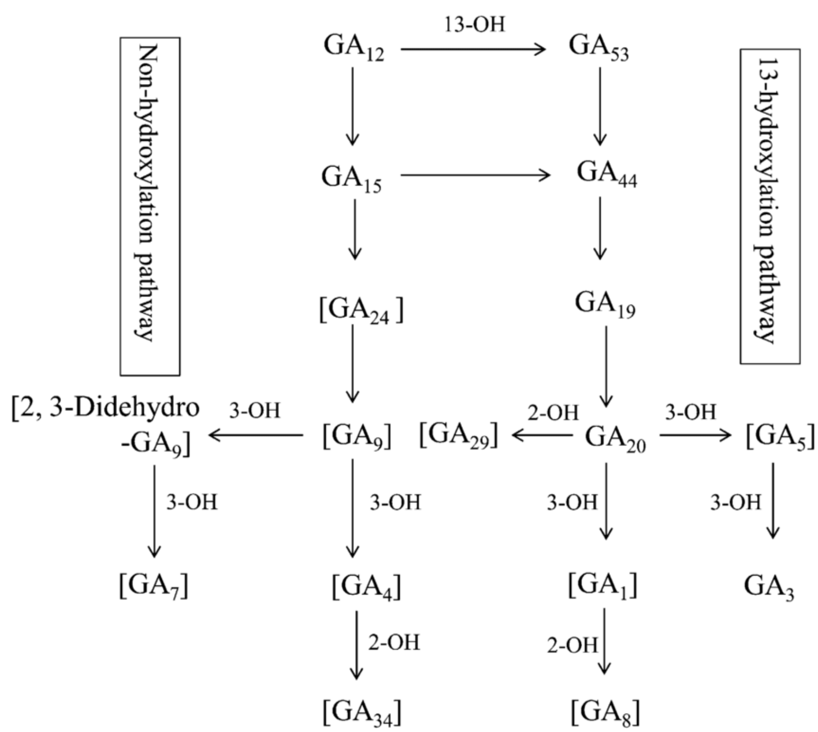

Figure 1-3. Metabolic pathway of gibberellic acids, reproduced from Yang et al. (2013).

Green (1987) found slightly higher movement of IAA (auxin) in more regular 'Dabinett' than in highly biennial 'Tremlett's Bitter'[††], though both cultivars had less than 1% diffusion of IAA. Green also found differences in the timing of IAA peaks in the seeds of these cultivars in

[††] Likewise, the true English bittersweet, not bittersharp 'Geneva Tremlett's Bitter'

relation to flower bud differentiation. Seed IAA concentration peaked 35, 57, and 106 DAFB in ‘Tremlett’s Bitter’, none of which coincided with the observed period of flower bud differentiation (72-83 DAFB) in that cultivar. On the other hand, the period of differentiation for ‘Dabinett’ in its “on” year (84 DAFB) was extremely close to the third peak in seed IAA concentration (82 DAFB), and in their “off” year, ‘Dabinett’ trees underwent flower bud differentiation 62-64 DAFB, immediately after the second reported peak in seed IAA (61 DAFB). These findings suggest that synchronicity of auxin and GA peaks contributes to the tendency of return bloom in ‘Dabinett’ to be less inhibited by the presence of seeded fruit than in ‘Tremlett’s Bitter’.

The existence in apples of a flower-promoting protein ‘florigen’ has long been speculated, and a genetic locus encoding such a protein has been characterized as flowering locus T (FT). Mimida et al. (2011) found that MdFT expression increased in SAMs during the early post-induction stage, particularly in leaf primordia and upper cell layers of shoot apices. Though they detected expression of MdFT primarily in shoot apices at the time of induction, Mimida et al. also identified low levels of MdFT transcript in the first leaf primordia surrounding the vegetative meristem and the precursors to flower primordia. For this reason, these authors posited that MdFT may also have a role in controlling seasonal growth cessation in vegetative tissue, as it does in Norway Spruce. Haberman et al. (2016) found that the level of FT-like transcript (namely MdFT1 and MdFT2) was not affected by crop load, supporting the hypothesis that seed-derived gibberellins counteract, rather than suppress, this putative flower-promoting hormone. They further found that a peak of MdFT1 transcripts occurred in bourse shoot (BS) apices at 68-83 DAFB, whereas no peak was found in leaves.

Nutrient diversion theory and carbon status

The nutrient-diversion theory of biennial bearing, that developing blossoms and fruit partition away resources that would otherwise go to developing flower buds for the following year, is supported in part by work in parthenocarpic apple and pear varieties. However, nutrient partitioning is not regarded as the primary mechanism of return bloom inhibition in *Malus*. Weinbaum et al. (2001) found that seedless fruit in 'Bartlett' pear had an inhibitory effect on return bloom—albeit smaller than that of seeded fruit—and found that seeded fruit grew larger than seedless fruit, pointing to the possible role of seed-derived gibberellins as a hormonal mediator of nutrient partitioning away from flower buds to developing fruitlets, as well as a direct signal for inhibition of flower bud induction.

Developing flowers and seeded fruit have also been shown to be sinks for carbohydrates. Hansen (1971) found that flowers developing in spring are strong sinks not only for current-year photosynthates, but also for the previous year's carbohydrate reserves within the tree; Hansen found further that spur leaves fixed 3-4 times more carbon in the early growth phase than did flowers. Fruitlets in the rapid cell-division phase are strong sinks for carbon assimilates from leaves (Hansen, 1970), particularly in the form of sorbitol, a glucose-alcohol, that diffuses quickly out of leaves and into fruits, where it is then converted to less-soluble sugars such as glucose, fructose, and sucrose. However, Hansen's experiments with ^{14}C-tagged assimilates in apple trees did not establish carbohydrate partitioning as a primary mediator of return-bloom inhibition.

Recent work by Xing et al. (2015) in 'Fuji' points to a more complex network of sugar- and hormone-mediated signaling pathways for induction of flower bud induction. Xing et al. put forth sucrose and trehalose-6-phosphate as proxies for spur carbohydrate status, and as initiation signals for flower induction, with abscisic acid (ABA) affecting levels of sugar and starch deposition in developing buds. Starch and sorbitol content were found to rise dramatically in flowering buds throughout all stages of induction, while sugar and nitrogen (N) levels in buds dropped dramatically in the early stages and changed little in later stages. Sugar levels in leaves began high, and then decreased sharply in later stages of induction, while leaf starch content and C/N ratio showed the opposite tendency. However, cytokinin was also identified as an important promoter of early-stage flower bud induction.

The influence of carbohydrate status on floral bud induction, and the role of carbon assimilates as a signal thereon, remains unclear. Belhassine et al. (2019) found that hormonal signals from leaves and fruit near a given SAM influenced flower bud induction, but that carbohydrate status did not. These authors found that SAM starch content did not differ between foliated and defoliated branches in non-bearing ‘Golden Delicious’ trees, but that in bearing trees of this cultivar, SAM starch content was much lower on defoliated shoots than on shoots with leaves intact. Although the proportion of induction was lower in defoliated portions of trees, the authors did not find a correlation between carbohydrate status and proportion of SAM induction. However, they did observe differences in SAM sorbitol concentration after defoliation and found that cropping trees had lower SAM sorbitol concentration than non-cropping trees.

The role of sucrose and closely-related trehalose-6-phosphate (T6P) in mediating flower induction is better established. Du et al. (2017) proposed a hypothetical model for the regulation of floral induction by sucrose and T6P. They found that trehalose-phosphate synthase (TPS) genes were significantly up-regulated immediately following sucrose application on apple buds, possibly via MdSPL2 4 and 5 and MdFT1 genes in the SAM. Li et al. (2019) found that treatment of buds with synthetic cytokinin 6-BA resulted in increased expression of many genes related to sucrose synthesis and T6P pathway, including TPS1 and 5, coincident with increased flower bud induction.

Xing et al. (2015), reported relatively high sucrose in flower buds during the early stage of flower induction and a decrease thereof into middle and late stages, and a simultaneous increase in leaf sucrose concentration from relatively low levels in the early stage of flower induction to higher levels in middle and late stages.

TFL1 flower repressors

The Terminal Flower 1 (TFL1) gene has been identified in many plant species, including in apple, as a site encoding flowering inhibition and prolongation of juvenility (non-flowering stage). Mimida et al. (2011) reported high expression of MdTFL1 in vegetative meristems, and drastic decrease thereof when meristems began differentiating into flowering meristems. Flachowsky et al. (2012) found that in transgenic *Malus domestica* (Md) tissue with silencing of the MdTFL1-1 gene, flowering was greatly advanced and vegetative growth either ceased or was strongly inhibited. Haberman et al. (2016) observed a peak in MdTFL1-1 expression in bourse shoot apices at the time of flowering, followed by a rapid decline. Although high crop load was correlated with a steeper decline in MdTFL1-1 expression than in shoots with all fruit removed, these authors could not establish that MdTFL1-1 was related to BS apical buds remaining vegetative.

Transcripts of MdTFL1-2 (as opposed to 1-1) were found by Haberman et al. (2016) to re-accumulate in BS apices after dropping to 0 soon after flowering: relative levels of this transcript began to increase again around 68 DAFB and continued increasing until at least 180 DAFB. In a similar experiment, expression of MdTFL1-2 was significantly higher at 94 DAFB even in spurs that had all fruitlets removed at 8 DAFB, compared to those with all fruitlets removed at 0 DAFB. Removal of leaves was also found to increase levels of MdTFL1-2 transcript in BS apices, even when adjacent spurs had all fruitlets removed. Application of GA_3 was found to result in a significant increase in MdFTL1-2 levels in BS apices, but relatively late, at 90-94 DAFB. The level of MdFTL1-2 transcript accumulation in response to comparable crop loads was found to differ among cultivars, with a concomitant difference in return bloom: cultivars that accumulated more MdFTL1-2 at the same crop load had less return bloom than those which had low accumulation of MdFTL1-2. However, no particular allele of this gene was reported to have an association with bearing habit. It is likely that some other factor, perhaps a GA compound, mediates the effect of crop load on expression of MdFTL1-2, and thus its downstream inhibitory effect on flowering.

Shoot length, growth cessation, and the localization of return-bloom inhibition

Because flower bud induction and initiation in apple generally require cessation of shoot growth (Koutinas et al., 2010), most commercial apple cultivars flower mainly on short spurs, which cease growth 2-4 weeks after bloom. The vast majority of flower buds in apple trees, located on these spurs, differentiate histologically in the spring between 3-6 weeks after petal fall, making this a critical period for adjusting bloom density or spring crop load (Buban and Faust, 2011). However, a few cider-specific cultivars described as being annual-bearing, such as ‘Breakwell’s Seedling’, ‘Teign Harvey’, ‘Harry Masters Jersey’ and ‘Ellis Bitter’ (Merwin, 2015), have also been described as at least partially tip-bearing (Swensen, 2006). But as previously mentioned, different sources contradict each other about the bearing habits of cultivars: Bradshaw et al. (2020) have described the aforementioned ‘Ellis Bitter’ as having “known biennial tendencies”. There are far more cultivars that are partially tip-bearing and partially spur-bearing, so a brief discussion of the relationship between shoot length, growth cessation, and flower bud initiation may be salient.

In May 2021, I counted flower clusters in a replicated variety trial of ten European cider cultivars (Peck et al. 2021) and assessed what percentage of clusters were located on shoot termini (Table A1-5 in Appendix). Reputedly annual cultivars ‘Ellis Bitter’ and ‘Harry Masters Jersey’ bore the highest proportion of flower clusters on shoot tips (56.6% and 58.4%, respectively), while notoriously biennial ‘Geneva Tremlett’s Bitter’ bore the least proportion on shoot tips (3.7%). However, some reputedly “annual” cultivars exhibited comparable or lower proportion of tip bloom than some reputedly “biennial” cultivars. I also observed that trees in their “off year”, regardless of cultivar, tended to exhibit far more tip bloom than trees in their “on” year. This would seem to indicate that spurs are much more prone to return bloom inhibition, and thus “biennial” flowering, while shoot tips are more likely to escape return bloom inhibition by developing fruitlets, thus flowering more annually. This would at least partly explain why tip bearing would be more prevalent in the “off” year. Overall, the total number of clusters on a tree correlated negatively with percent tip-bearing (data not shown).

The much later timing of flower bud formation on the terminal buds of growing shoots than on spurs has been hypothesized to account for the tendency of some tip-bearing varieties toward annual bearing (Wood 1979), and for spur-bearing varieties toward biennial bearing (Jonkers, 1979), based on the assumption that the vascular and temporal distance of terminal buds on shoots from developing fruit is a barrier to the inhibitory effect of seed-exuded gibberellins, particularly GA_3, on flower bud initiation in tip-bearing cultivars.

Neilsen and Dennis (2000) reported that the inhibitory effect on flower bud formation of GAs exuded by fruit and seeds was reduced as bourse shoot (BS) length increased: spurs with bourse shoots <2 mm in length failed to flower the following year, and spurs with a BS longer than 16 mm were almost always found to produce some bloom, regardless of the number of seeds formed. Other authors have found that a given cultivar can have a critical number of nodes that must be formed on a branch before flower bud induction can occur on shoot tips, and if the plastochron (the time between formation of successive nodes on a shoot) is too long, terminal buds may not become receptive to flower induction (Tromp, 1980; Zhu et al., 1997). Hansen (1971) found the nutrient 'sink' effect of developing fruits to be highly localized to individual spurs, though no conclusion about the effect on return bloom was drawn.

The localization of the inhibitory effect exerted by flowers and fruitlets on return bloom, though not total, is notable even in highly biennial cider cultivars. Wood (1979) reported success with part-tree stripping as a lower-risk method of managing biennial bearing: by removing all fruit from the upper portion of a tree's canopy, Wood found that annual yields could be achieved by reversing the biennial bearing phase of one part of the tree canopy and asserted that the presence of fruit in one portion of the canopy did not significantly inhibit flower bud formation in another portion in French bittersweet cultivar 'Reine des Hâtives'.

Figure 1-4. 'Harry Masters Jersey' setting fruit on shoot tips at the Cornell University Orchard in Ithaca, NY, 2021. (Author's photo)

Even in spur bearing varieties, vascular distance between fruit-bearing clusters and sites of flower bud formation can be an important barrier to the suppression of return bloom by seed-derived GA. Wood (1979) demonstrated in cider cultivars that many flower clusters must be 'freed' of fruit, when reporting that trees must have far fewer than 100 fruit per 100 flower clusters in order to achieve sufficient return bloom. However, the greater mobility of GA through vascular tissue in highly biennial cultivars, as noted by Hoad (1978) may mean that vascular distance between growing fruit and future flower buds is not a complete barrier to the inhibitory effect of the former on the latter, and thus the role of distance as a barrier should not be overstated.

Environmental conditions can exert a strong effect on the timing of shoot growth cessation. Warmer temperatures can prolong shoot growth and reduce flower bud formation (Tromp, 1980), and horticultural practices such as application of plant growth regulators (PGRs), in particular exogenous GAs, can delay growth cessation and inhibit flowering (Schmidt et al., 2009), though flower bud formation is not always affected (Byers et al., 2004). Conversely, ethephon treatment can promote both shoot growth cessation and return bloom in apples and pears (Duyvelshoff and Cline, 2013; Einhorn et al., 2014). Trees with high nitrogen status can have excessive shoot growth and inhibited return bloom (Stiles, 1999), but late-season nitrogen fertilization, including during leaf senescence, has been reported to enhance return bloom (Drake et al., 2002; Raese and Drake, 1993; Zubair et al., 2017), as has early-season fertilization (Beattie, 1958). In some cases, nitrogen application can counteract the bloom-suppressant effect of high crop load (Cmelik et al., 2006). The effect of nitrogen on return bloom differs depending on endogenous tree nitrogen status, and the timing and rate of exogenous nitrogen applications.

Rootstock effects

The flowering phase of rootstocks at grafting can have a significant effect on return bloom of a grafted tree. Green (1987) gathered budwood from bittersweet 'Michelin' trees in their 'on' and 'off' years and grafted buds onto stock trees in their "on" and "off" years. Trees grafted in the rootstock's "on" year had higher return bloom two years later than trees grafted in the rootstock's 'off' year, regardless of the flowering status of scion bud-wood source. This result seems to indicate some communicable signal from rootstock to scion controlling flowering. Differences in bearing patterns of the same scion among differing rootstocks has been observed in 'Honeycrisp' (Robinson et al., 2014a). Lordan et al. (2017) reported in a study of ten rootstocks, that 'Honeycrisp' scions had significantly different cumulative yield and BBI among different rootstocks; biennial bearing was reported to correlate positively with xylem auxin concentration and auxin/cytokinin ratio, while return bloom correlated negatively with auxin, particularly with IAA. Return bloom was reported to correlate positively with xylem ABA and cytokinin.

Barritt et al. (1997), in a study of forty rootstocks, found that rootstock vigor correlated positively with biennial bearing in 'Golden Delicious' and 'Granny Smith', but negatively in 'Redchief Delicious'. They attributed the difference among cultivars to the interaction of rootstock vigor and scion growth habit, concluding that the tendency toward biennial bearing in spur-type cultivar 'Redchief Delicious' was exacerbated by low rootstock vigor, but that:

> *"the reduction in shoot growth caused by dwarfing rootstocks may contribute to greater flower bud development and more consistent cropping" (Barritt et al., 1997).*

They also hypothesized the converse, that vigorous, less spur-bearing cultivars 'Golden Delicious' and 'Granny Smith' had delayed shoot growth cessation, and thus flower bud formation, on vigorous rootstocks.

Use of Plant Growth Regulators to Reduce Biennial Bearing

Though seed-derived gibberellins (GAs) are the main inhibitors of return bloom in alternate- or biennial-bearing apple cultivars, manipulation of fruit set and crop load are not the only avenues for counteracting the effects of GAs. On-year application of GA antagonists to counteract return-bloom inhibition, and off-year application of exogenous GA to reduce excessive flower bud formation, are both techniques used by apple growers to achieve annual bearing where blossom and/or fruitlet thinning are not deemed sufficient.

Wood (1979) investigated the efficacy of off-year PGR applications to reduce flower bud initiation for the following on-year, finding GA_3 applications to be slightly effective, and applications of bromacil (a photosystem II inhibitor used as an herbicide) to be more so. In a chemical thinning experiment in which triiodobenzoic acid (TIBA), an inhibitor of polar auxin and GA transport, was used in combination with 1-naphthaleneacetic acid (NAA) as a thinning agent, Wood found that GA transport-blocking TIBA alone was not very effective in the "on" year at counteracting GA-mediated inhibition of flower bud initiation, but that TIBA in combination with blossom-thinning NAA was highly effective at promoting return bloom.

More recent research into non-thinning PGR use to improve return bloom in alternate-bearing apples has focused on high-value dessert cultivars such as 'Honeycrisp'. Schmidt et al. (2009) found that on-year application of ethephon and off-year application of GA on alternate-bearing 'Honeycrisp' and 'Cameo' trees, were most effective when 50% of flower clusters were removed from trees, compared to trees with all or no flowers removed, over three years. Conversely, Robinson et al. (2010) found that application of NAA+Carbaryl or NAA+Benzyl adenine as a thinner at the 10 mm fruitlet stage alone was not effective in promoting return bloom, while these thinning sprays in combination with post-thinning summer applications of NAA or ethephon did significantly improve return bloom. It would appear from these authors' experiments that summer PGR application used in combination with spring bloom- or fruitlet-thinning agents can improve return bloom more than either approach alone.

Crop Load Management to Achieve Annual Bearing

The interaction between hormones in flowers, seeds, and shoots, and their effect on flower bud formation, is complicated. Nonetheless, it is widely recognized that bloom or fruitlet thinning are crucial to ensuring adequate bloom in the following spring (Iwanami et al., 2018; Nichols et al., 2004; Samuolienė et al., 2016). While blossom thinning is more effective than fruitlet thinning at promoting return bloom (Wood, 1979), thinning after fruit set can avoid excessive crop load reduction by late frost events. Yet little research has been done on the optimal thinning rates and crop load levels to reduce alternate/biennial bearing in bittersweet and bittersharp cider apple cultivars specifically, and almost none has been conducted in the last decade, despite the enormous growth in North American cider production since 2010 (Cyder Market, 2019). These apples are considered processing fruit, and the industry using them is quite small, moreover, so year-to-year yield consistency and optimal fruit quality have been given less attention than in fresh-market apple cultivars.

Wood (1979) conducted multi-year studies of various chemical thinning methods in several bitter cider apple cultivars, including 'Nehou', 'Reine des Hâtive', 'Yarlington Mill', 'Vilberie', 'Somerset Redstreak', and 'Tremlett's Bitter'. A few of Wood's experiments were conducted on 'bush' style trees on MM.106 rootstock or semi-dwarf MM.111, so Wood's findings are somewhat applicable to modern high-density cider orchards on dwarfing rootstocks. Because of the imprecise nature of chemical thinning, Wood was not able to achieve pre-targeted crop loads.

Nonetheless, Wood's work did determine effective thinning formulations and rates, and identified sufficient levels of crop load reduction to achieve acceptable yields and sufficient return bloom the following spring. For example, 'Reine des Hâtives' and 'Tremlett's Bitter' had sufficient return bloom to achieve equivalent yield efficiencies over two years when cropped at ~0.5 kg/cm^2 TCSA; for 'Somerset Redstreak' the yield efficiency for sufficient return bloom was ~0.4 kg/cm^2 TCSA. Wood also identified minimum necessary rates of fruit set reduction to achieve sufficient return bloom: 'Nehou' trees achieved significant return bloom at ~50 fruit per 100 flowering clusters, and 'Somerset Redstreak' had significant return bloom when reduced to 70 or fewer fruit per 100 clusters.

Reducing crop load is well known to result in larger average fruit size and mass (Guillermin et al., 2015; Henriod et al., 2011; Iwanami et al., 2018; Robinson and Watkins, 2003; Salvador et al., 2006). Wood (1979) found in a part-tree stripping experiment that the effect of whole-tree crop load on fruit size did not differ between part-stripped trees and thinned trees in 'Reine des Hâtives'. Wood (1979) also observed in multiple experiments that part-tree stripping and whole-tree thinning both resulted in increased retention (i.e., less "June drop") of remaining fruit, which he attributed to reduced competition among flowers or fruitlets. Cider cultivars have a strong tendency to overset fruit, and the ability of fruit thinning to reduce biennial bearing without unacceptable yield losses was noted by Wood when discussing the results of several experiments. Trees of cultivar 'Reine des Hâtives', when thinned to 50% of maximum fruit set, achieved 80% of maximum theoretical crop weight, and when thinned to 30% of maximum fruit set, achieved 50% of theoretical maximum crop weight, indicating that the observed increase in average fruit size due to thinning can compensate partially for reduced fruit number. In an experiment using NAA and ethephon (CEPA) as thinning agents, Wood reported that a 30% reduction in fruit number only reduced crop weight by 5% compared with control trees, and that a 50% reduction in fruit number still achieved 70% of crop weight compared to non-thinned control trees.

While blossom- and fruitlet-thinning have been frequently promoted as effective methods for reducing alternate bearing in apples (Cripps, 1962; Wood, 1979; Nichols et al., 2004; Robinson et al., 2010; Pellerin et al., 2011), the responses of individual cultivars to thinning treatments differ greatly, and different thinning agents and methods have varying rates of efficacy on different cultivars; timing of application is also an important factor in thinning efficacy. Williams and Edgerton (1974) reported that while yields in 'Golden Delicious' were more consistent over four years in chemically-thinned trees compared with untreated trees, cumulative yields did not differ greatly between treated and untreated trees. Wood (1979) on the other hand, reported "clearly increased accumulated crop" in chemically thinned 'Tremlett's Bitter' and 'Somerset Redstreak' trees over three years. Wood also reported that in twenty cider cultivars monitored for twelve years, higher cumulative yields coincided with lowest intensity of biennial bearing and bloom.

<u>Interaction of Crop Load Management and Midsummer PGR Sprays</u>

The interaction between crop load and summertime PGR applications is imperfectly understood, and depends on a number of factors: cultivar, long-term bearing history of a given tree, current-year crop load, and timing and rate of application, among others. Excessive crop load can reduce or negate the efficacy of bloom-promoting PGRs, while complete absence of crop does not necessarily make bloom-promoting PGRs more effective.

Byers et al. (2004) found that in 'Fuji', ethephon applied at 7 days after petal fall (DAPF) at 135 mg/L resulted in suppressed shoot growth and increased return bloom compared to unsprayed control but did not result in reduced crop load (i.e., did not thin fruitlets) in the year applied, at the aforementioned rate. However, when these authors applied ethephon at later stages

(14 and 28, and/or 42 and 56 DAPF), there was no significant difference in return bloom. Similarly, Cline et al. (2019) found that ethephon (Eth) at 150 mg/L had no effect on return bloom in biennial-tending ‘Honeycrisp’ when applied either three or six times, at 10-day intervals starting in late June, in two consecutive years of treatment. Taken together, Cline et al. (2019)’s and Byers et al. (2004)’s studies, using comparable rates of ethephon, demonstrate that spray timing has a strong influence on the efficacy of ethephon in promoting return bloom.

Duyvelshoff and Cline (2013) found that 1,500 mg/L ethephon—a rate much higher than typically seen in commercial application—at 5 and 8 weeks after full bloom (~35 and 56 DAFB) significantly increased return bloom in third-leaf ‘Northern Spy’/‘M.9’ trees, and that a higher rate, or a second application of the aforementioned rate, resulted in even greater return bloom the following spring. These differences in bloom subsequently resulted in significant differences in fruit yield at harvest. The authors conducted another experiment, also using third-leaf ‘Northern Spy’/‘M.9’ trees at a different site, and found that one application of 1,500 mg/L ethephon had a greater promoting effect on return bloom than one application at 750 mg/L, and likewise that two applications of 750 mg/L had a greater effect than either one application at that rate or two applications at 375 mg/L. This second experiment also found that the same cultivar, ‘Northern Spy’, showed greater responsivity to lower rates of ethephon on M.26 rootstock than on M.9 rootstock. These authors additionally reported that ‘Jonagold’ was more responsive to ethephon treatment, in terms of increased return bloom, than ‘Northern Spy’. A third experiment, at yet another site, found that third-leaf ‘Northern Spy’/‘M.9’ trees had increased return bloom and subsequent fruit yield in 2010 following two 2009 applications of 1,500 mg/L ethephon, but that one application at that rate, or two applications at 750 mg/L, did not yield significantly different fruit yield in 2010 compared to the control.

McArtney et al. (2007) reported that a combination of 5 mg/L NAA and 150 mg/L ethephon was no more effective in promoting return bloom than either alone, in ‘Fuji’/‘M.7’. In another experiment they found that a single application of 444 mg/L ethephon, six weeks after bloom, reduced the bloom-inhibiting effect of various crop loads compared to untreated trees at comparable crop loads, in ‘Golden Delicious’/‘M.7’ and ‘Fuji’/‘M.7’. In this experiment the authors found further that 666 mg/L ethephon was no more effective in promoting return bloom in ‘Golden Delicious’, while in ‘Fuji’ only the lower rate had any significant return bloom-promoting effect compared to control. In a third experiment these authors found that four applications of 316 mg/L ethephon and 13 mg/L GA_{4+7} increased return bloom in ‘Cameo’ but not in ‘Mutsu’ or ‘Golden Delicious’, hypothesizing that excessive crop load prior to hand thinning may have been the cause of the latter cultivars’ non-responsiveness to ethephon+GA_{4+7} application. These authors further reported that the efficacy of NAA and ethephon is greater when applied in the higher-crop load “on” year, but that the effect is cultivar dependent.

Other Effects of Crop Load Management

Maturity, ripeness, and pre-harvest drop

The effect of crop load on apple fruit maturity and juice quality is complex and may differ among individual cultivars. Wood (1979), for instance, found that heavily-cropped trees of bittersweet cider cultivar ‘Reine des Hâtives’ had later maturation and pre-harvest fruit drop than lighter-cropping trees of the same variety in 1977, while in the previous year (a drought year) the same trees showed no difference in drop rate among different crop load treatments. Wood’s 1977 results agree with the findings of Ward et al. (2001), while Peck et al. (2016) found that ‘York’ fruit were slightly more mature at time of harvest at higher crop loads than at lower crop loads.

Awad et al. (2001a) did not find significant differences in starch pattern index (SPI) among crop load levels in 'Jonagold' or 'Red Elstar', while Stopar et al. (2002) found lower SPI—i.e., delayed maturity—in lower-crop load 'Jonagold' fruit.

Ward et al. (2001) found that pre-harvest drop date increased linearly as crop load increased in 'Delicious', but those authors also noted that the range of dates was narrow (7 days) and that crop loads were low overall. However, strong year and cultivar effects on pre-harvest drop have also been observed, and the effects of cultivar, year, climate, and geography on fruit maturation and drop are complex and cultivar-dependent.

Sugar and acid content of fruit and juice

The effect of crop load reduction on apple flesh and juice quality has been studied somewhat extensively, with results differing by cultivar. Generally, the inverse relationship of crop load to soluble solid content (SSC) and fruit size is well established (Alegre et al., 2012; Musacchi, 2018). Awad et al. (2001a) found higher fruit weight, SSC, and malic acid content in 'Jonagold' and 'Red Elstar' fruit at lower crop loads; Stopar et al. (2002) likewise found higher SSC and fruit size in lower-cropped cv. 'Jonagold' fruit. Peck et al. (2016) similarly observed an inverse relationship of crop load to SSC, malic acid content, and fruit size in 'York' apples, despite the aforementioned positive relationship between crop load and fruit maturity as measured by SPI.

Polyphenol content of fruit and juice

The relationship of crop load to polyphenol content in fruit is less clear, in part because some studies have assessed polyphenol content in fruit flesh while others have done so in juice or fermented cider. However, Stopar et al. (2002) found that lower crop load coincided with higher flesh polyphenol content in 'Jonagold', agreeing with the results of Awad et al. (2001a) in the same cultivar. Peck et al. (2016), confoundingly, found no significant relationship between crop load and polyphenol content in raw ‘York’ juice, but a positive relationship in fermented ‘York’ juice. Guillermin et al. (2015) reported that crop load had a negative effect on average fruit weight, as well as density, tannin content, and acidity of juice in cider cultivars ‘Douce Coëtligné’ and ‘Douce Moën’.

Nitrogen content of fruit and juice

Peck et al. (2016) found that apple juice and fermented cider from heavily cropped ‘York’ apple branches had lower yeast assimilable nitrogen (YAN) than from those thinned to a lower crop load. There is, however, a severe shortage of other research into the effect of crop load on apple nitrogen content. Though much research has been conducted on this subject in wine grapes, the majority of research into crop load effects on apple mineral content has focused on apple calcium content, rather than nitrogen content, due to the role of calcium in bitter pit in culinary apples. The recent rapid growth of apple use in fermented cider has outpaced research into the effects of crop load management on apple mineral content as pertains to yeast nutrition and fermentation kinetics.

1.5 Conclusion

Though the primary incentive for crop load management in cider apples is consistent cropping, the manifold potential effects of fruit thinning—larger fruit size, and increased polyphenol and soluble solid content especially—highlight the need to develop effective crop load management regimes for these unusual high-polyphenol cultivars. The intense biennial-bearing tendencies of these cultivars, and their differing responsiveness to thinning agents, highlight the need for research specifically in these cultivars. The identification of additional horticultural practices, such as mid-summer PGR applications to supplement flower and fruitlet thinning, should also be an important goal for researchers in this period of renewed experimental research on cider apple cultivars.

In the following chapters, I describe three multi-year field experiments that investigated the effect of crop load on yield and return bloom (Chapters 2 and 4), as well as fruit maturity and juice quality (Chapters 3 and 4). A three-year hand-thinning experiment at a commercial orchard in Lyndonville, NY (Chapter 2) compared return bloom, cumulative yield, and BBI of seven cultivars between trees with crop load management to that of trees with no crop load management. A concurrent three-year experiment at the same orchard (Chapter 4) compared the effects of hand-thinning with midsummer PGR applications on return bloom, cumulative yield, and BBI in the same seven cultivars. A two-year experiment at a research orchard in Lansing, NY (Chapter 4) compared the effect of hand-thinning and midsummer PGR sprays on yield and return bloom and assessed the interactive effects on yield and return bloom of both these treatments in combination. A survey of cidermakers across North America (Chapter 5) examined the effects of biennial bearing on apple supply, and of apple supply on decision-making processes in the orchard and on cidermaking. In this survey I also solicited data on what high-tannin cultivars are commonly being grown in North America.

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Chapter 2: Fruitlet Thinning Reduces Biennial Bearing and Improves Juice Quality in Seven High-Tannin Cider Cultivars

Abstract

For three consecutive years, seven high-tannin cider apple cultivars (*Malus ×domestica* Borkh.) were hand-thinned to target crop densities of 0, 3, 6, and 9 fruit/cm^2 trunk cross-sectional area (TCSA) or left un-thinned as a control. Treatments were imposed on the same trees for all three years. Yield, return bloom, and tree growth were assessed. Biennial bearing index (BBI), a measure of year-to-year yield variability, correlated negatively with cumulative yields both within and among cultivars, due to a negative effect of crop density on average fruit weight and return bloom. The relationship between BBI and cumulative yield was more pronounced within more annual-bearing cultivars than in more alternate-bearing cultivars. Crop load had a negative correlation with return bloom (flower clusters/cm^2 TCSA) in all years, but the effect was negligible following thinning in the "off" year. Trees left un-thinned in the high-crop "on" years had little to no return bloom in the following "off" year. The 2019 return bloom data indicate that, had target crop density treatments been imposed for a fourth year, the pattern of lower-BBI trees having higher cumulative yields would have continued. Partial budget analysis found that thinning would only result in a positive net change in three-year profitability for 'Dabinett', but over four years, under conservative assumptions about fruit set, chemical thinning would result in increased cumulative profitability in all seven cultivars when thinning to a target crop load of 9 fruit/cm^2 TSCA. Hand thinning was less profitable overall but was still projected to result in increased net profitability over four years for five of seven cultivars.

2.1 Introduction

"Biennial" or "alternate" bearing is a well-known phenomenon in which an apple (*Malus ×domestica* Borkh.) tree will produce a large crop one year, and little to no crop the next. This phenomenon sometimes occurs on a cycle of more than two years and in such cases "irregular" rather than "biennial" might better describe the bearing habit. The phenomenon of "biennial" bearing has been recognized by orchardists, cidermakers, and horticulturists for centuries (Knight, 1797; Rathvon and Harris, 1877; Worlidge, 1678). Biennial bearing is usually quantified using the biennial bearing index (BBI, Equation 2-1 below), first put forth by Hoblyn et al. (1937). A value of 0 indicates completely annual bearing (no difference in yields from year to year), while a value of 1 indicates completely biennial bearing (no yield in the "off" year).

Equation 2-1. Biennial bearing index

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

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

Though since the early 20th century much quantitative research has been conducted on biennial bearing in apples, little has been done in high-tannin cider cultivars. The tendency of a highly biennial tree, or indeed an entire orchard on an extreme biennial cycle, to yield less fruit over time has also been reported in quantitative studies. Wood (1979) reported that highest cumulative yields over twelve years occurred in the least alternate trees of twenty cider cultivars. Individual trees' BBI may also not clearly relate to cumulative productivity, particularly in notoriously alternate cultivars such as 'Honeycrisp' and 'Fuji' (Robinson et al., 2014a).

Mechanisms of Biennial Bearing

It is well established that in many apple cultivars the presence of fruit—particularly seeded fruit—on a tree or branch inhibits return bloom the following spring (Chan and Cain, 1967; Weinbaum et al., 2001). The absence of fruit the next year often results in excessive bloom in the third year, perpetuating a cycle of dramatic yield fluctuations. The suppression of return bloom by fruit is largely mediated by the class of seed-derived phytohormones known as gibberellic acids (GAs). GAs exuded by seeds diffuse into vascular tissue adjacent to developing fruitlets, suppressing flower bud induction in shoot meristems (Hoad, 1978; Ramírez et al., 2004; Stephan et al., 1999). This suppressive effect depends on: (1) the timing of peak GA synthesis and diffusion and of flower bud induction in a given cultivar (Haberman et al., 2016; Jones et al., 1992), (2) a cultivar's particular complement of seed-derived GAs (Green, 1987; Hedden et al., 1993)—or its "gibberellome" to coin a term, and (3) the relative concentrations of given GAs in seed diffusate.

Although bloom-inhibiting GAs are seed-derived, a cultivar's average seed number per fruit is not predictive of its flowering or bearing habit (Green, 1987; Hoad, 1978). Rather, the vascular mobility of GAs, in large part a function of their chemical structure and polarity, affects the degree to which seeded fruits suppress return bloom. Nonetheless, the total number of seeds on a tree does correlate negatively with return bloom.

Thinning of flowers and/or developing fruitlets in spring is a widely employed practice to minimize yield variability by encouraging return bloom (Pellerin et al., 2011; Robinson et al., 2010; Wood, 1979). Reducing crop load in the "on" year can encourage moderate return bloom in the following presumptive "off" year, and a moderate crop in the "off" year can in turn prevent excessive or "snowball" bloom in the following "on" year, thereby disrupting the cycle of biennial flowering and bearing. Blossom and fruitlet thinning are often achieved by chemical means (Milić et al., 2011; Pellerin et al., 2011; Robinson et al., 2010; Wood, 1979), though hand-thinning is sometimes performed in high-value fresh-market production, often as a follow-up to chemical thinning.

Biennial Bearing in Cider Cultivars

Many heirloom European high-tannin cider apple cultivars, such as ‘Binet Rouge’ and ‘Brown Snout’, among many others being widely planted in the United States (Miles et al., 2015), have been documented to have biennial bearing habits (Copas, 2013; Green, 1987; Hoad, 1978; Merwin, 2015; Peck et al., 2021; Wood, 1979). Because the cider industry, and cultivation of these apples, has grown immensely in North America in a very short time (Cyder Market, 2019; Miles et al., 2020), horticultural research into proper crop load management regimes for cider apple cultivars has lagged, particularly for modern high-density cropping systems not yet developed when limited research was conducted in the mid-20th century.

Recently published work on cider apple production has either focused on the effect of crop load on juice quality (Guillermin et al., 2015; Guyot et al., 2003; Peck et al., 2016) or has only characterized the effects of crop load management over one pair of years—i.e., one “on” and one “off” year (Bradshaw et al., 2020). A few authors have reported BBI of high-tannin cider cultivars in variety trials using conventional thinning regimens (Miles et al., 2017; Peck et al., 2021; Plotkowski and Cline, 2021), but research comparing thinned and un-thinned trees, or identifying ideal crop loads for high-tannin cider cultivars, is needed to ensure the sustainability of the emerging cider industry.

As discussed in Chapter 1, both qualitative descriptions in pomological texts, and quantitative data from scientific sources have differed on the bearing habits of some cider cultivars

(Copas, 2013, 2001; Merwin, 2015; Miles et al., 2017; Peck et al., 2021; Plotkowski and Cline, 2021; Wood, 1979). Criteria for classifying a cider cultivar as being “annual” or “biennial” in its bearing pattern are not uniform, or indeed explicitly spelled out in most sources. By choosing a diverse array of cultivars with differing reputed bearing habits, we intended to improve understanding of these cultivars’ bearing tendencies and responses to thinning with empirical quantitative data.

<u>Economics of Biennial Bearing and Crop Load Management</u>

The general economic viability of planting and growing these cultivars, which due to their bitterness are useable only in cidermaking, is a major concern for growers (Farris et al., 2013; Peck and Knickerbocker, 2018; Wragg and Rendell, 1977). The effect of crop load management on long-term orchard productivity is a highly important but under-studied economic consideration for growers of high-tannin cider cultivars, as well as growers of tree fruit generally (Davis et al., 2004).

There is often a negative correlation between cumulative productivity of a tree or a whole orchard and “bienniality” of yields from year to year (Wilcox, 1944; Wood, 1979; Wragg and Rendell, 1977). Strategies to mitigate biennial bearing have the potential benefit to growers of increasing cumulative yields and thus revenue (Forshey, 1986; Stover et al., 2001). Crop load also negatively correlates with average fruit size (Guillermin et al., 2015; Robinson and Watkins, 2003; Wood, 1979), which is a concern for producers who harvest cider fruit by hand, currently the norm in the US and Canada unlike in England and France (Galinato et al., 2015; Miles et al., 2020; Miles and King, 2014). Whether pickers are paid by the hour or by the bin (i.e., on a weight basis), growers have a higher harvest cost for smaller fruit. Some pay pickers a higher wage per bin to compensate for slower harvest of often small-fruited cider varieties (Anonymous, personal comm.). Reduced harvest cost due to fruit thinning has been reported in apples and mandarins (Cripps, 1962; Davis et al., 2004; Stander and Cronjé, 2016), and detaching of apples can take as much as 30% of harvest time (Zhang et al., 2019). Miles and King (2014) reported that hand-harvest costs can be more than four-fold machine harvest costs per acre. If an equivalent weight of fruit can be harvested more quickly by detaching and picking fewer fruit which are larger on average, harvest costs can be reduced, particularly for smaller-scale growers without the financial resources to buy expensive harvest machinery.

The goals of this experiment were to determine the effect of crop load on bienniality, and to assess the relationship between bearing habit (as measured by BBI) and cumulative yields. Our hypotheses were: (1) reducing crop load would increase return bloom, (2) lower crop loads over three years would coincide with lower BBI, (3) cumulative yields would correlate negatively with BBI, and (4) average fruit size would correlate negatively with crop load. As regards the economic impact of crop load management, our hypothesis was that hand-thinning would result in a net increase in profitability over multiple years.

2.2 Materials and Methods

Experimental Design

Seven European high-tannin cider apple cultivars were hand-thinned to four target crop densities or left un-thinned, for three years. These cultivars were: ‘Binet Rouge’, ‘Brown Snout’, ‘Chisel Jersey’, ‘Dabinett’, ‘Harry Masters Jersey’, ‘Michelin’, and ‘Gevena Tremlett’s Bitter’. The latter cultivar is classified as a bitter-sharp according to the Long Ashton classification system (Barker and Ettle, 1903); the other six are classified as bittersweet cultivars. All trees were grafted onto ‘Budagovsky 9’ (‘B.9’) rootstock and planted in 2014 in three uniform rows per cultivar of approximately 120 trees each at 1.2 m × 3.7 m (4' × 12') or ~2,220 trees/hectare (900 trees/acre) spacing and trained in the tall spindle system using one trellis wire, at LynOaken Farms in Lyndonville, NY. The planting is located at (43.324, -78.373), on a Galen very fine sandy loam. LynOaken Farms is a commercial orchard located near the shores of Lake Ontario in Western New York.

On 21 June 2016, trees were assessed for fruit set (Table A2-2, Appendix) with groups of five trees having equivalent fruit set, for a total 25 trees per cultivar. Each of the five treatments was assigned to one tree within a given group. Trees were hand-thinned to four target crop densities—i.e., number of fruits per cm^2 trunk cross-sectional area (TCSA)—or left un-thinned. Target crop densities were as follows: 0, 3, 6, or 9 fruit per cm^2 TCSA, with un-thinned crop density varying depending on initial fruit set. Two trunk diameter measurements were taken approximately perpendicular to each other 40 cm above the graft union, averaged, and converted to trunk cross section area using the area formula for a circle. Measurements were taken prior to establishing the experiment and then after leaf fall in each consecutive year. All trees had far higher initial crop densities than their respective targets, and all treatment groups for a given cultivar had equivalent average fruit set prior to application.

Trees were managed with a conventional spray regime typical for a commercial orchard for the duration of the experiment. No chemical thinners or plant growth regulators affecting flower bud initiation were used.

Cultivar Selection

The seven French and English heirloom cider cultivars we chose for this experiment have been recommended by Dr. Gregory Peck, the author's advisor, to growers in New York State for their horticultural attributes and the qualities they confer to hard cider. 'Dabinett' has been and remains one of the most widely planted cider cultivars in the UK (Copas, 2013; Wood, 1979). Wragg and Rendell (1977) mention ‘Brown Snout’, ‘Chisel Jersey’, ‘Dabinett’, ‘Harry Masters Jersey’, and ‘Michelin’ as widely grown cultivars in “modern” bush-system cider orchards. Of the cultivars chosen, ‘Dabinett’, ‘Harry Masters Jersey’, and ‘Michelin’ have had reputations for being fairly “annual” bearers, while ‘Binet Rouge’, ‘Brown Snout’, and ‘Geneva Tremlett’s Bitter’ have reputations for being quite “biennial” (Merwin, 2015; Wood, 1979), with descriptions of ‘Chisel Jersey’ conflicting.

Hand-Thinning

Pre-thin fruitlet counts were recorded in June 2016 and 2017; 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 only post-thin fruitlets were counted. Those who performed hand-thinning self-reported post-thin fruitlet counts, which were generally within 1-2 fruitlets of targets.

Fruit set in 2016 (Table A2-2, Appendix) was counted using handheld tally counters and recorded prior to hand-thinning, on the same day that tree trunks were measured. Target crop numbers were calculated by multiplying TCSA (Table A2-1, Appendix) by target crop density and rounding up to the nearest integer. Fruitlets were then removed by hand to achieve the appropriate number per tree, leaving only one fruit per cluster whenever possible. Care was also taken to distribute remaining fruit uniformly throughout the tree canopy while thinning. ‘Brown Snout’ and ‘Michelin’ had highest initial fruit set (on average ~38 and ~28 fruit/cm^2 TCSA, respectively), while ‘Dabinett’ had initial fruit set of ~24 fruit/cm^2; ‘Binet Rouge’, ‘Harry Masters Jersey’, and ‘Geneva Tremlett’s Bitter’ all had initial fruit set of ~19-20 fruit/cm^2.

The same treatments were reapplied to the same trees on 30 June 2017 and 15 June 2018. Fruit set on control trees was counted and recorded in 2017, though control trees were not thinned in any of the three years. The number of days from full bloom to thinning in each year (Table A2-4, Appendix) varied somewhat due to scheduling constraints. Differing full bloom dates among cultivars and the long distance between LynOaken Farms and Cornell University made it infeasible to impose treatments at equivalent DAFB within or among years. In 2017, the "off" year for the whole planting, return bloom and fruit set were often insufficient to achieve target crop load. 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. In 2018, pre-thin fruit set was deemed too high to count in a timely manner.

Harvest

Pre-harvest maturity was assessed for each variety using fruit from non-experimental trees via the starch pattern index (SPI) assay to determine appropriate harvest dates, as close to SPI of 8 as possible. For cultivars with strong tendencies to pre-harvest drop, such as 'Harry Master's Jersey', fruit was harvested considerably before ripeness. Attempts were made to keep harvest dates similar from year to year (Table A2-5, Appendix), but different environmental conditions and time constraints occasionally made it difficult to do so. Fruits dropped prior to harvest were counted and removed before the fruit remaining on trees was picked. Pre-harvest drops were counted within the midpoints between an experimental tree and its neighbors on either side. All fruits harvested from trees were counted and weighed in the field on an Adam CPW 75 scale (Oxford, CT, USA).

Trunk Size and Return Bloom Assessment

Tree trunk diameter was measured 40 cm above the graft union in autumn or winter of 2016, 2017, and 2018 after growth had ceased for the season and leaves had fallen off trees, and before bud swell had begun the following year. Trunk growth was calculated for all three years as percent change. Negative values were converted to 0, under the assumption that negative values were an artifact of measuring rather than an indication that tree trunks had shrunk. Because the experiment began well 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 June) until growth ceased in late autumn. Trunk growth from the time of full bloom (20-27 May) until thinning in 2016, though unaccounted for, was likely minimal on young trees in their first heavy crop year. Bloom clusters were counted on all experimental trees in May 2017, 2018, and 2019 at the "pink" stage using a tally counter.

Second Hand-Thinning Experiment, 2017

Due to low bloom and fruit set in spring 2017, the same experimental design was replicated in 2017 on a different set of previously non-thinned trees of four cultivars that had sufficient bloom to replicate the study that was started in 2016. These were 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', and 'Michelin'. These four cultivars also had sufficient fruit set to achieve target crop loads in the original three-year experiment, but due to low bloom and fruit set in the other three cultivars, we set up this replicated experiment to better examine the efficacy of off-year crop load management. Initial fruit set in these varieties was significantly lower compared with 2016 but was more than sufficient to achieve target crop loads (Table A2-7, Appendix).

Pre-thin crop density was generally much lower for each cultivar in the second (2017 only) experiment than in the main one. Thinning treatments on these trees were only imposed in 2017. Fruit was harvested and analyzed as described above in 2017; yield and drop counts were also recorded in 2018. Return bloom was assessed in spring 2018.

Excluded Experimental Units, Original Experiment

Of a total 525 experimental units (175 trees × 3 years), 37 were excluded from the final dataset. The close spacing of trees sometimes made it difficult to be sure that drops had been attributed to the correct tree, particularly if there were far more drops on the ground than fruit left on the tree. Trees were excluded based on a combination of location, percent drop, and where possible by comparison of final total fruit count to initial fruit set. If a tree was flanked on one or both sides by a non-experimental tree, it was impossible to know if drop counts for that tree were accurate, or if a large number of fruits fell from non-experimental trees and were attributed to an experimental tree only a few feet away. It was most difficult to be sure of drop counts in 2018 due to universally high fruit set and crop load in the entire orchard. There was greater confidence in drop counts in 2017, because non-experimental trees had little or no fruit set in that "off" year for the whole orchard. For this same reason, we could be more confident in fruit counts in the second experiment, only conducted in 2017. Two trees of target crop 0 fruit/cm^2 were excluded from the dataset because they had accidentally not been thinned in 2018.

Fruit Analysis

External and internal quality of fruit, fruit maturity, and juice chemistry data were also analyzed; these analyses will be described in Chapter 3.

Calculation of Biennial Bearing Index

Biennial bearing indices (BBI) were calculated using Equation 2-1 (above), adapted from Hoblyn et al. (1937). BBI was calculated on both yield (kg) and yield efficiency (kg/cm^2 TCSA) bases. BBI by yield efficiency was chosen because trees were in their first productive years and still growing rapidly; and BBI by yield was chosen because total yield mass is more important for cider production than the number of individual fruit picked. BBI is a measure of variation in yield among consecutive year pairs. A value of 0 indicates completely consistent yields from year to year, while a value of 1 indicates that in one year there was a complete absence of fruit borne on the tree.

When comparing cumulative yield and BBI by cultivar, analyses were carried out both including and excluding BBI values of 1, because linear models of these data resulted in a line of infinite slope when analyzing un-thinned treatment groups. Un-thinned trees of ‘Binet Rouge’ and ‘Geneva Tremlett’s Bitter’ had BBI of 1 regardless of cumulative yield. When comparing cumulative yield and BBI across all cultivars, analyses were conducted both with un-thinned trees together and separate from thinned trees, because un-thinned control trees, when pooled by cultivar, had much higher average three-year cumulative yields, and because un-thinned control trees were most likely to have a BBI of 1.

Modifying the formula for BBI by substituting bloom density for yield mass, the degree of year-to-year fluctuation in bloom density was characterized as “biennial flower index”.

Statistical Analysis

This experiment was conducted in a complete, randomized block design. All statistical analysis was conducted in R (R Core Team, 2014). All relationships were analyzed as mixed models with a random block term, using the *lmer* function from the *lme4* package (Bates et al., 2021). 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). Modeling methods (linear, quadratic, logarithmic, etc.) were chosen after visualizing data; model assumptions were checked by assessing R^2 values and examining residuals.

When analyzing return bloom, 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. These lines of best fit were determined from intercept and slope estimates generated by the *lmer* function.

2019 Projected Yield

Yield projections were developed for the 2019 harvest using the bloom cluster counts in Spring 2019 and the relationship between crop load and fruit size observed in 2017. Flower clusters were conservatively assumed to set one fruit each. Most cultivars had sufficient return bloom to reimpose crop load treatments in 2019 (Table 2-2). Cumulative four-year projected yield, and projected four-year BBI were then calculated by adding projected 2019 yield to recorded yields from 2016-2018.

Specifications for Partial Budget Analysis

Recorded yields (kg/tree) were extrapolated to estimated yield per hectare, assuming a planting density of 2,220 trees/ha (900 trees/acre). All fruit were assumed to be sold at the farm gate at an average price of $0.77/kg ($0.35/lb) for high-tannin cider apples (Peck and Knickerbocker, 2018). An average picking rate of $0.044/kg ($18 per 900-lb bin) for apples above 90 g weight, and of $0.073/kg ($30 per 900-lb bin) for apples below 90 g weight, was used to estimate average harvest cost per acre. Fruit weight of 90 g corresponded to diameter of 2½ inches or ~64 mm (data not shown), the diameter cited by growers in private personal communication as the cutoff 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 ($140/acre), with a variable machinery cost of $75.40/ha ($30.52/acre) (Farris et al., 2013), totaling $421.40/ha ($170.52/acre) per year. PGR spray costs were considered to be $0/ha for an un-thinned model hectare. Annual hand-thinning cost was estimated based on communication with a business management extension specialist (Mark Wiltberger, personal comm.), as well as an estimate of 123.3 labor hours per hectare (45 hrs/acre); assuming a $15/hr adverse effect wage rate for New York State (Employment & Training Administration, 2021; Robinson et al. 2014b), hand-thinning cost for one hectare at 2,220 trees/ha planting density was estimated to be $1850/ha ($675/acre) per year. This estimate does not account for reduced thinning cost in the “off” year due to lower overall fruit set. It was assumed that a frost or disease event would not cause a crop failure, and that a frost would not cause a reversion to biennial bearing. Profit was calculated as return above variable costs; all fixed costs were taken to be constant.

2.3 Results

Yield and Biennial Bearing, 2016-2018

Three-Year Cumulative Yield and BBI

Cumulative yield (kg per tree) over three years correlated negatively with BBI. This relationship obtained across, but not always within cultivars (Figure 1). Even on a yield efficiency basis (i.e., accounting for tree trunk size), few trees overall, of any cultivar, (n=10, or ~9%) exhibited a BBI lower than 0.1. There was a highly significant ($p<0.001$) correlation between ln(BBI) and three-year cumulative yield. The comparative productivity of un-thinned trees compared to thinned trees differed by cultivar, as did the relationship between BBI and cumulative yield.

Although the un-thinned treatment had higher three-year cumulative yields on average, un-thinned trees were not always the most cumulatively productive (Table 2-1). Un-thinned trees of the most “annual” (lowest BBI) cultivars, ‘Chisel Jersey’, ‘Dabinett’, and ‘Harry Masters Jersey’ had higher average cumulative yield (36.8, 22.1, and 20.5 kg per tree, respectively) compared to un-thinned ‘Binet Rouge’, ‘Brown Snout’, ‘Michelin’, and ‘Geneva Tremlett’s Bitter’ (16.0, 14.1, 19.4, and 12.9 kg per tree, respectively). Even when thinned to 9 fruit/cm^2, ‘Chisel Jersey’, ‘Dabinett’, and ‘Harry Masters Jersey’ had higher or equivalent average cumulative yields (27.5, 19.5, and 19.6 kg respectively) compared to un-thinned ‘Binet Rouge’, ‘Brown Snout’, ‘Michelin’, and ‘Geneva Tremlett’s Bitter’. The latter four cultivars also had much higher BBI when un-thinned (1.00, 0.99, 0.95, and 1.00 respectively) than the former three (0.49, 0.87, and 0.58, respectively).

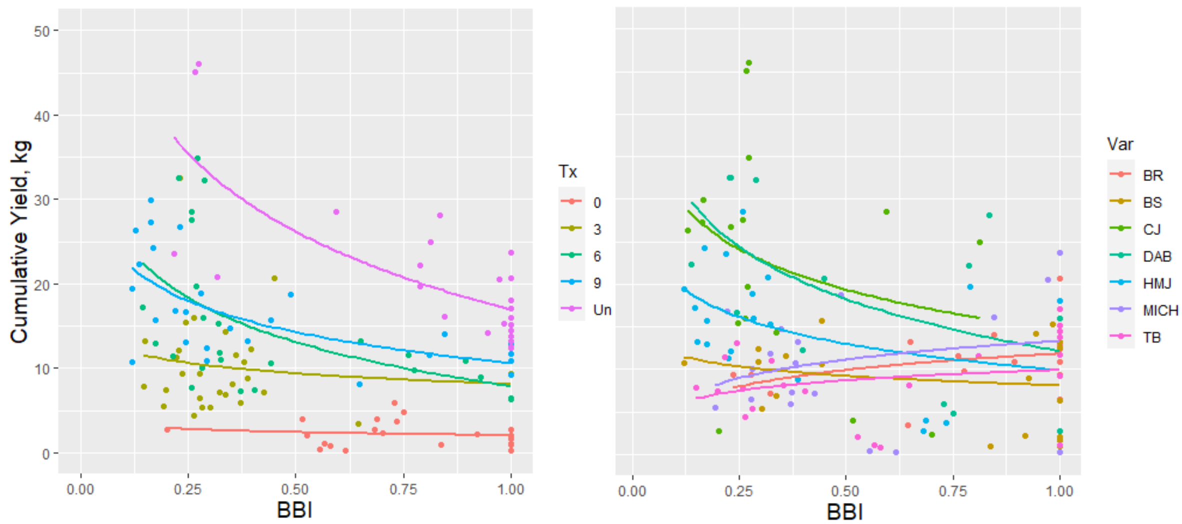

Figure 2-1. Regression of three-year cumulative yield (kg per tree) to biennial bearing index (BBI) from a three-year hand-thinning experiment at LynOaken Farms, 2016-2018. By treatment (left): 0, 3, 6, or 9 fruit/cm^2 TCSA and un-thinned (Un). By cultivar (right): Binet Rouge (BR), Brown Snout (BS), Chisel Jersey (CJ), Dabinett (DAB), Harry Masters Jersey (HMJ), Michelin (MICH), and Geneva Tremlett's Bitter (TB).

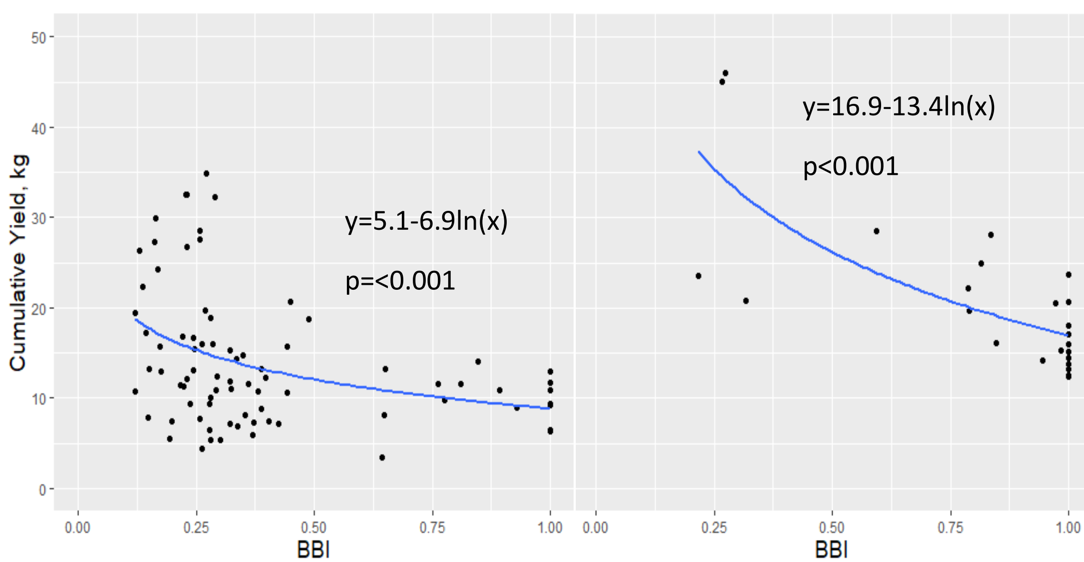

Figure 2-2. Regression of three-year cumulative yield (kg per tree) to biennial bearing index (BBI); thinned treatments: 3, 6, or 9 fruit/cm^2 TCSA only (left), and un-thinned only (right).

Table 2-1. Average estimated total yield (kg) per tree and biennial bearing index (BBI) of seven cultivars in a three-year hand-thinning experiment at LynOaken Farms, 2016-2018. Trunk cross sectional area (TCSA) was measured 40 cm above the graft union.

a. Binet Rouge

Target crop load (no. fruit/cm^2 TCSA)	2016 Average fruit yield (kg)	2017 Average fruit yield (kg)	2018 Average fruit yield (kg)	Three-yr. total yld. (kg)	BBI (Yield efficiency basis)	BBI (Yield basis)
0	0.0 d	0.0 b	0.5 c	0.5 d	—	—
3	2.0 c	1.9 a	4.2 bc	7.7 c	0.45 b	0.45 b
6	3.5 b	0.5 b	6.3 bc	10.4 bc	0.82 ab	0.82 ab
9	4.3 ab	0.1 b	7.4 b	11.7 ab	0.98 a	0.97 a
Control	5.5 a	0.0 b	13.6 a	16.0 a	1.00 a	1.00 a

b. Brown Snout

Target crop load (no. fruit/cm^2 TCSA)	2016 Average fruit yield (kg)	2017 Average fruit yield (kg)	2018 Average fruit yield (kg)	Three-yr. total yld. (kg)	BBI (Yield efficiency basis)	BBI (Yield basis)
0	0.1 d	0.1 c	1.4 c	1.6 d	—	—
3	1.5 c	1.1 b	5.2 b	7.9 c	0.30 b	0.33 b
6	2.5 bc	0.8 bc	5.4 b	8.6 bc	0.79 a	0.79 a
9	3.0 ab	2.2 a	6.8 ab	12.4 ab	0.28 b	0.29 b
Control	4.1 a	<0.1 c	10.0 a	14.1 a	0.99 a	0.99 a

c. Chisel Jersey

Target crop load (no. fruit/cm^2 TCSA)	2016 Average fruit yield (kg)	2017 Average fruit yield (kg)	2018 Average fruit yield (kg)	Three-yr. total yld. (kg)	BBI (Yield efficiency basis)	BBI (Yield basis)
0	0.1 d	1.2 b	1.6 c	3.0 c	—	—
3	2.9 c	5.0 ab	8.4 bc	15.2 bc	0.18 ab	0.28
6	4.6 b	9.0 a	12.7 b	27.4 ab	0.17 ab	0.27
9	6.5 a	8.0 a	12.6 b	27.5 ab	0.08 b	0.17
Control	7.6 a	7.0 a	22.2 a	36.8 a	0.49 a	0.49

d. Dabinett

Target crop load (no. fruit/cm^2 TCSA)	2016 Average fruit yield (kg)	2017 Average fruit yield (kg)	2018 Average fruit yield (kg)	Three-yr. total yld. (kg)	BBI (Yield efficiency basis)	BBI (Yield basis)
0	0.2 c	0.9 bc	2.7 b	3.4 b	—	—
3	3.0 bc	5.2 abc	12.5 a	21.8 a	0.26	0.36 b
6	5.8 a	9.3 a	14.3 a	32.4 a	0.19	0.26 b
9	5.0 ab	5.9 ab	7.8 ab	19.5 a	0.14	0.19 b
Control	5.6 ab	0.7 c	15.1 a	22.1 a	0.89	0.87 a

e. Harry Master's Jersey

Target crop load (no. fruit/cm^2 TCSA)	2016 Average fruit yield (kg)	2017 Average fruit yield (kg)	2018 Average fruit yield (kg)	Three-yr. total yld. (kg)	BBI (Yield efficiency basis)	BBI (Yield basis)
0	0.0 d	1.0 c	2.5 c	3.2 c	—	—
3	2.1 c	3.5 abc	5.6 bc	11.3 b	0.18 b	0.25
6	3.2 bc	6.2 ab	8.6 b	18.0 ab	0.15 b	0.24
9	4.2 ab	6.8 a	8.9 ab	19.6 a	0.09 b	0.19
Control	5.7 a	2.8 bc	12.0 a	20.5 a	0.61 a	0.58

f. Michelin

Target crop load (no. fruit/cm^2 TCSA)	2016 Average fruit yield (kg)	2017 Average fruit yield (kg)	2018 Average fruit yield (kg)	Three-yr. total yld. (kg)	BBI (Yield efficiency basis)	BBI (Yield basis)
0	0.1 c	0.2 b	—	0.3 c	—	—
3	1.0 bc	1.8 a	4.3 c	7.2 b	0.21 b	0.33 b
6	1.5 abc	2.2 a	5.6 c	9.7 b	0.24 b	0.33 b
9	2.4 ab	2.6 a	10.4 b	15.9 a	0.33 b	0.36 b
Control	3.2 a	0.1 b	16.4 a	19.4 a	0.97 a	0.95 a

g. Geneva Tremlett's Bitter

Target crop load (no. fruit/cm^2 TCSA)	2016 Average fruit yield (kg)	2017 Average fruit yield (kg)	2018 Average fruit yield (kg)	Three-yr. total yld. (kg)	BBI (Yield efficiency basis)	BBI (Yield basis)
0	0.1 d	0.2 b	1.1 c	1.4 c	—	—
3	1.6 c	1.7 ab	3.4 bc	6.6 bc	0.19 b	0.25 b
6	2.4 bc	2.9 a	4.7 bc	9.4 ab	0.34 b	0.30 b
9	2.9 b	1.8 ab	6.0 b	10.7 ab	0.74 a	0.74 a
Control	4.5 a	0.0 b	10.4 a	12.9 a	1.00 a	1.00 a

There were significant interactions between ln(BBI) and cultivar, correlating negatively with three-year cumulative yield for the three more “annual” cultivars ‘Chisel Jersey’ ($p<0.001$), ‘Dabinett’ ($p<0.001$), and ‘Harry Masters Jersey’ ($p=0.011$), but not in the other four cultivars (‘Brown Snout’, ‘Binet Rouge’, ‘Michelin’, and ‘Geneva Tremlett’s Bitter’) when all treatment groups were analyzed together (Figure 2-1). The more “biennial” (higher overall BBI) cultivars exhibited a wider range of BBI values when thinned, whereas BBI was relatively low in all thinned treatments in ‘Chisel Jersey’, ‘Dabinett’, and ‘Harry Masters Jersey’.

Yield in Each Year

In 2016 and 2018, the “on” years for the whole planting, un-thinned treatments had the greatest yields in terms of fruit number and mass. ‘Dabinett’ was the one exception, achieving highest yields in 2016 and 2017 when thinned to a target of 6 fruit/cm^2. In 2017, the “off” year for the whole planting, un-thinned trees of all cultivars except ‘Chisel Jersey’ were the least productive. Yields were highest in 2018 across all cultivars and treatment groups. In ‘Binet Rouge’, ‘Brown Snout’, ‘Michelin’, and ‘Geneva Tremlett’s Bitter’, yields on un-thinned trees in 2017 were 0 kg or less than 0.1 kg. By contrast, the un-thinned ‘Chisel Jersey’ treatment had comparable yields between 2016 and 2017.

Crop Load, Yield Weight, and Fruit Size

A non-linear, negative relationship between crop density and fruit size often resulted in a similar non-linear relationship between crop density and yield efficiency (Figure 2-8). Similar trends obtained across all cultivars: higher crop density correlated with smaller fruit and “diminishing returns” in yield, though this relationship differed slightly cultivar-to-cultivar. For example, ‘Dabinett’ and ‘Harry Masters Jersey’ yield efficiency plateaued at a crop density of approximately 15 fruit/cm^2 (Figure 2-3). Other cultivars did not exhibit such an inflection point but yield efficiency in those cultivars did increase less steeply as crop density increased.

Theoretical Yield 2019

‘Binet Rouge’ and ‘Geneva Tremlett’s Bitter’ did not always have sufficient return bloom in 2019 to reapply target crop density, when thinned to 6 or 9 fruit/cm^2 TCSA (Table 2-2). Following a heavy crop load in 2018, un-thinned trees of all cultivars had little to no return bloom in Spring 2019, resulting in little to no potential yield in Fall 2019 (Table 2-3). The tendency of less-biennial cultivars ‘Chisel Jersey’, ‘Dabinett’, and ‘Harry Masters Jersey’ to bear greater cumulative yields than the other four cultivars in this experiment would become even more pronounced had treatments been reapplied for a fourth year (Figure 2-4). In ‘Brown Snout’, ‘Chisel Jersey’, ‘Dabinett’, and ‘Harry Masters Jersey’, 2019 bloom was sufficient for thinned trees to achieve cumulative four-year yields equivalent to, or greater than, yields on un-thinned trees, had treatments been reapplied (Table 2-4). The tendency of ‘Dabinett’ to bear greatest cumulative yields when thinned to 6 fruit/cm^2 target crop load would have persisted in 2019. The more biennial cultivars ‘Binet Rouge’, ‘Michelin’, and ‘Geneva Tremlett’s Bitter’ would remain more productive if left un-thinned than if thinned.

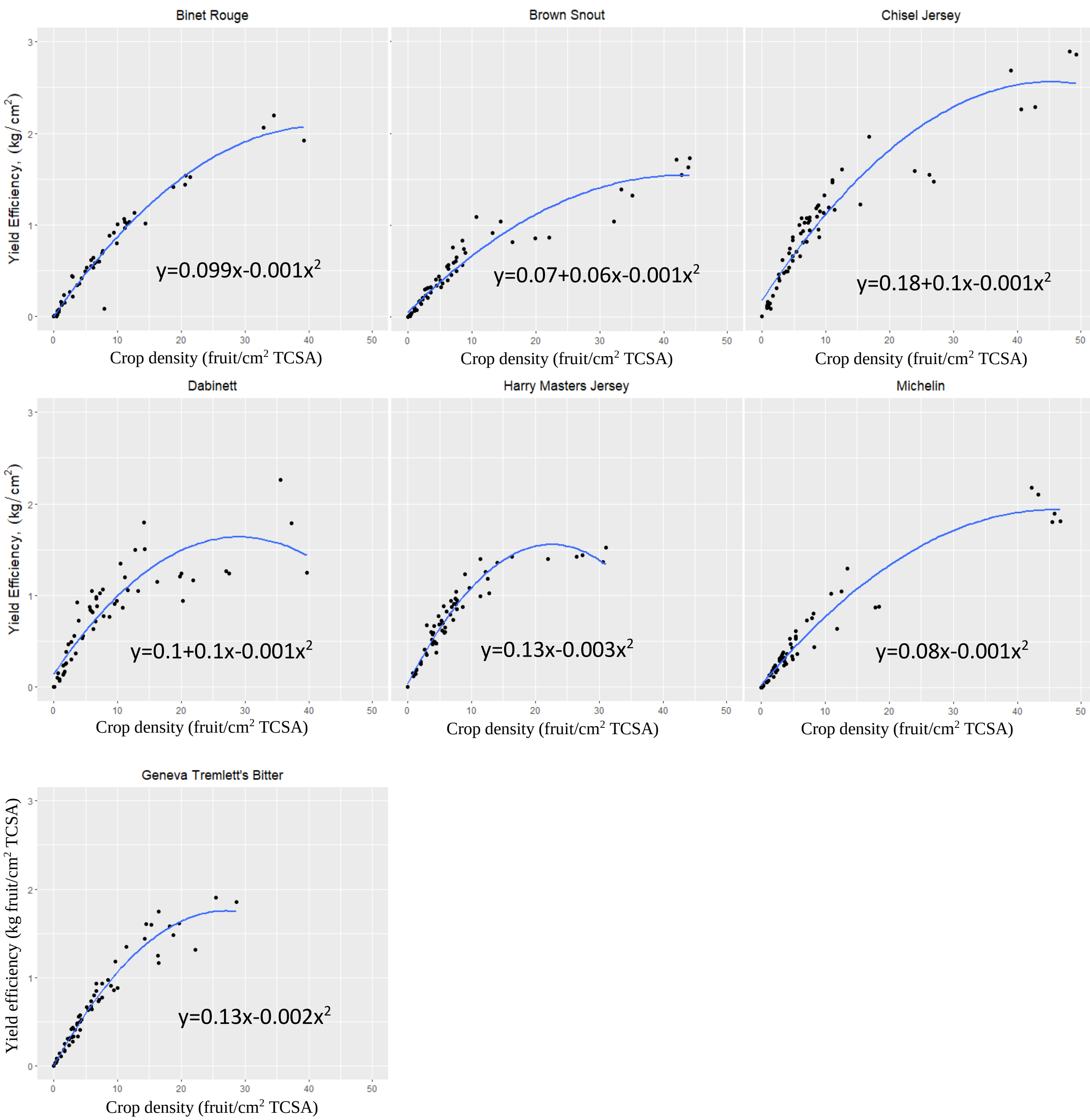

Figure 2-8. Regression of fall crop density (no. fruit/cm^2 TCSA) to yield efficiency (kg fruit/cm^2 TCSA) for seven cultivars in a three-year hand-thinning experiment at LynOaken Farms, 2016-2018. Each point represents a single tree in one year of the experiment. Trunk cross-sectional area (TCSA) measured 40 cm above the graft union.

Table 2-2. Proportion of trees with sufficient bloom in spring 2019 to reimpose target crop density for a fourth year, from a three-year hand-thinning experiment at LynOaken Farms.

	Proportion of trees with sufficient bloom in 2019						
Target crop load (no. fruit/cm^2 TCSA))	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
0	1	1	1	1	1	1	1
3	1	1	1	1	1	1	1
6	0.8	1	1	1	1	1	0.8
9	0.8	1	1	1	1	1	0.6
Control	—	—	—	—	—	—	—

Table 2-3. Projected yields per tree extrapolated from 2019 bloom cluster counts, from a three-year hand-thinning experiment at LynOaken Farms.

	2019 theoretical average yield, kg/tree						
Target crop load (fruit no. /cm^2)	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

Table 2-4. Projected cumulative yields per tree extrapolated from 2019 bloom cluster counts, from a three-year hand-thinning experiment at LynOaken Farms.

	Projected four-year cumulative yield, kg/tree						
Target crop load (fruit no. /cm^2)	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

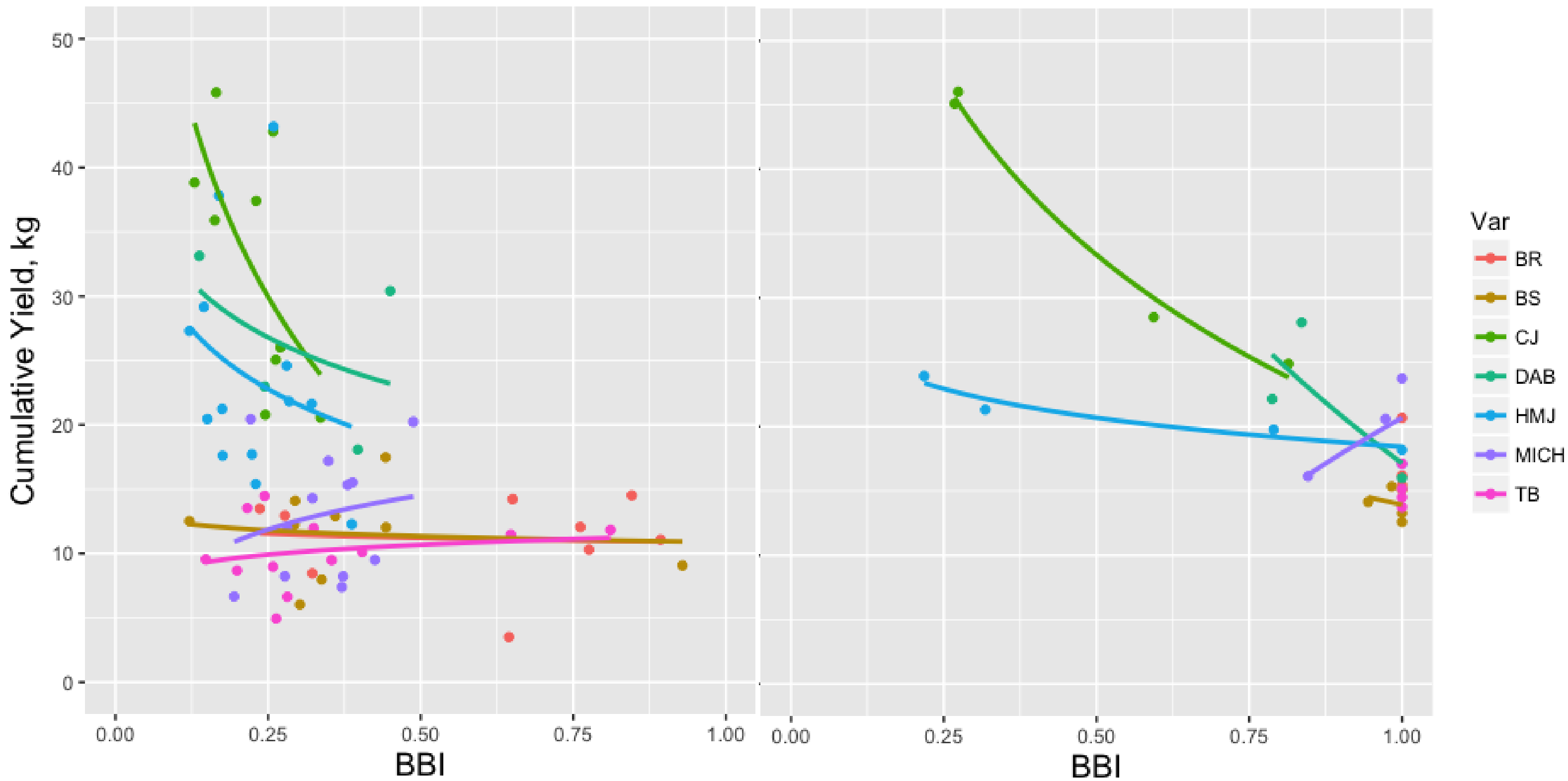

Figure 2-4. Regression of projected four-year cumulative yield (kg/tree) to projected biennial bearing index (BBI) based on spring 2019 bloom in a three-year hand-thinning experiment at LynOaken Farms 2016-2018. Thinned treatments: 3, 6, or 9 fruit/cm^2 TCSA only (left), and un-thinned only (right). Cultivars Binet Rouge (BR), Brown Snout (BS), Chisel Jersey (CJ), Dabinett (DAB), Harry Masters Jersey (HMJ), Michelin (MICH), Geneva Tremlett's Bitter (TB).

Return Bloom, Spring 2017-2019

There were significant negative linear relationships between fall crop density and return bloom in all cultivars. Each cultivar had a maximum crop density above which all return bloom was inhibited (indicated in red in Figure 2-5). The slope and x-intercept of these relationships differed among cultivars, with "annual" cultivars 'Chisel Jersey' and 'Dabinett' having the lowest slopes (i.e., weakest effect on return bloom) and highest x-intercepts (i.e., able to support the largest crop load).

Each cultivar responded differently, in terms of return bloom in Spring 2017, to hand-thinning in 2016. All seven cultivars produced significantly less bloom in 2017 ("off" year) when left un-thinned in 2016 ("on" year). 'Binet Rouge', 'Brown Snout', and 'Geneva Tremlett's Bitter' did not flower in 2017 when left un-thinned in 2016 (Table A2-11, Appendix), illustrating typical "biennial" flowering. 'Chisel Jersey' and 'Harry Masters Jersey' showed significant non-zero return bloom in 2017 (21.8 and 5.4 clusters/cm^2, respectively) when left un-thinned in 2016, but return bloom was still much lower when un-thinned than when thinned to any target crop load. Likewise, in Spring 2019, un-thinned trees of all seven cultivars had little or no return bloom, while trees thinned to any of the treatment crop loads in 2018 showed dramatically higher bloom density the following spring. However, the inverse was not necessarily the case in spring 2018 (following the "off" year 2017). Un-thinned trees, which had little to no bloom and bore little or no fruit in 2017, did not necessarily have the highest bloom density of any treatment group in spring 2018, except in 'Harry Masters Jersey' and 'Geneva Tremlett's Bitter'. In the latter cultivar this difference was not statistically significant.

The average spring bloom density (clusters per cm^2 TCSA) of trees thinned to a target crop load of 0 fruit/cm^2 TCSA (i.e., that had all fruit removed) showed significant differences

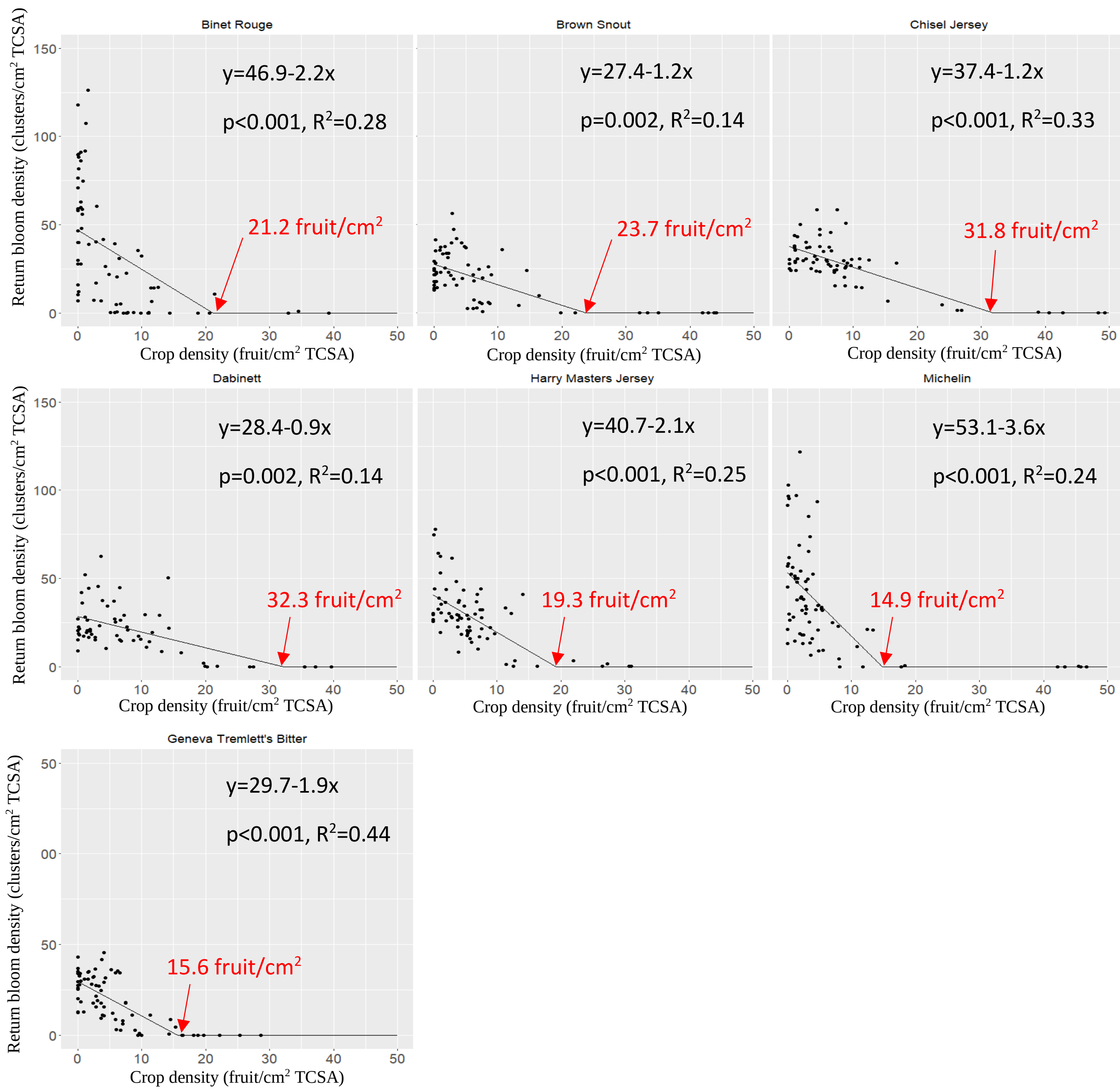

Figure 2-5. Regression of fall crop density and return bloom of seven cultivars at LynOaken Farms in a three-year hand-thinning experiment, 2016-2018. Each point represents a single measurement of one tree in one year. Trunk cross sectional area (TCSA) measured 40 cm above the graft union.

among years. Though 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 removal of all (or almost all) fruit did not completely remove the inhibitory effect of fruit presence on return bloom. Biennial flower index (BFI) was usually lowest on trees thinned to 0 fruit/cm^2 but was still significantly greater than 0 (Table 2-5).

Table 2-5. Biennial Flower Index (bloom density basis) of seven cultivars from a three-year hand-thinning experiment at LynOaken Farms, 2016-2018.

Target crop load (fruit no. /cm^2)	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
0	0.45 b	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

Off-Year Hand-Thinning Experiment, 2017

Mean total yield weight (kg) and yield efficiency (kg/cm^2 TCSA) were highest for un-thinned trees in all four cultivars in the second experiment, and both yield and yield efficiency decreased as target crop density decreased. In the main three-year experiment, crop density in 2017 only had a significant ($p<0.001$) effect on 2018 bloom in 'Harry Masters Jersey'. In the second experiment, crop density had an effect on return bloom in 'Chisel Jersey' ($p<0.001$) and 'Harry Masters Jersey' ($p<0.001$). The general trend was that crop load management in the "off" year did not significantly promote return bloom the following spring. No tree had a return bloom density of 0 clusters/cm^2 in Spring 2018.

There was no significant effect of 2017 crop density on 2018 return bloom in 'Dabinett' in either experiment ($p=0.564$). Nor was there any significant difference in average return bloom between experiments for ‘Dabinett’ ($p=0.272$). ‘Michelin’ was the only cultivar that had a significant difference in average 2018 bloom ($p<0.001$) between experiments 1 and 2 (Table A2-14, Appendix).

Off-Year Hand-Thinning Experiment, 2018

No significant treatment difference in 2018 yield efficiency was observed in any of the four cultivars in the second hand-thinning experiment. A small but significant difference in crop density was observed in ‘Chisel Jersey’ only, but differences in yield efficiency were not significant. Despite a significant effect of 2017 crop density on 2018 bloom density in ‘Harry Masters Jersey’, differences in 2018 crop density were not significant ($p=0.09$).

Partial Budget Analysis

The profitability (return above variable costs) of chemical thinning differed by cultivar, crop load, and timespan (Table 2-6). Over three years, chemical thinning was only profitable for ‘Dabinett’ thinned to 6 or 9 fruit/cm^2 target crop load. However, by the fourth year, under conservative assumptions about fruit set based on 2019 bloom data (see 2.3 Results: Theoretical Yield 2019), chemical thinning was projected to be profitable for all seven cultivars when thinned to 9 fruit/cm^2, due both to increased revenues and reduced harvest costs. Thinning to a target crop load of 6 fruit/cm^2 was also projected to be profitable over four years for ‘Chisel Jersey’, ‘Dabinett’, ‘Harry Masters Jersey’, and ‘Geneva Tremlett’s Bitter’.

Hand-thinning was far less profitable compared to chemical thinning (Table 2-7). Over three years, hand-thinning only resulted in a net increase in profitability when thinning ‘Dabinett’ to 6 fruit/cm^2 TCSA target crop load. No other crop load or cultivar resulted in a net increase in profitability. Over four years, hand-thinning resulted in greater profitability for ‘Binet Rouge’, ‘Brown Snout’, ‘Dabinett’, ‘Harry Masters Jersey’, and ‘Michelin’ when thinned to 9 fruit/cm^2, and for ‘Dabinett’ and ‘Harry Masters Jersey’ when thinned to 6 fruit/cm^2. Hand-thinning was not profitable for ‘Chisel Jersey’ or ‘Geneva Tremlett’s Bitter’ at any crop load.

Tree Trunk Growth 2016-2018

In 2016, the first “on” year, trunk growth was greatest on trees with the lowest crop load. In 2017, the “off” year, this trend did not obtain for ‘Binet Rouge’ or ‘Brown Snout’ but did for other cultivars. Crop density had a significant ($p<0.001$) negative logarithmic correlation with TCSA growth overall. 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. Year interacted significantly ($p=0.006$) with crop density, and crop density had the strongest negative effect on tree growth in 2016, the first year of the study.

2017 Fruit Set

It was only possible in this experiment to count both return bloom and pre-thin fruit set in 2017, the “off” year for the whole planting in this experiment. The greatest bloom density recorded in 2017 was 36.8 clusters/cm^2 TCSA in ‘Geneva Tremlett’s Bitter’, whereas in 2018 the greatest bloom density recorded was 126.1 clusters/cm^2 TCSA in ‘Binet Rouge’. Nonetheless, bloom density had a negative logarithmic relationship to fruit-to-bloom cluster ratio (FBR), with a strong cultivar effect (Figure 2-6). In other words, more flowers on a tree resulted in lower fruit set efficiency. Data presented do not represent an average fruit set per cluster, but rather a ratio between total fruitlets and total bloom clusters. A ratio <1 indicates that not all bloom clusters set fruit, but a ratio >1 does not necessarily indicate that all bloom clusters did set fruit.

Table 2-6. Potential revenues and costs of a model hectare when chemically thinned to 3, 6, or 9 fruit/cm^2 TCSA, compared to the same acre with no thinning, based on yield data from a hand-thinning experiment at LynOaken Farms 2016-2019. Three-year estimates based on observed data; four-year estimates incorporate yield projections based on Spring 2019 bloom data.

Partial Budget									
Problem: Applying chemical thinning sprays for crop load management									
		Revenue (compared to un-thinned)		Costs (compared to un-thinned)					
Variety	Target Crop Load	Three-Year Revenue ($/ha)	Projected Four-Year Revenue ($/ha)	Three-Year Harvest Cost ($/ha)	Projected Four-Year Harvest Cost ($/ha)	Three-Year PGR Spray Cost ($/ha)	Four-Year PGR Spray Cost ($/ha)	Net Change in Profit ($/ha, Three Years)	Projected Net Change in Profit ($/ha, Four years)
Binet Rouge	3 fruit/cm^2	-14835	-11723 b	-1688	-1510	1,264	1,685	-14411	-11899 b
	6 fruit/cm^2	-10012	-6318 ab	-1303	-1092	" "	" "	-9973	-6912 ab
	9 fruit/cm^2	-5386	+7918 a	-898	-138	" "	" "	-5752	+6370 a
Brown Snout	3 fruit/cm^2	-9965	-5850	-1377	-1141 b	" "	" "	-9853	-6394
	6 fruit/cm^2	-8749	-1741	-833	-166 ab	" "	" "	-9180	-3261
	9 fruit/cm^2	-2457	+8172	-517	+495 a	" "	" "	-3204	+5991
Chisel Jersey	3 fruit/cm^2	-36094	-27881	-2675	-2206	" "	" "	-34683	-27361
	6 fruit/cm^2	-13857	+1826	-1140	-244	" "	" "	-13981	+384
	9 fruit/cm^2	-18599	+4507	-1280	+40	" "	" "	-18582	+2783
Dabinett	3 fruit/cm^2	-14740	-6179	-1010	-521	" "	" "	-13094	-5709
	6 fruit/cm^2	+12415	+32260	+949	+2083	" "	" "	+5889	+21469
	9 fruit/cm^2	+352	+19065	+91	+1161	" "	" "	-1003	+16249
Harry Masters Jersey	3 fruit/cm^2	-16658	-10490	-1368	-1016	" "	" "	-16554	-11160
	6 fruit/cm^2	-2174	+12057	-278	+535	" "	" "	-3160	+9836
	9 fruit/cm^2	-1117	+17848	-248	+836	" "	" "	-2133	+15327
Michelin	3 fruit/cm^2	-20186 b	-13201 b	-2228 b	-1831 b	" "	" "	-19223 b	-13055 b
	6 fruit/cm^2	-17818 ab	-8907 b	-2089 b	-1583 b	" "	" "	-16993 ab	-9010 b
	9 fruit/cm^2	-3835 a	+11709 a	-668 a	+219 a	" "	" "	-4431 a	+9805 a
Geneva Tremlett's Bitter	3 fruit/cm^2	-10650	-7004	-1335	-1127	" "	" "	-10579	-7563
	6 fruit/cm^2	-5212	+1817	-943	-541	" "	" "	-5533	+673
	9 fruit/cm^2	-3680	+5896	-700	-153	" "	" "	-4244	+4364

Table 2-7. Comparison of revenues of a model hectare when hand-thinned to 3, 6, or 9 fruit/cm^2 TCSA, compared to the same acre with no thinning, based on yield data from an experiment at LynOaken Farms 2016-2019. Three-year estimates based on observed data; four-year estimates incorporate yield projections based on Spring 2019 bloom data.

Partial Budget									
Problem: Performing hand-thinning for crop load management									
		Revenue (compared to un-thinned)		Costs (compared to un-thinned)					
Variety	Target Crop Load	Three-Year Revenue ($/ha)	Projected Four-Year Revenue ($/ha)	Three-Year Harvest Cost ($/ha)	Projected Four-Year Harvest Cost ($/ha)	Three-Year Hand-Thin Cost ($/ha)	Four-Year Hand-Thin Cost ($/ha)	Net Change in Profit (Three Years)	Projected Net Change in Profit (Four years)
Binet Rouge	3 fruit/cm^2	-14835	-11723 b	-1688	-1510	5,550	7,400	-18697	-17613 b
	6 fruit/cm^2	-10012	-6318 ab	-1303	-1092	“ ”	“ ”	-14259	-12626 ab
	9 fruit/cm^2	-5386	+7918 a	-898	-138	“ ”	“ ”	-10038	+656 a
Brown Snout	3 fruit/cm^2	-9965	-5850	-1377	-1141 b	“ ”	“ ”	-14139	-12109
	6 fruit/cm^2	-8749	-1741	-833	-166 ab	“ ”	“ ”	13466	-8975
	9 fruit/cm^2	-2457	+8172	-517	+495 a	“ ”	“ ”	-7490	+277
Chisel Jersey	3 fruit/cm^2	-36094	-27881	-2675	-2206	“ ”	“ ”	-38969	-33075
	6 fruit/cm^2	-13857	+1826	-1140	-244	“ ”	“ ”	-18266	-5330
	9 fruit/cm^2	-18599	+4507	-1280	+40	“ ”	“ ”	-22868	-2931
Dabinett	3 fruit/cm^2	-14740	-6179	-1010	-521	“ ”	“ ”	-17379	-11424
	6 fruit/cm^2	+12415	+32260	+949	+2083	“ ”	“ ”	+1604	+15754
	9 fruit/cm^2	+352	+19065	+91	+1161	“ ”	“ ”	-5289	+10504
Harry Masters Jersey	3 fruit/cm^2	-16658	-10490	-1368	-1016	“ ”	“ ”	-20840	-16874
	6 fruit/cm^2	-2174	+12057	-278	+535	“ ”	“ ”	-7446	+4122
	9 fruit/cm^2	-1117	+17848	-248	+836	“ ”	“ ”	-6419	+9612
Michelin	3 fruit/cm^2	-20186 b	-13201 b	-2228 b	-1831 b	“ ”	“ ”	-23508 b	-18780 b
	6 fruit/cm^2	-17818 ab	-8907 b	-2089 b	-1583 b	“ ”	“ ”	-21279 ab	-14724 b
	9 fruit/cm^2	-3835 a	+11709 a	-668 a	+219 a	“ ”	“ ”	-8717 a	+4091 a
Geneva Tremlett’s Bitter	3 fruit/cm^2	-10650	-7004	-1335	-1127	“ ”	“ ”	-14865	-13277
	6 fruit/cm^2	-5212	+1817	-943	-541	“ ”	“ ”	-9819	-5042
	9 fruit/cm^2	-3680	+5896	-700	-153	“ ”	“ ”	-8530	-1350

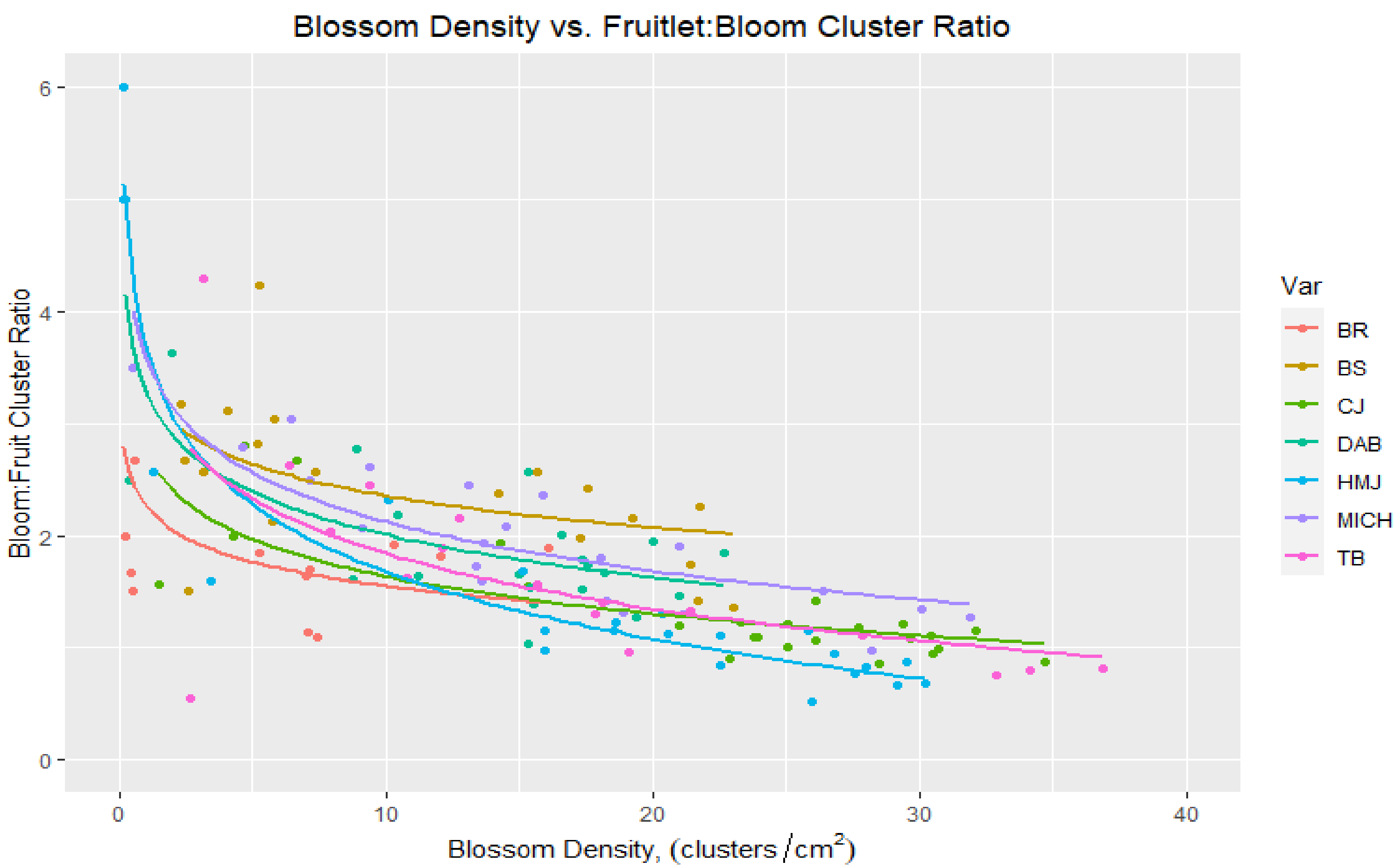

Figure 2-6. Correlation of Fruitlet:Bloom Cluster Ratio (FBR) to bloom density (clusters/cm^2 TCSA) of seven cultivars at LynOaken Farms, Spring 2017. Cultivars Binet Rouge (BR), Brown Snout (BS), Chisel Jersey (CJ), Dabinett (DAB), Harry Masters Jersey (HMJ), Michelin (MICH), and Geneva Tremlett's Bitter (TB).

2018 Average Seed Number

2018 Average Seed Number vs. 2019 Return Bloom

Estimated seed density (seed number/cm^2 TCSA) in Fall 2018 had a significant ($p<0.001$) negative logarithmic relationship with Spring 2019 bloom density. There were also significant interactions between estimated seed density and cultivar for 'Harry Masters Jersey' ($p=0.027$) and 'Geneva Tremlett's Bitter' ($p>0.001$). However, a cultivar's average seed number *per fruit* did not correlate with return bloom, across or among cultivars. In fact, the most annual cultivars ('Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey') had highest average seed count per fruit.

Spring 2018 Bloom vs. Fall 2018 Average Seed Number

The interplay between cultivar, spring bloom density, and fall seed count was complex (Figure 2-7). Within cultivar, apparent relationships between Spring 2018 bloom density and average seed count in Fall 2018 were non-significant. However, cultivars do appear to cluster by average seed number per fruit, with those experiencing lower spring bloom density ('Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey') having higher average seed count per fruit at harvest, and those with highest bloom density having lower average seed count per fruit at harvest. There was no significant relationship between fall crop density and average seed number per fruit. The number of seeds formed in a fruit appears to be congenital rather than environmental, at least as pertains to bloom density and fruit set.

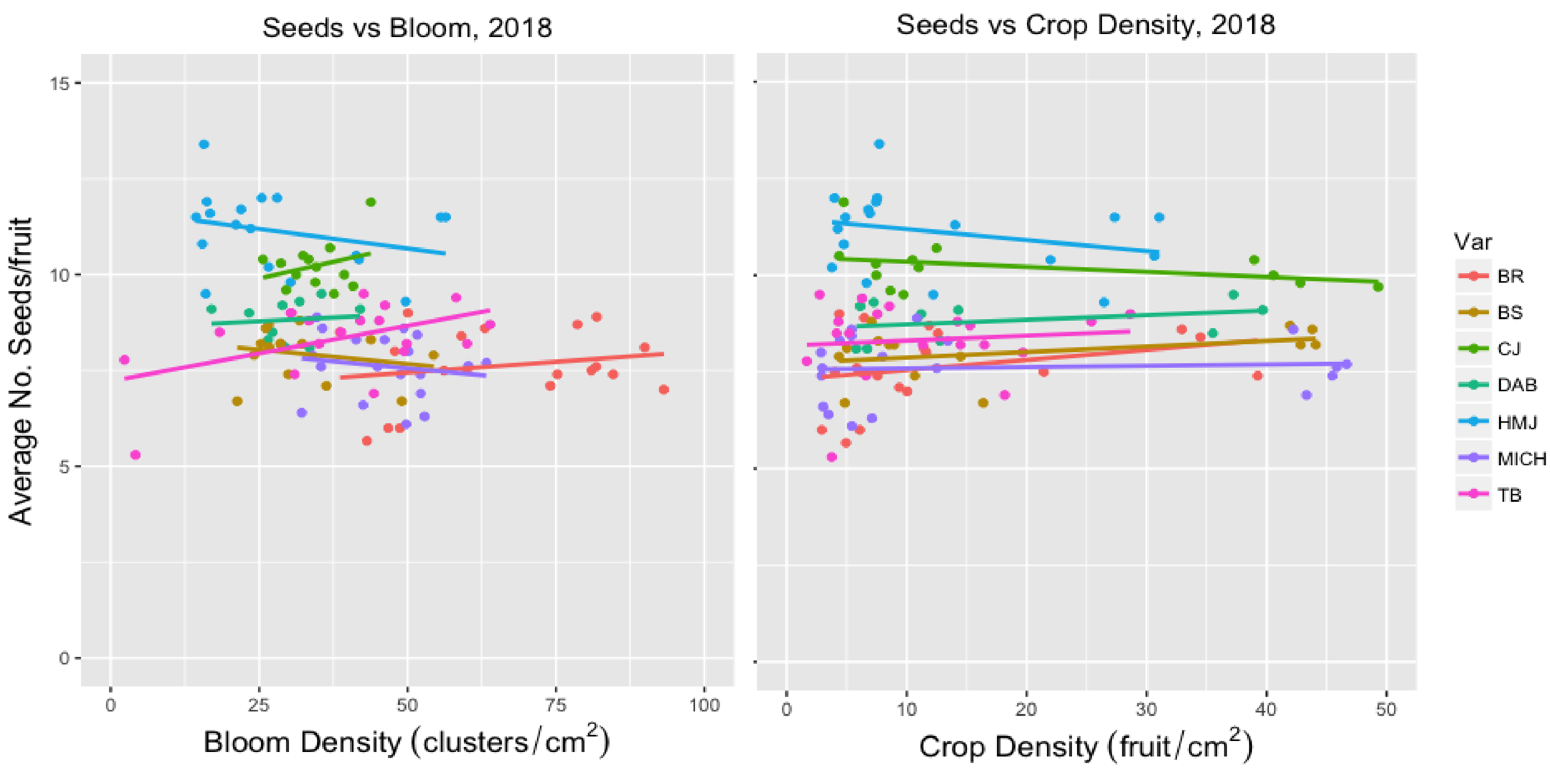

Figure 2-7. Comparison of fall 2018 average seed number per fruit to spring 2018 bloom density (left) and fall 2018 crop density (right), in seven cultivars at LynOaken Farms, 2018: Binet Rouge (BR), Brown Snout (BS), Chisel Jersey (CJ), Dabinett (DAB), Harry Masters Jersey (HMJ), Michelin (MICH), Geneva Tremlett's Bitter (TB).

Thinning Accuracy

Self-reported post-thin fruitlet counts were often lower than the final fruit counts at harvest—i.e., more fruit was counted at harvest on-tree and on the ground than should have been. Even on trees assigned the “0” target crop load, final numbers of drops and fruit picked on-tree were often greater than zero. Trees also frequently had fewer total fruit harvested (picked on-tree + drops counted) at harvest than their target crop load. Total fruit counts per tree (on tree + drops) at harvest were frequently higher or lower than target crop loads: 295 trees had more total fruit than target crop load, 85 had fewer, and 38 had exactly as many total fruits as their target crop load.

However, the discrepancy (as a percent) between target crop load and at-harvest fruit count did not correlate with target crop load ($p=0.13$, $R^2=0.003$), so inaccuracy of thinning was not worse for any particular treatment group than for any other. Nonetheless, a majority of trees had a final total fruit count that did not match the target. Many trees were under- or over-thinned, and a much smaller number of trees had drops misattributed, particularly those next to non-experimental trees in high-crop years 2016 and 2018. Fall crop density (fruit/cm^2 TCSA) was usually quite discrepant from spring post-thin crop density, a result of increased trunk size. As previously discussed, tree growth rates differed by the amount of fruit on the tree over the course of the season.

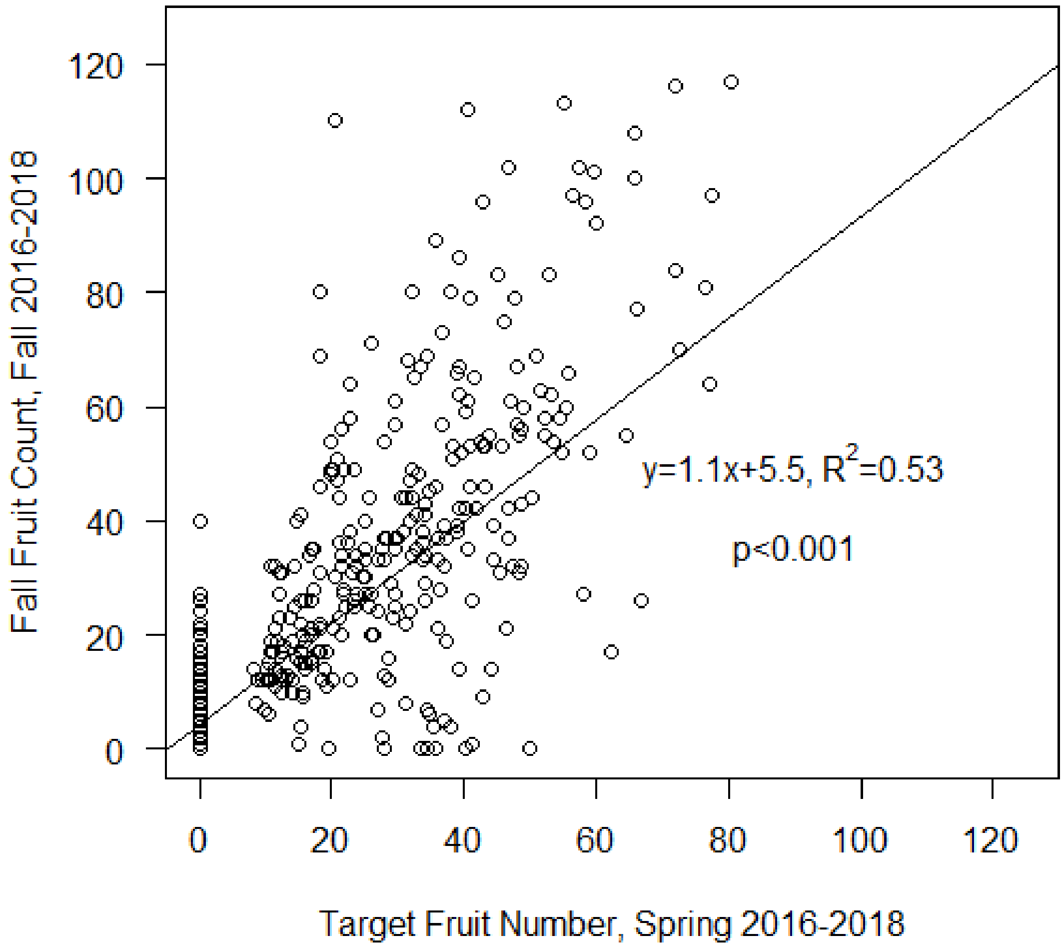

Figure 2-7. Target crop number compared to fall fruit counts for seven cultivars in a three-year hand-thinning experiment at LynOaken Farms, 2016-2018.

2.4 Discussion

Yields and biennial bearing

The relationship between BBI and cumulative yield was complicated by both inter- and intra-cultivar trends. Although some cultivars were more productive over three years when un-thinned and more biennial, these higher-BBI cultivars (‘Binet Rouge’, ‘Brown Snout’, ‘Michelin’, and ‘Geneva Tremlett’s Bitter’) were less productive overall than more “annual” cultivars (‘Chisel Jersey’, ‘Dabinett’, and ‘Harry Masters Jersey’), thus affirming our hypothesis that BBI would correlate negatively with cumulative yields. The relationship between BBI and cumulative yield was non-significant within each of the four more “biennial” cultivars, while in the three more “annual” cultivars the relationship was significant and negative.

Our finding that biennial bearing coincided with reduced cumulative yields over multiple years concurs with the findings of Wood (1979), Crassweller et al. (2005), and Czynczyk et al. (2008), although the latter authors did not publish BBI values. Czynczyk et al. (2008) found that, in a seven-year trial of eight English cider cultivars on three different rootstocks, ‘Chisel Jersey’ and ‘Dabinett’ had the greatest cumulative yields, ‘Harry Masters Jersey’ was somewhat less productive, and ‘Michelin’ even less so. Plotkowski and Cline (2021) reported that hand-thinned ‘Dabinett’ trees had significantly lower BBI and significantly higher cumulative yield over three years than hand-thinned ‘Binet Rouge’, ‘Brown Snout’ and ‘Michelin’, agreeing with our findings, though they did not observe un-thinned trees.

A standardized quantitative framework for describing the bearing habits of apple cultivars, particularly cider cultivars, is lacking in literature. Sources occasionally differ on whether a given cultivar is “annual” or “biennial” in its bearing habit, and references to a cultivar’s responsiveness to thinning are rare, presumably because of a dearth of quantitative research. Even growers and researchers with many years' experience with these cultivars do not necessarily agree on the "annual" or "biennial" nature of these cultivars, or even spell out concrete criteria for how a cultivar's bearing habit might be described.

The BBI values for un-thinned trees can provide a reasonable framework for classifying cultivars as "annual" or "alternate", but there is also a need for classifying cultivars by their responsivity to thinning. For instance, the BBI observed in this experiment for un-thinned 'Dabinett', which is called "annual-bearing" by Merwin (2015), was comparable to BBI values observed on un-thinned 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, developing a system of classifying cultivars as 'responsive to crop load management' or 'nonresponsive to crop load management' would be useful to cider apple growers. Such a classification would need to be based on (1) a cultivar's BBI when left un-thinned, (2) the effect of crop load management on cumulative yield in a cultivar, and (3) the effect of crop load management on BBI in a cultivar.

I propose further that a BBI of less than 0.50 be considered 'annual', a BBI of 0.50-0.65 as 'somewhat annual', 0.66-0.80 as 'somewhat biennial' and 0.81-1.00 as 'highly biennial'. Thus, we might describe the seven cultivars in this experiment using a schematic such as the one below:

Table 2-8. Proposed schematic for categorizing cider cultivars by bearing habit.

Cultivar	Innate Tendency	Thinning response (BBI)	Thinning response (Yield)
Binet Rouge	Highly biennial	Reduced bienniality	Reduced yields at 9 fruit/cm^2
Brown Snout	Highly biennial	Reduced bienniality	Equivalent yields at 9 fruit/cm^2
Chisel Jersey	Somewhat biennial	Annual bearing	Improved yields at 9 fruit/cm^2
Dabinett	Somewhat biennial	Annual bearing	Improved yields at 9 fruit/cm^2
Harry Masters Jersey	Somewhat annual	Annual bearing	Improved yields at 9 fruit/cm^2
Michelin	Highly biennial	Annual bearing	Reduced yields at 9 fruit/cm^2
Geneva Tremlett's Bitter	Highly biennial	Reduced bienniality	Reduced yields at 9 fruit/cm^2

Because of the lack of data from other authors at different sites using different rootstocks and tree types, these 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 only conducted for three years.

Length of Experiment

The three-year span of this study means that only one "off" year, but two "on" years were observed. Three-year cumulative yields do not tell the whole story. Analysis of return bloom in 2019 (the second "off" year) allowed us to extrapolate a fourth year's potential yield, but a fourth year of treatment would have better enabled us to compare two "on" and two "off" years. Nonetheless, the finding that BBI correlated negatively with decreased cumulative productivity over three years confirms that, at least in the short term, crop load management and selection of more annual-bearing cultivars can have a positive impact on productivity. Whether three years of crop load management is sufficient to induce long-term regular bearing is a question demanding further research.

Return Bloom

The tendency of return bloom in all seven cultivars to decrease as the previous season's crop load increased concurs with previous research, and with the general consensus of how crop load affects return bloom in apples (Chan and Cain, 1967; Embree et al., 2007; Pellerin et al., 2011, 2011; Robinson and Watkins, 2003; Wood, 1979). Neither the maximum crop density before complete suppression of bloom nor the slope of a line of best fit alone were good predictors of a cultivar's bearing habit when left un-thinned (Figure 2-5. Regression of fall crop density and return bloom of seven cultivars at LynOaken Farms in a three-year hand-thinning experiment, 2016-2018. Each point represents a single measurement of one tree in one year.). For example, 'Dabinett' had a much higher threshold for total bloom suppression than did 'Harry Masters Jersey', and yet un-thinned 'Dabinett' trees had much higher average BBI than did un-thinned 'Harry Masters Jersey'.

The equivalent or higher bloom density on trees that had borne and/or set fruit in 2017, compared to un-thinned trees that set little to no fruit, is counter to our hypothesis and difficult to explain. Presumably, trees with no crop would have highest return bloom the following spring, but evidently, the absence of fruitlets or mature fruit in an "off" year does not promote return bloom as strongly as partial, let alone total removal of fruit in an "on" year. Nor does the complete absence of bloom in an "off" year. The year-to-year differences in return bloom density on trees thinned to 0 fruit/cm^2 indicate that some suppression of return bloom occurs within 20-45 DAFB when fruitlets are forming and undergoing cell division. For maximum return bloom, thinning may need to be timed earlier in the growing season than the hand-thinning done in this study, though the need for earlier thinning may be cultivar specific (Haberman et al., 2016; Iwanami et al., 2018; Jones et al., 1992).

Effect of tree age on yields

The dramatic increase in average yields from 2017 to 2018 across all treatments and cultivars (including 'Dabinett') may be attributable to the fact that trees were finally entering full production: the entire planting was only established in 2014. Given that this experiment was carried out on young trees in their first three bearing years, and that only one "off" year was observed, is it difficult to extrapolate these data to the 25-year productive lifespan typical of a tall-spindle apple planting. Although the above projection of crop load in 2019 goes one step further toward providing a more complete picture, the dramatic overall increase in yield from 2017 to 2018, due to trees entering "full production" likely skewed biennial bearing indices upward, even when calculated on a yield efficiency basis (i.e., adjusting for tree size). Ideally, a study of bearing habits would continue several years into trees' period of "full production".

Second Hand-Thinning Experiment, 2017 & 2018

The lack of a thinning effect on return bloom in the second experiment indicates that crop load management in a lower-crop year may not be necessary. However, the results of these two experiments cannot tell us whether crop load management in the first "on" year would be sufficient to set trees on a multi-year cycle of regular bearing.

Thinning in 2017 (the "off" year) did not result in differences in yield the following year, despite the fact that 2017 crop load significantly affected 2018 bloom density in cultivars 'Chisel Jersey' and 'Harry Masters Jersey' and that both these cultivars showed significant differences in crop density in 2018. This contradiction can be explained by the negative relationship between crop density and fruit size. The non- or negligible efficacy of thinning in the "off" year may be reason enough for orchardists not to expend the time and resources on fruit or blossom thinning in "off" years. Even in trees that had been thinned for two years (main experiment), bloom density in Spring 2018 (following the "off" year) did not differ significantly, except in 'Binet Rouge' and 'Harry Masters Jersey'.

Partial Budget Analysis

Though over three years fruit thinning was only profitable for ‘Dabinett’, the projected increase in four-year profitability of thinning to a target crop load of 9 fruit/cm^2 indicates that, just as horticultural assessment of biennial bearing needs to be long-term in order to give a more complete understanding, economic assessment also needs to be long-term to be most informative. The lower overall profitability of hand-thinning compared to chemical thinning is expected and highlights the need for further research to determine ideal thinning spray formulations and rates for these cultivars. Given that these high-tannin cider fruit are “processing” fruit, hand-thinning (a practice typically employed on high-value fresh-market fruit) is likely impractical for growers. The lack of a bloom-promoting affect for hand-thinning in the “off” year indicates that hand-thinning may be unnecessary in a low-crop year, suggesting our multi-year chemical- and hand-thinning cost estimates may be excessive.

The partial budgeting performed here relies on specifications and assumptions that may not apply to all growers in all situations. For instance, the effect of a massive crop failure due to a frost event, which can cause reversion to extreme biennial bearing (Peifer et al., 2018; Wood, 1979), cannot be quantified using these models. For growers in climates with a regular risk of bloom-killing frosts, the conclusions of this partial budget analysis may not be applicable. Though many cider cultivars are late-blooming compared to dessert cultivars (Merwin, 2015; Miles et al., 2017; Wood, 1979), avoidance of late frosts is not guaranteed.

Due to the influence 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. Further long-term crop load studies (ideally fours year or longer), on other rootstocks and in other training systems, are needed to assess the economic viability of crop thinning in cider apples. Nonetheless, the projected profitability of chemical thinning over four years in all seven cultivars is noteworthy.

Practibalility of Hand Thinning

The use of hand thinning, as opposed to chemical thinning, means that our findings and crop load recommendations are somewhat idealized. Hand thinning was chosen because: (1) the object of this experiment was to observe the effects of exact crop loads on tree bearing habit and fruit quality; (2) neither effective chemical thinning formulations, nor effective rates to achieve target crop loads, have been determined for these cider cultivars; and (3) applying different rates of thinning agents on individual trees in a row while avoiding drift is infeasible, particularly when initial bloom and fruit set are discrepant from tree to tree. The influence of weather on spray efficacy during and following chemical thinning also makes this method very inexact. Having quantified seven cider cultivars' responsivities—or lack thereof—to crop load manipulation over multiple years, as we contend to have done in this study, the next step for future researchers is to determine effective chemical thinning formulations and rates to thin blooms and fruitlets on these and other widely-grown cider cultivars.

2017 Fruit Set

Our finding that bloom density correlated negatively with fruit set efficiency (i.e., FBR) concurs with those of Wood (1979), who observed that in trees with lower bloom density, fruit set per 100 blossom clusters was often significantly higher than on trees with greater bloom density. Wood attributed increased relative fruit set to reduced competition between fruitlets on branches. Massive "snowball" bloom is not a guarantee of high fruit set; maximizing return bloom may be less important than achieving moderate but consistent bloom over multiple years. Over-cropping in one year leading to low return bloom, may make trees less responsive to thinning in the second year. On the other hand, increased fruit set and retention in low-bloom trees may compensate partially for reduced potential crop in an ‘off’ year. Orchardists wishing to thin cider cultivars by chemical means will likely need to adjust spray formulations and/or timing when bloom density is lower, and not to underestimate the tendency of trees with lower bloom to set and retain relatively more fruit per flower cluster.

2018 Average Seed Counts

Though average seed count did differ among cultivars, it was not the case that more alternate-bearing cultivars had higher average seed count, or that more regular-bearing cultivars had lower average seed count per fruit. In fact, ‘Binet Rouge’ and ‘Geneva Tremlett’s Bitter’ had lower average seed count (7.6 and 8.3 seeds per fruit, respectively) than did ‘Harry Master’s Jersey’ (11.1). This finding agrees with those of Hoad (1978), Wood (1979), and Green (1987). Though the average number of seeds per fruit is not a good 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. We may think of crop density as a proxy for the total seed number per tree, particularly given that average seed number per fruit was not significantly affected by crop load.

Thinning Accuracy

As previously discussed, the close spacing of trees made it impossible to be certain that pre-harvest drops were attributed to the correct tree. Discrepancy between target crop number and final crop count can be attributed either to inaccurate thinning or to inaccurate counting of drops.

Where fruit size and color were obviously different between adjacent trees, it was possible to tell which fruit had fallen from a given treatment tree. Often this was not possible, and dropped fruits were counted from the mid-point between trees inward.

In 2016, an “on” year, un-thinned trees most commonly had fewer fruit than they were expected to based on initial fruit set. This strongly suggests that un-thinned trees underwent significant fruit drop early in that growing season. In 2017 the opposite was the case, indicating that fruitlets were undercounted in 2017. It was not possible to compare spring and fall fruit counts on un-thinned trees in 2018 because pre-thin fruit set was too great to assess in 2018. Only post-thin counts were checked in 2018. It is often difficult to determine whether thinning was truly inaccurate, or if discrepancies are due to over- or under-counting of drops. The high proclivity of many cider cultivars to drop fruit before ripening meant that it was not possible to pick all fruit from on-tree at a stage of ripeness relevant for analysis of fruit maturity and juice quality characteristics. The vast majority of trees in 2016 or 2017 had as much fruit or less fruit at harvest than were initially counted on the tree. In other words, there was very little undercounting of fruitlets in June of 2016 or 2017. Thus, it is possible that some of the discrepancy between target fruit count and final fruit count (fruit on tree + drops) is an artifact of drop counting at harvest, rather than of fruitlet counting at time of hand-thinning.

2.5 Conclusion

In these two experiments, we found several main trends that comport with the findings of previous authors. Thinning in the “on” year had a moderating effect on bearing patterns, a promoting effect on return bloom, 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 long-term trend of more alternate-bearing trees and cultivars achieving lower cumulative yields than more annual-bearing trees and cultivars. Spring bloom density also correlated negatively with fruit set efficiency, meaning that maximizing return bloom may not be a goal in and of itself, but that spring bloom density is one consideration in the larger complicated puzzle of crop load management. The young age of the trees used in these experiments, and the short span of the study, limit our ability to draw conclusions about the long-term relationships between BBI and yield in these notoriously ‘biennial’ cultivars, but the trends observed over three years—and a projected fourth year—comport 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 to leaving trees un-thinned over four years. Given that hand thinning was only profitable over four years for five of seven cultivars, effective chemical thinning formulations and rates, or other more affordable non-chemical methods, are needed.

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Chapter 3: Reducing Crop Load Improves Juice Quality in Seven High-Tannin Cider Cultivars

Abstract

Seven high-tannin cider apple *(Malus ×domestica* Borkh.*)* cultivars were either: stripped of all fruit, thinned to crop densities of 3, 6, or 9 fruit/cm^2 trunk cross-sectional area, or left un-thinned, for three years. Maturity, ripeness, and juice quality were analyzed for the three non-zero crop load treatments and the un-thinned control. Crop load had a significant effect on all maturity and juice quality variables, though effects were weakest in 2017, the "off" year for the whole planting, when initial fruit set was low. As crop load increased, total polyphenol concentration, titratable acidity, soluble solid concentration, and primary amino nitrogen decreased in all seven cultivars. Crop load had different effects on maturity for each cultivar, as measured by starch pattern index. Crop load effects on maturity alone did not explain differences in juice quality variables. Partial budget analysis found that reduced costs of nitrogen supplements due to increased PAN alone would not justify costs of thinning over three years. Overall, reducing crop load was found to improve all juice quality measures, and over four years, thinning was projected to increase total production of tannins.

3.1 Introduction

Production and sales of cider (i.e., "hard" or alcoholic cider) have grown rapidly in the United States over the last decade (Cyder Market, 2019; NBWA, 2016). From 2008 to 2019, the number of producers nationwide has increased from 94 to more than 900; off-premise sales have increased ten-fold from ~$50 million in 2009 to ~$500 million in 2018 (Brager, 2020). The number of acres planted with high-tannin apple *(Malus spp.)* cultivars—the majority of which are European *M.* ×*domestica* cultivars—is also increasing, though not enough to meet demand for these specialty fruit (Merwin et al., 2008; Miles et al., 2015; Pashow and Mahr, 2018; Weinstock, 2016).

Of recent experimental research on these cultivars, very little has specifically considered the effect of crop load on measures of juice quality, such as sugar, acid, nitrogen, or phenolic content (Merwin et al., 2008; Miles et al., 2020). The need for crop load management strategies to mitigate "biennial" or "alternate" bearing tendencies of many cider cultivars, discussed in depth in Chapters 1 and 2, raises the issue of what effect manipulating crop load will have on the juice quality of cider cultivars. Recent horticultural research has focused on the effects of other practices, such as pre-harvest nitrogen fertilization or juice filtration, on juice quality and fermentation kinetics (Karl et al., 2020a, 2020b; Villière et al., 2015), or else focused on the effect of crop load on juice quality—primarily sugar and acid content—of multipurpose, low-polyphenol cultivars (Kelner et al., 1999; Peck et al., 2016; Robinson and Watkins, 2003; Stopar et al., 2002). Little attention has been given to nitrogen or phenolic content or the effect thereupon of horticultural practices. Phenolics in fresh market cultivars are generally well below detection threshold (Lea and Arnold, 1978; Symoneaux et al., 2014), and certainly under the 2.0 g/L threshold[‡‡] put forth by the National Fruit and Cider Institute at Long Ashton, England (Barker and Ettle, 1903). Phenolics in fresh-market cultivars are thus of little interest to the fresh market except for their purported health benefits as "antioxidants" (Khanizadeh et al., 2008; Kondo et al., 2002).

[‡‡] [‡‡] Lowenthal-Permanganate Assay, equivalent to ~1.2 g/L by Folin-Ciocalteu assay

Relationship between crop load and juice quality

The effect of crop load on juice quality is of particular importance in the cidermaking context, though cidermakers do not currently appear to pay premiums for fruit with high tannin or sugar content the way winemakers do for premium-quality wine grapes. However, the costs of nitrogen supplements to ensure healthy fermentations free of microbial spoilage and "off" odors (Cairns, 2019; Karl et al., 2020b; Song et al., 2020; Zhang et al., 2008), can be mitigated by horticultural practices in the orchard that increase juice nitrogen content. Juice nitrogen content can be improved by reducing crop load (Guillermin et al., 2015; Peck et al., 2016) or by nitrogen fertilization (Karl et al., 2020a, 2020b). Minimum recommended nitrogen content for healthy fermentation is ~140 mg/L yeast assimilable nitrogen (YAN), and apple juice is generally deficient to that minimum recommendation (Bell and Henschke, 2005; Peck et al., 2016; Valois et al., 2006).

Phenolic content

A subset of polyphenols (often referred to as "phenolics") functionally defined as "tannins", lend bitterness and astringency to a cider, sometimes referred to as "mouthfeel" or "body" (Lea and Arnold, 1978). In the French and English cidermaking traditions, and to a degree in the pre-revival American tradition, tannins have for centuries been considered essential for a balanced, full-bodied cider (Alwood, 1903; Chambray, 1764; Ellis, 1754; Knight, 1797; Latham, 1873; Macmahon, 1819; Thacher, 1825). Of studies examining the effect of crop load on polyphenol content, most focus on peel- or flesh-derived "antioxidants" in low-tannin dessert apple cultivars (Awad et al., 2001b; Stopar et al., 2002; Unuk et al., 2006). The classes of phenolic compounds derived from apple peel tissue such as flavonols and anthocyanins (Devic et al., 2010; Khanizadeh et al., 2008), are of limited relevance to cider, unlike in grape wine, given that these are minimally extractable by traditional pressing practices (Devic et al., 2010; Guyot et al., 2003).

Though some recent research has directly or indirectly found that crop load has a negative effect on tannin content of juice (Guillermin et al., 2015; Karl et al., 2020a), multi-year studies examining the effect of crop load on tannin, or the intersection between juice quality and total fruit yield, are lacking. The overall tannin yield per tree, rather than concentration per volume of juice, may be the more meaningful metric from a horticultural and cidermaking perspective, yet research has not assessed tannins in this way. Although cidermakers do not yet pay growers a premium for fruit with higher tannin contents, the ultimate goal of growing these cider cultivars is to produce as much tannin as possible. Thus, the mass of fruit yielded and the concentration of tannins in juice will here be taken together, as "cumulative tannin yield", a stoichiometric proxy.

Acidity

Organic acids—predominantly malic acid in apples—lend sourness or tartness to a cider (Jolicoeur, 2011), and lower the pH, contributing to microbial stability during and after alcoholic fermentation. Particularly in a high-tannin cider, acidity can balance out the bitter and drying sensations conferred by tannins (Lea, 1992). The relatively small range of crop loads observed in previous studies (generally 12 fruit/cm^2 TCSA or less) limits the applicability of this research to cider apple orchard management (Alegre et al., 2012; Awad et al., 2001b; Unuk et al., 2006). Due to their highly biennial bearing patterns, cider cultivars can bear crop loads (40 fruit/cm^2 or more in an "on" year), far exceeding those observed in fresh-market production (Chapter 2; Wood, 1979).

Though a high proportion of high-tannin cider cultivars fall well below the threshold of 4.5 g/L (0.45% w/v) titratable acidity (TA) (Barker and Ettle, 1903), thus fitting squarely into the "bittersweet" category (Valois et al., 2006; Wojtyna, 2018), there are nonetheless commercially important bittersharp cultivars such as 'Geneva Tremlett's Bitter' and 'Porter's Perfection' (Lea and Drilleau, 2003; Merwin, 2015). Multi-purpose or fresh-market cultivars can supplement acidity in a blend of mostly low-acid bittersweets, and TA in many of these cultivars has been shown to be influenced by crop load (Alegre et al., 2012; Henriod et al., 2011; Peck et al., 2016). Thus, the effect of a wide range of crop loads on the acid content of some high-tannin cider apples—namely, subacid bittersweets and bittersharps—is an important research topic for growers and cidermakers.

Sugar Content

Sugars, reported as soluble solids concentration (SSC, ºBrix), are needed for yeast metabolism, and are the precursors of ethanol, the predominant alcohol in fermented beverages, including cider (Lea and Drilleau, 2003). Higher total sugars result in higher alcohol content in a finished cider. Residual sugar after fermentation, conferring sweetness, can also moderate the perception of bitterness, astringency, and acidity, making for a more balanced cider (Symoneaux et al., 2015, 2014). The negative relationship between crop load and average SSC is well characterized in previous research (Alegre et al., 2012; Henriod et al., 2011; Link, 1973; Stopar et al., 2002).

Nitrogen Content

Nitrogen, in the form of amino acids and ammonium (known as yeast assimilable nitrogen), is an essential nutrient source for yeast cells, and in raw apple juice is usually deficient to the minimum recommendations for a healthy fermentation free of off-odors and other sensory faults (Alberti et al., 2011; Bely et al., 1990; Boudreau et al., 2018; Burroughs, 1957; Valois et al., 2006). Evolution of hydrogen sulfide (H_2S) during fermentation due to nitrogen deficiency, resulting in a "rotten-egg" odor (Mestres et al., 2000), is a particularly common problem in cidermaking (Jiranek et al., 1995; Karl et al., 2020a). Higher amino acid concentration in juice, conversely, has been found to correlate with increased metabolic evolution of esters (Santos et al., 2016, 2015), which confer desirable aromas to cider (Xu et al., 2007). Conversely, nitrogen deficiency has been found to correlate with higher evolution of undesirable higher alcohols such as isobutyl and isoamyl (Ough and Bell, 1980). However, within certain parameters, lower nitrogen content resulting in slower fermentation can achieve greater yeast production of desirable aromatic esters, though excessively deficient nitrogen status risks stuck fermentations, microbial spoilage, and H_2S formation (Villière et al., 2015).

Yeast assimilable nitrogen is supplied by all apple cultivars, but at different concentrations (Ma et al., 2018; Valois et al., 2006). Little research into the effect of crop load on the nitrogen content of apple juice, as measured by YAN and/or primary amino nitrogen (PAN)—which is YAN without the inorganic ammonium included—has been conducted (Guillermin et al., 2015; Peck et al., 2016).

Fruit Development and Nutrient Partitioning

The growth of an apple fruit between anthesis and maturity can be divided into two phases: the cell proliferation phase, and the cell expansion phase. These phases are better thought of as a continuum; some cell expansion takes place shortly after pollination, though meaningful expansion occurs after cell proliferation has plateaued or nearly ceased (Denne, 1960). Cell proliferation occurs in developing fruitlets in the first 30-50 days after full bloom (DAFB) (Smith, 1950), though this period varies among cultivars and particularly among species within the genus *Malus* (Denne, 1960). The nutrient-intensive nature of cell division means that manipulation of crop load during this early phase is most likely to be effective at improving juice quality.

Extraction Volume

The effect, if any, of crop load on juice extraction is not a commonly measured fruit quality trait. Juice extraction, measured as a percentage of pomace weight, should conceivably be of interest to both the fresh-market and cider sectors in the apple industry, given consumer preference for juicy apples, and the economic desirability of maximizing juice yield for cidermaking. Juice extraction data for high-tannin cider apples, if reported at all, is generally only reported by cultivar (Bore and Fleckinger, 1997; Peck et al., 2021; Plotkowski and Cline, 2021).

Relationship between crop load and fruit maturity

The interaction between crop load and fruit maturity is much more widely researched and better understood. Though TA and SSC can be considered measures of fruit maturity as much as measures of fruit quality, for our purposes those will be considered separately. Starch pattern index (SPI), a qualitative measure of starch degradation, is more indicative of a fruit's ripeness than any other measurement (Blanpied and Silsby, 1992). Sources conflict about the effect of crop load on SPI, as well as on preharvest drop (Awad et al., 2001b; Stopar et al., 2002; Ward et al., 2001; Wood, 1979).

The goals of this study were to quantify and analyze the effects of crop load on fruit maturity, as measured by SPI, fruit peel color, and pre-harvest drop, and the effects of crop load on juice quality, as measured by SSC, TA, FC, YAN, and extraction volume. The following hypotheses were tested: (1) SPI and peel color would correlate negatively with crop load; (2) pre-harvest drop would correlate positively with crop load; (3) FC, YAN, extraction volume, and SSC would correlate negatively with crop load; (4) TA would correlate positively with crop load.

3.2 Materials and Methods

Experimental Design

The experimental design of the two studies analyzed in this chapter was explained in detail in Chapter 2 and will be briefly reviewed here. Seven high-tannin European cider cultivars were thinned to different crop densities at LynOaken Farms in Lyndonville, NY, near Lake Ontario. The planting, established in 2014, is located at (43.324, -78.373), on a Galen very fine sandy loam. All trees were grafted onto 'Budagovsky 9' ('B.9') rootstock and planted in 2014 in three uniform rows per cultivar of approximately 120 trees each at 1.2 m × 3.7 m (4' × 12') or ~2,220 trees/ha (900 trees/acre) spacing and trained in the tall spindle system using one trellis wire, at LynOaken Farms in Lyndonville, NY.

This study was conducted in the years 2016-2018 on seven cultivars, and an identically designed replicate study involving a second set of trees of four of those cultivars was conducted in 2017 only. Trees were hand-thinned to four target crop densities or left un-thinned. Target crop densities were as follows: 0, 3, 6, and 9 fruit per cm^2 TCSA. Five trees per cultivar were assigned to each treatment group, for a total of twenty-five experimental units per cultivar. The cultivars used in the first experiment were: 'Binet Rouge', 'Brown Snout', 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', 'Michelin', and 'Geneva Tremlett's Bitter'. A second experiment (2017 only) was performed on 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', and 'Michelin'. Fruit from Experiment 2 was analyzed identically to fruit from Experiment 1.

Harvest

Pre-harvest maturity was assessed for each variety using fruit from non-experimental trees via the SPI assay to determine appropriate harvest dates (Blanpied and Silsby, 1992). For cultivars with strong tendencies to pre-harvest drop, such as 'Harry Master's Jersey', fruit was harvested considerably before the fruit on the tree was ripe. Attempts were made to keep harvest dates similar from year to year, but different bloom dates, climatic conditions, and time constraints occasionally made it difficult to do so (Table A2-5, Appendix). Fruits dropped prior to harvest were counted and removed before the fruit remaining on trees was picked. Harvest for the second experiment (2017 only) was conducted on the same respective dates for each cultivar as in the main three-year experiment. Fruit and juice were analyzed in fall of 2017.

External Fruit Analysis

Subsets of ten tree-harvested fruit per tree were randomly sampled and taken back to Cornell University for analysis. Where fewer than ten fruit remained on a tree, drops were included in subsets. For trees with fewer than ten total fruit all fruits were used. Subsets were refrigerated at 4 °C for several days until it was possible to analyze fruit maturity. Fruits were first weighed, and then visually assessed for whole-fruit peel background color or percent blush. Cultivars with a predominantly green-to-yellow background peel color were scored on the RosBreed 1-5 scale, where 1=yellow and 5=dark green (Evans et al., 2012). Percent surface area covered by red blush was visually estimated from 0-100% for cultivars with red peel.

Internal Fruit Analysis

Subset fruits were then assessed for flesh firmness in Newtons (N) 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 and then probed once at each location. Subsequent to penetration, SPI was determined by removing equatorial wedges 5-10 mm thick and wetting with a (0.22% w/v iodine, 0.88% w/v potassium iodide) solution, (Blanpied and Silsby, 1992). Seeds per fruit were counted in 2018.

Juice Extraction

The remaining fruit was diced and then ground on 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 became discontinuous. This method closely mimics a typical "rack and cloth" cider press. Juice samples were aliquoted into 50-mL, 15-mL, and 1.5-mL vials; 1.5-mL vials were frozen at –80 °C, and 15-mL and 50-mL vials were frozen at –20 °C. In 2018, pulp was weighed prior to pressing, and total juice yield was weighed subsequent to pressing. Extraction percentage was calculated by dividing final juice weight by initial pulp weight.

Juice Chemistry

Samples were thawed to room temperature and homogenized using a VWR Analog Vortex Mixer (Radnor, PA, USA). Soluble solids concentration (SSC) was measured as ºBrix on a PAL-1 BLT digital refractometer (Omaeda, Saitama, Japan). Titratable acidity was measured on a Metrohm 809 Titrando autotitrator (Herisau, Switzerland) by titrating 5 mL juice aliquot in 40 L 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 and starting pH.

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

Using the relationships of crop density to total polyphenol content calculated for each cultivar from 2016-2018 data (Figure 3-3), the projected total polyphenol content was calculated as if target crop densities were imposed for a fourth year. By multiplying each tree's recorded total fruit yield by average juice extraction percentage for each cultivar, and then by total polyphenol concentration (FC) for each year, and finally adding these values over three years for each tree, the "cumulative tannin yield" per tree was assessed. For years 1-3 (2016-2018), recorded yield and FC values were used. In year 4 (2019), predicted FC values (from regression formulae for each cultivar, Figure 3-3) and projected total yield mass per tree were used (Table A2-2, Appendix).

Primary amino nitrogen was determined using a modified Megazyme protocol (Bray, Ireland). Subsets of juice samples in 1.5-mL microfuge tubes and stored at -80 °C were thawed in a warm water bath, vortexed to homogenize, and then gently spin in a centrifuge at 1,100 g for 5 minutes. A standard curve was prepared by diluting standard solution (140 mg N/L as isoleucine) to the following concentrations: 0, 20, 40, 60, 80, 100, 120, and 140 mg N/L. Standards and samples were analyzed in duplicate (two wells each), with 3.33 µL of samples or standards suspended in 200 µL buffer solution and 3.33 µL Milli-Q deionized water. Absorbance at 340 nm was read approximately two minutes after the last cell was pipetted. Subsequently, 6.67 µL o-phthaldialdehyde (OPA) was added to each sample or standard. Approximately 15 minutes after adding OPA to the last cell, absorbance at 340 nm was read again. The difference in absorbances ($\Delta\ ABS_{340\ nm}$) is then used to calculate PAN content of the sample using the following formula:

Equation 3-1 $PAN = \frac{(\Delta\, ABS_{340\ nm} - b)}{a}$

…where a is the slope and b is the y-intercept of the standard curve. When sample PAN was out of the range of the standard curve, samples were diluted prior to analysis and a multiplication factor the inverse of the dilution rate was used in the calculation.

<u>Specifications and Assumptions for Economic Analysis of Nitrogen Supplement Cost</u>

The cost of exogenous nitrogen supplements in a model cider was estimated by extrapolating 2016-2018 yield data (Chapter 2) from the same experiment, assuming a planting density of 2,220 trees/ha (900 trees/acre), and multiplying yield by juice extraction volume data (Table A3-13, Appendix) to estimate total volume of juice per acre under different crop loads. Nitrogen deficiency was calculated on a mg/L basis and then extrapolated to grams of supplement needed per acre. If PAN was not deficient, cost was considered to be $0.00/ha. Supplement costs for diammonium phosphate (DAP), FermAid O (inactivated yeast hulls), and FermAid K (DAP + hulls + micronutrients) were calculated as follows (Karl et al., 2020b):

DAP: 18% nitrogen, $2.60/kg
FermAid O: 40 mg N/g, $33.80/kg
FermAid K: 100 mg N/g, $15.70/kg

These nitrogen supplement products are commonly used by cidermakers to boost PAN to encourage healthy, steady fermentations.

<u>Excluded Experimental Units, Original Experiment</u>

Of a total 525 experimental units (175 trees × 3 years), 37 were excluded from the final dataset, as previously described in Chapter 2. The close spacing of trees made it so that drops could have been attributed to the incorrect tree, particularly when there were far more drops on the ground than fruit left on the tree. Given that this study examines the relationship of crop load to juice quality variables, trees for which crop load was uncertain were excluded from the dataset, based on a combination of location, percent drop, and where possible, by comparison of final total fruit count to initial fruit set. Confidence in drop counts was lowest in 2018 due to universally high fruit set and crop load in the entire orchard. There was greater confidence in drop counts in 2017, because non-experimental trees had little or no fruit set in that "off" year for the whole orchard. For this same reason, we could be more confident in fruit counts in the second experiment, only conducted in 2017.

Statistical Analysis

This experiment was conducted in a complete, randomized block design. All statistical analysis was conducted in R (R Core Team, 2014). All regressions were analyzed as mixed models with a random block term, using the *lmer* function from the *lme4* package (Bates et al., 2021). 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).

3.3 Results

Polyphenol Concentration and Cumulative Tannin Yield

For all seven cultivars, there was a significant negative logarithmic relationship between crop density and FC (Figure 3-3). Thinning only affected 2017 FC for 'Harry Masters Jersey' in the original three-year experiment. In the second experiment (2017 only) FC correlated negatively with crop density in 'Chisel Jersey', 'Harry Masters Jersey', and 'Michelin', and not at all in

‘Dabinett’ (Table 3-2). The overall trend was that as crop load increased, FC decreased in all cultivars. Though over three years there was no clear overall trend in “cumulative tannin yield” across all cultivars (Table A3-3, Appendix), by year 4 all cultivars in this study would achieve higher “cumulative tannin yield” when thinned than when left un-thinned (Table A3-4, Appendix).

Cultivars ‘Binet Rouge’ and ‘Chisel Jersey’ had highest overall FC (~3.0 and ~2.8 g/L GAE, respectively), ‘Harry Masters Jersey’ and ‘Geneva Tremlett’s Bitter’ somewhat lower (~2.5 and ~2.2, respectively), followed by ‘Dabinett’ (~2.1); ‘Michelin’ and ‘Brown Snout’ had lowest FC (~1.8 and ~1.6 g/L GAE).

Soluble Solids Concentration

There were negative logarithmic relationships between crop density and SSC in all seven cultivars (Figure 3-1). Differences in SSC by crop load were less pronounced in the “off” year 2017 than in the two “on” years, 2016 and 2018. SSC was also highest overall in the low-crop “off” year 2017. ‘Brown Snout’ and ‘Binet Rouge’ had highest overall SSC (~17 ºBrix), followed by ‘Chisel Jersey’ and ‘Dabinett’ (~14.6 ºBrix), ‘Harry Masters Jersey’ and ‘Dabinett’ (~14.3 ºBrix), and finally ‘Geneva Tremlett’s Bitter’ (~13 ºBrix). In the second experiment (2017 only, Table 3-2) SSC correlated negatively to crop density in ‘Chisel Jersey’ and ‘Harry Masters Jersey’ but not for ‘Dabinett’ or ‘Michelin’.

Acidity

Titratable acidity was not strongly affected by crop density. ‘Dabinett’ and ‘Harry Masters Jersey’, which had low TA overall, did not exhibit significant relationships between crop density and TA (Figure 3-2). ‘Binet Rouge’, ‘Brown Snout’, ‘Chisel Jersey’, and ‘Geneva Tremlett’s Bitter’ exhibited significant negative relationships between crop density and TA, but the slope of these relationships was slight, except in ‘Geneva Tremlett’s Bitter’. TA on lowest-crop trees was approximately double (~20 g/L MAE) that of the most heavily cropped trees (~10 g/L MAE). Crop density correlated positively with TA in ‘Michelin’, though TA was also low overall in this bittersweet cultivar, as in bittersweet cultivars ‘Binet Rouge’, ‘Brown Snout’, and ‘Chisel Jersey’. In the second experiment (2017 only, Table 3-2) TA was only affected by crop density in ‘Chisel Jersey’ (negative correlation).

Year-to-year variability of TA differed by cultivar. There was no year effect on TA in ‘Binet Rouge’ and ‘Chisel Jersey’, while in ‘Harry Masters Jersey’ overall TA increased with each successive year of the experiment (Table A3-9e, Appendix). ‘Michelin’ had higher overall TA in the “on” years 2016 and 2018 than in the “off” year 2017. By contrast, ‘Geneva Tremlett’s Bitter’ had highest overall TA in 2017. pH correlated negatively with crop density in ‘Binet Rouge’, ‘Brown Snout’, ‘Dabinett’, and ‘Michelin’, and positively in ‘Geneva Tremlett’s Bitter’. ‘Chisel Jersey’ and ‘Harry Masters Jersey’ did not exhibit a significant relationship between crop density and pH.

Primary Amino Nitrogen

There were negative logarithmic relationships between crop density and PAN in all cultivars (Figure 3-4). ‘Chisel Jersey’, ‘Dabinett’, and ‘Harry Masters Jersey’ had relatively low PAN overall, while ‘Michelin’ and ‘Geneva Tremlett’s Bitter’ had relatively high PAN overall. PAN was generally highest in 2017, the “off” year for the whole planting. Treatment differences in 2017 were not significant for any cultivar. The more “annual” cultivars ‘Chisel Jersey’, ‘Dabinett’, and ‘Harry Masters Jersey’ had lower overall PAN, across treatment and year, than the four more “biennial” cultivars ‘Binet Rouge’, ‘Brown Snout’, ‘Michelin’, and ‘Geneva Tremlett’s Bitter’.

Figure 3-1. Regressions of crop density (fruits/cm^2 TCSA) to soluble solid concentration (SSC) of seven cider apple cultivars harvested at LynOaken Farms in Lyndonville, NY 2016-2018. Each point represents a single sampling from one tree in one year. Trunk cross sectional area (TCSA) measured 40 cm above the graft union.

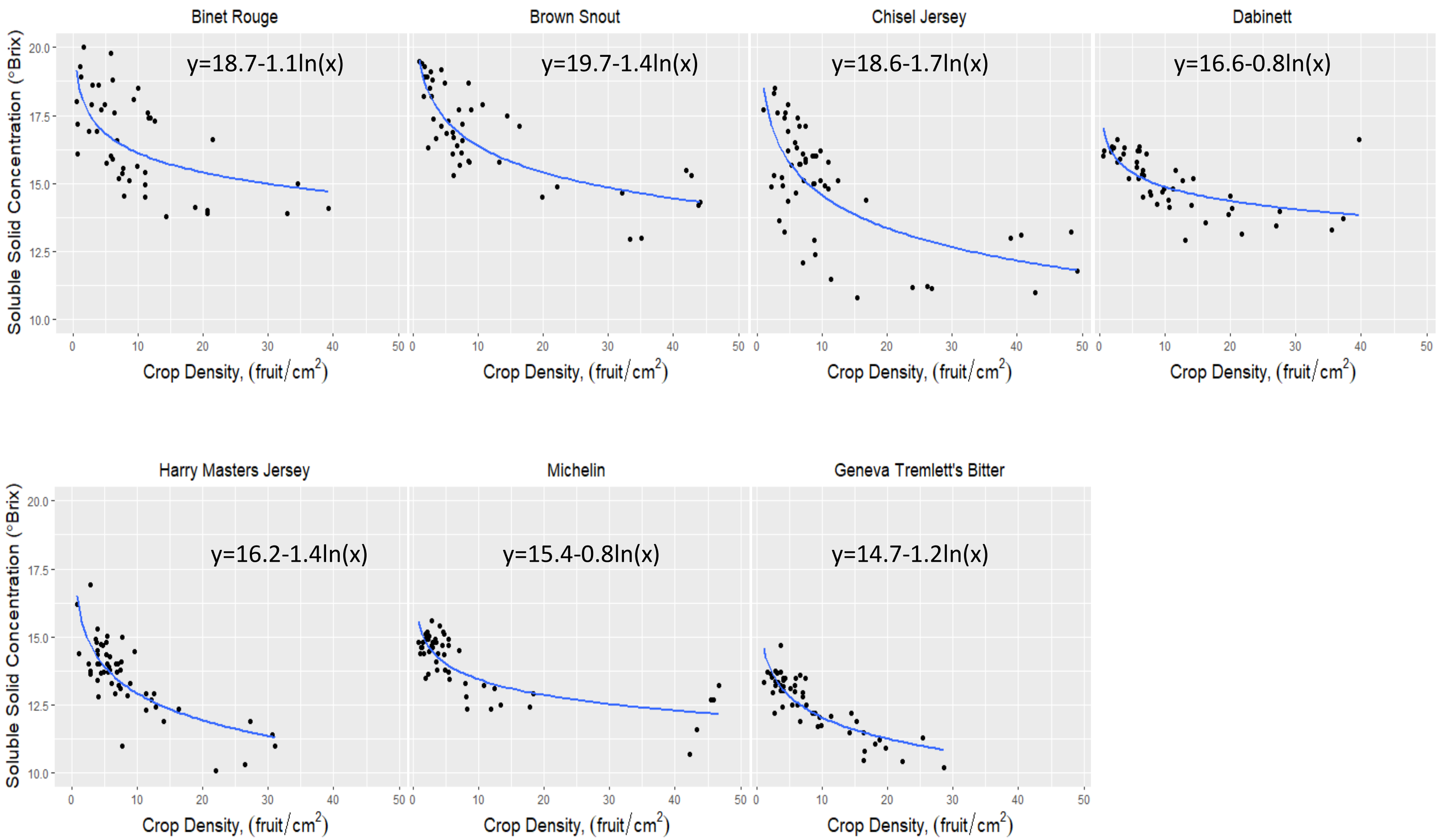


Figure 3-2. Regressions of crop density (fruits/cm^2 TCSA) to titratable acidity (g/L malic acid equivalent) of seven cider apple cultivars harvested at LynOaken Farms in Lyndonville, NY 2016-2018. Each point represents a single sampling from one tree in one year. Trunk cross sectional area (TCSA) measured 40 cm above the graft union.

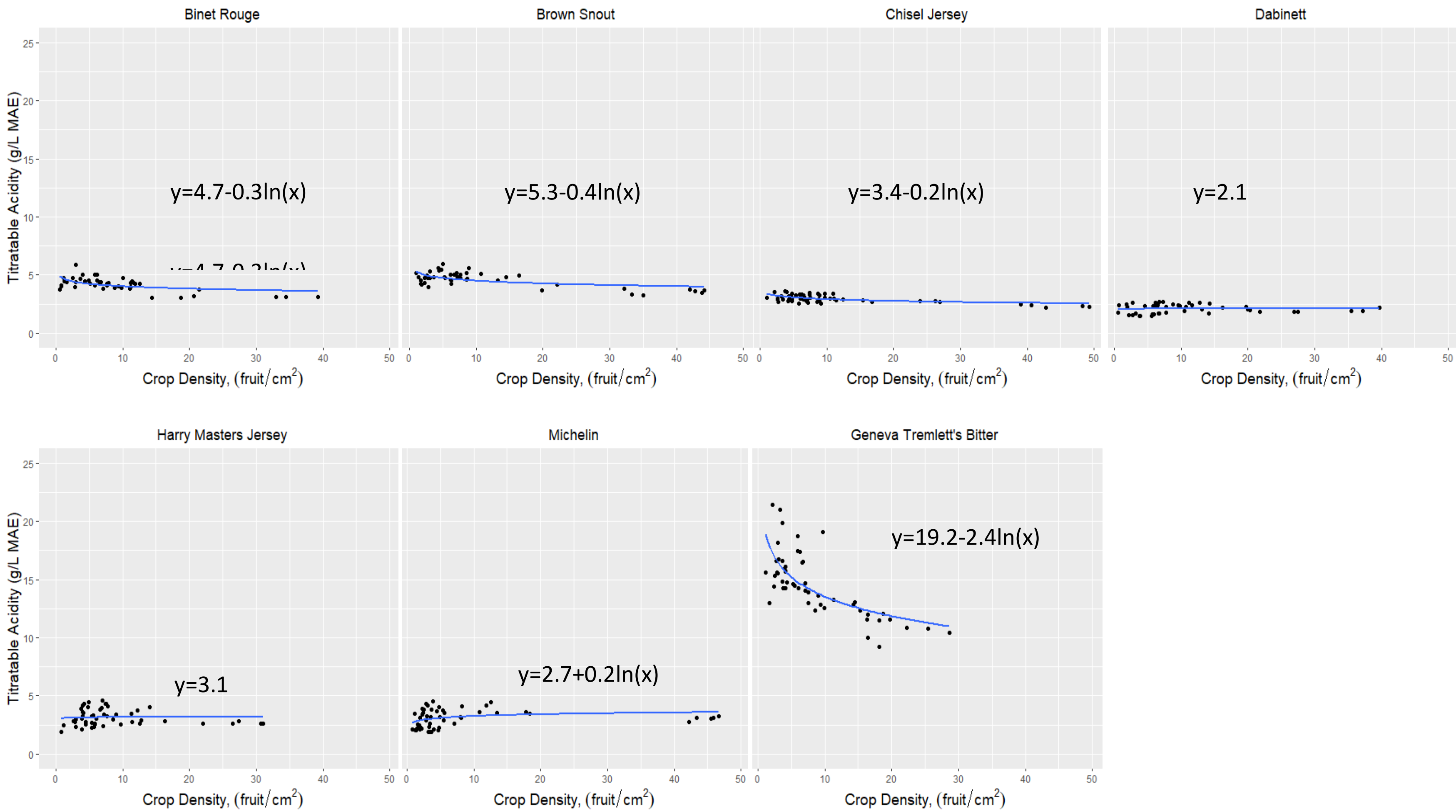


Figure 3-3. Regressions of crop density (fruits/cm^2 TCSA) to Folin-Ciocalteu total polyphenol concentration (g/L gallic acid equivalent) of seven cider apple cultivars harvested at LynOaken Farms in Lyndonville, NY 2016-2018. Each point represents a single sampling from one tree in one year. Trunk cross sectional area (TCSA) measured 40 cm above the graft union.

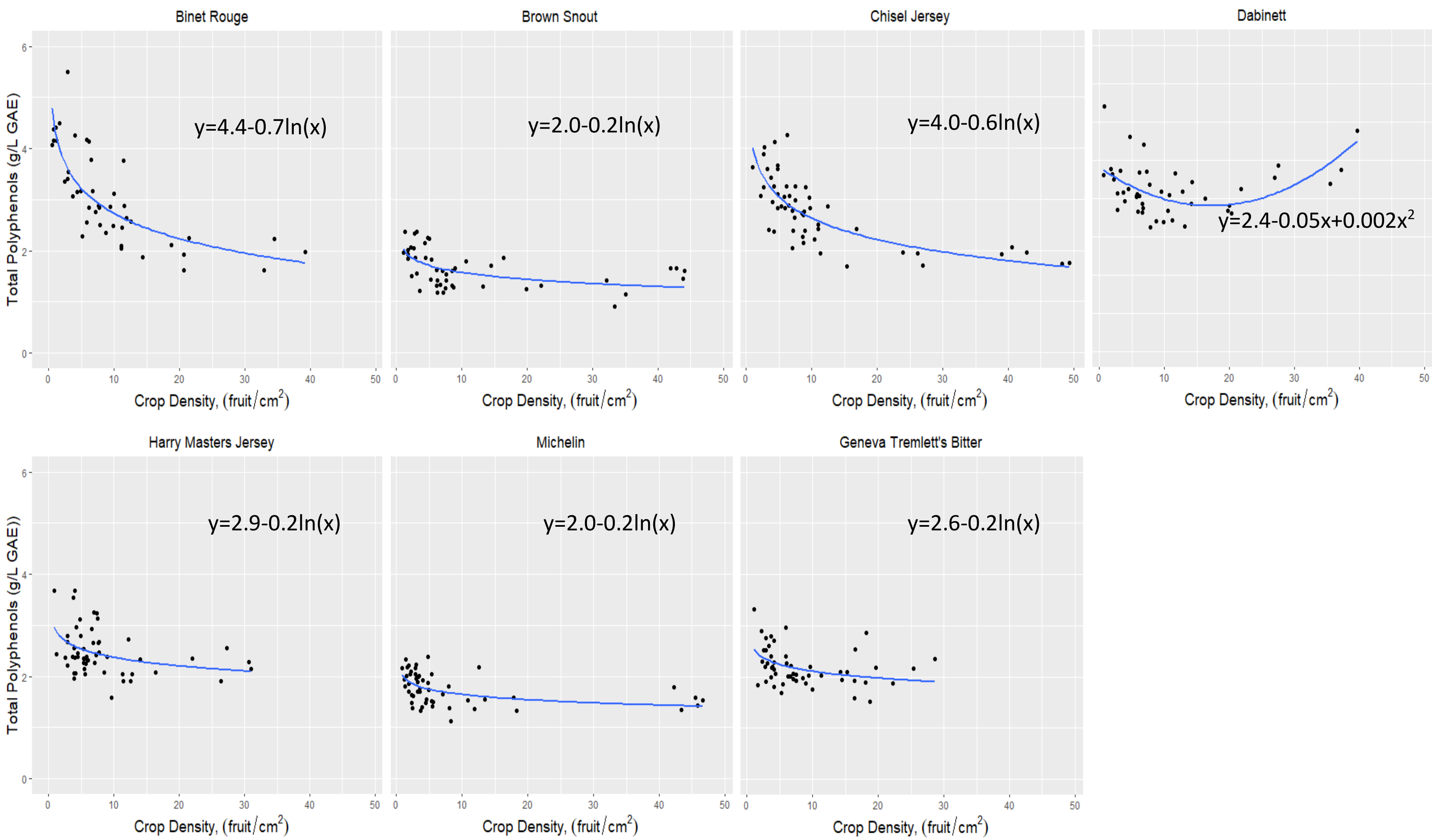
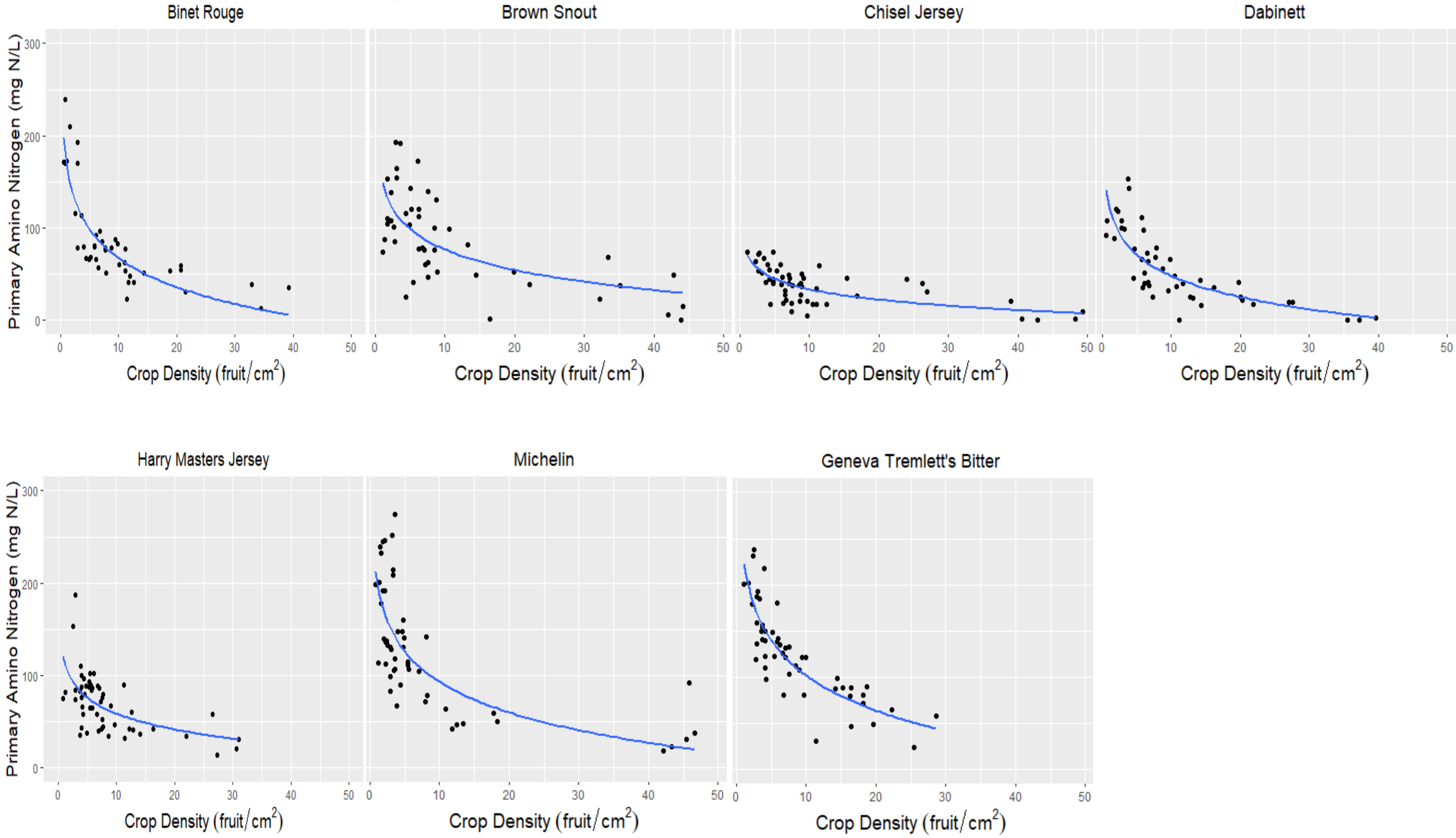


Figure 3-4. Regressions of crop density (fruits/cm^2 TCSA) to primary amino nitrogen concentration (mg/L) of seven cider apple cultivars harvested at LynOaken Farms in Lyndonville, NY 2016-2018. Each point represents a single sampling from one tree in one year. Trunk cross sectional area (TCSA) measured 40 cm above the graft union.



Ripeness and Maturity

SPI did not correlate consistently with crop density (Figure 3-5). ‘Binet Rouge’, ‘Brown Snout’, ‘Chisel Jersey’, ‘Dabinett’, and ‘Michelin’ exhibited advanced ripeness (high SPI) at either very high or very low crop loads, and delayed ripeness (low SPI) around 20-25 fruit/cm^2 TCSA. Crop density correlated negatively to SPI in ‘Harry Masters Jersey’, while in ‘Geneva Tremlett’s Bitter’ the relationship was positive. However, SPI was high overall in ‘Geneva Tremlett’s Bitter’.

Pre-harvest drop and SPI behaved similarly in relation to crop density in ‘Binet Rouge’ and ‘Dabinett’, being greatest at low or high crop loads. Likewise, drop in ‘Harry Masters Jersey’ had a negative relationship to crop density, and ‘Geneva Tremlett’s Bitter’ exhibited a positive linear relationship. ‘Chisel Jersey’ and ‘Michelin’ exhibited linear, negative relationships between crop density and preharvest drop. ‘Brown Snout’ showed no significant relationship between crop density and pre-harvest drop. ‘Binet Rouge’ and ‘Geneva Tremlett’s Bitter’ had low pre-harvest drop overall; ‘Brown Snout’, ‘Chisel Jersey’, ‘Dabinett’, and ‘Harry Masters Jersey’ had moderate propensity overall; and ‘Michelin’ showed a high propensity overall. Pre-harvest fruit drop correlated positively with SPI in six cultivars, with ‘Geneva Tremlett’s Bitter’ being the exception (not significant, $p=0.350$). For ‘Geneva Tremlett’s Bitter’, drop was low overall (Table A3-6, Appendix), and SPI was high overall (Figure 3-5).

In the second experiment (2017 only) SPI and flesh firmness both decreased as crop load increased in ‘Chisel Jersey’, ‘Dabinett’, and ‘Harry Masters Jersey’, but neither correlated significantly with crop density in ‘Michelin’ (Table 3-2). Conversely, pre-harvest drop correlated negatively with crop density in ‘Michelin’ only, and not at all in ‘Chisel Jersey’, ‘Dabinett’, or ‘Harry Masters Jersey’.

Figure 3-5. Regressions of crop density (fruits/cm^2 TCSA) to starch pattern index (SPI) of seven cider apple cultivars harvested at LynOaken Farms in Lyndonville, NY 2016-2018. Each point represents a single sampling from one tree in one year. Trunk cross-sectional area (TCSA) measured 40 cm above the graft union.

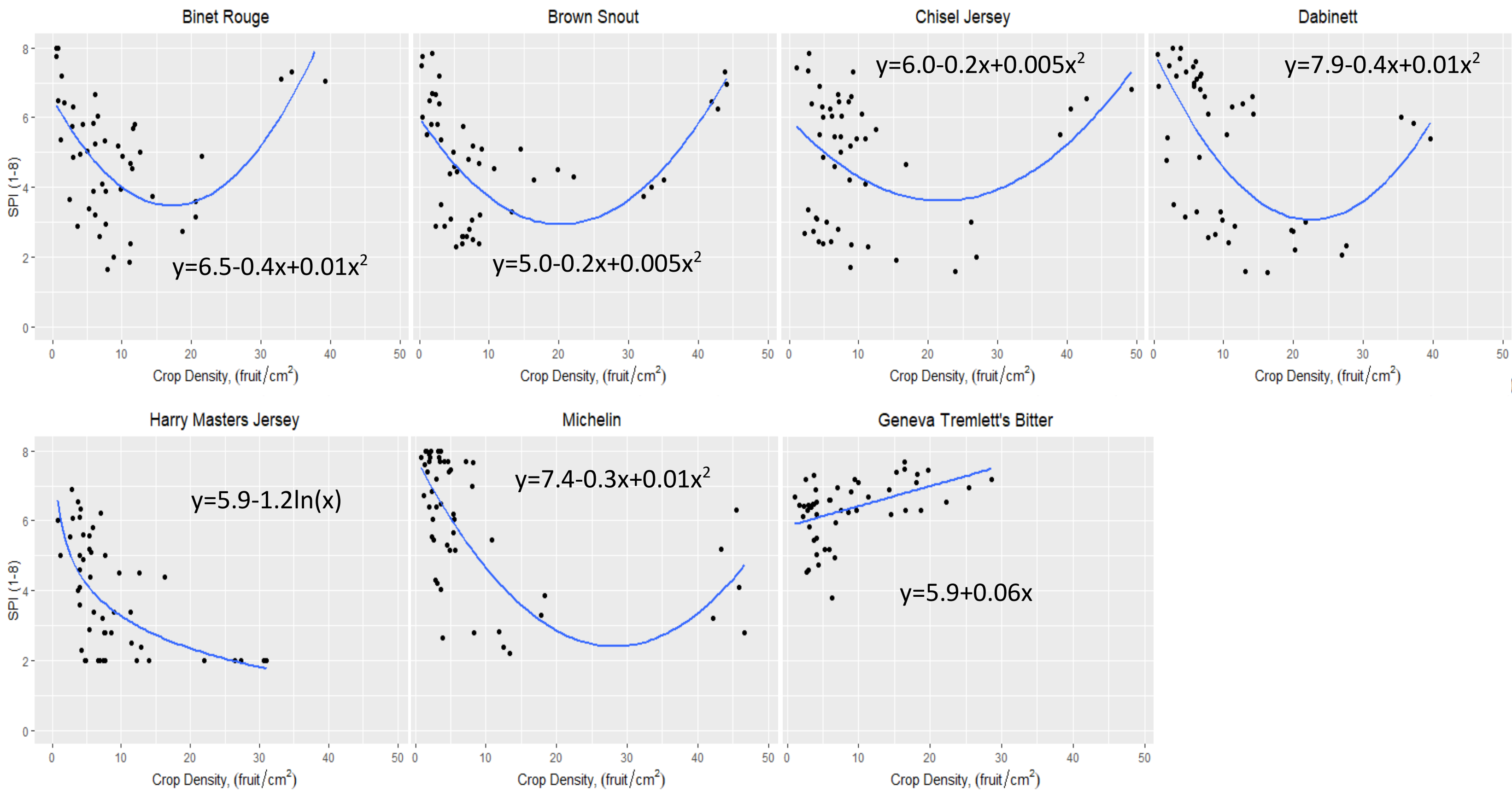


Figure 3-6. Regressions of crop density (fruits/cm[2] TCSA) to flesh firmness (N) of seven cider apple cultivars harvested at LynOaken Farms in Lyndonville, NY 2016-2018. Each point represents a single sampling from one tree in one year.

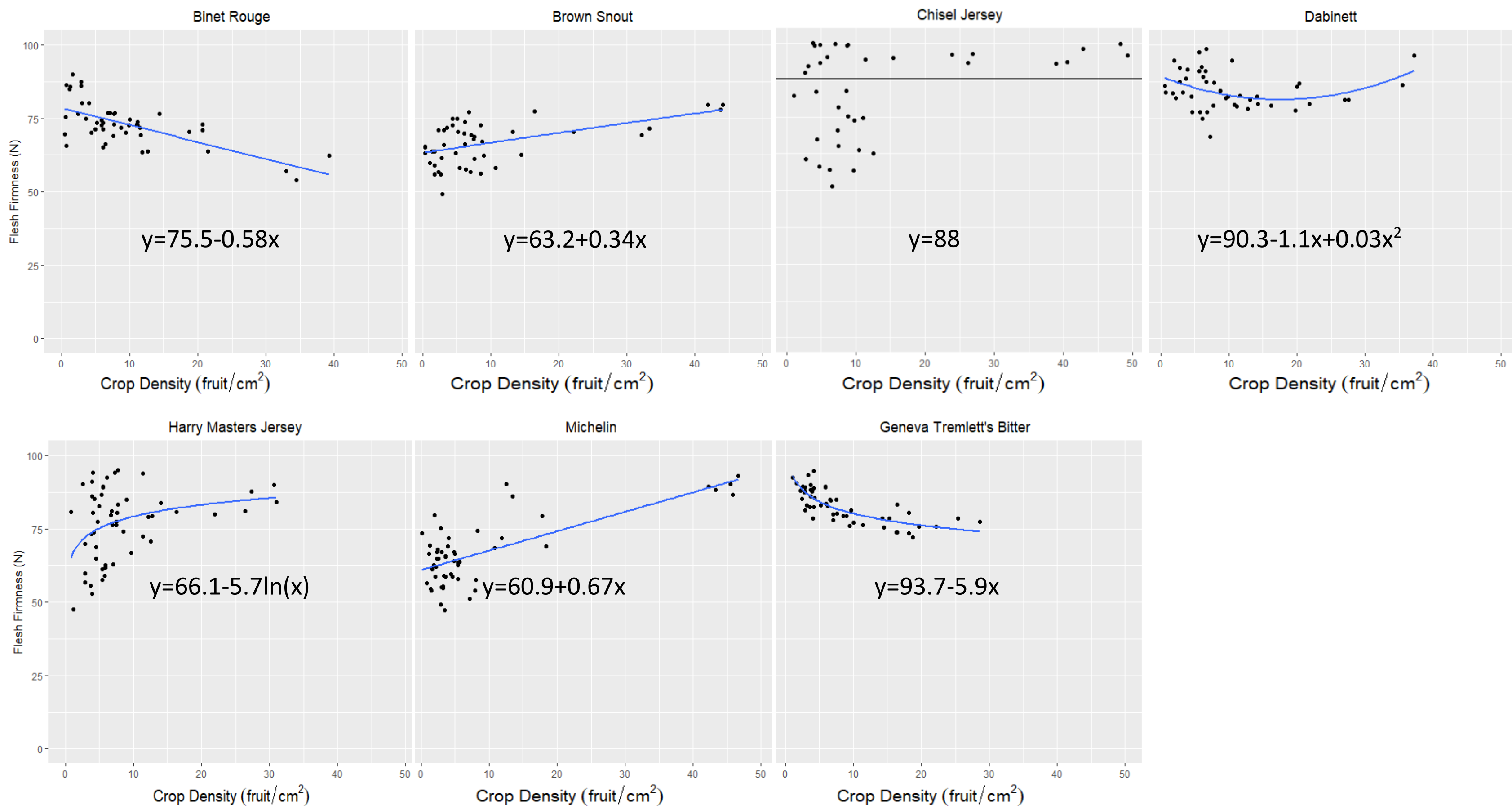
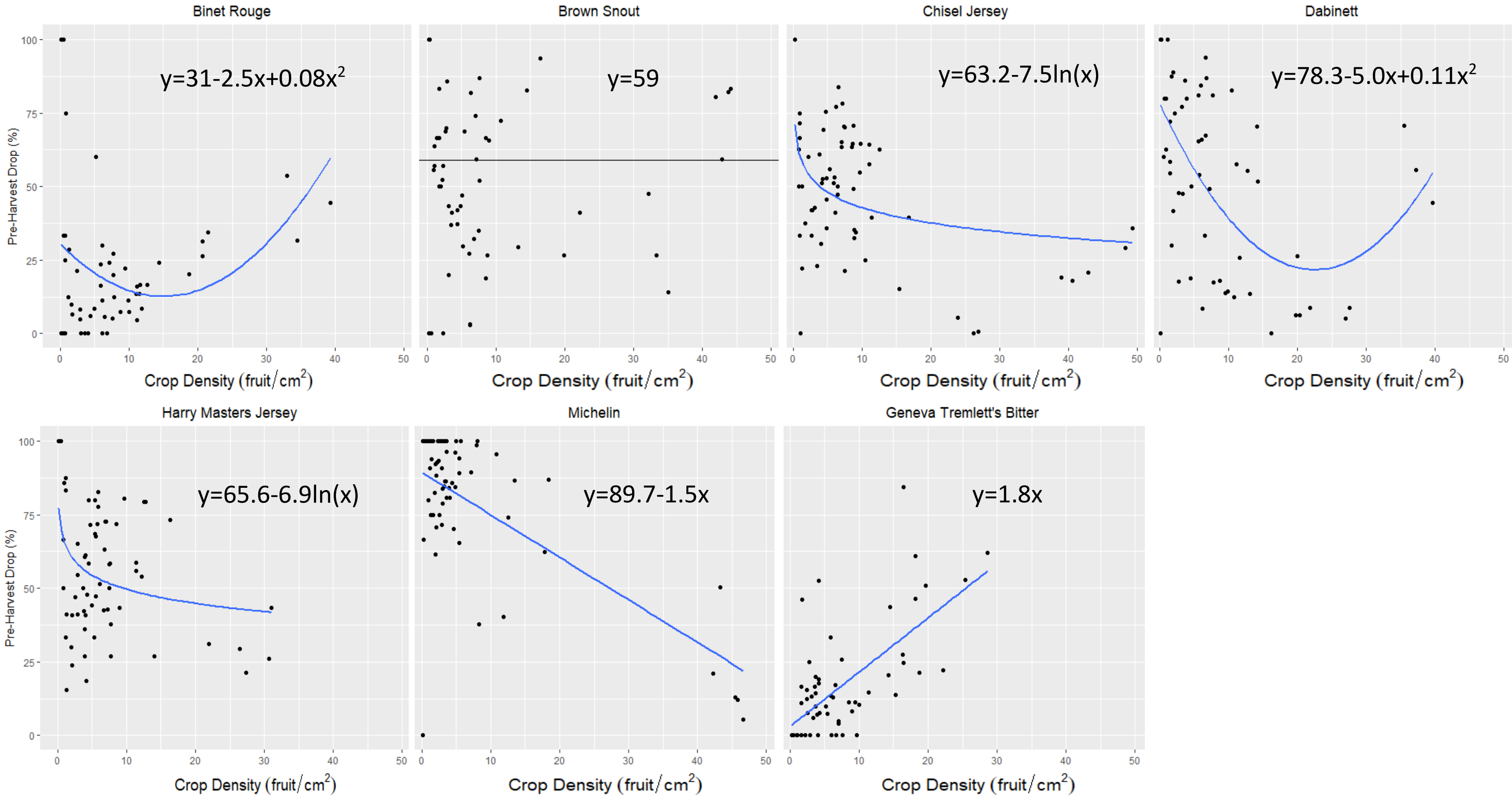


Figure 3-7. Regressions of crop density (fruits/cm^2 TCSA) to preharvest drop (% of total fruits) of seven cider apple cultivars harvested at LynOaken Farms in Lyndonville, NY 2016-2018. Each point represents a single sampling from one tree in one year.



Flesh firmness correlated negatively with crop load in ‘Binet Rouge’ and ‘Geneva Tremlett’s Bitter’; positively in ‘Brown Snout’, ‘Harry Masters Jersey’, and ‘Michelin’; and quadratically in ‘Dabinett’, with firmness being lowest around 15-20 fruit/cm^2. Firmness was high (>75 N) overall in ‘Dabinett’ and ‘Geneva Tremlett’s Bitter’, moderate in ‘Binet Rouge’, ‘Brown Snout’, ‘Harry Masters Jersey’, and ‘Michelin’ (50-85 N). Flesh firmness did not correlate with crop density in ‘Chisel Jersey’. Firmness correlated negatively with SPI in ‘Binet Rouge’, ‘Chisel Jersey’, ‘Harry Masters Jersey’, ‘Michelin’, and ‘Geneva Tremlett’s Bitter’; there was no significant correlation between SPI and flesh firmness in ‘Brown Snout’ or ‘Dabinett’.

Juice Extraction

2018 juice yield, as a percent of fruit weight, had statistically significant but small positive correlations with crop density in ‘Brown Snout’, ‘Chisel Jersey’, ‘Michelin’, and ‘Geneva Tremlett’s Bitter’. Differences were not meaningful from a cidermaking perspective. Extraction volume differed more by cultivar than by crop load, with ‘Chisel Jersey’ and ‘Dabinett’ being juiciest overall and ‘Michelin’ being driest.

Partial Budget Analysis of Nitrogen Supplement Costs

Nitrogen supplement costs (Table A3-18, Appendix) were highest for a model acre receiving no thinning treatment in all cultivars; treatment differences were not significantly different for ‘Chisel Jersey’ or ‘Dabinett’. The reduction of three-year cumulative nitrogen supplement costs alone did not compensate for the increased cost of thinning spray applications for any cultivar or treatment, except for ‘Chisel Jersey’ thinned to 3 fruit/cm^2. Hand-thinning likewise would not result in a net increase in profitability (data not shown).

Table 3-1. Partial budget based on 2016-2018 yield and juice primary amino nitrogen (PAN) data from a three-year hand-thinning experiment at LynOaken Farms. Estimated costs of diammonium phosphate (DAP), FermAid K and Fermaid O supplements for a model hectare (ha).

Variety	Target Crop Load	Reduced cost of nitrogen supplement to achieve 140 mg/L N ($/ha)			Increased spray cost ($/ha)	Change in profitability ($/ha)		
		DAP	FermAid K	FermAid O		DAP	FermAid K	FermAid O
Binet Rouge	3 fruit/cm^2	-27	-746	-642	1,264	-1,237	-518	-622
	6 fruit/cm^2	-19	-525	-452	“ ”	-1,245	-739	-812
	9 fruit/cm^2	-11	-305	-263	“ ”	-1,253	-959	-1,001
Brown Snout	3 fruit/cm^2	-32	-882	-760	“ ”	-1,232	-382	-504
	6 fruit/cm^2	-26	-698	-600	“ ”	-1,239	-567	-664
	9 fruit/cm^2	-18	-502	-432	“ ”	-1,246	-762	-832
Chisel Jersey	3 fruit/cm^2	-66	-1804	-1554	“ ”	-1,198	+540	+289
	6 fruit/cm^2	-26	-699	-602	“ ”	-1,238	-565	-662
	9 fruit/cm^2	-34	-919	-791	“ ”	-1,230	-346	-473
Dabinett	3 fruit/cm^2	-42	-1147	-988	“ ”	-1,222	-117	-276
	6 fruit/cm^2	+6	+169	+145	“ ”	-1,270	-1,433	-1,410
	9 fruit/cm^2	-16	-437	-376	“ ”	-1,248	-828	-888
Harry Masters Jersey	3 fruit/cm^2	-25	-688	-593	“ ”	-1,239	-576	-671
	6 fruit/cm^2	-11	-305	-263	“ ”	-1,253	-959	-1001
	9 fruit/cm^2	-6	-157	-135	“ ”	-1,258	-1,107	-1129
Michelin	3 fruit/cm^2	-37	-1004	-865	“ ”	-1,227	-260	-400
	6 fruit/cm^2	-35	-949	-817	“ ”	-1,229	-315	-447
	9 fruit/cm^2	-23	-628	-541	“ ”	-1,241	-636	-723
Geneva Tremlett’s Bitter	3 fruit/cm^2	-23	-614	-528	“ ”	-1,242	-651	-736
	6 fruit/cm^2	-19	-527	-454	“ ”	-1,245	-737	-810
	9 fruit/cm^2	-13	-359	-309	“ ”	-1,251	-906	-955

Table 3-2. Slope coefficient estimates from regressions of crop density to Folin-Ciocalteu total polyphenol concentration, titratable acidity, soluble solids concentration, starch pattern index, and pre-harvest drop rate, in a one-year crop load experiment at LynOaken Farms. Significance indicated by asterisk: * at p<0.05, ** at p<0.01, *** at p<0.001

Cultivar	Coefficient estimate (crop density effect)					
	Folin-Ciocalteu Total Polyphenols	Titratable Acidity	Soluble Solids Concentration	Starch Pattern Index	Pre-Harvest Drop (%)	Flesh Firmness
Chisel Jersey	–0.053*	–0.026*	–0.195***	–0.086***	–0.332	1.694***
Dabinett	–0.006	–0.004	–0.052	–0.069**	–0.981	1.191**
Harry Masters Jersey	–0.048***	0.003	–0.209***	–0.155***	–1.429	0.976*
Michelin	–0.116***	–0.075	0.181	0.024	–5.850***	–0.354

3.4 Discussion

Ripeness and Maturity

Because of environmental conditions and time constraints, we were not able to harvest all cultivars at the same number of DAFB, within year or across years. Very often, pre-harvest drop was so severe that we were forced to harvest fruit from trees at SPI of less than 6. Nonetheless, maturity (measured by SPI) was delayed as crop density increased up to 20-25 fruit/cm^2 TCSA, above which maturity became advanced, with the exception of 'Geneva Tremlett's Bitter' which bore a relatively lower range of crop densities (up to ~30 fruit/cm^2 TCSA) compared to the other six cultivars in this experiment.

It is difficult to compare our findings with those of other authors because previous work has involved smaller ranges of crop load than the ranges observed in our experiments, and because fruit in many studies were harvested at much earlier stages of ripeness than in our study. The quadratic relationship between SPI and crop density we observed (higher SPI at very low or very high crop loads) does not comport with previous research, like because the range of crop densities in our experiments is much wider than that of any one experiment: conflicting trends among previous authors may represent "snapshots" of the larger picture. Our finding in 'Harry Masters Jersey' agrees with that of Palmer et al. (1997) who found that SPI was higher (i.e., maturity was advanced) as thinning became more severe, and that this relationship was linear in fresh-market cultivar 'Braeburn'.

Differences in fruit set and overall crop load from year to year may have contributed to an overall year effect on ripening. As shown in Table A2-5 (Appendix), some cultivars were harvested at roughly the same number of days after full bloom (DAFB) in all three years, but 'Chisel Jersey' 'Dabinett' and 'Geneva Tremlett's Bitter' had quite variable harvest timing from year to year in terms of DAFB. For instance, ‘Dabinett’ fruit in 2017 and 2018 were much riper overall than in 2016, corresponding to the later timing of ‘Dabinett’ harvest in those years. However, all fruit were harvested on the same date, and likewise analyzed simultaneously a few days later, so within-year differences in SPI represent a snapshot of ripening.

Crop density did not always correlate with pre-harvest drop and SPI in the same way within the same cultivar. Both relationships were quadratic in ‘Binet Rouge’ and ‘Dabinett’, negatively logarithmic in ‘Harry Masters Jersey’, and linearly positive in ‘Geneva Tremlett’s Bitter’; by contrast pre-harvest drop was not significantly affected by crop density in ‘Brown Snout’ while SPI was affected. In ‘Chisel Jersey’ and ‘Michelin’ drop rate decreased linearly with crop density while SPI had a quadratic correlation to crop density. ‘Michelin’ had a high overall propensity for drop, and harvest date remained fairly consistent among years. ‘Chisel Jersey’ and ‘Dabinett’ had lower overall drop in 2016 compared to 2017 or 2018, corresponding to a much earlier harvest in 2016. By contrast, ‘Brown Snout’ harvest timing was quite consistent, yet 2016 drop was much lower than 2017 or 2018 in that cultivar. Drop in ‘Binet Rouge’ was higher overall in 2017 than either 2016 or 2018, despite the small differences in harvest timing among years.

Polyphenol concentration

Our finding that crop load correlates negatively with total polyphenols concurs with those of Guillermin et al. (2015), who found that crop load had a predominant effect on tannin content in French bittersweet cultivars ‘Douce Moen’ and ‘Douce Coetligne’, and Karl et al. (2020a) who reported that lower overall crop load in one year correlated with higher polyphenol concentration, compared to the following year, in French bittersweet ‘Medaille d’Or’. Our results did not concur with Peck et al. (2016), perhaps because the latter authors were investigating the effects of crop load in a low-polyphenol cultivar.

Though polyphenol concentration in juice is not the same as total polyphenol content per fruit, the small differences in 2018 juice extraction indicates that polyphenols were not simply diluted by more water at higher crop densities, but that there was much lower total phenolic content per fruit in the un-thinned treatment compared to thinned treatments.

An overall negative correlation between crop density and polyphenol concentration still obtained in 2017. Given that in some cider cultivars most polyphenol synthesis occurs by 40 DAFB (Renard et al., 2007), corresponding to the cell-division phase of fruitlet growth, the smaller effect of crop load on FC in 2017 may be an artifact of the much later thinning in 2017 (Table A2-4, Appendix), as well as the lower overall pre-thin fruit set in 2017, the "off" year for the whole planting. Thinning may not be necessary in an "off" year to improve juice quality, since low fruit set would already result in higher polyphenol content, and thinning might result in excessive crop loss.

The differences in average FC among cultivars generally agree with the findings of Peck et al. (2021), though the latter authors found in a replicated variety trial that 'Chisel Jersey' had much higher average FC than 'Binet Rouge'. Otherwise, relative cultivar differences in FC agreed with those authors. The high relative tannin content of 'Binet Rouge' compared to 'Michelin' and 'Brown Snout' also agrees with Plotkowski et al. (2021), though these authors reported much lower tannin content in 'Dabinett' compared to the latter two cultivars in a replicated variety trial, disagreeing with our findings. The other cultivars in this study were not examined by Plotkowski et al. The high tannin content of 'Chisel Jersey' compared to 'Geneva Tremlett's Bitter' also concurs with Miles et al. (2017), though those authors did not analyze juice from the other five cultivars in our experiment.

Cumulative tannin yield

Increased fruit yields and improved tannin content achieved through thinning would result in increased in overall tannin yield per tree by the fourth year. Though the underlying assumptions are conservative and based on measured data from previous years, it is important to keep in mind that these projections are just that: projections. Ideally a study of crop load management, and its effect on bearing patterns, cumulative yields, and juice quality, would span at least four growing seasons: two "on" and two "off" years. Future longer-term research, using these cultivars and other high-tannin cider cultivars, is needed.

Soluble Solids Concentration

It is important to distinguish between higher SSC due to advanced maturity, and higher overall SSC if fruits were analyzed at peak maturity. The different correlations of SSC and SPI to crop density indicate that reduced SSC at high crop loads is not attributable to delayed ripeness, but rather that, even if all fruits were pressed and analyzed at peak maturity, SSC would correlate negatively with crop density. In 'Geneva Tremlett's Bitter' in particular, the positive linear correlation between SPI and crop density directly opposes the negative logarithmic correlation between SSC and crop density.

Primary Amino Nitrogen

Our finding that juice nitrogen content correlated negatively with crop load agrees with Peck et al. (2016), Karl et al. (2020a), and Guillermin et al. (2015). Given that cell division is a highly nitrogen-intensive physiological process, it should not be surprising that reducing the number of fruitlets during the cell division phase of fruit growth would correspond with higher extractable nitrogen content in fruit juice.

The differences in PAN content among cultivars partly conflict with the findings of Valois et al. (2006). The latter authors reported juice chemistry data from a study of the USDA *Malus* germplasm collection, though only from single specimen trees, without uniform crop load. Five of the cultivars in this experiment were among the many reported by those authors (excerpted in Table 3-3). 'Brown Snout', 'Chisel Jersey', and 'Geneva Tremlett's Bitter' all had high YAN and comparable to each other, while 'Dabinett' and 'Michelin' had much lower YAN. The comparatively higher YAN of 'Geneva Tremlett's Bitter' compared to 'Dabinett' agrees with our findings.

Table 3-3. Yeast assimilable nitrogen data of five cultivars at the *Malus* germplasm collection in Geneva, NY, excerpted from Valois et al. (2006)

Cultivar	YAN (mg N/L)	
	2002	2003
Brown Snout	94 ± 19	
Chisel Jersey	90 ± 14	
Dabinette [sic]	13.3 ± 1.9	45 ± 20
Michelin	58.2 ± 9.0	20.3 ± 1.9
[Geneva] Tremlett's Bitter	95.6 ± 1.8	75 ± 18

Nitrogen Supplement Costs

The reduced three-year costs of nitrogen supplements alone did not compensate for the increased costs associated with PGR spray. Nor did these reduced costs, when considered alongside the three-year revenues and reduced harvest costs discussed in Chapter 2, bring about a positive change in profitability over three years. Though it is likely that PAN would be high in a low-crop load fourth year based on 2017 data, and though bloom on thinned trees in 2019 would likely have led to increased revenue from greater yields, we cannot conclude that improved PAN due to thinning has a net positive effect on profitability.

Acidity

The effect of crop density on TA was statistically significant but not meaningful in 'Binet Rouge', 'Brown Snout', 'Chisel Jersey', and 'Michelin' (Figure 3-2). TA and pH were similarly low in 'Dabinett' and 'Harry Masters Jersey' and did not correlate with crop density in those cultivars anyway. Variation in acidity among apple genotypes is primarily controlled genetically (Krishna Kumar et al., 2021; Xu et al., 2012), and only 'Geneva Tremlett's Bitter' has congenitally high enough TA for sensory significance, and low enough pH to be meaningful in terms of microbial stability. 'Geneva Tremlett's Bitter' also exhibited the strongest correlation of crop density to TA and pH, and the only meaningful vis a vis flavor or microbial stability.

The positive correlation between SPI and crop density in 'Geneva Tremlett's Bitter', combined with the negative relationship between TA and crop density, indicates that lower TA may in part be an artifact of advanced maturity. However, SPI was high in 'Geneva Tremlett's Bitter' overall, so differences in TA, at least in this cultivar are attributable to some effect of crop load, with the maturity effect contributing only marginally.

3.5 Conclusion

Crop load had a significant effect on all maturity and juice quality variables. Reduced polyphenol and soluble solid concentration at higher crop loads were not attributable to dilution but represented a true reduction in overall yield of polyphenols and sugars per tree. Crop load effects on maturity did not explain differences in TA, pH, or SSC among treatments. Nutrient competition among developing fruitlets, resulting in diversion of nutrients to cell wall rather than to sugar/starch accumulation and polyphenol synthesis, persisting until harvest, is suggested by our findings. Though cumulative tannin yield per tree was improved by thinning, there is currently no way to quantify that benefit economically. Partial budget analysis of PAN content found that although improved PAN on thinned trees would reduce nitrogen supplement costs, these reduced costs alone would not justify the expense of chemical thinning, let alone hand thinning. It is necessary to identify a “sweet spot” where thinning results in improved juice quality without yield losses due to over-thinning. Our data suggest that 9 fruit/cm^2 TCSA may be appropriate.

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Chapter 4: Exogenous 1-Naphthaleneacetic Acid and Ethephon Do Not Promote Return Bloom for Reducing Biennial Bearing in High-Tannin Cider Apple Trees

Abstract

Biennial bearing in high-tannin cider apples *(Malus ×domestica Borkh.)* is a longstanding supply chain issue for cidermakers in North America where supply is small. Crop load management and plant growth regulator (PGR) applications are two common strategies used to promote return bloom and regular bearing. Two experiments investigated the efficacy of 1-naphthaleneacetic acid (NAA) and ethephon applications to promote return bloom in cider apple trees, and the effects thereof on yield, one over three years at a commercial orchard in Lyndonville, NY, and the other over two years at a research orchard in Lansing, NY. The latter also assessed PGR and crop load effects on fruit maturity and juice quality. The three-year experiment at LynOaken Farms compared hand-thinning to PGR sprays, while the two-year experiment in Lansing, NY compared the effects of hand-thinning, PGR sprays, and a combination of the two imposed on different trees in each year. In the three-year study at the commercial farm, bloom and yields, for all seven cultivars, followed a highly "biennial" pattern in the unsprayed control and PGR treatments, while bloom and yields were more consistent for the hand-thinned treatment. None of the PGR treatments increased return bloom in any year compared to the control, while hand-thinning promoted return bloom following both high-crop "on" years (2016 and 2018) in all cultivars. No treatment had significantly different return bloom from the control following the "off" year (2017). Hand thinning to 6 fruit/cm^2 reduced three-year biennial bearing index (BBI) in all seven cultivars, but also reduced three-year cumulative yield (kg/tree) compared to control and spray treatments. Cumulative yield and BBI were not significantly different among spray treatments and the control for any cultivar. In the two-year experiment at the research orchard in

Lansing, NY, neither hand thinning, Eth+NAA sprays, nor a combination of the two had increased return bloom relative to the control. Thin-only and thin+spray treatments had reduced yield per tree compared to control and spray-only treatments in both years. Spray-only and thin+spray treatments had reduced pre-harvest drop in ‘Chisel Jersey’ compared to control, while drop was equivalent and low for all treatments and the control in ‘Brown Snout’. The non-efficacy of hand thinning and PGR sprays over a single season may be attributable to extreme long-term biennial tendencies in this orchard, which had little to no crop load management in the years preceding this experiment. Further study is needed to identify ideal crop load and application rates for bloom-promoting PGRs for these and other cider cultivars. A crop load of 9 fruit/cm^2 may be more appropriate for cider cultivars, though further long-term study is needed.

4.1 Introduction

The influence of seeded fruits, and particularly seed-derived phytohormones, primarily gibberellic acids (GAs) on return bloom in apples is well established and has been discussed at length in several review articles (Dennis and Neilsen, 1999; Green, 1987; Hoad, 1978; Wood, 1979). In particular, GA_1, GA_3, and GA_7 are considered the main inhibitors of return bloom in apples (Dennis and Neilsen, 1999; Hoad, 1978). The “biennial” or “alternate” bearing patterns mediated in large part by seed-derived GAs, though also by other bloom-suppressing and -promoting phytohormones and the putative ‘florigen’ (FT) protein, is a major horticultural, logistical, and supply-chain challenge to growers (Pashow, 2018). Strategies to manage crop load and mitigate alternate bearing, particularly in high-tannin cider cultivars which are often genetically prone to alternate bearing, are needed (Bradshaw et al., 2020; Hoad, 1978; Merwin, 2015; Miles et al., 2017; Wood, 1979).

Manipulation of fruit set through flower and early-season fruitlet thinning, whether by hand or by chemical means, are not the only methods by which a grower can reduce or counteract the bloom-inhibiting effects of seed-derived GAs. Plant growth regulators (PGRs) have been routinely applied to apple trees in commercial orchards in midsummer to promote or suppress return bloom, for decades (McArtney et al., 2007; Robinson et al., 2010; Schmidt et al., 2009; Wood, 1979). In apple cultivars with a strong tendency for biennial bearing, these flowering and bearing patterns can be moderated through post-thinning PGR applications in two ways: (1) by applying bloom-promoting compounds such as synthetic auxins or ethylene in the "on" year to counteract the suppressive effects of high crop load on return bloom, and (2) by applying bloom-suppressing compounds such as exogenous GAs in the "off" year to prevent excessive return bloom (McArtney et al., 2007). This review will focus on the use of synthetic auxins such as 1-napthaleneacetic acid (NAA), and ethylene (in the form of the liquid product "ethephon") to promote return bloom.

The interaction between crop load and summertime PGR applications is imperfectly understood, and depends on a number of factors: cultivar, long-term bearing history of a given tree, current-year crop load, and timing and rate of application, among others. Excessive crop load can reduce or negate the efficacy of bloom-promoting PGRs, while low or no crop load does not necessarily make bloom-promoting PGRs more effective (McArtney et al., 2007; Schmidt et al., 2009).

Crop load is widely understood to correlate negatively with various juice quality measures, such as soluble solid concentration (Alegre et al., 2012; Awad et al., 2001b; Guillermin et al., 2015; Musacchi, 2018; Stopar et al., 2002) and titratable acidity (Henriod et al., 2011; Peck et al., 2016). The effect of crop load on polyphenol concentration is less well-studied, particularly in high-tannin cider cultivars. Guillermin et al. (2015) found crop load to have a negative effect on polyphenol content in cider cultivars ‘Douce Coëtligné’ and ‘Douce Moën’. Karl et al. (2020a) reported higher overall polyphenol concentration in the lower-crop first year of their experiment than in the higher-crop second year.

The ripeness-advancing effects of both ethephon and NAA is well-known (Cline, 2019; Singh et al., 2008; Stover et al., 2003; Wendt et al., 2020). Ethephon promotes pre-harvest fruit drop (Singh et al., 2008; Stover et al., 2003), while the opposite is the case for NAA (Cline, 2019; Dal Cin et al., 2008; Stover et al., 2003). The effect, if any, of PGR sprays on polyphenol concentration in cider apples has been under-explored. Polyphenol synthesis is thought to take place early in the growing season, within the first 40 or so DAFB (Renard et al., 2007), making it difficult to speculate what effect, if any, midsummer PGR applications may have on polyphenol concentration at harvest.

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

4.2 Materials and Methods

4.2.1 Experiment at LynOaken Farms

Experimental Design

In June 2016, an experiment was initiated to investigate the effectiveness of different PGR spray combinations at promoting return bloom in seven high-tannin European cider cultivars. This experiment was carried out at LynOaken Farms, a commercial orchard in Lyndonville, NY. The cultivars were: 'Binet Rouge', 'Brown Snout', 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', 'Michelin', and 'Geneva Tremlett's Bitter'[§§]. All trees were grafted on 'Budagovsky 9' ('B.9') rootstock and planted in 1.2 m × 3.7 m (4' × 12') or ~2,220 trees/hectare (900 trees/acre) in a tall-spindle training system with a single high trellis wire and a conduit on each tree. Conventional disease, insect, and weed control was used throughout the orchard. There was no irrigation. The planting is located at (43.324, -78.373), on a Galen very fine sandy loam. LynOaken Farms is a commercial orchard located near the shores of Lake Ontario in Western New York.

The experiment was set up in a randomized complete block design. Five trees of each cultivar were randomly assigned to a given treatment group, for a total of 5 treatments × 5 blocks = 25 trees per cultivar. The same treatments were applied to the same trees for three consecutive years, blocked by location within the orchard. Trees were visually assessed to have similar fruit set before treatments were implemented. Each tree had a buffer tree on either side, with buffer trees not overlapping, so that two buffer trees separated each experimental tree from the next. Treatments were as follows:

[§§] This is a bittersharp cultivar of unknown provenance being planted by in the US by cider apple growers, despite not being the true-to-type bittersweet cultivar 'Tremlett's Bitter' from the UK.

1. Hand thinning to 6 fruit/cm^2 TCSA
2. Non-thin control
3. Four applications of 5 $mg \cdot L^{-1}$ NAA
4. One application of 150 mg/L Eth followed by three applications of 5 mg/L NAA
5. Two applications of 150 mg/L Eth followed by two applications of 5 mg/L NAA

Full bloom dates (Table A4-1, Appendix), and thus DAFB for hand-thinning (Table A4-2, Appendix) and PGR treatments (Table A4-3, Appendix) differed slightly among cultivars and years due to weather and time constraints.

Return Bloom

Blossom clusters were counting using a tally counter at the "pink" stage in May 2017 and 2019. In Spring 2018 fruitlet clusters were counted in late June on the day of hand-thinning (Table A4-2, Appendix).

Trunk Measurement

Tree trunk diameter was measured 40 cm above the graft union in autumn or winter of 2016, 2017, and 2018, after growth had ceased for the season, and before bud swell had begun the following year. Trunk cross-sectional area (TCSA) was calculated using the formula for the surface area of a circle.

Harvest

Pre-harvest maturity was assessed for each variety using fruit from non-experimental trees via the starch pattern index (SPI) assay to determine appropriate harvest dates. For cultivars with strong tendencies to pre-harvest drop, such as 'Harry Master's Jersey', fruit was harvested before horticultural maturity for cider production (> 6 SPI) (Table A4-4, Appendix). Pre-harvest fruit drops were counted and removed before the fruit remaining on trees was picked. Pre-harvest drops were counted within the midpoints between an experimental tree and its neighbors on either side. All fruits harvested from trees were counted and weighed in the field.

Calculation of Biennial Bearing Index

Biennial bearing indices (BBI) were calculated using **Error! Reference source not found.** b elow, adapted from Hoblyn et al. (1937). BBI is a measure of variation in yield among consecutive year pairs. A value of 0 indicates completely consistent yields from year to year; while a value of 1 indicates that in one year there was a complete absence of fruit borne on the tree. BBI was calculated on both yield (kg) and yield efficiency (kg/cm^2 TCSA) bases. BBI by yield efficiency was chosen because trees were young and still growing rapidly; and BBI by yield was chosen because fruit mass is more important for cider production than the number of individual fruit.

Equation 4-1. Biennial bearing index

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

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

Projected Yield at LynOaken Farms, 2019

Yields for 2019 were estimated assuming that each bloom cluster counted that spring would set one fruit. Given the lack of a significant PGR effect on crop load or yield in the first three years, it is reasonable to assume there would not be an effect in the fourth year either at the rates applied.

4.2.2 Experiment at Cornell Orchard

Experimental Design

An experiment was carried out at one of Cornell University’s research orchards in Lansing, NY to investigate the efficacy of hand-thinning and PGR sprays in two high-tannin cider cultivars, ‘Binet Rouge’ and ‘Chisel Jersey’. The planting, located at (42.57004°, -76.59507°), was established in 2003, and is located on a hillside leading down to Lake Cayuga, on a Hudson Cayuga silt loam of 12-20 percent slope. Cultivars are grafted onto several different rootstocks. 'Chisel Jersey' and 'Brown Snout' trees on 'G.16', 'G.30', and 'M.9' were chosen. Trees were assigned to one of four treatments:

Table 3-1. Treatments, Cornell Orchard experiment, 2016-2017.

Treatment	Hand-thinned to 1 fruitlet per cluster	PGR Sprays
1	Yes	No
2	Yes	Yes
3	No	No
4	No	Yes

All trees within a given experimental block had the same rootstock. In 2016, sixteen 'Chisel Jersey'/'M.9' and eight 'Chisel Jersey'/'G.30' trees were used, with six trees assigned to each treatment. In 2017, a different set of twenty-four 'Chisel Jersey' trees, and sixteen 'Brown Snout' trees, were used, with six and four trees assigned to each treatment group, respectively. Treatments were assigned randomly. Spray treatments (2 and 4) were as follows:

Table 3-2. PGR spray formulations, Cornell Orchard experiment, 2016-2017.

Year	Spray 1	Spray 2	Spray 3	Spray 4
2016	150 mg/L Ethephon	5 mg/L NAA	5 mg/L NAA	—
2017	150 mg/L Ethephon	5 mg/L NAA	5 mg/L NAA	5 mg/L NAA

After assessing return bloom from the first year of the experiment, a fourth spray was added in 2017 to determine if an additional PGR application might have a positive effect on return bloom. Sprays were applied from a Solo MistBlower backpack sprayer. Hand thinning and first sprays were applied approximately 5 weeks after full bloom in both years, with subsequent sprays approximately two weeks apart (dates and DAFB shown in Table A4-5, Appendix).

Tree Selection

Trees were visually assessed for bloom and assigned a rating of 1-100 in Spring 2016 and 2017, around the time of full bloom, with 100 being visually equivalent to the bloom density of the highest-bloom tree in the planting. Trees deemed to have sufficient bloom were selected for this experiment. Subsequently, several branches from each tree were quantitatively assessed for initial fruit set, and branch fruit set was used as a proxy for whole-tree fruit set. Treatments were randomly assigned, with blocking by fruit set.

Harvest

Harvest dates (Table A4-5, Appendix) were chosen based on previous years' harvest dates for the Lansing Orchard, and on harvest date recommendations in literature (Table 4-15). Pre-harvest drops were counted and removed from under experimental trees on three dates before harvest in 2016, and on four dates before harvest in 2017. Pre-harvest drops were also counted and removed on the day of harvest prior to picking fruit remaining on trees. In 2016 all fruit harvested on tree were counted and weighed using an Adam CPW 75 scale (Oxford, CT, USA); average fruit weight was calculated by dividing harvest weight by harvest count. In 2017, crop was so great that counting on-tree fruit in a timely manner was not feasible; the first 100 fruit harvested were counted and weighed, and then the remaining on-tree fruit were weighed without counting. Total on-tree fruit count was estimated by dividing total on-tree harvest weight by the average weight of subsets. Total tree yield weight in 2016 was estimated by multiplying average fruit weight by the total number of drops and on-tree fruits. In 2017, total tree yield weight was estimated by multiplying average fruit weight by total drop count and adding this number to the total weight of fruit harvested on-tree.

Return Bloom

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

Trunk Measurement

Trunk circumference of experimental trees was measured at 30 cm above the graft union and converted to TCSA using the formula for area of a circle.

External Fruit Analysis

Subsets of ten tree-harvested fruit per tree were randomly sampled and taken back to Cornell University for analysis. Subsets were refrigerated at 4 °C for no more than three days until it was possible to analyze fruit maturity. Fruits were first weighed, and then visually assessed for whole-fruit peel background color or percent blush. Cultivars with a predominantly green-to-yellow background peel color were scored on a 1-5 scale where 1=yellow and 5=dark green (Evans et al., 2012). Percent surface area covered by red blush was visually estimated from 0-100% for cultivars with red peel. Chlorophyll degradation was assessed using a Sintelela DA (Delta Absorbance) meter (Bologna, Italy). Two readings with the DA meter were taken, one on the blushed side of each fruit, and one on the non-blushed side.

Internal Fruit Analysis

Subset fruits were then assessed for flesh firmness in Newtons (N) using a Lake City Techical Products EPT-1-R penetrometer (Kelowna, BC, Canada). Peel was removed at two opposite locations at the equator of each apple and then probed once at each location. Subsequent to penetration, starch pattern index (SPI) was determined by removing equatorial wedges 5-10 mm thick and wetting with a (0.22% w/v iodine, 0.88% w/v potassium iodide) solution (Blanpied and Silsby, 1992).

Juice Extraction

The remaining fruit was diced and then ground on 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 became discontinuous. Juice samples were aliquoted into 50-mL, 15-mL, and 1.5-mL vials; 1.5-mL vials were frozen at -80 °C, and 15-mL and 50-mL vials were frozen at -20 °C.

Juice Chemistry

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

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

4.2.3 Statistical Analysis

All statistical analysis was conducted in R (R Core Team, 2014). For the LynOaken Farms experiment, treatment averages were compared against the non-thinned control using Dunnett's Test (Dunnett and Tamhane, 1992), performed via the 'DunnettTest' function in the *DescTools* package in R (Signorelli, 2021). All regressions for the Cornell Orchards experiment were analyzed as mixed models with a random block term, using the *lmer* function from the *lme4* package (Bates et al., 2021). For the Cornell Orchards experiment, 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) at 0.05 significance (Hothorn et al., 2021).

4.3 Results

Return Bloom

Hand-thinned treatment at LynOaken Farms had the greatest return bloom following both high crop "on" years, 2016 and 2018, for all cultivars (Table A4-7, Appendix). No treatment had significantly different return fruit set from the control in June 2018 (following the "off" year, 2017). Cultivars 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', and 'Michelin' had some return bloom in spring 2017 (following the "on" year in 2016) regardless of treatment, while cultivars 'Brown Snout', 'Binet Rouge', and 'Geneva Tremlett's Bitter' had little to no return bloom in spring 2017 unless hand-thinned the previous year. Nevertheless, return bloom in spring 2017 for the four former cultivars was low (0.9-8.6 clusters/cm^2 TCSA) except for hand-thinned treatment. In spring 2019 (following the second "on" year, 2018) 'Harry Masters Jersey' was the only cultivar which had substantial return bloom (>3 clusters/cm^2 TCSA) regardless of treatment. All other cultivars had low return bloom in spring 2019 unless hand-thinned the previous year. Return bloom generally had a significant negative correlation with the previous autumn's crop density (data not shown).

For the Cornell Orchard experiment, crop density in 2016 had a significant ($p=0.026$) negative effect on return bloom for 'Chisel Jersey', but 2017 crop density had no significant effect on return bloom for either 'Brown Snout' or 'Chisel Jersey' ($p=0.063$ and $p=0.218$, respectively). Spray had a horticulturally unimportant positive effect ($p=0.016$) on return bloom for 'Brown Snout' in 2017. Return bloom and return fruit set was greater overall for 'Chisel Jersey' than for 'Brown Snout' (Table 4-5).

Yield, Cornell Orchard

Midsummer PGR application did not negatively affect crop density in either year. For 'Chisel Jersey' in 2016, spray-only trees had significantly greater crop density than no-thin control trees. Thin and thin+spray treatments both had lower crop density than spray-only and control trees in both years, though differences were not significant for 'Chisel Jersey' in 2017. Differences between the two thinning treatments and the control were not significant for 'Chisel Jersey' in 2017. Crop density was lower overall for 'Chisel Jersey', yet yield weight per tree was often greater, compared with 'Brown Snout'.

Table 4-1. Average fruit yield per tree from a hand-thinning and plant-growth regulator (PGR) experiment at the Cornell University research orchard in Lansing, NY

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

Table 4-2. Average crop density per tree from a hand-thinning and plant-growth regulator (PGR) experiment at the Cornell University research orchard in Lansing, NY

	Crop Density (fruit/cm^2 TCSA)		
Treatment	Chisel Jersey, 2016	Chisel Jersey, 2017	Brown Snout, 2017
Thin only	6.7 b	3.0	11.6 b
Thin + PGR	6.6 b	3.8	9.6 b
Control	12.3 ab	8.8	26.7 a
PGR Only	19.5 a	1.7	24.9 a
Thinning	p<0.001	p=0.308	p<0.001
Spray	p=0.080	p=0.097	p=0.449
Thinning:Spray	p=0.064	p=0.056	p=0.984

Cumulative Yield 2016-2018, LynOaken Farms

All seven cultivars had significantly ($p<0.05$) lower cumulative yield over three years when hand-thinned to 6 fruit/cm^2 TCSA than if left un-thinned (Table 4-3). Spray treatments did not have significantly different cumulative yield from the control over three years. ‘Chisel Jersey’, ‘Dabinett’, and ‘Harry Masters Jersey’ were the most productive, with ‘Binet Rouge’ and ‘Michelin’ being moderately productive, and ‘Brown Snout’ and ‘Geneva Tremlett’s Bitter’ being unproductive.

2019 Projected Yield, LynOaken Farms

Under our assumptions about average fruit weight and fruit set, un-thinned and sprayed treatments in all seven cultivars would still have higher four-year cumulative yields than hand-thin treatment (Table 4-7). With the exception of ‘Harry Masters Jersey’, only hand-thinned trees had significant return bloom in 2019 (Table A4-7, Appendix). Even when hand-thinned for three years, ‘Binet Rouge’ and ‘Brown Snout’ trees did not always have sufficient bloom in 2019 to achieve the same crop load (6 fruit/cm^2) for a fourth year, while the other cultivars did (Table A4-6, Appendix). The non-thinned control and spray treatments mostly had little return bloom (<2 clusters/cm^2 TCSA) in 2019, and thus would have had little to no crop in 2019, an “off” year for the entire planting.

Bearing Habit, LynOaken Farms

Of the seven cultivars used in this experiment, ‘Chisel Jersey’, ‘Dabinett’, and ‘Harry Masters Jersey’ bore fruit fairly regularly (BBI was relatively low) when left un-thinned and unsprayed; ‘Binet Rouge’, ‘Brown Snout’, ‘Michelin’, and ‘Geneva Tremlett’s Bitter’, were nearly or entirely biennial (BBI of ~1.00, Table A4-8, Appendix). ‘Michelin’ was somewhat less biennial than ‘Binet Rouge’, ‘Brown Snout’, or ‘Geneva Tremlett’s Bitter’ when sprayed with any of the three PGR treatments.

Table 4-3. Three-year cumulative yields per tree of seven cultivars from a three-year plant-growth regulator (PGR) experiment at LynOaken Farms. Ethephon (Eth), 1-Napthaleneacetic acid (NAA). Significance indicated by asterisk: * at p<0.05, ** at p<0.01, *** at p<0.001

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

Table 4-4. Biennial bearing index (BBI), yield weight basis, for seven cultivars from a three-year plant-growth regulator (PGR) experiment at LynOaken Farms. Eth=ethephon, NAA=1-Napthaleneacetic acid. Significance indicated by asterisk: * at p<0.05, ** at p<0.01, *** at p<0.001

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

Table 4-5. Return bloom of trees at the Cornell University research orchard in Lansing, NY following Year 1 (2016), and return fruit set following Year 2 (2017) of a hand-thinning and plant-growth regulator (PGR) experiment.

	Spring 2017 Bloom Density (clusters /cm^2)	Spring 2018 Fruitlet Density (clusters/cm^2)	
Treatment	Chisel Jersey, 2016	Chisel Jersey, 2017	Brown Snout, 2017
Thin only	2.67	4.89	0.01
Thin + PGR	2.45	5.98	0.12
Control	2.70	4.90	0.00
PGR Only	0.43	8.52	0.00
Crop Density	p=0.026	p=0.218	p=0.063
Spray	p=0.498	p=0.177	p=0.016
Crop Density:Spray	p=0.783	p=0.252	p=0.105

Table 4-6. Projected yields per tree extrapolated from 2019 bloom cluster counts in a three-year plant-growth regulator (PGR) experiment at LynOaken Farms

	2019 projected yield per tree, kg						
Treatment	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
Control	0.03	7.88	0.11	0.00	10.99	0.00	0.00
Hand-thin (6 fruit/cm^2)	4.05	0.92	4.56	6.74	3.48	3.21	3.01
NAA, NAA, NAA, NAA	0.08	0.00	0.11	0.58	7.68	0.56	0.00
Eth, NAA, NAA, NAA	0.06	0.02	2.21	0.72	10.73	0.94	0.00
Eth, Eth, NAA, NAA	0.71	2.60	1.03	0.07	9.76	0.01	0.00

Table 4-7. Project cumulative four-year yields per tree extrapolated from 2019 bloom cluster counts in a three-year plant-growth regulator (PGR) experiment at LynOaken Farms

	Projected four-year cumulative yield per tree, kg						
Treatment	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
Control	17.4	19.4	24.2	30.9	32.1	18.0	14.6
Hand-thin (6 fruit/cm^2)	15.6	7.0	22.1	24.0	17.0	14.1	11.9
NAA, NAA, NAA, NAA	17.7	14.5	24.5	20.2	24.8	19.7	10.2
Eth, NAA, NAA, NAA	18.3	12.6	29.6	24.2	33.9	20.8	12.3
Eth, Eth, NAA, NAA	18.3	16.8	30.2	36.5	33.7	16.2	14.9

TCSA

There was no difference in TCSA or TCSA growth among treatments for six of seven cultivars at LynOaken Farms. For 'Geneva Tremlett's Bitter', TCSA only differed among treatments at the end of the 2016 growing season. By 2017, differences disappeared (Table A4-11, Appendix). 'Chisel Jersey', 'Dabinett', and 'Michelin' had highest TCSA in all three years; 'Binet Rouge', 'Brown Snout', and 'Harry Masters Jersey' had lower TCSA in all three years, and 'Geneva Tremlett's Bitter' had lowest TCSA in all three years. TCSA growth (percent change) over 2017 was greatest for 'Dabinett', followed by 'Binet Rouge' and 'Brown Snout'. 'Chisel Jersey', 'Harry Masters Jersey', 'Michelin', and 'Geneva Tremlett's Bitter' had lowest TCSA growth over the 2017 growing season. Differences in TCSA growth among cultivars from Fall 2016 to Fall 2018 were not significant. There were no treatment differences in TCSA in the Cornell Orchard experiment (data not shown).

Pre-Harvest Drop

For the LynOaken Farms experiment, the hand-thinning treatment had differing effects on pre-harvest drop depending on cultivar and year. Thinned treatment had lower pre-harvest drop than control for 'Binet Rouge', 'Dabinett', and 'Geneva Tremlett's Bitter', but higher pre-harvest drop for 'Brown Snout', 'Chisel Jersey', and 'Michelin'. Drop was quite high for 'Harry Masters Jersey' though drop in this cultivar decreased as the number of NAA applications increased. NAA also significantly reduced drop for 'Binet Rouge' in 2017. Drop was greatest in 2017 for 'Chisel Jersey' and 'Dabinett', while for 'Harry Masters Jersey' drop was greatest in 2016. For 'Brown Snout' drop was greatest in 2018. 'Geneva Tremlett's Bitter' generally had low pre-harvest drop, while 'Harry Masters Jersey' and 'Michelin' generally had high pre-harvest drop.

For the Cornell Orchard experiment, pre-harvest drop was low overall in ‘Brown Snout’ but had a slight positive correlation with crop density (p=0.009). Drop in ‘Chisel Jersey’ was greater overall compared to ‘Brown Snout’, and in 2016, there was a significant negative spray effect (p=0.009) on drop. Pre-harvest drop in Chisel Jersey in 2017 was not significantly affected by either crop density or spray.

Table 4-8. Pre-harvest drop (% of total crop) from a hand-thinning and plant-growth regulator (PGR) experiment at the Cornell University research orchard in Lansing, NY

Treatment	Chisel Jersey, 2016	Chisel Jersey, 2017	Brown Snout, 2017
Thin only	55.8 a	19.0	48.3
Thin + PGR	28.0 b	12.7	26.4
Control	45.7 ab	27.2	74.0
PGR Only	21.0 b	27.1	47.2
Crop Density	p=0.124	p=0.418	p=0.009
Spray	p=0.009	p=0.479	p=0.148
Crop Density:Spray	p=0.362	p=0.567	p=0.176

Maturity, Ripeness, and Juice Chemistry, Cornell Orchard

Neither crop density nor spray affected SPI for ‘Chisel Jersey’ in either year, while in ‘Brown Snout’, there were significant positive crop density and spray effects on SPI (p<0.001 and p=0.005, respectively), as well as a significant (p<0.001) positive crop density-spray interaction (Table 4-9). Juice pH was high and TA was low regardless of treatment and year for both cultivars (Table 4-10). Crop density had a significant (p=0.007), but practically meaningless negative effect on TA for ‘Chisel Jersey’ in 2016. Crop density had no correlation with pH. Crop density had a significant negative effect on SSC for ‘Chisel Jersey’ in 2016 (p=0.01) but had no significant effect on SSC in ‘Brown Snout’. Likewise, crop density correlated negatively with FC for ‘Chisel Jersey’ in both years but had no effect on FC in ‘Brown Snout’. Sprays had no effect on juice chemistry.

Table 4-9. Average starch pattern index (SPI) of fruit subsets from a hand-thinning and plant-growth regulator (PGR) experiment at the Cornell University research orchard in Lansing, NY

Treatment	Chisel Jersey, 2016	Chisel Jersey, 2017	Brown Snout, 2017
Thin only	3.9 b	6.9	4.1 c
Thin + PGR	3.9 b	5.6	3.3 c
Control	4.7 a	4.8	5.0 b
PGR Only	4.2 ab	5.4	7.0 a
Crop Density	p=0.890	p=0.968	p<0.001
Spray	p=0.351	p=0.892	p=0.005
Crop Density:Spray	p=0.546	p=0.865	p<0.001

Table 4-10. Juice quality measures from a hand-thinning and plant-growth regulator (PGR) experiment at the Cornell University research orchard in Lansing, NY. Significance of crop density and PGR effects indicated by p-values. Significant values (p<0.05) indicated in bold.

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

4.4 Discussion

Return Bloom, LynOaken Farms

None of the spray applications succeeded in promoting return bloom compared to the control following either "on" year (2016 or 2018). Conversely, hand thinning promoted return bloom following the two "on" years. The lack of any significant hand-thinning effect on return bloom following 2017, the "off" year for the whole planting, may in part be attributable to the later timing of hand-thinning in 2017 (Table A4-2, Appendix). Even in the total absence of fruit in the cultivars 'Brown Snout' and 'Geneva Tremlett's Bitter' in 2017, no combination of NAA or Eth had any additional promoting effect on return bloom. This finding agrees with that of Schmidt et al. (2009), who reported in a planting with a history of severe alternate bearing tendencies, that no concentration of ethephon (300, 600, or 900 mg/L) in combination with total de-fruiting substantially increased return bloom, compared to total de-fruiting alone, in 'Cameo' on either 'B.9' or 'M.9' rootstocks. By contrast, return bloom on 'Cameo'/'B.9' trees with 50% of fruit removed in spring increased as ethephon concentration increased, compared to trees with 50% of fruit removed but no ethephon treatment.

Our findings, together with those of Schmidt et al. (2009), strongly suggest that the total absence of fruit is so dis-inhibitory to return bloom that use of ethephon for other purposes on trees with no crop does not risk exacerbating alternate flowering tendencies. Typically GAs or other return bloom-inhibiting PGRs, rather than bloom-promoting ethephon, would be applied in the "off" year in a highly biennial planting to prevent excessive "snowball" bloom in the following "on" year.

Our finding that 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', and 'Michelin' had substantial return bloom following the first "on" year, 2016, agrees with previous descriptions of these cultivars as being “annual” or “less biennial” than other English and French cider cultivars (Copas, 2013, 2001; Green, 1987; Merwin, 2015; Wood, 1979). Likewise, the absence of return bloom in ‘Brown Snout’, ‘Binet Rouge’, and ‘Geneva Tremlett’s Bitter’ following the first “on” year agrees with previous descriptions of these cultivars as “biennial” (Merwin, 2015). The fact that only ‘Harry Masters Jersey’ had substantial return bloom in spring 2019, following the second “on” year 2018, is likely attributable both to this cultivar’s “annual” tendencies, and to the relatively low crop load borne by ‘Harry Masters Jersey’ in 2018 compared to the other three more “annual” cultivars (Table A4-9, Appendix), which had been much more resistant to bloom inhibition following the previous “on” year, 2016. Crop density and yield efficiency were highest across treatments and cultivars in 2018, the final year of the experiment, when trees first entered “full production”; this higher overall productivity in 2018 compared to 2016 likely explains lower return bloom in ‘Chisel Jersey’, ‘Dabinett’, and ‘Michelin’ which had been resistant to return bloom inhibition by crop load in 2016.

As the number of acres planted with European cider varieties increases, the need for strategies to counteract these varieties’ biennial bearing tendencies is becoming more critical (Bradshaw et al., 2020; Miles et al., 2020; Peck et al., 2021). Greater understanding of the interaction between crop load and the efficacy of PGR applications, which is needed for these cultivars, cannot be derived from our findings in the LynOaken Farms experiment, as we did not manipulate crop load on any of the spray treatment trees.

Return Bloom, Cornell Orchard

The lack of a significant relationship between crop density and return bloom in ‘Brown Snout’ may be an artifact of the relatively high range of crop densities, and very low range of return crop the following spring, observed for ‘Brown Snout’ in this experiment. Crop densities observed in ‘Brown Snout’ for each treatment in 2017 were greater than those observed in ‘Chisel Jersey’ for either year. ‘Brown Snout’ in this experiment also had higher average crop density than any thinning treatment (0, 3, 6, or 9 fruit/cm^2) in the hand-thinning experiment at LynOaken Farms (Chapter 2) or the 6 fruit/cm^2 crop load imposed in the three-year PGR experiment at LynOaken Farms (present chapter). In Chapter 2, it was found that ‘Brown Snout’ would not produce any return bloom at a crop density greater than ~24 fruit/cm^2. Thus, the lack of significant non-zero return crop for ‘Brown Snout’ in this experiment is explainable: overall crop load in 2017 was likely too great for hand-thinning, PGR sprays, or a combination thereof, to have any significant effect on return bloom or return crop.

Our finding that the suppressive effect of crop load overwhelmed any return bloom-promoting effect of NAA or ethephon agrees with that of Schmidt et al. (2009), who reported that crop load “was the primary determinant of return bloom”, and that ethephon was effective at promoting return bloom only when initial crop load was reduced by 50%. Those authors also reported that when trees were either un-thinned or had all fruitlets removed, ethephon had no significant effect on return bloom in ‘Cameo’ and the notoriously biennial cultivar ‘Honeycrisp’. Other authors have noted variable results in promoting flowering through crop load management and PGRs. For example, Robinson et al. (2010) found in one experiment that chemical thinning alone was not effective at promoting return bloom in ‘Honeycrisp’, but that chemical thinning in combination with midsummer NAA or ethephon application was effective. In a subsequent experiment, these authors found that thinning at the 10 mm fruitlet stage alone was effective at promoting return bloom, while summer applications of NAA in combination with thinning had no additional effect on return bloom. Likewise, in a third experiment, three midsummer applications of 5 mg/L NAA had no effect on return bloom in ‘Honeycrisp’ at any crop load from 0 to 20 fruit/cm^2 TCSA.

Wood (1979) found in French cider cultivar ‘Reine des Hatives’, that triiodobenzoic acid (TIBA), an inhibitor of polar auxin and GA transport, was not very effective in the ‘on’ year at counteracting GA-mediated inhibition of flower bud initiation when used alone, but that in combination with chemical thinning using NAA, TIBA was highly effective at promoting return bloom. Though TIBA operates via a different mechanism from either NAA or ethephon, Wood’s findings are nonetheless another example of crop load overwhelming the bloom-promoting effect of PGRs in highly biennial cider cultivars. Even with chemical thinning alone, Wood reported, “Virtually no flower initiation occurred…until [fruit] set was reduced to about 50 to 60 fruits per 100 blossom clusters, or if cropping was much above 0.4 kg/cm^2.”

In contrast to ‘Brown Snout’, ‘Chisel Jersey’ was found in the hand-thinning experiment at LynOaken Farms (Chapter 2) to produce some return bloom up to ~32 fruit/cm^2, well above the range of crop densities observed for that cultivar in either year of the Cornell Orchard experiment (present chapter). This explains, at least partly, the much greater return bloom for ‘Chisel Jersey’ in both years of this experiment compared to ‘Brown Snout’, which had little to none. Though we do not have multiple years’ data from the same trees, and thus cannot calculate BBI for either cultivar in this experiment, we can infer that ‘Chisel Jersey’ was on a less extreme flowering and bearing pattern than ‘Brown Snout’. Considering that these trees were mature and that crop load had not been managed for several years, both cultivars might have settled into fairly “biennial” flowering patterns well before this experiment was begun, with ‘Brown Snout’ being much more extreme than ‘Chisel Jersey’.

Nonetheless, the difference in return bloom responses of these two cultivars to crop load and PGR applications agrees not only with our findings in the PGR study at LynOaken Farms (present chapter) and the hand-thinning experiment at LynOaken Farm (Chapter 2), but also with the descriptions of the "biennial" bearing habit of 'Brown Snout' by Wood (1979) and Merwin (2015), and the "annual" habit of 'Chisel Jersey' by Copas (2001). Thus, it is important to note that there is a very strong genetic control for the bearing habit of each cultivar and that different management strategies will need to be tailored towards those with lower versus higher biennial bearing tendencies.

Bearing Habit of Un-thinned Trees, LynOaken Farms

It is a useful but difficult exercise to compare findings in this experiment with other authors' descriptions of these cultivars' bearing habits because of the differences in regional observations and reporting metrics. 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey' had the lowest BBI when left un-thinned of the seven cultivars (0.65, 0.65, and 0.47, respectively) and had the highest cumulative yield (24.0, 30.9, and 21.1 kg/tree, respectively); Merwin (2015) described 'Chisel Jersey' as "biennial but productive", 'Dabinett' as "annual", and 'Harry Masters Jersey' as "annual and productive". 'Chisel Jersey' and 'Dabinett' had identical mean BBI when left un-thinned, disagreeing with the data reported by Wood (1979) and the descriptions of bearing habit by Merwin (2015). Wood (1979) reported that in a twelve-year trial, 'Chisel Jersey' had lower cumulative yield and higher BBI (282 kg/tree, 0.70, respectively) than 'Dabinett' (292 kg/tree, 0.52, respectively).

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

Our findings in the PGR experiment at LynOaken Farms also partially concur with our findings in the hand-thinning experiment (Chapter 2) conducted concurrently with this one at LynOaken Farms over the same period. In the hand-thinning experiment (Chapter 2), un-thinned 'Binet Rouge', 'Brown Snout', 'Michelin', and 'Geneva Tremlett's Bitter' all had very high BBI (1.00, 0.99, 0.95, and 1.00, respectively), and relatively low three-year cumulative yield (16.0, 14.1, 19.4, and 12.9 kg/tree, respectively). By comparison, un-thinned 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey' had lower BBI (0.49, 0.87, and 0.58, respectively) and higher cumulative yield of (36.8, 22.1, and 20.5 kg/tree, respectively). In the hand-thinning experiment (Chapter 2), un-thinned 'Chisel Jersey' had higher cumulative yield than 'Dabinett', while in this PGR experiment (present chapter), the opposite was the case. Un-thinned 'Dabinett' trees also had much higher BBI in the hand-thinning experiment than in the return bloom study reported here. The differences between the same treatments in these two concurrent experiments will be commented on below.

Comparing Experiments

The lack of any meaningful PGR effect on return bloom or bearing habit in either of the experiments described in this chapter should not be taken to show definitively that these seven cider cultivars are unresponsive to NAA or ethephon treatment, but rather that the timing and rates applied in these experiments may simply have been insufficient to overcome the suppressive effect of crop load on return bloom, even when crop load was reduced as in the Cornell Orchard experiment. The three-year experiment at LynOaken Farms only compared hand-thinning to one target crop load with PGR sprays but did not include a combination of both hand-thinning and midsummer PGR sprays. The experiment at the Cornell Orchard did not follow the same trees over multiple years.

Interaction of Scion Vigor and BBI, LynOaken Farms

'Geneva Tremlett's Bitter' was the least vigorous cultivar in the LynOaken experiment, matching Merwin's (2015) description of this cultivar as a "low-vigor spur-bearing type". 'Harry Masters Jersey' was moderately low-vigor in this study, likewise matching Merwin's description of that cultivar, though in a trial of ten cider cultivars at the Cornell Orchards in Ithaca, NY (Peck et al. 2021), I observed the highest percentage of shoot tip-bloom in 'Harry Masters Jersey' and the lowest percentage of tip-bloom in 'Geneva Tremlett's Bitter', with 'Binet Rouge', 'Brown Snout', 'Chisel Jersey', and 'Dabinett' being intermediate (Chapter 1). The combination of low-vigor rootstock 'B.9' with a low-vigor and strongly spur-type scion, namely 'Geneva Tremlett's Bitter', may explain the extreme biennial bearing observed in this cultivar, while a heavily tip-bearing cultivar, namely 'Harry Masters Jersey', on the same low-vigor rootstock may explain this cultivar's much lower overall BBI, as hypothesized by Barritt et al. (1997). However, neither my own observations of tip-bloom habit (Chapter 1) nor TCSA data from the PGR experiment at LynOaken Farms (present chapter) fully explains the low overall BBI of 'Chisel Jersey' and 'Dabinett' or the high BBI of un-thinned 'Binet Rouge', 'Brown Snout', or 'Michelin'.

PGR Sprays and Biennial Bearing Index, LynOaken Farms

Because so many trees had the maximum possible BBI value of 1.00, modeling a relationship between BBI and cumulative yield would often result in an estimate of infinite slope. It is thus difficult to characterize this relationship quantitatively. We can nonetheless say that higher BBI was associated with higher three-year cumulative yields in all seven cultivars. We can say further that none of the spray treatments had any significant effect on BBI or three-year cumulative yields. Though combinations of NAA and ethephon did slightly increase return bloom following the "on" years compared to the control, this difference was not statistically significant. Treatments containing ethephon did significantly increase 2017 yield weight compared to the control in 'Dabinett' and 'Michelin', but these differences did not translate into significantly lower three-year BBI or greater cumulative yield compared to the control in those cultivars. NAA or ethephon applications alone, at least at the rates used in this study, were not effective at counteracting the bloom-inhibiting effect of crop load.

Yield and Crop Density, Cornell Orchards

Despite 'Chisel Jersey' in both years having lower overall crop density than 'Brown Snout', the former cultivar frequently had equivalent or greater total yield mass per tree. This can be explained both by the innately larger average fruit size of 'Chisel Jersey' compared to 'Brown Snout' (Valois et al., 2006), and by the negative effect of crop density on fruit size generally (Awad et al., 2001b; Kelner et al., 1999; Robinson and Watkins, 2003; Stopar et al., 2002). We similarly found in the hand-thinning (Chapter 2) and PGR experiments (present chapter) at LynOaken Farms that increased crop density correlated with smaller average fruit size in all seven cultivars used in those experiments.

Cumulative Yield, LynOaken Farms

The differences in productivity among cultivars agree with findings by other authors and with non-quantitative descriptions of these cultivars. Czynczyk et al. (2008) found that in a study from 1998-2003, on multiple rootstocks, 'Chisel Jersey' and 'Dabinett' had the highest cumulative yields, with 'Harry Masters Jersey' somewhat lower, and 'Michelin' lower still. The low overall BBI for 'Chisel Jersey' agrees with the results reported by Miles et al. (2017), though the latter authors only reported data based on visual assessment of yield on thinned trees, not quantitative yield data on un-thinned trees. The low BBI in hand-thinned 'Geneva Tremlett's Bitter' (0.42) likewise agrees with Miles et al. (2017), while the extremely high BBI of control and un-thinned spray treatments comports with Merwin's (2015) description of this cultivar as being very biennial.

Our finding that all cultivars had lower cumulative yields over three years when thinned to 6 fruit/cm^2 than when left un-thinned actually concurs with our findings in the hand-thinning experiment (Chapter 2) carried out concurrently with this PGR experiment, with the exception of 'Dabinett', which in the hand-thinning experiment was more productive over three years when thinned to 6 fruit/cm^2 than when un-thinned or when thinned to 3 or 9 fruit/cm^2. In the hand-thinning experiment 'Binet Rouge', 'Brown Snout', 'Chisel Jersey', and 'Geneva Tremlett's Bitter' all had highest three-year cumulative yields (kg/tree) when left un-thinned, while 'Harry Masters Jersey' and 'Michelin' had equivalent cumulative yields over three years when thinned to 9 fruit/cm^2 as when left un-thinned. Because we hand-thinned to 6 fruit/cm^2 in the PGR experiment (present chapter), rather than 9 fruit/cm^2, we cannot make a direct comparison. Thus, our findings in this experiment should not be taken to prove that crop load management in general does not result in greater cumulative yields. Rather, a comparison of our findings in the two experiments indicates that thinning these European cider cultivars to 6 fruit/cm^2 TCSA, a common recommendation for fresh-market fruit (Anthony et al., 2019; Kon and Schupp, 2013; Robinson, 2008), may simply be excessive, causing greater losses from thinning than gains from enhanced return bloom. A higher crop load, such as 9 fruit/cm^2, may be more appropriate for these cultivars, though further long-term study is needed.

Moreover, as discussed in Chapter 2, cumulative yields over three years do not necessarily give a full picture of this relationship, because we are assessing two high-crop "on" years and only one low-crop "off" year. Ideally, any study on the effect of horticultural practices on bearing habits, particularly in highly biennial cultivars, should observe two high-crop "on" years and two low-crop "off" years. To get a fuller picture, the return bloom data from 2019 were examined and theoretical yield was projected imagining that the treatments had been imposed for a fourth year.

2019 Projected Yield, LynOaken Farms

Our finding that un-thinned trees would have higher cumulative yield than trees thinned to 6 fruit/cm^2 partially agrees with our finding in the hand-thinning experiment (Chapter 2): in that experiment the more "biennial" cultivars 'Binet Rouge', 'Brown Snout', 'Michelin', and 'Geneva Tremlett's Bitter' were projected to have lower four-year cumulative yield when thinned to 6 fruit/cm^2 than when un-thinned, as was the case in this experiment (present chapter). By contrast, the more "annual" cultivars 'Chisel Jersey', 'Dabinett', and 'Harry Masters Jersey' were projected to have higher four-year cumulative yield when thinned to 6 or 9 fruit/cm^2 than when un-thinned. This contradiction is not easy to explain; trees were grafted on the same rootstocks, in the same nursery, located in the same planting, planted on the same day, and used the same training system. The same treatments (thinning to 6 fruit/cm^2 or leaving un-thinned) were imposed on the same day by the same people. The difference in yield over three years in these three cultivars ('Chisel

Jersey', 'Dabinett', and 'Harry Masters Jersey') between the two experiments, despite identical treatment, is confounding.

Rootstock Effect, Cornell Orchard

There was no significant rootstock effect on return bloom or yield.

Juice Chemistry, Cornell Orchard

Given that both cultivars in the Cornell Orchard experiment are classified as "bittersweets" (TA<4.5 g/L)[***] under the Long Ashton classification system (Barker and Ettle, 1903; Valois et al., 2006), it should not be surprising that pH was high and TA was low regardless of treatment. The slight negative effect of crop density on TA for 'Chisel Jersey' in 2016 is not meaningful from a cidermaking perspective.

The negative effect of crop density on SSC and FC for 'Chisel Jersey' agrees with our findings in the hand-thinning experiment at LynOaken Farms (Chapter 3), as well as with Guillermin et al. (2015). The higher phenolic content and soluble solid content of 'Chisel Jersey' in 2017 compared to 2016, corresponding with the much lower overall crop density for this cultivar in 2017 than in 2016, agrees with Karl et al. (2020a), who reported that polyphenol content was lower overall in French bittersweet cultivar 'Medaille d'Or' in the lower-crop load first year of their experiment than the higher-crop second year. Likewise, low overall FC for 'Brown Snout' corresponded to higher overall crop density in this cultivar compared to 'Chisel Jersey'. The lack of a PGR effect on juice quality variables, such as SSC, FC, or TA, agrees with the findings of Peck et al. (2020).

[***]'Brown Snout' can have TA of 4.5 g/L under some circumstances, and as such is perhaps better described as a "subacid bittersweet".

Maturity and Ripeness, Cornell Orchard

Our finding that SPI was unaffected by crop load in ‘Chisel Jersey’, but that crop density and spray both had a positive effect on SPI for ‘Brown Snout’, disagrees with our findings from the hand-thinning experiment at LynOaken Farms (Chapter 3). In the latter experiment we found that increased crop load correlated with delayed maturity in both cultivars. The lack of a crop load effect on SPI for ‘Chisel Jersey’ is likely due to lower overall crop load in that cultivar compared with ‘Brown Snout’ (Table 4-2). The ripeness-advancing effects of NAA and ethephon is well established (Cline, 2019; Singh et al., 2008; Stover et al., 2003; Wendt et al., 2020).

Pre-harvest fruit drop in ‘Brown Snout’ was lower than ‘Chisel Jersey’ in the Cornell Orchard experiment, while the opposite was the case at LynOaken Farms. The drop-reducing effect of NAA observed in the case of ‘Brown Snout’ and ‘Harry Masters Jersey’ at LynOaken Farms in low-crop year 2017, and for ‘Chisel Jersey’ at Cornell Orchards in 2016, agrees with the general understanding of this PGR’s effect on pre-harvest drop, including in drop-prone cider cultivars (Byers, 1997; Cline, 2019; Dal Cin et al., 2008; Peck et al., 2020; Stover et al., 2003). However, the interaction of crop load and spray in relation to both SPI and drop is less well-studied, so further study is needed.

4.5 Conclusion

The results of these two experiments confirm the findings of previous researchers that midsummer PGR sprays alone are insufficient to increase return bloom in biennial-tending cultivars. A lack of PGR effect on return bloom in the LynOaken Farms experiment indicates that crop load management is likely necessary to make PGR sprays effective, and the lack of an effect by PGR on return bloom for ‘Brown Snout’ in the Cornell Orchards experiment indicates that the crop density necessary for PGRs to be effective in ‘Brown Snout’, if one exists, is likely less than 9 fruit/cm^2. Thinning to 6 fruit/cm^2 alone may be excessive, resulting in greater cumulative yield losses due to fruit removal than gains due to improved return bloom in the “off” year. Optimal crop loads to make PGR sprays effective were not conclusively identified for any of the seven cultivars examined in these two experiments, though 9 fruit/cm^2 TCSA may be appropriate. Further multi-year research, comparing different crop loads, different rates of NAA and ethephon, and combinations thereof, is necessary. The negative correlation between crop load and juice quality, as measured by SSC, TA, and FC total polyphenols, agrees with findings in Chapter 3, and with the findings of previous authors. Growers will need to perform crop thinning quite early in the season, and perhaps experiment with higher rates of PGR application, to encourage return bloom in these cultivars.

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Chapter 5: Cider Supply Chain Survey

Abstract

Commercial cidermakers (n=198) across the United States (176) and Canada (22) were surveyed about a wide range of topics relating to high-tannin apple supply, biennial bearing in these cultivars, and strategies to manage the latter. Inconsistent supply was the top reason cidermakers reported for not purchasing high-tannin cider apples. Of the 68.7% of respondents who self-reported that they are using bitter (high-tannin) cultivars, a large majority (84%) of those who grow their own reported that biennial bearing affected their high-tannin apple supply. By contrast, only 25% of cider makers who use but do not grow high-tannin apples reported supply chain disruptions due to biennial bearing. Thinning or midsummer plant growth regulators to promote annual bearing were not common practices among cider apple growers. Only 6% of respondents reported that “bitter” apples constitute a majority of their cider blends. Partnerships between growers and purchasers of this fruit are in flux, with some becoming long-term. The four most-mentioned high-tannin cultivars by both cider apple growers and non-growers were the English cultivars ‘Dabinett’, ‘Kingston Black’, ‘Porter’s Perfection’, and ‘Yarlington Mill’. This survey highlights the fact that although biennial bearing has a serious impact on cider apple supply, growers and cidermaker strategies to manage this issue are inconsistent. Reliance on mostly English high-tannin cultivars poses a risk to North American growers due to biennial bearing habits and disease susceptibility.

5.1 Introduction

Cider, also referred to as "hard cider" in the United States, is an alcoholic beverage derived from the fermented juice of apples *(Malus spp.)*. The modern American hard cider industry has grown rapidly in the last decade, both in the volume of cider sold, as well as in the number of cider producers and the diversity of products marketed as cider (Brager, 2020, 2019; Cyder Market, 2019; NBWA, 2016; Thériault, 2019). Apples used for cider may have been originally planted for the fresh market, for processing, for hard cider, or a combination thereof. High-tannin cider apple cultivars, particularly those originating in England and France, have gained popularity in the United States and Canada as sources of bitter and astringent phenolic compounds or "tannins" to lend complexity to cider (Merwin et al., 2008; Valois et al., 2006). Yet supply of these high-tannin apples is greatly exceeded by demand (Pashow and Mahr, 2018; Raboin, 2017; Weinstock, 2016).

High-tannin cider apple cultivars are often prone to biennial or "alternate" bearing patterns in which trees over-produce in one year and have little to no crop the following year (Bradshaw et al., 2020; Green, 1987; Hedden et al., 1993; Hoad, 1978; Merwin, 2015; Wood, 1979). Excessive crop load (i.e., the number of fruits on a tree) has long been known to inhibit affect return bloom in cider apple cultivars and in apples in general (Bradshaw et al., 2020; Green, 1987; Wood, 1979). The commercial implications of biennial bearing on cider apple supply chain, and thus cider style, is underexplored in the North American context. Cider supply chain issues have been explored on a state or regional basis (Becot et al., 2016; Pashow and Mahr, 2018), but the larger question of what proportion of North American commercial cideries use these high-tannin apples, and how many would like to but cannot access them, remains an open question with a constantly evolving answer: acreage and production of these apples is increasing in North America, as is the number of businesses producing cider (Peck and Miles, 2015). How cideries source these apples (growing their own or buying from grower partners), and the intersection of geography and climate on access, is likely to have a regionally disparate effect on the profitability of cidermaking and perhaps on cider style.

5.2. Methods

In May of 2019, a random selection of North American commercial orchardists and cidermakers from Cydermarket.com (now defunct) were interviewed by phone. These producers were asked about a wide range of topics, including what apple cultivars they grow and/or use in their ciders, the volume of their annual production and sales, what factors they consider when deciding what style(s) of cider to make, prices they pay or charge for fruit or juice, and how biennial bearing affects their apple supply. Some thirty phone interviews were conducted with commercial cidermakers and several grower partners in 2019, using a standardized script, but occasionally asking clarifying questions. A set of recurring issues salient to the cider industry were then identified and used to create a standardized questionnaire using the online Google Form application (see Appendix pp. 267-271).

The Google Form questionnaire was first distributed in March 2021 and the survey was closed on May. Cideries across the U.S. and Canada were identified via the American Cider Association (ACA)'s website, as well as various state and province cider association websites. A standard email was sent to cideries on an individual basis. At least one follow-up request was sent to producers who did not respond after the first email, generally within 7 days. Of those contacted directly, there was a 49% response rate. The American Cider Association (ACA) further advertised the survey on its website on 30 April 2021, also promoting the notice via their Facebook, Twitter, and Instagram accounts.

In the surveys, the term “bitter” rather than “high-tannin” due to the tendency of growers and cidermakers to refer to some multi-purpose cultivars as “high-tannin” in casual conversation, regardless of their actual polyphenol content. Not all growers have access to affordable testing to determine the polyphenol content of their fruit or cider, and commercial cidermakers may not think of tannin in numeric or chemical terms. “Bitter”, a generally understood hedonic descriptor, was thus chosen instead.

Spellings were standardized for the cultivar data, as many cultivar names were rendered slightly differently in the Google Form responses. Demographic data was not collected. Interviewees and respondents skewed somewhat towards being male. Some head cidermakers and orchardists were female. The commercial apple growers who sell high-tannin fruit to cidermakers were all male. Some respondents did not identify by name or by sex over email, and a sizeable proportion filled out the survey without identifying themselves by name, or indeed by cidery.

Percentages were calculated by Google Forms. Written responses to short-answer or long-answer questions were occasionally exported to Microsoft Excel to be standardized, and percentages were calculated in Excel.

5.3. Results and Discussion

<u>Location, Production, and Distribution</u>

There were 198 responses from commercial cideries representing 37 states and six provinces (Table 5-1). The most represented states and provinces were Oregon, California, and New York (15 each), Pennsylvania (13), Virginia and Massachusetts (12 each), and Ontario (10). A majority (164) of respondents were primarily cideries, though several were breweries, meaderies, wineries, and distilleries who also produce cider. About two-thirds (64%) reported being located in “rural” locations, the rest being in “urban” locations (36%).

Approximately half (51.3%) of 195 respondents reported that they distribute their cider at a multi-county or state/province-wide level (Table 5-3). Cideries distributing locally or on-site comprised 23.1% of respondents, and 16.4% reported distributing at a multi-state/province or regional level. Only 4.1% reported distributing nationally or internationally, and 5.1% reported they were not yet selling cider. The share of sales represented by on-site versus off-site varied greatly. Cideries in rural locations tended to report selling cider on-premises more often than cideries in urban locations. Three-quarters (74%) of 195 respondents reported having a tasting room or taproom, with an additional 15% reporting they were building one or planning to do so (Table 5-4). These figures are similar to those reported by Pullman (2015) and Snyder (2016), the latter of whom reported in a recent survey of commercial cidermakers in the mid-Atlantic region that 63% of respondents owned their own taproom, while a mere 16% of consumers reported purchasing cider at tasting rooms. Though taprooms or tasting rooms appear to be the norm, that does not necessarily mean that these facilities are primary locations for cider sales in North America. Taprooms can often be a venue for cideries to build a relationship with consumers, rather than to sell at high volume. Subsequent off-premise sales of local or regional cider brands may be driven by consumer introduction to a cidery's products in the taproom or tasting room. Regional cideries have grown their share of total off-premise cider sales over the last few years (Brager, 2020, 2019),

Scale of annual production, in terms of volume, also varied widely (Table 5-2). Nearly two-thirds (65.1%) of 195 respondents reported annual production of 10,000 or fewer gallons per year, and 24.6% reported production of 10,000-50,000 gallons per year. In retrospect, 30,000 and 130,000 gal/year would have been more useful category cutoffs when constructing the survey, given that these are the cutoffs for US federal excise tax brackets (these tax bracket cutoffs do not apply to Canadian cideries) (TTB, 2020). However, with a majority of respondents producing less than 10,000 gal/year, it is clear that in terms of number of operations, the North American cider industry skews towards small-scale producers. Like many other agriculture, food, and beverage industries, it is also clear that just a few large-scale operations produce the vast majority of the cider volume in North America. Several respondents chose not to disclose their scale of yearly cider production. These data represent a snapshot of individual cideries' current production at the time of response; given the recent founding of most commercial cideries (Cyder Market, 2019), and the current growth in sales, particularly among smaller regional cideries, a given cidery's annual production, as well as overall volume, the makeup of the North American cider industry is very much evolving (Brager, 2020). Continued surveying of the cider industry will be incredibly useful as it is unclear if the recent growth in regional brands will translate to a larger number of companies having a notable percentage of the overall market.

Use and Non-Use of High-Tannin Apples

Sixty-nine percent of 198 respondents reported that they use some "bitter" apples, including juice or concentrate, in their cider (Table 5-5). An additional 16.7% reported that they plan to use bitter apples in the future. However, of those who reported that they currently use bitter apples in their cider (n=137), almost half reported that bitter fruit represent 10% or less of their cider blends (Table 5-7). About one-fourth (27%) reported that bitter fruit/juice represented between 11-25% of their raw material. Only 6% stated that bitter fruit/juice was the majority of their blend. This agrees with Pashow (2018), who reported that "sweet" and "sharp" dessert cultivars each represented approximately 30% of fruit used by respondents in New York State, with bittersharp and bittersweet cultivars representing 9% and 10%, respectively.

Among those who reported they do not use bitter fruit/juice/concentrate (n=62), the leading reason by far was lack of availability (60%), with one-third reporting they intended to source or plant bitter apples in the future (Table 5-6). Previous surveys have found lack of availability to be a leading concern for cidermakers working with high-tannin or "bitter" cultivars (Becot et al., 2016; Pashow and Mahr, 2018; Raboin, 2017). Several producers stated that they have planted bitter apples but that they are not yet producing. Lack of local supply and high purchasing cost were cited as reasons for not buying bitter fruit or juice. Unreliability of supply and inability to make a consistent product were also cited. A few respondents reported that they were not interested in making cider with high-tannin fruit, with one respondent citing "terroir" and another citing "flavor profile". One respondent reported that they sell bitter fruit to other cidermakers but do not currently use bitter fruit in their own cider. Of those using bitter fruit (n=137), more than half (55%) reported growing some or all, with an additional 18% reporting they would be growing bitter fruit in the future (Table 5-8). Approximately one-fourth (27%) said they do not grow their own bitter apples.

Diversity of High-Tannin Cultivars Planted

Respondents (n=67) reported that they grow a wide range of bitter cultivars, with many reporting they grow between eleven and twenty cultivars; few reported growing only one or two (Figure 5-1). There was no clear trend between how many years a respondent had been growing bitter cultivars (i.e., level of experience) and how many bitter cultivars respondents reported they work with. Nor was there a clear trend between acres planted and number of cultivars. Diversification may be as much a strategy for the emerging cider industry to identify cultivars that are best suited to a site, as it is a strategy for experienced grower-cidermakers to mitigate risk of crop failure due to frost, disease pressure, biennial bearing, etc. Diversity also enables cidermakers to make more “complex” or “balanced” cider blends (Lea, 1978; Merwin et al., 2008; Villière et al., 2015).

Of the many cultivars cidermakers who reported growing cider apples, a dozen cultivars stood out as being frequently mentioned (Table 5-9). Six of the seven cultivars included in this author’s experiments (Chapters 2-4) were among that top dozen. ‘Dabinett’ was the topmost mentioned—it is also the most widely grown cider apple in the United Kingdom. ‘Kingston Black’, a highly prized but notoriously biennial cultivar (Bradshaw et al., 2020;Merwin, 2015) was the second-most frequently mentioned. Becot et al. (2016) likewise found these two cultivars to be the most reported by survey respondents in Vermont, and Pashow (2018) likewise found that reported acreage of these two cultivars held the top two spots among cider cultivars in New York State. It is unclear whether by “Tremlett’s Bitter” respondents were referring to the bittersharp ‘Geneva Tremlett’s Bitter’—the seventh cultivar assessed by this author, widely grown in the U.S.—or the true English bittersweet ‘Tremlett’s Bitter’[†††]. Nine of the top dozen cultivars were low-acid bittersweets; given the glut of subacid or acid dessert “cull” apples, acidity is likely not a major concern for growers of “bitter” cider cultivars. Only two of the top dozen were French in origin, the others being either English (9) or American (1). Of all the “bitter” cultivars (n=62) mentioned by respondents, the vast majority originate in England, France, or the United States (21, 18, and 17, respectively).

The high proportion of cider cultivars from England and France, and the lack of domestically developed germplasm, poses a risk to North American growers in climates with hotter summers or colder winters than Western Europe. For example, the susceptibility of widely planted ‘Dabinett’ to cold damage (Peck et al., 2021) was occasionally mentioned by interviewees.

[†††] Given that the true English bittersweet has only recently been imported to the United States, it is more likely that the spurious ‘Geneva Tremlett’s Bitter’ is the one referred to by respondents.

The late bloom of many European cider cultivars, leading to increased risk of fire blight (*Erwinia amylovora*), is also an issue (Byrde et al., 1986; Gwynne, 1984; Locke et al., 1993). A recent fire-blight outbreak in the American Northeast has underscored the risks of growing these late-blooming cultivars which, due to biennial bearing, often have extremely high bloom density in some years (Francis, 2021). Growers in the Northwest region have reported removing many European cider cultivars from their orchards due to fire-blight susceptibility (Miller et al., 2020).

Bitter cultivars originating in the U.S. were a mix of a few cultivars predating Prohibition, some introduced in the 1960s-1980s, and many discovered in the last decade. Bitter cultivars originating in North America included: ‘Banane Amere’, ‘Bitter Pew’, ‘Brown’s Best’, ‘Douce de Charlevoix’, ‘Franklin’, ‘Kronebusch’, ‘Lost Crab’, ‘Puget Spice’, ‘Shavel Sharp’, and ‘Witch’s Kiss’, as well as North American red-fleshed cultivars ‘Burford Redflesh’, ‘Geneva’, and ‘Redfield’. Three respondents simply reported growing “crabapples” without specifying what species or cultivar(s) they grow. Five growers reported testing the fruit from young seedlings and mature “wild” trees, in some cases propagating these in their orchards by grafting. This practice, though still uncommon, is beginning to be adopted (Courtney and Mullinax, 2018; Shirvell, 2020).

Several lower-tannin cultivars were also frequently mentioned by grower-cidermakers, including ‘Ashmead’s Kernel’, ‘Golden Russet’, ‘Harrison’, ‘Reine Des Pommes’ and ‘Wickson Crab’. Many respondents included lower-tannin multi-purpose cider cultivars when listing the “bitter” cultivars they grow, reinforcing the disconnect between juice chemistry data obtained through analytical equipment and the perception among cidermakers of what constitutes a “bitter” or “high-tannin” cultivar.

The range of bitter cultivars that non-growers reported using was much less diverse (Table 5-21). The most commonly mentioned were ‘Dabinett’ (8), ‘Kingston Black’, ‘Porter’s

Perfection', and 'Hewes Virginia Crab' (5 each), and 'Yarlington Mill' (4); of these top five, the four English cultivars were also the four most mentioned by cidermakers who grow their own fruit (Table 5-9). Mildly tannic 'Harrison' was also frequently mentioned. Some respondents did not know what cultivars go into the bitter juice blends they bought from growers. Several respondents listed dessert apples, such as 'McIntosh' and 'Ida Red', as "bitter" varieties; multi-purpose cultivars like 'Northern Spy' and 'Golden Russet' were also mentioned, underscoring the misconception among some cidermakers, particularly non-growers, as to what constitutes a "high-tannin" or "bitter" cultivar.

Size and Age of High-Tannin Plantings

The reported size of high-tannin plantings ranged from 0.2 to 20 acres, though of respondents to this question (n=65), 89% reported a planting size of 5 acres or less (Figure 5-2). Approximately one-third (33%) of those growing bitter cultivars reported that their trees had come into production, with 47% reporting some varieties had come into production (Table 5-10). Half (50%) characterized their plantings of bitter apples as "experimental", with another 15.6% saying their planting started out that way (Table 5-11). Only about one-third (34.4%) said their planting was not currently "experimental". The high percentage of growers with currently or previously "experimental" high-tannin cider apple plantings underscores the need for sound, empirical cultivar recommendations, as well as good information on horticultural practices to grow cider cultivars. The recency of most "bitter" cider apple plantings agrees with other surveys (Miller et al., 2020; Pashow and Mahr, 2018).

Biennial Bearing and Thinning

Among those growing bitter apple cultivars (n=96), a large majority (84.4%) said biennial bearing affected their apple supply (Table 5-14). By contrast, among non-growers who responded to the same question (n=32), a large majority (75%) said biennial bearing had not been an obstacle to sourcing bitter fruit, juice, or concentrate (Table 5-18). Among growers affected by biennial bearing (n=73), many employed multiple strategies (Table 5-15). The most common response was to use whatever fruit they do have for that year’s blend (65.8%); horticultural management or saving fermented cider to blend across multiple years were also common strategies (34.2% and 37%, respectively). Very few growers (9.6%) reported storing bitter fruit or juice as a strategy to compensate for biennial bearing, which is understandable given the cost of cold storage and loss of juice quality during long-term storage. Among non-growers affected by biennial bearing (n=10), strategies included trying to source from another grower or supplier, fermenting and blending across multiple years, freezing juice for subsequent years, using tannin supplements, or simply forgoing use of bitter fruit or juice (Table 5-19).

Cidermakers who don’t grow their own bitter fruit (n=32) generally reported buying from either one source (n=15) or two sources (n=7), with a few buying from three or four. Only three respondents said they bought from more than five sources (Table 5-19). Most non-growers reported buying from in-state or -province (24 out of 34 respondents), with a sizeable minority buying from out-of-state or -province (13 of 34); only four respondents reported buying from out-of-country, namely, France and the United Kingdom.

Thinning of cider apples was not commonly practiced among growers who responded (n=78): 46% reported they do not thin bitter apple varieties, with an additional 5% reporting that they had tried doing so and stopped. Six respondents said trees were too young, and thus yields were too low, to consider thinning yet. Of those reporting that they do thin their bitter cultivars, a wide range of reasons was given for doing so: improvement of sugar content (10 respondents) and tannin content (6 respondents), improvement of acid content (3 respondents) and reduction of stress on trees (9 respondents). Eight said they thinned to mitigate biennial bearing or promote return bloom, with several others simply citing “harvest volume” or “overcropping”. When asked if they would accept lower cumulative yields if they could guarantee more consistent yields from year to year (n=75 responses), only 29% said “yes”; 56% said “maybe”, while 14.7% stated affirmatively “no”. Given that this tradeoff may be unavoidable in some cultivars (Chapters 2 & 4), crop load management research in cider cultivars is of great value to the industry.

Fruit size, often a consideration in fresh-market production, was sometimes important to growers of bitter apples for cider. Approximately two-thirds of respondents (n=78) said they do not pay pickers a different rate per bin to harvest small-fruited cider varieties compared to larger-fruited varieties. About one-fifth (19.2%) said they do, and 15.4% preferred not to say. Some respondents reported they pick fruit themselves and do not employ a picking crew. Several growers stated that though the rate per pound was the same, the time required was greater for smaller fruit, thus increasing harvest cost and picker compensation for growers paying pickers by the hour. One respondent reported a cost of $5 per bushel for larger-fruited cider apples and $25 per bushel for smaller-fruited ones. More systematic field research, including economic analysis, of the influence of crop load management on harvest cost, as pertains to fruit number and size, is needed (Davis et al., 2004; Miles and King, 2014; Zhang et al., 2019).

<u>Buying and Selling Raw Material</u>

A vast majority (81.8%) of those growing bitter apples (n=88) said they do not sell bitter fruit or juice to other cideries (Table 5-12). A few (6.6%) reported they were open to or hoped to do so in the future. Only 9.1% said they currently sell bitter fruit. However, approximately half (48%) of growers (n=92 responses) reported that they buy bitter fruit or juice from other growers, with 8.7% saying they had done so in the past. Of those buying bitter fruit or juice, the vast majority reported they do not sell to other cideries; only three respondents reported that they have both sold and bought bitter apples or juice.

Prices paid for bitter fruit and juice were difficult to compare given that the various units reported. Dollars per bushel, per gallon, per pound, or per bin were all reported. Bin size was usually not specified and can range from 690 to 900 lbs in the apple industry. Prices that growers reported paying to other growers for bitter fruit or juice generally ranged from $2-6/gallon, but one respondent in the northeastern U.S. reported paying $30/gallon for juice of specific crab apple varieties, with shipping across country nearly doubling the final cost to ~$60/gallon. Prices per pound ranged from $0.25-0.90/lb, and prices per bushel ranged from $8-$30. Prices per bin could be as low as $100, but as high as $1,800. Growers who sell to other cidermakers (n=10) reported charging prices of anywhere from $4-12/gal, $0.50-0.60/lb, or $25-28/bushel, with one respondent reporting $400/bin. Non-growers who volunteered price data (n=12) reported a similar range of prices for bitter fruit or juice: $2.50-12/gallon, with one respondent reporting $30/gallon, $0.25-0.75/lb, $18-35/bushel, or $450 CAD/bin. Per-pound prices reported by respondents are similar to those reported in a case study of six commercial cider orchards in New York State by Peck et al. (2018), ranging between $0.35-0.71/lb.

By contrast, among those not using high-tannin cultivars, reported costs of low-tannin juice were much lower. Canadian respondents (n=7) reported prices of $0.85-1.50 CAD per liter, while American respondents paid $1.20-6.00 USD per gallon; one respondent in the deep south reported paying $9-14 per gallon for low-tannin juice, an unusually high price perhaps attributable to the high cost of long-distance refrigerated shipping (though this was not specified). Costs for low-tannin juice in the U.S. were not very different at the low end compared to costs of high-tannin juice, but the upper end of the price range was much higher for the latter than the former. In retrospect, it may have been useful to ask about low-tannin juice costs for cideries using bitter fruit as well, but raw apple juice prices are generally better studied by agricultural economists.

Only 3 out of 59 growers reported using a formal contract to guarantee a price, a buyer, or a seller. Six respondents said they planned to use a contract, and 43 respondents said they do not, but would be open to doing so. Seven respondents said that they neither use a contract nor were they interested in doing so (Table 5-22). A few interviewees noted that “handshake agreements” are more popular among growers with a longer history of growing apples, and that these agreements are self-enforcing by word-of-mouth: if a buyer reneges on an agreement to buy fruit, other growers become less willing to do business with that buyer. Among cidermakers not growing bitter fruit themselves (n=34 responses), use of a contract or openness to contracts was greater. A full 20.6% reported using a contract, with more than half (55.9%) reporting that they would use a contract if possible. About one-fifth (20.6%) said they do not use a contract, and one respondent said definitively that they would not use a contract with a grower. The preference among growers for “handshake agreements” over formal contracts was also reported by Fabien-Ouellet & Conner (2018) who studied the cider supply chain in New England.

Most non-growers who use bitter cultivars (n=34) reported buying in the form of fruit or juice; some cidermakers purchased bitter fruit in more than one form. Only six reported that they buy bitter concentrate, generally being those who operate on a large scale of production and multi-state or national distribution scale. The diversity of bitter varieties non-growers reported using was considerably smaller than those growing their own bitter fruit: non-growers reported only 21 different bitter cultivars, compared to 63 mentioned by cidermakers growing their own bitter fruit (Table 5-21). The most commonly mentioned were ‘Dabinett’ (8), ‘Porter’s Perfection’, ‘Kingston Black’, and ‘Hewes Virginia Crab’ (5 each), and ‘Yarlington Mill’ (4). The four English cultivars aforementioned were also the four most mentioned by growers, with 'Hewes Virginia Crab' being near the top as well. The strongly biennial tendency of 'Kingston Black' (Bradshaw et al., 2020; Cuthbertson and Stickley, 1949; Merwin, 2015), taken together with its popularity among respondents, means that horticultural research to promote annual bearing in this cultivar is worthwhile and needed.

Grower-Cidery Partnerships in Growing High-Tannin Cider Apples

Several respondents who do not grow their own apples reported partnering with nearby growers to establish plantings of bitter cider cultivars. Respondents mentioned encountering skepticism from growers, in part due to lack of experience working with these varieties, but also because growers were uncertain whether the cideries proposing to establish a planting would remain long-term, reliable buyers for bitter fruit which are not useful for anything other than hard-cider production. However, several respondents reported successfully convincing nearby grower partners to establish small, experimental plantings of bitter apples for them to use in cider.

Comparison with Other Beverage Industries

The current "growing pains" identified in this and other surveys are in many ways quite opposite to those experienced by the American wine industry in the latter half of the twentieth century. The American wine industry, which initially embraced hybrids between European *Vitis vinifera* and native *Vitis* species, eventually came to reject hybrids and shift toward cultivation of older European *V. vinifera* wine grapes on hybrid rootstocks. The American cider industry, by contrast, primarily uses multipurpose or table varieties in the form of cull apples from the fresh market, with comparatively small, though increasing, cultivation of high-tannin cider-specific cultivars. Of the high-tannin or "bitter" cultivars being grown in North America, most of the cultivars comprising the majority of acres under cultivation appear to be English and French. The practice of breeding new cider apples or propagating indigenous “found” apple cultivars is gaining limited traction as growers encounter horticultural challenges in growing European cultivars. In this respect, North American cider orcharding seems to be on an opposite trajectory to North American wine viticulture.

The recent and rapid growth of the cider industry has had comparable effects on the public’s taste in ways similar to how Prohibition and its immediate aftermath affected the American beer industry. More than a decade of cheaply and illicitly made beer, and the collapse of hops and grain supply chains, led to a loss of discernment in American tastes for beer, extending long after Prohibition through the rest of the twentieth century (Choi and Stack, 2005; Hall, 2005). Mass-produced beer remained bland, homogenous, and watered-down for many decades because American drinkers did not have a collective cultural memory of what “good” beer tasted like.

By contrast, the resurgence in cider sales and the explosion in new commercial cideries has not followed the pattern of beer after Prohibition. Small-scale orchard-based “craft” cideries, a majority of which report using some high-tannin cider apples, have been at the forefront of the cider revival of the last decade or so. Massive industrial scaleup and a “craft revolution” have been occurring in the U.S. more or less simultaneously. Mass-market commercial cideries which have made comparably homogenous, sweet ciders, such as Woodchuck (founded 1991) or Angry Orchard (founded 2012), have not existed any longer than the many small “craft” cideries in America, though their market share has been enormous. Cider, which had retreated in popularity long before Prohibition, did not recover as an industry until the early 21st century, and still represents less than 1% of alcohol sales in this country (Brager, 2019). Thus, public perception of cider may still be very much up for grabs, and large-scale producers—a relative term in such a small industry—seem to be adjusting their style and marketing accordingly. It is unclear to what degree public perception of cider has been shaped by these sweeter mass-produced products and by national advertising campaigns from Angry Orchard. Fabien-Ouellet & Conner (2018) observed that the marketing of cider is remarkably variable, often within the same commercial cidery: a given producer might liken one of their products to ale and another to rosé wine or champagne. These authors characterized American hard cider as undergoing an "identity crisis".

Consumer preferences may be shifting toward less sweet, more tannic ciders (Tozer et al., 2015), though single-varietal ciders made with only high-tannin apples are sometimes perceived negatively by consumers (Dawson et al., 2019). Very few respondents to this survey reported that a lack of consumer interest or knowledge about tannic cider apples discouraged them from trying to source high-tannin cider apples. Demand for these apples among cidermakers exceeds supply, regardless of consumer education or lack thereof (Fabien-Ouellet and Conner, 2018). Smaller "craft" cideries appear determined to make complex, balanced ciders with at least some tannin, and even the nation's largest producer, Angry Orchard, has advertised two new mass-market cider lines, "Unfiltered" and "Stone Dry", as being made with "bittersweet apples" and containing the "tannins of traditional cider making apples" (Angry Orchard, 2021a, 2021b). The simultaneous scaleup and "craft revolution" in American cider will likely put further strain on an already strained supply chain of high-tannin apples.

Demand for high-tannin apples among cidermakers has led to a rapid growth in the number of acres under cultivation. I say "among cidermakers" because this demand appears to be led by the industry rather than by consumers, most of whom have never even heard of high-tannin cider apples. This rapid growth in cultivation differs from, say, the stock of hops held in the United States from 1948 until 1970, which hovered below 50 million pounds over that period, and which barely exceeded 100 million pounds until 2010 (USDA, 2014). This cycle of supply and demand for bitter hops both remaining low long after the repeal of Prohibition is vastly different from the situation in cider.

Nearly three-quarters of respondents to this survey reported planting their high-tannin apples in the last six years (Figure 5-3), and other surveys have found that growers have been establishing small high-tannin plantings over the last three or four years (Miller et al., 2020; Pashow, 2018). The number of commercial cideries in the U.S. really only began its upward climb around 2009, so the nation's supply and acreage of high-tannin apples has lagged behind overall industry growth by less than a decade (Cyder Market, 2019). Whether this lag will continue is unclear and depends on the willingness of growers to invest in planting apples useless for any other purpose. Several interviewees noted that grower partners are unsure whether hard cider is viable long term, and thus, whether they will have a long-term buyer for these single-purpose cultivars which are often difficult to grow.

5.4. Conclusions

Survey responses indicate the cider industry in North America is currently uncertain about how to work with high-tannin apples. Supply of these apples is much smaller than demand among cidermakers, leading many cidermakers to forgo trying to source them, a phenomenon sometimes referred to as "supply elasticity of demand". Plantings are small and relatively young, with many growers awaiting their plantings' entry into full production, often describing plantings as "experimental". A large majority of growers report their supply of high-tannin apples is affected by biennial bearing. Yet a high proportion of growers do not perform crop thinning to promote return bloom, indicating the need for effective chemical or alternative thinning strategies and better communication between researchers and growers, and further research into the responsivity of different cultivars to crop load management.

Among the high-tannin cultivars mentioned most frequently by both grower- and non-grower cidermakers, the much-beloved ‘Kingston Black’ is notoriously biennial (Bradshaw et al., 2020; Merwin, 2015); strategies to promote less biennial bearing in this cultivar would thus be of value to the cider industry. The predominance of English high-tannin cultivars among those mentioned in this survey underscores the need for more research into how to grow these cultivars in North America, and perhaps for breeding or propagating alternative high-tannin cultivars better adapted to the diverse climates of this continent.

5.5. Tables and Figures

Table 5-1. Total survey responses by state and province

	State/Province	Responses
	California, New York, Oregon	15
	Pennsylvania	13
	Massachusetts, Virginia	12
	Ontario	10
	Michigan, Minnesota	9
	Washington	7
	Wisconsin	6
	Colorado	5
	British Columbia, Montana, New Hampshire, North Carolina, Nova Scotia	4
	Arizona, Connecticut, Iowa, Maine, Ohio	3
	Georgia, Illinois, Indiana, Kentucky, Maryland, Nebraska, New Mexico, Utah	2
	Alabama, Delaware, Idaho, Louisiana, Manitoba, New Brunswick, New Jersey, North Dakota, Rhode Island, South Dakota, Tennessee, Texas, Vermont	1
	No answer	6
Total	43	198

Table 5-2. Annual scale of production (gal/year or L/year) reported by respondents

Scale of Production (gal/year)	Scale of Production (L/year)	Percentage of Respondents (n=195)
<1,000	<3,800	10.3%
1,000-5,000	3,800-19,000	36.9%
5,000-10,000	19,000-38,000	17.9%
10,000-50,000	38,000-190,000	24.6%
50,000-250,000	190,000-950,000	7.7%
250,000-500,000	950,000-1.9 million	0.5%
500,000-1 million	1.9-3.8 million	0.5%
>1 million	>3.8 million	1.5%
No answer: 2 respondents		

Table 5-3. Cidery distribution scale

Scale of distribution	Percentage of Respondents (n=195)
Not currently selling cider	5.1%
Local/on-site	23.1%
Multi-county or state/province-wide	51.3%
Multi-state/province or regional	16.4%
National/international	4.1%
No answer: 3 respondents	

Table 5-4. Do you have a taproom/tasting room?

Response	Percentage of Respondents (n=195)
Yes	73.8%
No	10.8%
Planning to/building one	15.4%
No answer: 3 respondents	

Table 5-5. Do you use bitter apple varieties (including juice/concentrate) in your cider?

Response	Percentage of Respondents (n=198)
Yes	68.7%
No	14.6%
Plan to use	16.7%

Table 5-6. Reasons given for not using bitter cultivars in cider

Response	Percentage of Respondents[a] (n=61)
Inconsistent/no availability	60.7%
Looking to plant/supply bitter apples in the future	31.1%
Not interested	23.0%
Lack of experience with bitter cultivars	14.8%
Trees are not yet bearing	6.6%
Too expensive	6.6%
Lack of consumer education	3.3%

[a]Many respondents gave more than one reason

Questions for cideries using bitter varieties (n=137)

Table 5-7. What proportion of the fruit/juice you use in all your ciders comes from bitter varieties?

Response	Percentage of Respondents (n=132)
10% or less	46.2%
11-25%	27.3%
26-50%	20.5%
51-75%	4.5%
76-100%	1.5%
No answer: 5 respondents	

Table 5-8. Do you grow some or all of the bitter apples you use in your cider?

Response	Percentage of Respondents (n=135)
Yes	55.5%
No	26.7%
Will be in future	17.8%
No answer: 2 respondents	

Questions for cideries growing bitter varieties (n=96)

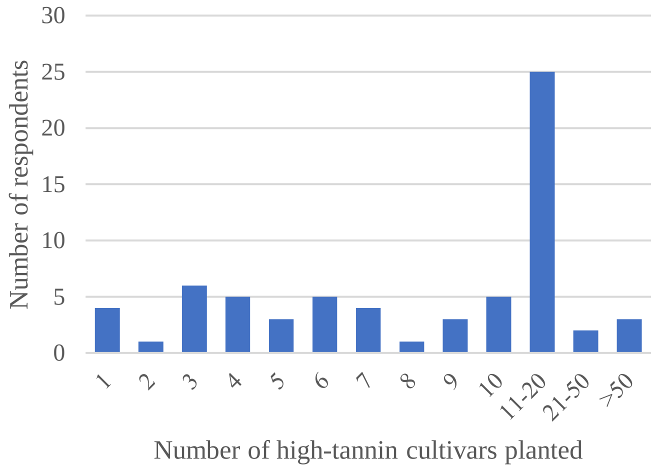

Figure 5-1. How many bittersweet or bittersharp varieties do you grow? (n=67 responses)

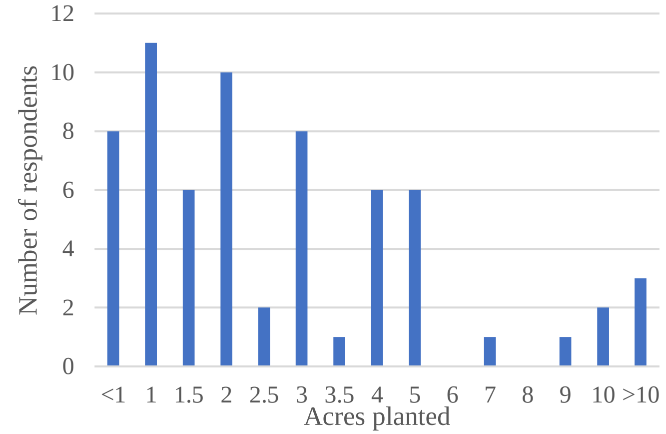

Figure 5-2. How many acres of bitter apples do you have planted? (n=65 responses)

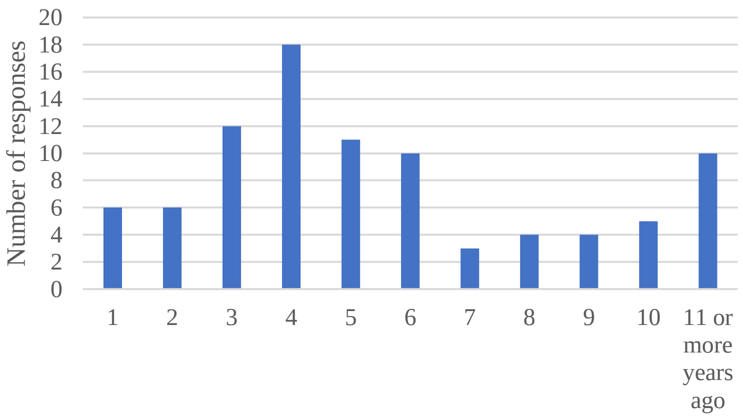

Figure 5-3. How many years ago did you plant your bitter cider trees? (n=88 responses)

Table 5-9. What bittersweet or bittersharp varieties do you grow? (Dozen most frequently mentioned)

Cultivar	Number of Growers (n=67)
Dabinett	49
Kingston Black	44
Yarlington Mill[‡‡‡]	35
Porter's Perfection	22
Ellis Bitter	17
Chisel Jersey	17
Harry Masters Jersey	17
Michelin	15
Bulmer Norman	15
Brown Snout	15
Hewes Virginia Crab	13
Binet Rouge	12
Tremlett's Bitter[§§§]	12

Table 5-10. Have your bitter varieties come into production?

Response	Percentage of Respondents (n=89)
Yes	32.6%
No	20.2%
Some	47.2%
No answer: 7 respondents	

Table 5-11. Would you characterize your bitter apple planting as currently 'experimental'?

Response	Percentage of Respondents (n=90)
Yes	50.0%
No	34.4%
Started that way	15.6%
No answer: 6 respondents	

Table 5-12. Do you sell bitter apples/juice to other cideries?

Response	Percentage of Respondents[b] (n=88)
Yes	9.1%
No	81.8%
Have sold to others but no longer do so	2.3%
Will sell/may do so in the future	6.6%
No answer: 8 respondents	

[b]Includes some growers not currently using their own bitter fruit

Table 5-13. Do you buy bitter apples/juice from other cideries?

Response	Percentage of Respondents (n=92)
Yes	48.9%
No	42.4%
I have in the past	8.7%
No answer: 4 respondents	

Table 5-14. Do alternate/biennial yields affect your apple supply?

Response	Percentage of Respondents (n=96)
Yes	84.4%
No	15.6%

Table 5-15. Strategies for biennial bearing

Response	Percentage of Respondents[c] (n=73)
In-orchard horticultural means (thinning, PGR sprays, etc.)	34.2%
Use whatever you have for that year's blend	65.8%
Store fruit/juice longer	9.6%
Ferment what you have and save some for subsequent years	37.0%
No answer: 8 respondents	

[c]Many respondents chose more than one response

[‡‡‡]Several European bittersweet cider cultivars have been sold erroneously under the name 'Yarlington Mill', though the true-to-type 'Yarlington Mill' is also being grown in the U.S.

[§§§]A bittersharp cultivar of unknown provenance was mistakenly labeled "Tremlett's Bitter" and widely propagated. This is now referred to as 'Geneva Tremlett's Bitter' or 'Geneva Tremlett'. However, it is unclear how many orchardists have the true English bittersweet 'Tremlett's Bitter' as opposed to the spuriously named bittersharp which has been widely cultivated.

Questions for cideries using but not growing bitter varieties (n=39)

Table 5-16. Where do you source bitter fruit/juice/concentrate?

Response	Percentage of Respondents (n=34)[d]
In-state/province	70.6%
Out-of-state/province	38.2%
Out-of-country	11.8%

No answer: 14 respondents

[d]Some respondents gave multiple answers

Table 5-17. What form do you buy your bitter cider apples?

Response	Percentage of Respondents (n=34)[e]
Juice (fresh/frozen)	58.8%
Concentrate	17.6%
Fruit	47.1%

No answer: 14 respondents

[e]Some respondents gave multiple answers

Table 5-18. Has alternate/biennial bearing ever been an obstacle to your sourcing bitter fruit/juice/concentrate?

Response	Percentage of Respondents (n=32)
Yes	25.0%
No	75.0%

No answer: 7 respondents

Table 5-19. How many sources do you buy bitter fruit/juice/concentrate from?

Response	Percentage of Respondents (n=32)
1	46.9%
2	21.9%
3	12.5%
4	9.4%
>5	9.3%

No answer: 7 respondents

Table 5-20. If bitter fruit/juice/concentrate is unavailable do you…

Response	Percentage of Respondents (n=10)
Try to source from another supplier	50%
Not use bitter fruit/juice that year	10%
Ferment what you have and save some to blend the next year	30%
Freeze juice	20%
Use tannin supplements	20%

Table 5-21. What bitter varieties are you working with?

Cultivar	Number of Respondents (n=30)
Dabinett	8
Porter's Perfection	5
Kingston Black	5
Harrison	5
Hewes Virginia Crab	5
Yarlington Mill	4
Dolgo Crab	2
Redfield	2
Tremlett's Bitter	2
Chisel Jersey, Columbia Crab, Franklin, Frequin Rouge, Geneva, Harry Masters Jersey, Major, Manchurian Crab, Marie Menard, Muscadet de Dieppe, Muscadet de Lense	1 each

Table 5-22. Do you use a contract to supply a buyer/seller for bitter fruit/juice?

Response	Percentage of Respondents Growing Own Bitter Varieties (n=59)	Percentage of Respondents Not Growing Bitter Varieties (n=34)
I do	5.0%	20.6%
I plan to	10.2%	—
I don't	—	20.6%
I would	72.9%	55.9%
I wouldn't	11.9%	2.9%
No response:	37 respondents	5 respondents

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Conclusion

The four field experiments described in this thesis investigated the effects of hand-thinning and plant growth regulator (PGR) sprays on return bloom, long-term bearing habit and productivity, as well as juice quality and fruit maturity, for seven high-tannin European cider apple (*Malus* ×*domestica*) cultivars. The first experiment (Chapters 2 & 3), conducted at LynOaken Farms in Lyndonville, NY showed that hand-thinning rarely resulted in equivalent or greater cumulative yield over three years, but projections of yield from the final year's return bloom data showed that imposition of the same crop loads for a fourth year, under conservative assumptions about fruit set, would result in four of seven cultivars bearing equivalent or greater cumulative yields when thinned to a target crop load of 9 fruit/cm^2 trunk cross sectional area (TCSA) than when left un-thinned for four years.

An identical one-year experiment performed at the same orchard in Lyndonville, NY, but on different trees (Chapters 2 & 3), found that for 'Chisel Jersey', 'Dabinett', 'Harry Masters Jersey', and 'Michelin' hand-thinning in the low-crop "off" year was not effective at promoting return bloom. The two hand-thinning experiments at LynOaken Farms, taken together, indicate that while hand-thinning in the high-crop "on" year is extremely effective at improving cumulative yield and year-to-year yield consistency, as well as juice quality, thinning in the "off" year may be unnecessary. Increased biennial bearing index (BBI) was found to correlate with reduced cumulative productivity in the three-year hand-thinning experiment (Chapter 2), both within and across cultivars. Though hand-thinning did not always result in greater projected four-year cumulative yields, improved fruit size and reduced crop load had the potential to reduce harvest costs over four years; combined with some increases in projected four-yield cumulative yield.

Additionally, chemical thinning to 9 fruit/cm^2 TCSA was projected to result in a net increase in profitability for all seven cultivars, while hand-thinning to 9 fruit/cm^2 TCSA was projected to be more profitable than not thinning over four years in five of seven cultivars. Thinning also had the potential to increase cumulative production of tannins, the primary reason for growing these cultivars, over four years (Chapter 3).

The English cultivars ‘Chisel Jersey’, ‘Dabinett’, and ‘Harry Masters Jersey’, which are reputedly more “annual” (Copas, 2013, 2001; Merwin, 2015; Wood, 1979), lived up to their reputations: they had lowest BBI when un-thinned, had the greatest cumulative productivity, and were also most responsive to thinning in terms of increased return bloom and fruit yields. Though hand-thinning greatly reduced BBI and improved juice quality for ‘Michelin’, which is generally considered to be very annual (Copas, 2013, 2001; Wood, 1979), it was actually quite biennial when left un-thinned, and would still have been slightly less productive over four years when hand-thinned than when left un-thinned. The cultivars ‘Binet Rouge’, ‘Brown Snout’, and ‘Geneva Tremlett’s Bitter’ lived up to their reputations for biennial bearing (Merwin, 2015), both when thinned and un-thinned, and were the least cumulatively productive of the seven cultivars in the experiments conducted at LynOaken Farms. These three cultivars were also less responsive to thinning in terms of BBI, also failing to achieve equivalent or greater yields by the projected fourth year when hand-thinned than when un-thinned.

A third concurrent experiment at the same orchard (Chapter 4) compared the efficacy of hand-thinning to 6 fruit/cm^2 TCSA and mid-summer plant growth regulator (PGR) sprays at promoting return bloom in the same seven cultivars, also comparing the effect of these horticultural practices on cumulative yield and yield variability, over three consecutive years. Midsummer applications of ethephon and naphthalene-acetic acid (NAA) alone could not overcome the bloom-inhibiting effect of crop load at the rates we applied having no discernible bloom-promoting effect. Hand-thinning to 6 fruit/cm^2 TCSA, though effective at promoting return bloom, led to excessive yield losses in the "on" year that were not compensated for by improved return bloom and yield in the subsequent "off" years. Combining fruit thinning with more efficacious rates of these PGRs may be an important goal for future researchers, though bloom-promoting PGRs may not be needed in 'Chisel Jersey', 'Dabinett', or 'Harry Masters Jersey', given the efficacy of hand-thinning alone at increasing cumulative yield and decreasing biennial bearing found in Chapter 2.

A fourth experiment (Chapter 4), conducted at a Cornell University research orchard, investigated the efficacy of hand-thinning, mid-summer PGR sprays, and a combination thereof, at promoting return bloom in high-tannin cultivars 'Brown Snout' and 'Chisel Jersey'. This experiment found that PGR applications, either alone or in combination with hand-thinning, were ineffective at promoting return bloom, compared to hand-thinning alone, at the rates we applied.

A survey of cidermakers in the U.S. and Canada (Chapter 5) examined which high-tannin cider cultivars have gained popularity in North America, how biennial bearing affects high-tannin apple supply among growers and non-growers, and what strategies cidermakers use to manage or adapt to biennial bearing. Most respondents reported using some high-tannin apples in their cider, but these cultivars typically represent a minority of the total fruit used. Both those who grow and those who only purchase high-tannin fruit most frequently cited cultivars of English origin. Interestingly, North American cidermakers are growing cultivars with both extreme "biennial" bearing habits and also cultivars with more "annual" habits. Six of the seven cultivars used in our experiments (Chapters 2-4) were among the dozen most mentioned by grower-cidermakers, along with the notoriously biennial 'Kingston Black' (Copas, 2013; Merwin, 2015).

A majority of apple growers who are also cidermakers reported that their high-tannin apple supply is affected by biennial bearing, while a minority of cidermakers who do not grow high-tannin apples are working with high-tannin cider apples said the same. Lack of availability or inconsistent supply was the leading reason respondents listed for not using high-tannin apples in their cider. Horticultural practices to promote "annual" bearing, such as chemical and hand thinning, or midsummer PGR sprays, were not commonly used by the surveyed apple growers. These two findings indicate the strong need for effective crop load management practices for growers of these high-tannin cultivars, and for empirical data about innate bearing habit and thinning responsivity in high-tannin cider cultivars.

The experiments described in this thesis show that reducing crop load by thinning is more effective at promoting return bloom, reducing "biennial" bearing, and increasing cumulative yield over four years, than application of PGRs at rates typical of commercial apple production. Thinning in a low-crop "off" year may be unnecessary, while thinning in a high-crop "on" year is extremely important for annual bearing, improved juice quality, and increased productivity over four years. Further study in different tree training systems, on different rootstocks, and using higher rates of PGR sprays, is needed. The efficacy of hand-thinning at increasing cumulative yield by the fourth year may obviate the need to identify optimal midsummer PGR rates and formulations to counteract biennial bearing, at least in some high-tannin cider cultivars. Precision thinning practices to achieve target crop load are needed for these often highly biennial cider cultivars.

The lower profitability of hand-thinning compared to chemical thinning (Chapter 2) highlights the need for research to identify effective rates and formulations for chemical thinning, or other less labor-intensive means of bloom or fruitlet thinning, in high-tannin cider cultivars. The rarity of growers who sell high-tannin fruit to other cidermakers (Chapter 5) means that, in most cases, the assumptions and specifications of partial budgeting performed in Chapter 2 may not be the best assessment of the merits of crop thinning. Cumulative tannin yield (Chapter 3) may be more meaningful for most growers of high-tannin cider apples, who grow these apples for use in their own cider. The projected greater four-year cumulative tannin yield of trees thinned to 9 fruit/cm^2 TCSA, compared to un-thinned trees, for all seven cultivars in the hand-thinning experiment at LynOaken Farms, suggests that thinning might be less profitable for an apple grower selling high-tannin fruit by weight. However, thinning to 9 fruit/cm^2 TCSA may be a worthwhile practice for vertically integrated commercial cideries whose objective is to maximize the amount of tannin they produce. Given the startup costs of establishing new orchards, any practice that can increase tannin yields should be considered by commercial cider apple growers.

The research presented in the preceding chapters, I trust, represents a large stride toward improved crop load management for high-tannin cider apple orchards. The rapid growth in production and sales of cider over the last decade (Cyder Market, 2019), and the rapid increase in acreage planted with high-tannin cider apple cultivars (Miles et al., 2020; Pashow and Mahr, 2018), mostly of English origin, has greatly outpaced crop-load research in these cultivars to achieve annual bearing and maximize cumulative yields, while also improving juice quality. Further multi-year research is needed to identify the innate bearing habit and thinning response of other cider cultivars widely planted in North America, and to identify appropriate crop loads for these cultivars in other training systems and rootstocks.

High-tannin cultivars that are less prone to biennial bearing are desperately needed. The North American cider industry's reliance on highly biennial cultivars originating in Western England, Brittany, or Normandy poses a significant risk, particularly those living in regions with much hotter and drier summers and/or colder winters than the regions in which these cultivars originated. Susceptibility to fireblight, scab, and other diseases endemic to North America, is also a significant risk.

Finally, some reflections on the process of completing this research may be germane. Having never conducted scientific research before undertaking this thesis, the challenges were often formidable. Working as a lab technician under my advisor, Dr. Gregory Peck, prior to beginning this thesis certainly helped me to understand experimental design, data collection, data management, etc., and I strongly advise aspiring graduate students, regardless of their field, to try to find work related to their chosen field before pursuing an advanced degree. Taking a course in statistics, data management, experimental design, etc. can only teach you so much. Experience is the best teacher.

I also appreciate my advisor giving me the latitude to rethink and interrogate my analysis of the data presented in this thesis. The idea of assessing potential yield in 2019 (Chapter 2) occurred to me several months after collecting bloom data that year, when I had already considered the experiment to be finished. As a result, I wound up drawing very different conclusions about the effect of thinning on cumulative productivity than I would have if I had only looked at 2016-2018 yield data. In retrospect, the hand thinning experiment would have benefited from a fourth year to confirm or refute my projections.

When investigating any question in perennial crops such as apples, it is best to collect data over multiple consecutive years, if possible from the same trees. Had we only conducted hand thinning for one year, we might have erroneously concluded that thinning reduces overall productivity. Had that year been an "off" year, as in the one-year hand thinning experiment (Chapters 2 and 3), we might have erroneously concluded that thinning does not promote return bloom or affect juice quality in cider cultivars. While reviewing previous crop load research in apples (Chapter 1), I often wondered if such a Type II Error might not have occurred for previous researchers. Of course, even with a projected fourth year, thinning did not result in greater cumulative yield for some cultivars in our experiments. It is also important to understand crop load as a continuous variable, rather than as a discrete thinning "treatment".

A potentially useful future experiment would compare the effects on cumulative productivity of thinning in the high-crop "on" year only with thinning in both the "on" year and the following "off" year. Given the non-efficacy of off-year thinning (Chapter 2), growers of cider apples would benefit from knowing whether exerting the time, labor, and inputs to thin is worthwhile every year for these cultivars.

My advisor's suggestion to think of yield in terms of "tannins per acre" was ingenious, and I think that should be the way, or at least one lens through which, future researchers view yield in high-tannin cider apples. As I have written several times throughout this thesis, the primary reason for growing these cultivars is, ostensibly, to generate tannins.

As American cidermakers begin to rediscover the historical cider traditions of their own country, it is my hope that they unlearn the notion that dry or tannic ciders are merely "English" or "European": astringency and "body" have been part of the American cidermaking tradition since before 1776, north and south, east and west. I hope and trust that the research presented in this thesis will be a credit to my institution, Cornell University, and a boon to growers of high-tannin cider apples in New York State and beyond. As a cider partisan, I hope my work will result in commercial cideries near and far working more with these high-tannin apples, and moreover, result in me drinking more complex, tannin-rich ciders in the coming years.

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Appendix

Yield data reproduced from Cuthbertson, J.D. and Stickley, R.M. 'The Production of Cider Fruit on Bush Trees. Observations on Yields, 1945-1949', by *The Annual Report of the Agricultural and Horticultural Research Station (The National Fruit and Cider Institute) Long Ashton, Bristol. 1949*, pp. 25-30.

Table A1-1. Three years' yield data from a variety trial by the National Fruit and Cider Institute

a. Faversham (Kent)

Cultivar	Cumulative Yield 1947-1949 (tons/acre)	Biennial Bearing Index
Bulmer's Norman	41.3	0.47
Dabinett	12.2	0.53
Ellis Bitter	33.5	0.41
Foxwhelp	8.8	0.96
Kingston Black	18.2	0.89
Knotted Kernel	16.6	0.81
Medaille d'Or II	27.9	0.77
Michelin	40.6	0.85
Reine des Pommes	36.9	0.50
Royal Wilding	23.6	0.76
Sherrington Norman	36.7	0.67
Silver Cup	21.8	0.64
Sweet Alford	13.2	0.08
Tardive Forestier	30.5	1.00
Yarlington Mill	33.4	0.71
Perthyre	37.9	0.35
Broadleaf Norman	33.4	0.42
Chisel Jersey	27.9	0.31

b. Kings Acre, Hereford

Cultivar	Cumulative Yield 1947-1949 (tons/acre)	Biennial Bearing Index
Bulmer's Norman	31	0.87
Dabinett	22	0.69
Ellis Bitter	21.9	0.53
Foxwhelp	4.2	1.00
Kingston Black	2.8	0.42
Knotted Kernel	4.4	1.00
Medaille d'Or II	5.9	0.95
Michelin	27.9	0.72
Reine des Pommes	15.2	0.66
Royal Wilding	1.1	1.00
Sherrington Norman	10.1	0.65
Silver Cup	4.6	1.00
Sweet Alford	15.2	0.55
Tardive Forestier	9.6	0.90
Yarlington Mill	28.1	0.93
White Close Pippin	20.3	0.24
White Jersey	20.3	0.31
Red Jersey	13.1	0.35
Woodbine	23	0.83

Table A1-2. Cumulative yield and biennial bearing index data from a variety trial at Long Ashton, England, 1945-1949. Reproduced from Cuthbertson & Stickley (1949).

Cultivar	Cumulative Yield 1945-1949 (tons/acre)	Biennial Bearing Index
Sweet Alford	16.8	0.40
Stoke Red	15.0	0.64
Dabinett	13.9	0.58
Knotted Kernel*	3.1	0.13
Woodbine*	2.6	0.60

*No yield in 1945. BBI calculated using yields 1946-1949

Table A1-3. Yield data from a variety trial at Mount Vernon, Washington, USA. Reproduced from Miles et al. (2018). Biennial bearing index (BBI) calculated by David Zakalik.

Cultivar	Rootstock	No. Trees	BBI	Cumulative Yield (lbs/tree)	No. Consecutive Years Observed
Amere de Berthecourt	Bud.9	3	0.34	108	5
Blanc Mollet	Bud.9	1	1.00	149	5
Boutteville	M9	1	0.52	59	5
Bramley's Seedling	M26	1	0.33	634	5
Breakwell's Seedling	M26	3	0.45	466	5
Brown Snout	M106	1	0.25	578	3
Cap of Liberty	M106	2	0.86	472	5
Chisel Jersey	M106	3	0.19	311	5
Cimitiere	M9	1	1.00	160	5
Dabinett	M106	5	0.46	486	5
Finkenwerder Herbstprinz	M106 (3) M9 (1)	4	0.27	267	5
Frequin Rouge	M106	5	0.17	252	5
Golden Russet	M26	2	0.27	364	5
Granniwinkle	M106 (3) Bud.9 (1)	4	0.44	139	5
Gravenstein, Red Worthen	M9	2	0.08	72	4
Harry Masters Jersey	M106	1	0.32	478	5
Hewes Virginia Crab	M9	1	0.32	109	5
Kermerrien	M106	5	0.72	279	5
Major	M9	1	0.67	246	5
Michelin	M106	1	0.67	691	5
Mott Pink	M9	1	0.72	451	5
Muscadet Bernay	M106	3	—	142	—
Peau de Vache	Bud.9	1	0.17	232	5
Redstreak	M106	1	0.18	95	3
Roxbury Russet	Bud.9	1	0.42	28	3
Smith's Cider	Bud.9	1	0.25	150	5
Sweet Alford	M9	1	0.47	117	5
Taliaferro	Bud.9	1	0.21	95	5
Track Zero (Ross Cider)	Bud.9	1	0.68	301	5
Tom Putt	M106 (3) M26 (2)	5	—	465	—
Vilberie	M106	1	—	654	—
Whidbey	M9	1	0.15	105	5
Yarlington Mill	M106	2	0.46	784	4
Zabergau Reinette	M9	1	0.69	473	5

Table A1-4. Yield and biennial bearing index (BBI) data from a trial of four bittersweet cider cultivars planted on 'MM.106' rootstock at Rosemaunde, Herefordshire, England. Reproduced from Wood (1979).

Cultivar	Accumulative crop 1974-79 (tons/hectare)	Mean BBI
Dabinett	105	0.69
Chisel Jersey	103	0.54
Yarlington Mill	91	0.94
Bulmer's Norman	86	0.94

Table A1-5. Percentage of flower clusters borne on shoot termini (as opposed to spurs) in May 2021 in a trial of ten European cider cultivars at the Cornell University Orchards in Ithaca, NY, planted in 2015.

Cultivar	Percent tip bloom (%)	Reputed bearing tendency
Binet Rouge	43.3	Biennial
Brown's Apple	45.6	Biennial
Brown Snout	42.7	Biennial
Chisel Jersey	31.7	Sources conflict
Dabinett*	25.3	Annual
Ellis Bitter	56.6	Annual
Geneva Tremlett's Bitter	3.7	Highly biennial
Harry Masters Jersey	58.4	Annual
Porter's Perfection	37.0	Sources conflict
Vilberie	23.6	Somewhat annual

*'Dabinett' trees in this trial suffered cold damage before planting and grew poorly, with several dying in the first year. Findings for 'Dabinett' should not be taken as representative of this cultivar in general.

Table A1-6. Comparison of different sources' descriptions of the bearing habits of commonly grown cider cultivars

Cultivar	Description of bearing habit				
	Wood (1979)	Green (1987)	Copas (2001, 2013)	Merwin (2015)	Miles et al. (2018)
Brown's Apple	—	"extremely biennial"	"…capable of phenomenal crops, even if biennially."	—	—
Brown Snout	BBI=0.68	—	—	"…biennial but productive…"	—
Bulmer's Norman	BBI=0.68	—	"…do not keep well, especially in the off-year"	—	Biennial
Chisel Jersey	BBI=0.70, 0.54	—	"Bush trees […] crop annually"	"…biennial but productive…"	Consistent
Dabinett	"…only relatively less biennial"; "better than most…"	"more regular" "crops regularly"	"usually heavy and regular"	"annual"	—
Ellis Bitter	—	—	"Cropping is fairly regular and the fruit is heavy."	"…annual and productive…"	—
Geneva Tremlett's Bitter (bittersharp)	—	—	—	"…biennial but productive…"	Consistent
Harry Masters Jersey	—	—	"As a bush tree its crops are not heavy but are fairly regular. Crops from traditional orchards are biennial but good."	"…productive & annual…"	—
Michelin	"…the least biennial of all the bittersweet cultivars currently grown on a large scale."	"very productive (I=0.42)"	"…one of the most reliably annual cropping varieties…"	—	—
Porter's Perfection	BBI=0.87	—	"…heavy crops of small fruit."	"…annual & productive…"	—
Somerset Redstreak	BBI=0.70	"extremely biennial"	"…predictably biennial in its cropping habit…"	"…productive but biennial…"	—
Tremlett's Bitter (true, bittersweet)	"…showing biennial bearing"	"…extremely biennial…" "invariably biennial"	"…very biennial in its cropping…"	—	—
Yarlington Mill	BBI=0.81, 0.94	"very biennial" (citing Wood, 1979)	"…produces reliably, but rather biennially…"	"…biennial but productive…"	Strongly Consistent

Table A2-1. Average trunk cross sectional area (cm^2)[a] of trees in June 2016, three-year hand-thinning experiment, LynOaken Farms.

Target crop load (no. fruit/cm^2 TCSA)	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
0	4.2	3.8	4.0	4.3 ab	4.5	4.3	2.9
3	4.1	3.6	4.7	4.7 ab	3.9	5.2	3.2
6	4.3	3.7	4.8	5.3 a	4.3	4.3	3.2
9	4.1	4.0	5.1	4.0 b	4.0	4.6	3.2
Control	4.1	3.7	4.3	4.2 ab	3.8	4.2	3.0
	NSD	NSD	NSD	$P<0.05$	NSD	NSD	NSD

[a]TCSA was measured 40 cm above the graft union

Table A2-2. Average spring pre-thin crop density (fruit per cm^2 TCSA)[a] in June 2016 of seven cultivars at the outset of a three-year hand-thinning experiment, LynOaken Farms.

Target crop load (no. fruit/cm^2 TCSA)	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
0	21.0	39.3	29.0	24.0	20.3	29.7	20.4
3	18.9	37.3	27.8	23.1	18.8	27.4	19.2
6	19.6	38.3	29.3	24.4	19.1	29.7	20.0
9	19.9	37.6	27.6	23.8	18.7	28.4	19.9
Control	20.2	39.1	30.4	24.8	20.8	29.6	20.2
	NSD	NSD	NSD	NSD	NSD	NSD	NSD

[a]TCSA was measured 40 cm above the graft union

Table A2-3. Estimated full bloom dates (>50% of blossoms open), 2016-2018, of seven cultivars at LynOaken Farms.

Cultivar	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
Full bloom 2016	20th May	26th May	27th May	27th May	26th May	22nd May	23rd May
Full bloom 2017	12th May	28th May	18th May	17th May	17th May	17th May	16th May
Full bloom 2018	16th May	26th May	24th May	20th May	20th May	19th May	18th May

Table A2-4. Number of days from full bloom (DAFB) to fruitlet thinning, 2016-2018, three-year hand-thinning experiment (Exp. 1) and one-year hand-thinning experiment (Exp. 2) at LynOaken Farms.

Cultivar	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
June 21st 2016 DAFB	32	26	25	25	26	30	29
June 30th 2017 DAFB	49	33	43	44	44	44	45
June 15th 2018 DAFB	30	20	22	26	26	27	28

Table A2-5. Harvest dates for seven cultivars in a three-year hand-thinning experiment (Exp. 1) and one-year hand-thinning experiment (Exp. 2), 2016-2018.

Cultivar	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
Harvest date 2016	3^{rd} Oct.	11^{th} Oct.	26^{th} Sept.	11^{th} Oct.	26^{th} Sept.	3^{rd} Oct.	9^{th} Sept.
No. DAFB	136	138	122	137	123	134	109
Harvest date 2017	2^{nd} Oct.	16^{th} Oct.	2^{nd} Oct.	16^{th} Oct.	15^{th} Sept.	25^{th} Sept.	11^{th} Sept.
No. DAFB	143	141	137	152	121	131	118
Harvest date 2018	4^{th} Oct.	16^{th} Oct.	16^{th} Oct.	25^{th} Oct.	13^{th} Sept.	24^{th} Sept.	6^{th} Sept.
No. DAFB	141	143	145	158	116	129	111

Table A2-6. Spring 2017 trunk cross-sectional area (cm^2)[a] of trees used in both hand-thinning experiments at LynOaken Farms.

Target crop load (no. fruit/cm^2 TCSA)	Chisel Jersey (1st Exp.)	Chisel Jersey (2^{nd} Exp.)	Dabinett (1st Exp,)	Dabinett (2^{nd} Exp.)	Harry Masters Jersey (1st Exp.)	Harry Masters Jersey (2^{nd} Exp.)	Michelin (1st Exp.)	Michelin (2^{nd} Exp.)
0	6.9 ab	6.0	6.8 a	5.8	6.6	4.3 a	6.5 ab	4.2
3	6.7 ab	6.2	6.4 a	5.8	5.7	3.2 b	7.3 a	4.4
6	7.1 a	5.8	7.1 a	6.9	5.7	3.6 ab	6.1 ab	4.7
9	6.6 ab	6.0	4.6 b	5.4	5.2	3.6 ab	5.9 ab	4.9
Control	5.5 b	5.6	4.7 b	6.3	5.1	4.2 ab	4.8 b	4.6
	p=0.06	NSD	p<0.001	NSD	NSD		p<0.05	NSD

[a]TCSA was measured 40 cm above the graft union

Table A2-7. Spring 2017 pre-thin crop density (fruitlets/cm^2 TCSA)[a] of trees used in both hand-thinning experiments at LynOaken Farms.

Target crop load (no. fruit/cm^2 TCSA)	Chisel Jersey (1st Exp.)	Chisel Jersey (2^{nd} Exp.)	Dabinett (1st Exp,)	Dabinett (2^{nd} Exp.)	Harry Masters Jersey (1st Exp.)	Harry Masters Jersey (2^{nd} Exp.)	Michelin (1st Exp.)	Michelin (2^{nd} Exp.)
0	30.6 a	23.6	33.5 a	16.4	22.9 a	11.8	31.6 a	16.2
3	29.5 a	21.2	28.1 a	15.8	19.2 a	19.4	30.7 a	14.6
6	29.1 a	23.2	25.3 ab	15.8	20.7 a	15.6	27.6 a	16.6
9	27.3 a	23.0	16.5 b	16.0	22.6 a	14.6	22.7 a	12.8
Control	8.4 b	23.4	0.4 c	15.2	2.4 b	14.4	0.4 b	13.8
	p<0.001	NSD	p<0.001	NSD	p<0.001	NSD	p<0.001	NSD

[a]TCSA was measured 40 cm above the graft union

Table A2-8. Spring 2017 average bloom counts, bloom density, fruitlet count, pre-thin crop density, and fruit:bloom cluster ratios (FBR) of seven cultivars in a three-year hand-thinning experiment at LynOaken Farms.

a. Binet Rouge

Target crop load (no. fruit/cm^2 TCSA)[a]	Flower clusters (no./tree)	Bloom Density (clusters/ cm^2)	Fruitlets (no./ tree)	Pre-thin crop density (no. fruit/ cm^2 TCSA)	Fruit:Bloom cluster ratio
0	52.2 a	10.5 a	94.4 c	19.1 a	1.79
3	21.6 b	4.1 b	29.4 bc	5.7 b	2.35
6	1.0 c	0.2 b	5.4 bc	1.0 b	2.08
9	0.6 c	0.1 b	1.0 b	0.2 b	1.75
Control	0.0 c	0.0 b	0.0 a	0.0 b	—

[a]TCSA measured 40 cm above the graft union

b. Brown Snout

Target crop load (no. fruit/cm^2 TCSA)	Flower clusters (no./tree)	Bloom Density (clusters/ cm^2)	Fruitlets (no./ tree)	Pre-thin crop density (no. fruit/ cm^2 TCSA)	Fruit:Bloom cluster ratio
0	92.4 a	18.4 a	179.4 a	35.7 a	1.99
3	62.4 ab	12.7 ab	125.2 ab	25.7 ab	2.36
6	14.0 bc	3.1 bc	37.0 bc	8.2 bc	2.06
9	47.0 abc	9.1 abc	121.2 ab	23.4 ab	2.80
Control	0.0 c	0.0 c	0.0 c	0.0 c	—

c. Chisel Jersey

Target crop load (no. fruit/cm^2 TCSA)	Flower clusters (no./tree)	Bloom Density (clusters/ cm^2)	Fruitlets (no./ tree)	Pre-thin crop density (no. fruit/ cm^2 TCSA)	Fruit:Bloom cluster ratio
0	188.0 a	27.6 ab	209.0 a	30.6 a	1.11
3	193.0 a	29.2 a	194.8 a	29.5 a	1.01
6	184.8 a	26.4 ab	203.6 a	29.1 a	1.12
9	137.6 a	21.0 b	175.0 a	27.3 a	1.37
Control	21.8 b	3.7 c	50.4 b	8.4 b	1.81

d. Dabinett

Target crop load (no. fruit/cm^2 TCSA)	Flower clusters (no./tree)	Bloom Density (clusters/ cm^2)	Fruitlets (no./ tree)	Pre-thin crop density (no. fruit/ cm^2 TCSA)	Fruit:Bloom cluster ratio
0	114.0 a	16.5 a	227.4 a	33.5 a	2.13 ab
3	98.2 a	15.6 a	176.4 a	28.1 a	1.82 ab
6	113.6 a	15.9 a	180.8 a	25.3 ab	1.60 b
9	56.4 ab	11.2 a	70.4 b	14.3 b	1.66 b
Control	0.6 b	0.1 b	2.0 b	0.4 c	3.75 a

e. Harry Masters Jersey

Target crop load (no. fruit/cm^2 TCSA)	Flower clusters (no./tree)	Bloom Density (clusters/ cm^2)	Fruitlets (no./ tree)	Pre-thin crop density (no. fruit/ cm^2 TCSA)	Fruit:Bloom cluster ratio
0	184.0 a	27.7 a	153.8 a	22.9 a	0.83 b
3	128.0 ab	24.2 a	107.2 a	19.9 a	0.82 b
6	130.0 ab	22.3 ab	120.0 a	20.7 a	0.97 b
9	84.0 b	16.1 b	118.2 a	22.6 a	1.50 b
Control	5.4 c	1.1 c	12.2 b	2.4 b	4.03 a

f. Michelin

Target crop load (no. fruit/cm^2 TCSA)	Flower clusters (no./tree)	Bloom Density (clusters/ cm^2)	Fruitlets (no./ tree)	Pre-thin crop density (no. fruit/ cm^2 TCSA)	Fruit:Bloom cluster ratio
0	147.0 a	23.8 a	199.0 ab	31.6 a	1.37 c
3	136.6 a	19.3 ab	220.2 a	30.7 a	1.71 c
6	8.8 b	14.7 bc	161.4 ab	27.6 a	1.94 bc
9	52.6 b	9.1 c	133.2 b	22.7 a	2.57 ab
Control	0.4 c	0.1 d	1.4 c	0.4 b	3.50 a

g. Geneva Tremlett's Bitter

Target crop load (no. fruit/cm^2 TCSA)	Flower clusters (no./tree)	Bloom Density (clusters/ cm^2)	Fruitlets (no./ tree)	Pre-thin crop density (no. fruit/ cm^2 TCSA)	Fruit:Bloom cluster ratio
0	116.6 a	28.9 a	108.4 a	28.1 a	1.13
3	59.2 ab	15.0 b	91.2 ab	23.4 a	1.65
6	49.2 b	11.8 bc	77.2 ab	19.4 ab	2.24
9	22.0 b	5.3 bc	34.6 bc	8.4 bc	1.38
Control	0.0 b	0.0 c	0.0 c	0.0 c	—

Table A2-9. Fall crop density and yield efficiency of seven cultivars in a three-year hand-thinning experiment at LynOaken Farms, 2016-2018.

a. 'Binet Rouge'

Target crop load (no. fruit/cm^2 TCSA)[a]	Fall 2016 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2017 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2018 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2016 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2017 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2018 Yield efficiency (fruit wt. ·TCSA^{-1})
0	<0.1 d	0.2 b	0.8 c	0.0 d	0.0 b	<0.1 c
3	5.4 c	1.6 a	4.5 bc	0.4 c	0.3 a	0.4 c
6	6.7 c	0.8 ab	8.6 b	0.6 c	<0.1 b	0.8 b
9	10.4 b	0.1 b	10.0 b	0.9 b	<0.1 b	0.9 b
Control	18.6 a	<0.1 b	32.0 a	1.4 a	0.0 b	1.9 a

b. 'Brown Snout'

Target crop load (no. fruit/cm^2 TCSA)	Fall 2016 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2017 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2018 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2016 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2017 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2018 Yield efficiency (fruit wt. ·TCSA^{-1})
0	0.2 c	0.2 b	2.0 c	<0.1 c	<0.1 bc	0.2 c
3	3.6 bc	1.9 b	6.7 bc	0.3 c	0.2 b	0.6 b
6	8.2 b	1.5 b	7.0 bc	0.6 b	0.1 bc	0.6 b
9	7.4 b	4.3 a	11.7 b	0.6 b	0.4 a	0.8 b
Control	28.5 a	0.2 b	44.9 a	1.1 a	<0.1 c	1.7 a

c. 'Chisel Jersey'

Target crop load (no. fruit/cm^2 TCSA)	Fall 2016 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2017 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2018 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2016 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2017 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2018 Yield efficiency (fruit wt. ·TCSA^{-1})
0	0.3 c	1.1 b	0.9 c	<0.1 d	0.1 b	0.1 c
3	3.2 c	3.9 ab	5.4 bc	0.4 c	0.7 ab	0.9 b
6	5.1 bc	7.8 a	9.9 b	0.6 c	1.1 a	1.2 b
9	9.1 b	7.5 a	9.6 b	1.0 b	1.1 a	1.3 b
Control	22.8 a	7.4 a	44.0 a	1.5 a	0.9 a	2.6 a

d. 'Dabinett'

Target crop load (no. fruit/cm^2 TCSA)	Fall 2016 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2017 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2018 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2016 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2017 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2018 Yield efficiency (fruit wt. ·TCSA^{-1})
0	0.3 c	1.1 b	1.8 c	<0.1 c	0.1 b	0.2 b
3	4.2 cd	3.7 ab	11.1 bc	0.5 b	0.6 ab	1.3 a
6	9.1 bc	7.2 a	9.2 b	0.8 a	1.0 a	1.1 a
9	13.0 b	7.2 a	6.2 b	1.0 a	1.0 a	0.9 ab
Control	23.3 a	0.4 b	37.5 a	1.2 a	<0.1 b	1.8 a

e. 'Harry Masters Jersey'

Target crop load (no. fruit/cm^2 TCSA)	Fall 2016 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2017 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2018 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2016 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2017 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2018 Yield efficiency (fruit wt. ·TCSA^{-1})
0	0.0 d	0.7 c	1.7 c	0.0 b	0.1 b	0.2 c
3	3.3 c	3.7 bc	4.9 bc	0.4 a	0.5 ab	0.6 b
6	5.1 bc	6.5 ab	7.4 b	0.6 ab	0.9 a	0.9 b
9	7.8 b	7.4 a	8.6 b	0.8 a	1.0 a	1.0 b
Control	14.1 a	1.8 c	27.5 a	1.2 a	0.4 b	1.4 a

f. 'Michelin'

Target crop load (no. fruit/cm^2 TCSA)	Fall 2016 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2017 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2018 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2016 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2017 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2018 Yield efficiency (fruit wt. ·TCSA^{-1})
0	0.3 c	0.3 b	2.1 d	<0.1	<0.1 c	—
3	2.0 bc	1.6 b	3.0 cd	0.2	0.2 b	0.3 c
6	3.6 bc	3.2 a	5.7 c	0.8	0.3 a	0.6 c
9	5.2 b	3.4 a	11.0 b	0.4	0.3 a	1.0 b
Control	14.1 a	0.2 b	44.7 a	0.7	<0.1 c	2.0 a

g. 'Geneva Tremlett's Bitter'

Target crop load (no. fruit/cm^2 TCSA)	Fall 2016 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2017 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2018 Post-thin crop density (fruit no. ·TCSA^{-1})	Fall 2016 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2017 Yield efficiency (fruit wt. ·TCSA^{-1})	Fall 2018 Yield efficiency (fruit wt. ·TCSA^{-1})
0	0.1 d	0.0 b	1.6 c	<0.1 d	<0.1 b	0.2 c
3	3.4 cd	3.0 ab	4.8 bc	0.4 c	0.4 ab	0.6 bc
6	5.8 bc	4.8 a	7.7 bc	0.6 bc	0.6 a	0.9 bc
9	7.7 b	3.3 ab	10.2 b	0.7 b	0.4 ab	1.1 b
Control	18.4 a	0.0 b	21.7 a	1.4 a	0.0 b	1.8 a

Table A2-10. Average fruit weight of seven cultivars harvested from a three-year hand-thinning experiment at LynOaken Farms in Lyndonville, NY 2016-2018.

a. Binet Rouge

Target crop load (no. fruit/cm² TCSA)[a]	Fall 2016 Average Fruit Weight (g)	Fall 2017 Average Fruit Weight (g)	Fall 2018 Average Fruit Weight (g)
0	—	0.0 b	96.7 a
3	95.8 a	117.4 a	89.9 a
6	95.8 a	79.5 ab	94.6 a
9	91.2 a	30.0 b	89.3 a
Control	74.8 b	0.0 b	61.6 b

[a]TCSA was measured 40 cm above the graft union

b. Brown Snout

Target crop load (no. fruit/cm² TCSA)	Fall 2016 Average Fruit Weight (g)	Fall 2017 Average Fruit Weight (g)	Fall 2018 Average Fruit Weight (g)
0	93.0 a	42.5 ab	78.8 a
3	81.8 a	93.7 a	94.9 a
6	70.2 a	78.6 ab	78.5 a
9	81.2 a	84.8 ab	74.6 a
Control	38.4 b	20.0 b	38.2 b

c. Chisel Jersey

Target crop load (no. fruit/cm² TCSA)	Fall 2016 Average Fruit Weight (g)	Fall 2017 Average Fruit Weight (g)	Fall 2018 Average Fruit Weight (g)
0	65.0 b	127.2 b	157.7 ab
3	138.0 a	169.3 a	171.7 a
6	121.4 a	140.1 ab	129.0 c
9	107.2 a	144.7 ab	133.3 bc
Control	67.4 b	134.2 b	59.2 b

d. Dabinett

Target crop load (no. fruit/cm² TCSA)	Fall 2016 Average Fruit Weight (g)	Fall 2017 Average Fruit Weight (g)	Fall 2018 Average Fruit Weight (g)
0	93.0 a	66.7 b	126.4 a
3	118.2 a	188.5 a	123.4 a
6	92.4 ab	152.1 ab	127.2 a
9	82.4 ab	135.5 ab	129.6 a
Control	50.6 b	130.0 ab	32.6 b

e. Harry Masters Jersey

Target crop load (no. fruit/cm² TCSA)	Fall 2016 Average Fruit Weight (g)	Fall 2017 Average Fruit Weight (g)	Fall 2018 Average Fruit Weight (g)
0	—	142.2	137.9 a
3	122.0 a	153.5	127.9 a
6	107.6 a	141.1	133.0 a
9	106.6 a	131.9	111.4 a
Control	82.0 b	172.9	52.8 b

f. Michelin

Target crop load (no. fruit/cm² TCSA)	Fall 2016 Average Fruit Weight (g)	Fall 2017 Average Fruit Weight (g)	Fall 2018 Average Fruit Weight (g)
0	—	75.0 ab	—
3	81.1	99.5 a	107.6 a
6	86.5	92.5 a	106.3 a
9	77.3	94.4 a	95.0 b
Control	50.2	36.0 b	44.0 c

g. Geneva Tremlett's Bitter

Target crop load (no. fruit/cm² TCSA)	Fall 2016 Average Fruit Weight (g)	Fall 2017 Average Fruit Weight (g)	Fall 2018 Average Fruit Weight (g)
0	120.0 a	104.7 a	119.1 ab
3	113.6 a	136.1 a	133.6 a
6	108.0 a	124.6 a	114.3 ab
9	99.4 ab	67.7 ab	108.6 ab
Control	74.4 b	0.0 b	92.2 b

Table A2-11. Return bloom of seven cultivars in a three-year hand-thinning experiment counted at LynOaken Farms in Lyndonville, NY 2017-2019.

a. 'Binet Rouge'

Target crop load (no. fruit/cm² TCSA)[a,b]	Spring 2017 Flower clusters/tree	Spring 2017 Flower clusters/cm² TCSA	Spring 2018 Flower clusters/tree	Spring 2018 Flower clusters/cm² TCSA	Spring 2019 Flower clusters/tree	Spring 2019 Flower clusters/cm² TCSA
0	52.2 a	10.5 a	290 b	58.9	370 a	52.9 a
3	21.6 b	4.1 b	397 ab	79.0	254 ab	25.5 b
6	1.0 c	0.2 b	469 a	74.6	180 b	25.3 b
9	0.6 c	0.1 b	433 a	74.4	156 bc	17.8 b
Control	0.0 c	0.0 b	368 ab	61.1	18 c	3.6 b

[a]TCSA was measured 40 cm above the graft union

[b]Treatments applied spring Spring 2016-2018, bloom counts recorded spring 2017-2019

b. 'Brown Snout'

Target crop load (no. fruit/cm² TCSA)	Spring 2017 Flower clusters/tree	Spring 2017 Flower clusters/cm² TCSA	Spring 2018 Flower clusters/tree	Spring 2018 Flower clusters/cm² TCSA	Spring 2019 Flower clusters/tree	Spring 2019 Flower clusters/cm² TCSA
0	92.4 a	18.4 a	218	31.6	341 a	35.9 ab
3	62.4 ab	12.7 ab	194	26.6	334 a	36.4 a
6	14.0 bc	3.1 bc	265	31.6	226 ab	24.4 bc
9	47.0 abc	9.1 abc	223	31.0	154 b	19.1 c
Control	0.0 c	0.0 c	144	16.4	0 c	0.0 d

c. 'Chisel Jersey'

Target crop load (no. fruit/cm² TCSA)	Spring 2017 Flower clusters/tree	Spring 2017 Flower clusters/cm² TCSA	Spring 2018 Flower clusters/tree	Spring 2018 Flower clusters/cm² TCSA	Spring 2019 Flower clusters/tree	Spring 2019 Flower clusters/cm² TCSA
0	188.0 a	27.6 ab	295	37.6	338 a	39.1 a
3	193.0 a	29.2 a	284	45.4	364 a	35.5 a
6	184.8 a	26.4 ab	255	27.6	248 a	24.4 b
9	137.6 a	21.0 b	209	28.9	270 a	26.8 b
Control	21.8 b	3.7 c	287	39.7	0 b	0.0 c

d. 'Dabinett'

Target crop load (no. fruit/cm² TCSA)	Spring 2017 Flower clusters/tree	Spring 2017 Flower clusters/cm² TCSA	Spring 2018 Flower clusters/tree	Spring 2018 Flower clusters/cm² TCSA	Spring 2019 Flower clusters/tree	Spring 2019 Flower clusters/cm² TCSA
0	114.0 a	16.5 a	245	35.7	241 a	20.4 a
3	98.2 a	15.6 a	230	31.6	217 a	21.3 a
6	113.6 a	15.9 a	257	41.5	257 a	21.6 a
9	56.4 ab	11.2 a	202	29.0	217 a	27.2 a
Control	0.6 b	0.1 b	188	27.8	1 b	0.1 b

e. 'Harry Masters Jersey'

Target crop load (no. fruit/cm² TCSA)	Spring 2017 Flower clusters/tree	Spring 2017 Flower clusters/cm² TCSA	Spring 2018 Flower clusters/tree	Spring 2018 Flower clusters/cm² TCSA	Spring 2019 Flower clusters/tree	Spring 2019 Flower clusters/cm² TCSA
0	184.0 a	27.7 a	325 b	50.7 ab	368 a	34.6 a
3	128.0 ab	24.2 a	161 a	25.0 bc	289 a	32.1 a
6	130.0 ab	22.3 ab	145 a	26.2 bc	246 a	36.6 a
9	84.0 b	16.1 b	132 a	21.3 c	326 a	34.6 a
Control	5.4 c	1.1 c	346 b	61.1 a	10 b	1.2 b

f. 'Michelin'

Target crop load (no. fruit/cm² TCSA)	Spring 2017 Flower clusters/tree	Spring 2017 Flower clusters/cm² TCSA	Spring 2018 Flower clusters/tree	Spring 2018 Flower clusters/cm² TCSA	Spring 2019 Flower clusters/tree	Spring 2019 Flower clusters/cm² TCSA
0	147.0 a	23.8 a	429	71.9	427 a	40.2 a
3	136.6 a	19.3 ab	421	77.6	448 a	36.1 a
6	85.8 b	14.7 bc	307	65.0	285 b	30.8 ab
9	52.6 b	9.1 c	325	54.4	211 b	21.4 b
Control	0.4 c	0.1 d	391	71.6	1 c	0.1 c

g. 'Tremlett's Bitter'

Target crop load (no. fruit/cm² TCSA)	Spring 2017 Flower clusters/tree	Spring 2017 Flower clusters/cm² TCSA	Spring 2018 Flower clusters/tree	Spring 2018 Flower clusters/cm² TCSA	Spring 2019 Flower clusters/tree	Spring 2019 Flower clusters/cm² TCSA
0	116.6 a	28.9 a	170	22.6	181 ab	32.6 a
3	59.2 ab	15.0 b	162	25.2	189 a	36.7 a
6	49.2 b	11.8 bc	108	16.6	119 ab	21.2 ab
9	22.0 b	5.3 bc	186	24.0	69 bc	12.5 bc
Control	0.0 b	0.0 c	218	29.1	0 c	0.0 c

Table A2-12. Trunk cross sectional area (TCSA)[a] of seven cultivars in a three-year hand-thinning experiment counted at LynOaken Farms in Lyndonville, NY 2016-2018.

a. 'Binet Rouge'

Target crop load (no. fruit/cm² TCSA)	June 2016 TCSA (cm²)	Dec. 2016 TCSA (cm²)	Nov. 2017 TCSA (cm²)	Apr. 2019 TCSA (cm²)
0	4.2	5.2	5.7	7.3
3	4.1	5.1	7.2	10.4
6	4.3	5.5	6.2	8.0
9	4.1	4.5	6.6	8.5
Control	4.2	4.6	5.7	6.6

[a]TCSA was measured 40 cm above the graft union

b. 'Brown Snout'

Target crop load (no. fruit/cm² TCSA)	June 2016 TCSA (cm²)	Dec. 2016 TCSA (cm²)	Nov. 2017 TCSA (cm²)	Apr. 2019 TCSA (cm²)
0	3.8	5.0 a	6.7 a	9.6 a
3	3.6	4.9 ab	6.4 ab	9.2 a
6	3.7	4.3 bc	6.3 ab	8.9 a
9	4.0	5.1 a	6.3 ab	8.1 ab
Control	3.7	3.7 c	5.1 b	5.9 b

c. 'Chisel Jersey'

Target crop load (no. fruit/cm² TCSA)	June 2016 TCSA (cm²)	Dec. 2016 TCSA (cm²)	Nov. 2017 TCSA (cm²)	Apr. 2019 TCSA (cm²)
0	4.0	6.9	7.9	10.3
3	4.7	6.7	7.5	10.3
6	4.6	7.1	8.2	10.7
9	4.8	6.6	7.6	10.1
Control	4.4	5.5	7.4	8.5

d. 'Dabinett'

Target crop load (no. fruit/cm² TCSA)	June 2016 TCSA (cm²)	Dec. 2016 TCSA (cm²)	Nov. 2017 TCSA (cm²)	Apr. 2019 TCSA (cm²)
0	4.3 ab	6.8 a	8.6 ab	11.8 a
3	4.7 ab	6.4 a	7.8 abc	10.5 ab
6	5.3 a	7.1 a	9.1 a	12.1 a
9	4.0 b	4.9 b	6.1 c	8.0 b
Control	4.2 ab	4.7 b	6.9 bc	7.7 b

e. 'Harry Masters Jersey'

Target crop load (no. fruit/cm² TCSA)	June 2016 TCSA (cm²)	Dec. 2016 TCSA (cm²)	Nov. 2017 TCSA (cm²)	Apr. 2019 TCSA (cm²)
0	4.5	6.6	8.1	10.8
3	3.9	5.3	6.2	9.0
6	4.3	5.7	7.0	9.7
9	4.1	5.2	7.1	9.6
Control	4.0	5.1	7.0	8.4

f. 'Michelin'

Target crop load (no. fruit/cm² TCSA)	June 2016 TCSA (cm²)	Dec. 2016 TCSA (cm²)	Nov. 2017 TCSA (cm²)	Apr. 2019 TCSA (cm²)
0	4.3	6.5 ab	8.2 ab	10.7 ab
3	5.2	7.3 a	10.1 a	13.0 a
6	4.6	6.1 ab	7.1 ab	9.3 ab
9	4.6	5.9 ab	7.4 ab	9.8 ab
Control	4.4	4.8 b	7.1 b	8.4 b

g. 'Geneva Tremlett'

Target crop load (no. fruit/cm² TCSA)	June 2016 TCSA (cm²)	Dec. 2016 TCSA (cm²)	Nov. 2017 TCSA (cm²)	Apr. 2019 TCSA (cm²)
0	2.9	3.9	4.4	5.6
3	3.2	3.9	4.2	5.2
6	3.2	3.9	4.8	6.0
9	3.2	3.9	4.6	5.5
Control	3.0	3.4	5.1	5.6

Table A2-13. Percent change in trunk cross-sectional area (TCSA) of seven cultivars in a three-year hand-thinning experiment counted at LynOaken Farms in Lyndonville, NY 2016-2018.

a. 'Binet Rouge'

Target crop load (no. fruit/cm^2 TCSA)	Percent Change, 2016	Percent Change, 2017	Percent Change, 2018
0	32.3 a	13.3	27.1 ab
3	27.8 ab	40.1	45.1 a
6	28.6 ab	17.2	27.9 ab
9	20.3 ab	47.3	28.8 ab
Control	10.4 b	25.0	16.0 b

e. 'Harry Masters Jersey'

Target crop load (no. fruit/cm^2 TCSA)	Percent Change, 2016	Percent Change, 2017	Percent Change, 2018
0	48.7	21.7 ab	34.0
3	36.4	12.8 b	45.1
6	33.6	21.2 ab	38.0
9	25.3	35.6 a	33.7
Control	30.4	40.4 a	20.0

a. 'Brown Snout'

Target crop load (no. fruit/cm^2 TCSA)	Percent Change, 2016	Percent Change, 2017	Percent Change, 2018
0	33.2 a	33.6	42.3 a
3	38.1 a	32.5	36.5 ab
6	17.5 ab	46.7	48.6 a
9	27.5 a	25.7	26.9 ab
Control	1.8 b	36.2	15.5 b

f. 'Michelin'

Target crop load (no. fruit/cm^2 TCSA)	Percent Change, 2016	Percent Change, 2017	Percent Change, 2018
0	49.7 a	26.6	32.0
3	42.3 ab	39.5	28.9
6	35.3 ab	20.5	31.0
9	29.9 ab	27.5	31.8
Control	6.3 b	49.8	18.1

c. 'Chisel Jersey'

Target crop load (no. fruit/cm^2 TCSA)	Percent Change, 2016	Percent Change, 2017	Percent Change, 2018
0	69.8 a	15.1 ab	38.3
3	41.7 bc	13.7 b	34.1
6	53.4 ab	15.8 ab	32.0
9	36.3 bc	15.6 ab	34.2
Control	22.3 c	35.4 a	15.7

g. 'Geneva Tremlett'

Target crop load (no. fruit/cm^2 TCSA)	Percent Change, 2016	Percent Change, 2017	Percent Change, 2018
0	34.8	15.5 b	24.3
3	21.2	10.1 b	25.3
6	24.4	27.1 ab	24.8
9	23.4	16.6 b	20.6
Control	12.8	50.2 a	10.2

d. 'Dabinett'

Target crop load (no. fruit/cm^2 TCSA)	Percent Change, 2016	Percent Change, 2017	Percent Change, 2018
0	58.2 a	28.2	37.1
3	38.2 ab	21.9	23.6
6	34.7 ab	29.2	43.2
9	22.5 b	29.3	44.8
Control	13.5 b	48.3	13.1

Table A2-14. Comparison of return bloom of four cultivars in the main three-year hand-thinning experiment (Exp. 1) and one-year hand-thinning experiment (Exp. 2).

Spring 2018 Return Bloom Density (Flower clusters/cm² TCSA)								
2017 Crop load treatment (fruit no. /cm²)	Chisel Jersey (Exp. 1)	Chisel Jersey (Exp. 2)	Dabinett (Exp. 1)	Dabinett (Exp. 2)	Harry Masters Jersey (Exp. 1)	Harry Masters Jersey (Exp. 2)	Michelin (Exp. 1)	Michelin (Exp. 2)
0	43.3	60.9 c	35.7	41.7 b	50.7 ab	31.1 a	71.9	39.0
3	41.4	46.2 bc	31.9	33.2 ab	23.5 bc	30.1 a	77.6	49.4
6	27.8	31.7 ab	47.7	37.2 ab	26.2 bc	25.9 ab	55.4	46.7
9	28.7	46.7 bc	27.5	36.9 ab	19.7 c	34.5 a	58.1	42.6
Control	35.0	14.8 a	33.0	19.7 a	60.3 a	8.8 b	65.4	43.4
Treatment	0.09	<0.001	<0.01	<0.001	<0.01	<0.001	<0.001	0.14
Experiment	0.30		0.82		0.06		<0.001	

Second Hand-Thinning Experiment (2017 Only)

Table A2-15. Spring and fall trunk cross sectional area (TCSA), spring crop density (prior to hand thinning), yield (fruit no. and fruit wt., including drops), crop density (including drops), yield efficiency (including drops), preharvest drops, and mean fruit weight of four cultivars in a one year hand-thinning experiment (Exp. 2) thinned in 2017 only.

a. Chisel Jersey

Target crop load (no. fruit/cm² TCSA)	Sp. 2017 TCSA (cm²)	Nov. 2017 TCSA (cm²)	Pre-thin crop density (fruit no. ·TCSA⁻¹)	Yield (fruit no.)	Yield (kg fruit)	Post-thin crop density (fruit no. ·TCSA⁻¹)	Yield efficiency (fruit wt. ·TCSA⁻¹)	Preharvest drops (%)	Mean fruit wt. (g)	May 2018 Flower no./tree	May 2018 Flower density (flower cluster no.·TCSA⁻¹)
0	6.0	7.4	23.6	4.6 c	0.6 c	0.7 c	0.1 c	27.0	110.0 b	276 b	60.9 c
3	6.2	8.0	21.2	28.0 bc	5.5 b	3.5 bc	0.7 bc	55.6	201.3 a	258 b	46.2 bc
6	5.8	7.6	23.2	39.2 b	6.2 b	5.2 bc	0.8 b	66.0	159.4 ab	195 ab	31.7 ab
9	6.0	7.9	23.0	51.4 b	8.1 b	7.2 b	1.1 ab	47.6	160.0 ab	239 b	46.7 bc
Control	5.6	7.0	23.4	98.6 a	11.2 a	14.4 a	1.7 a	46.8	113.4 b	118 a	14.8 a

b. Dabinett

Target crop load (no. fruit/cm² TCSA)	TCSA (cm²)	Nov. 2017 TCSA (cm²)	Pre-thin crop density (fruit no. ·TCSA⁻¹)	Yield (fruit no.)	Yield (kg fruit)	Post-thin crop density (fruit no. ·TCSA⁻¹)	Yield efficiency (fruit wt. ·TCSA⁻¹)	Preharvest drops (%)	Mean fruit wt. (g)	May 2018 Flower no./tree	May 2018 Flower density (flower cluster no.·TCSA⁻¹)
0	5.8	8.5	16.4	5.0 d	1.0 c	0.6 d	0.1 b	80.0	79.6 b	267	41.7 b
3	5.8	7.1	15.8	28.6 cd	4.6 bc	4.0 cd	0.7 ab	74.8	173.1 a	231	33.2 ab
6	6.9	9.2	15.8	42.8 bc	6.4 b	4.8 bc	0.7 ab	68.4	149.9 ab	217	37.2 ab
9	5.4	7.5	16.0	55.6 b	7.6 ab	8.0 ab	1.1 a	79.0	137.1 ab	200	36.9 ab
Control	6.3	8.6	15.2	96.6 a	11.1 a	11.2 a	1.3 a	61.6	113.5 ab	163	19.7 a

c. Harry Masters Jersey

Target crop load (no. fruit/cm^2 TCSA)	TCSA (cm^2)	Nov. 2017 TCSA (cm^2)	Pre-thin crop density (fruit no. ·TCSA^{-1})	Yield (fruit no.)	Yield (kg fruit)	Post-thin crop density (fruit no. ·TCSA^{-1})	Yield efficiency (fruit wt. ·TCSA^{-1})	Preharvest drops (%)	Mean fruit wt. (g)	May 2018 Flower no./tree	May 2018 Flower density (flower cluster no.·TCSA^{-1})
0	4.3 a	5.5	11.8	7.6 b	1.2 c	1.3 b	0.2 c	5.7 b	94.1 b	232 b	31.1 a
3	3.2 b	4.8	19.4	14.4 b	2.9 bc	3.0 b	0.6 bc	57.8 a	205.7 a	215 b	30.1 a
6	3.6 ab	5.4	15.6	26.0 b	4.4 ab	4.9 b	0.8 abc	49.0 a	168.2 ab	191 b	25.9 ab
9	3.6 ab	4.6	14.6	32.4 b	6.0 ab	7.5 ab	1.4 ab	53.4 a	156.0 ab	194 b	34.5 a
Control	4.2 ab	5.0	14.4	62.0 a	7.0 a	12.8 a	1.4 a	42.0 a	113.3 b	56 a	8.8 b

d. Michelin

Target crop load (no. fruit/cm^2 TCSA)	TCSA (cm^2)	Nov. 2017 TCSA (cm^2)	Pre-thin crop density (fruit no. ·TCSA^{-1})	Yield (fruit no.)	Yield (kg fruit)	Post-thin crop density (fruit no. ·TCSA^{-1})	Yield efficiency (fruit wt. ·TCSA^{-1})	Preharvest drops (%)	Mean fruit wt. (g)	May 2018 Flower no./tree	May 2018 Flower density (flower cluster no.·TCSA^{-1})
0	4.2	6.6	16.2	4.2	0.3	0.6	0.05	95.0	42.2	307 b	39.0
3	4.4	6.2	14.6	15.6	1.4	2.6	0.22	83.6	90.8	326 ab	49.4
6	4.7	7.0	16.6	15.8	1.4	2.5	0.22	81.0	89.0	333 ab	46.7
9	4.9	7.0	12.8	23.4	1.8	3.5	0.27	73.0	77.9	291 b	42.6
Control	4.6	6.8	13.8	14.2	1.2	2.3	0.20	73.8	73.4	345 a	43.4

Table A2-16. Crop density and yield efficiency of four cultivars in a one-year hand-thinning experiment at LynOaken Farms (Exp. 2), thinned in 2017 only.

Target crop load treatment (fruit no. /cm^2)	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin
Crop Density (fruit/cm^2 TCSA)				
0	35.1 ab	44.7	41.2	39.6
3	39.9 a	38.5	37.4	45.6
6	33.9 ab	33.0	30.9	46.3
9	37.5 ab	39.8	32.5	47.8
Control	27.5 b	40.8	18.9	43.2
$p_{treatment}$	0.019	0.486	0.09	0.727
Yield Efficiency (kg/cm^2 TCSA)				
0	2.2	2.0	1.8	1.8
3	2.5	2.3	1.9	1.7
6	2.2	1.8	1.6	1.9
9	2.2	2.2	1.8	1.9
Control	2.0	2.3	1.1	1.9
$p_{treatment}$	0.190	0.568	0.077	0.797

Table A2-17. Comparison of expected revenues and harvest costs of seven cultivars from a three-year hand-thinning experiment at LynOaken Farms. Three-year expected revenues and costs were based on observed data; four-year revenues and costs were based on projected yields from Spring 2019 bloom data.

Variety	Three-Year Revenue ($/ha)	Three-Year Harvest Cost ($/ha)	Projected Four-Year Revenue ($/ha)	Projected Four-Year Harvest Cost ($/ha)
Binet Rouge				
3 fruit/cm^2	13,193 b	1,013 b	19,786 c	1,390 b
6 fruit/cm^2	17,731 ab	1,297 b	25,852 bc	1,761 b
9 fruit/cm^2	20,083 ab	1,629 b	35,725 ab	2,523 a
Un-thinned	27,421 a	2,611 a	31,250 a	2,830 a
Brown Snout				
3 fruit/cm^2	13,512 b	859 c	17,627 b	1,094 b
6 fruit/cm^2	14,728 b	1,403 bc	21,736 b	2,070 a
9 fruit/cm^2	21,199 ab	1,736 b	31,828 a	2,748 a
Un-thinned	24,085 a	2,294 a	24,085 ab	2,294 a
Chisel Jersey				
3 fruit/cm^2	26,013 b	1,758 b	34,470 b	2,241 b
6 fruit/cm^2	46,838 ab	2,976 ab	63,582 ab	3,933 ab
9 fruit/cm^2	47,044 ab	3,217 ab	69,501 a	4,500 a
Un-thinned	61,744 a	4,243 a	61,757 ab	4,244 a
Dabinett				
3 fruit/cm^2	37,341	2,530	46,709	3,066
6 fruit/cm^2	55,347	3,875	75,210	5,010
9 fruit/cm^2	33,381	2,379	51,298	3,403
Un-thinned	37,744	2,819	37,756	2,820
Harry Masters Jersey				
3 fruit/cm^2	19,394 b	1,333 b	26,808 b	1,757 b
6 fruit/cm^2	30,753 ab	2,189 ab	44,755 a	2,989 a
9 fruit/cm^2	33,438 ab	2,334 ab	52,186 a	3,406 a
Un-thinned	35,082 a	2,625 a	35,698 ab	2,660 ab
Michelin				
3 fruit/cm^2	12,231 b	883 c	18,866 c	1,262 b
6 fruit/cm^2	16,617 b	1,190 bc	25,605 bc	1,704 b
9 fruit/cm^2	27,104 a	2,213 ab	41,869 a	3,057 a
Un-thinned	33,131 a	3,155 a	33,190 ab	3,161 a
Geneva Tremlett's Bitter				
3 fruit/cm^2	11,326 b	758 b	14,972 b	966 b
6 fruit/cm^2	16,057 ab	1,083 b	23,087 ab	1,484 ab
9 fruit/cm^2	18,296 ab	1,393 ab	27,873 a	1,940 a
Un-thinned	21,976 a	2,093 a	21,976 ab	2,093 a

Table A3-1. Cumulative three-year yield (kg/tree) of seven cultivars in a three-year hand-thinning experiment at LynOaken Farms, reproduced from Chapter 2.

Target crop load (no. fruit/cm^2 TCSA)	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
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	7.9 c	15.2 bc	21.8 a	11.3 b	7.2 b	6.6 bc
6	10.4 bc	8.6 bc	27.4 ab	32.4 a	18.0 ab	9.7 b	9.4 ab
9	11.7 ab	12.4 ab	27.5 ab	19.5 a	19.6 a	15.9 a	10.7 ab
Control	16.0 a	14.1 a	36.8 a	22.1 a	20.5 a	19.4 a	12.9 a

Table A3-2. Projected 2019 fruit yield (kg/per tree) of seven cultivars in a three-year hand-thinning experiment at LynOaken Farms, extrapolated from spring bloom data. Reproduced from Chapter 2.

Target crop load (no. fruit/cm^2 TCSA)	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

Table A3-3. Estimated cumulative three-year tannin yield per tree (g GAE/tree) of seven cultivars in a three-year hand-thinning experiment at LynOaken Farms. Estimates are extrapolated from measured total polyphenol, extraction volume, and yield data (2016-2018).

Target crop load (no. fruit/cm^2 TCSA)	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
0	—	—	—	—	—	—	—
3	27.9	14.8	57.3	46.8	30.5	14.3 c	14.6 b
6	29.1	14.4	66.2	60.8	45.3	16.5 bc	19.8 b
9	28.6	19.8	72.0	38.4	50.1	27.0 ab	22.3 ab
Control	32.1	20.4	73.9	51.3	44.9	30.0 a	29.8 a

Table A3-4. Projected cumulative four-year tannin yield (g GAE/tree) of seven cultivars in a three-year hand-thinning experiment at LynOaken Farms. Projections are extrapolated from spring 2019 bloom data and previous years' yield and juice quality data.

Target crop load (no. fruit/cm^2 TCSA)	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
0	—	—	—	—	—	—	—
3	41.9	19.1	73.9	59.2	42.1	21.2	19.7
6	44.3	21.1	94.9	86.0	66.1	25.1	29.0
9	55.2	29.5	107.2	60.5	77.1	40.4	35.1
Control	38.6	20.4	73.9	51.3	46.0	30.1	29.8

Table A3-5. Average starch pattern index (SPI) of ten-fruit subsets from seven apple cultivars harvested at LynOaken Farms 2016-2018.

a. 'Binet Rouge'

Target crop load (no. fruit/cm² TCSA)	Fall 2016 SPI (1-8)	Fall 2017 SPI (1-8)	Fall 2018 SPI (1-8)
0	—	—	—
3	2.8	6.3	5.2
6	3.7	6.6	5.4
9	3.0	7.8	5.6
Control	3.3	—	6.7

b. 'Brown Snout'

Target crop load (no. fruit/cm² TCSA)	Fall 2016 SPI (1-8)	Fall 2017 SPI (1-8)	Fall 2018 SPI (1-8)
0	—	—	—
3	2.9 b	6.5	4.5 b
6	2.7 b	6.2	5.0 b
9	2.8 b	5.4	4.8 b
Control	4.2 a	6.9	6.8 a

c. 'Chisel Jersey'

Target crop load (no. fruit/cm² TCSA)	Fall 2016 SPI (1-8)	Fall 2017 SPI (1-8)	Fall 2018 SPI (1-8)
0	—	—	—
3	3.0 a	6.3	5.9
6	2.6 ab	5.8	5.2
9	2.3 ab	6.1	5.1
Control	2.1 b	6.5	6.3

d. 'Dabinett'

Target crop load (no. fruit/cm² TCSA)	Fall 2016 SPI (1-8)	Fall 2017 SPI (1-8)	Fall 2018 SPI (1-8)
0	—	—	—
3	4.0	7.5	6.6
6	2.7	7.2	6.5
9	2.9	6.6	6.9
Control	2.5	7.4	5.8

e. 'Harry Masters Jersey'

Target crop load (no. fruit/cm² TCSA)	Fall 2016 SPI (1-8)	Fall 2017 SPI (1-8)	Fall 2018 SPI (1-8)
0	—	—	—
3	3.6	4.8 ab	2.5
6	4.3	4.5 bc	2.4
9	4.8	3.5 c	2.2
Control	3.5	6.2 a	2.0

f. 'Michelin'

Target crop load (no. fruit/cm² TCSA)	Fall 2016 SPI (1-8)	Fall 2017 SPI (1-8)	Fall 2018 SPI (1-8)
0	—	—	—
3	6.3 a	7.7	6.0
6	5.7 a	7.9	6.0
9	5.4 ab	7.8	4.7
Control	3.2 b	3.9	4.3

g. 'Geneva Tremlett's Bitter'

Target crop load (no. fruit/cm² TCSA)	Fall 2016 SPI (1-8)	Fall 2017 SPI (1-8)	Fall 2018 SPI (1-8)
0	—	—	—
3	5.9	6.6	4.6 c
6	6.4	6.3	6.1 b
9	6.9	6.1	6.7 ab
Control	7.0	—	7.1 a

Table A3-6. Pre-harvest drop (% of total apples) of seven apple cultivars from a three-year hand-thinning experiment at LynOaken Farms 2016-2018

a. ‘Binet Rouge’

Target crop load (no. fruit/cm^2 TCSA)	Fall 2016 Pre-harvest drops (%)	Fall 2017 Pre-harvest drops (%)	Fall 2018 Pre-harvest drops (%)
0	0.0 b	16.5	16.3 ab
3	6.8 ab	43.0	6.8 b
6	29.5 a	25.0	19.3 ab
9	10.6 ab	50.0	10.5 ab
Control	25.6 ab	100.0	41.1 a

b. ‘Brown Snout’

Target crop load (no. fruit/cm^2 TCSA)	Fall 2016 Pre-harvest drops (%)	Fall 2017 Pre-harvest drops (%)	Fall 2018 Pre-harvest drops (%)
0	—	100.0	51.7 b
3	22.7	67.1	52.2 b
6	35.3	67.7	65.7 ab
9	22.2	67.1	79.0 a
Control	31.2	100.0	73.5 a

c. ‘Chisel Jersey’

Target crop load (no. fruit/cm^2 TCSA)	Fall 2016 Pre-harvest drops (%)	Fall 2017 Pre-harvest drops (%)	Fall 2018 Pre-harvest drops (%)
0	75.0 a	51.2	54.2 ab
3	43.3 a	45.5	74.0 a
6	49.0 a	55.5	59.5 a
9	46.8 a	56.3	64.5 a
Control	5.4 b	27.1	24.5 b

d. ‘Dabinett’

Target crop load (no. fruit/cm^2 TCSA)	Fall 2016 Pre-harvest drops (%)	Fall 2017 Pre-harvest drops (%)	Fall 2018 Pre-harvest drops (%)
0	54.2	86.5	68.6
3	24.5	74.6	57.8
6	14.3	78.2	53.5
9	15.6	74.5	60.6
Control	11.0	85.0	57.0

e. ‘Harry Masters Jersey’

Target crop load (no. fruit/cm^2 TCSA)	Fall 2016 Pre-harvest drops (%)	Fall 2017 Pre-harvest drops (%)	Fall 2018 Pre-harvest drops (%)
0	—	73.8	30.3
3	57.4	43.9	48.9
6	72.9	48.1	52.4
9	76.9	43.2	50.9
Control	72.7	73.9	30.3

f. ‘Michelin’

Target crop load (no. fruit/cm^2 TCSA)	Fall 2016 Pre-harvest drops (%)	Fall 2017 Pre-harvest drops (%)	Fall 2018 Pre-harvest drops (%)
0	93.3 a	66.7	89.2 a
3	95.3 a	77.5	82.2 a
6	98.7 a	89.6	86.6 a
9	96.1 a	84.1	86.4 a
Control	56.9 b	66.7	20.4 b

g. ‘Geneva Tremlett’s Bitter’

Target crop load (no. fruit/cm^2 TCSA)	Fall 2016 Pre-harvest drops (%)	Fall 2017 Pre-harvest drops (%)	Fall 2018 Pre-harvest drops (%)
0	0.0 b	0.0	15.6 b
3	9.6 b	4.1	23.1 b
6	10.3 b	11.1	18.4 b
9	6.8 b	11.1	14.3 b
Control	28.4 a	—	62.2 a

Table A3-7. Flesh firmness (N) of seven apple cultivars from a three-year hand-thinning experiment harvested at LynOaken Farms 2016-2018

a. 'Binet Rouge'

Target crop load (no. fruit/cm^2 TCSA)	2016 Flesh firmness (N)	2017 Flesh firmness (N)	2018 Flesh firmness (N)
0	—	—	—
3	75.8	81.5	76.1 a
6	74.5	80.7	71.2 ab
9	72.8	75.6	66.4 bc
Control	72.7	—	59.2 c

b. 'Brown Snout'

Target crop load (no. fruit/cm^2 TCSA)	2016 Flesh firmness (N)	2017 Flesh firmness (N)	2018 Flesh firmness (N)
0	—	—	—
3	71.1	59.6	68.6 ab
6	71.9	63.1	60.2 b
9	68.7	59.4	64.8 ab
Control	70.4	64.4	79.5 a

c. 'Chisel Jersey'

Target crop load (no. fruit/cm^2 TCSA)	2016 Flesh firmness (N)	2017 Flesh firmness (N)	2018 Flesh firmness (N)
0	—	—	—
3	100.6 ab	92.5 ab	60.9 b
6	104.1 a	103.6 a	68.2 b
9	99.5 ab	102.8 a	66.0 b
Control	95.2 b	80.8 b	96.1 a

d. 'Dabinett'

Target crop load (no. fruit/cm^2 TCSA)	2016 Flesh firmness (N)	2017 Flesh firmness (N)	2018 Flesh firmness (N)
0	—	—	—
3	86.2	84.8	77.7
6	84.7	90.1	73.8
9	82.1	86.0	87.8
Control	83.1	84.9	97.2

e. 'Harry Masters Jersey'

Target crop load (no. fruit/cm^2 TCSA)	2016 Flesh firmness (N)	2017 Flesh firmness (N)	2018 Flesh firmness (N)
0	—	—	—
3	55.2 c	90.4 a	82.0
6	63.1 bc	87.7 a	78.3
9	66.4 ab	88.2 a	79.1
Control	75.8 a	68.8 b	84.6

f. 'Michelin'

Target crop load (no. fruit/cm^2 TCSA)	2016 Flesh firmness (N)	2017 Flesh firmness (N)	2018 Flesh firmness (N)
0	—	—	—
3	65.8 b	65.5	58.8 b
6	64.7 b	59.6	59.5 b
9	64.6 b	60.5	74.0 ab
Control	73.6 a	65.0	89.5 a

g. 'Geneva Tremlett'

Target crop load (no. fruit/cm^2 TCSA)	2016 Flesh firmness (N)	2017 Flesh firmness (N)	2018 Flesh firmness (N)
0	—	—	—
3	83.3 a	89.5	85.9
6	82.8 a	89.4	81.2
9	78.3 b	87.7	80.6
Control	73.8 c	—	79.1

Table A3-8. Soluble solid content (SSC) of juice from seven apple cultivars in a three-year hand-thinning experiment harvested at LynOaken Farms in Lyndonville, NY 2016-2018

a. 'Binet Rouge'

Target crop load (no. fruit/cm^2 TCSA)	2016 SSC (°Brix)	2017 SSC (°Brix)	2018 SSC (°Brix)
0	—	—	—
3	16.2 a	18.8	18.9 a
6	15.6 ab	17.9	18.5 a
9	15.1 b	18.0	17.4 a
Control	14.0 c	—	14.9 b

e. 'Harry Masters Jersey'

Target crop load (no. fruit/cm^2 TCSA)	2016 SSC (°Brix)	2017 SSC (°Brix)	2018 SSC (°Brix)
0	—	—	—
3	14.0 a	14.2 ab	13.8 a
6	14.4 a	13.3 b	13.8 a
9	13.8 a	14.1 b	12.7 a
Control	12.5 b	16.0 a	10.9 b

b. 'Brown Snout'

Target crop load (no. fruit/cm^2 TCSA)	2016 SSC (°Brix)	2017 SSC (°Brix)	2018 SSC (°Brix)
0	—	—	—
3	16.2 a	18.9 a	19.1 a
6	15.5 a	19.1 a	18.2 a
9	16.0 a	17.6 b	17.5 a
Control	14.0 b	—	14.7 b

f. 'Michelin'

Target crop load (no. fruit/cm^2 TCSA)	2016 SSC (°Brix)	2017 SSC (°Brix)	2018 SSC (°Brix)
0	—	—	—
3	14.2 a	14.7	14.9 a
6	14.5 a	14.9	14.3 ab
9	13.6 a	15.1	13.3 bc
Control	12.5 b	14.8	12.2 c

c. 'Chisel Jersey'

Target crop load (no. fruit/cm^2 TCSA)	2016 SSC (°Brix)	2017 SSC (°Brix)	2018 SSC (°Brix)
0	—	—	—
3	14.8 a	17.5	17.3 a
6	14.5 a	16.1	15.2 b
9	12.2 b	15.7	15.8 b
Control	11.1 b	16.7	12.4 c

g. 'Geneva Tremlett's Bitter'

Target crop load (no. fruit/cm^2 TCSA)	2016 SSC (°Brix)	2017 SSC (°Brix)	2018 SSC (°Brix)
0	—	—	—
3	13.4 a	13.2	13.0 a
6	13.2 a	12.9	13.1 a
9	12.4 b	12.9	12.3 a
Control	10.9 c	—	10.6 b

d. 'Dabinett'

Target crop load (no. fruit/cm^2 TCSA)	2016 SSC (°Brix)	2017 SSC (°Brix)	2018 SSC (°Brix)
0	—	—	—
3	15.8 a	15.9	15.5
6	14.6 ab	15.3	15.5
9	14.5 ab	14.8	15.9
Control	13.8 b	16.1	14.5

Table A3-9. Titrateable acidity (TA) of juice from seven apple cultivars in a three-year hand-thinning experiment harvested at LynOaken Farms in Lyndonville, NY 2016-2018

a. 'Binet Rouge'

Target crop load (no. fruit/cm^2 TCSA)	2016 TA ($g \cdot L^{-1}$)	2017 TA ($g \cdot L^{-1}$)	2018 TA ($g \cdot L^{-1}$)
0	—	—	—
3	4.5 a	4.3	5.0 a
6	4.1 b	4.3	4.6 ab
9	4.0 b	3.7	4.3 b
Control	3.1 c	—	3.3 c

b. 'Brown Snout'

Target crop load (no. fruit/cm^2 TCSA)	2016 TA ($g \cdot L^{-1}$)	2017 TA ($g \cdot L^{-1}$)	2018 TA ($g \cdot L^{-1}$)
0	—	—	—
3	4.9 a	4.6	5.6 a
6	4.8 a	4.9	5.2 a
9	4.6 a	4.5	5.1 a
Control	3.6 b	—	3.6 b

c. 'Chisel Jersey'

Target crop load (no. fruit/cm^2 TCSA)	2016 TA ($g \cdot L^{-1}$)	2017 TA ($g \cdot L^{-1}$)	2018 TA ($g \cdot L^{-1}$)
0	—	—	—
3	3.3	3.0	3.0 a
6	3.2	2.9	3.2 a
9	3.1	2.7	3.2 a
Control	2.8	2.9	2.3 b

d. 'Dabinett'

Target crop load (no. fruit/cm^2 TCSA)	2016 TA ($g \cdot L^{-1}$)	2017 TA ($g \cdot L^{-1}$)	2018 TA ($g \cdot L^{-1}$)
0	—	—	—
3	2.4 a	1.6	2.5 ab
6	2.4 a	1.6	2.6 a
9	2.3 a	1.8	2.5 ab
Control	1.9 b	2.1	2.0 b

e. 'Harry Masters Jersey'

Target crop load (no. fruit/cm^2 TCSA)	2016 TA ($g \cdot L^{-1}$)	2017 TA ($g \cdot L^{-1}$)	2018 TA ($g \cdot L^{-1}$)
0	—	—	—
3	2.4	3.2 ab	4.2 a
6	2.6	3.3 a	4.1 a
9	2.6	3.3 a	4.2 a
Control	2.8	2.5 b	2.7 b

f. 'Michelin'

Target crop load (no. fruit/cm^2 TCSA)	2016 TA ($g \cdot L^{-1}$)	2017 TA ($g \cdot L^{-1}$)	2018 TA ($g \cdot L^{-1}$)
0	—	—	—
3	3.5	2.3	3.5
6	3.7	2.1	3.5
9	3.7	2.1	3.6
Control	3.8	2.1	3.1

g. 'Geneva Tremlett's Bitter'

Target crop load (no. fruit/cm^2 TCSA)	2016 TA ($g \cdot L^{-1}$)	2017 TA ($g \cdot L^{-1}$)	2018 TA ($g \cdot L^{-1}$)
0	—	—	—
3	15.5 a	17.9	16.2 a
6	14.8 a	17.3	13.7 b
9	13.7 ab	17.8	12.8 b
Control	11.6 b	—	10.4 c

Table A3-10. Folin-Ciocalteu total polyphenols (FC) of juice from seven apple cultivars in a three-year hand-thinning experiment harvested at LynOaken Farms in Lyndonville, NY 2016-2018

a. 'Binet Rouge'

Target crop load (no. fruit/cm^2 TCSA)	2016 FC ($mg \cdot L^{-1}$ GAE)	2017 FC ($mg \cdot L^{-1}$ GAE)	2018 FC ($mg \cdot L^{-1}$ GAE)
0	—	—	—
3	3.0 a	3.8	4.0 a
6	2.7 ab	4.3	3.5 ab
9	2.3 bc	4.1	3.0 ab
Control	1.9 c	—	2.0 b

b. 'Brown Snout'

Target crop load (no. fruit/cm^2 TCSA)	2016 FC ($mg \cdot L^{-1}$ GAE)	2017 FC ($mg \cdot L^{-1}$ GAE)	2018 FC ($mg \cdot L^{-1}$ GAE)
0	—	—	—
3	1.4	2.0	2.1
6	1.4	2.2	1.8
9	1.3	1.8	1.7
Control	1.2	—	1.6

c. 'Chisel Jersey'

Target crop load (no. fruit/cm^2 TCSA)	2016 FC ($mg \cdot L^{-1}$ GAE)	2017 FC ($mg \cdot L^{-1}$ GAE)	2018 FC ($mg \cdot L^{-1}$ GAE)
0	—	—	—
3	3.0 a	3.5	4.0 a
6	2.6 a	2.8	2.6 b
9	2.1 b	2.9	2.8 b
Control	1.8 b	3.2	1.9 c

d. 'Dabinett'

Target crop load (no. fruit/cm^2 TCSA)	2016 FC ($mg \cdot L^{-1}$ GAE)	2017 FC ($mg \cdot L^{-1}$ GAE)	2018 FC ($mg \cdot L^{-1}$ GAE)
0	—	—	—
3	2.1	2.2	2.1
6	1.9	2.0	2.0
9	2.0	2.2	2.0
Control	2.1	2.8	2.5

e. 'Harry Masters Jersey'

Target crop load (no. fruit/cm^2 TCSA)	2016 FC ($mg \cdot L^{-1}$ GAE)	2017 FC ($mg \cdot L^{-1}$ GAE)	2018 FC ($mg \cdot L^{-1}$ GAE)
0	—	—	—
3	2.3	2.4 ab	3.1 a
6	2.4	2.1 b	3.0 a
9	2.1	2.5 ab	2.9 a
Control	2.0	3.0 a	2.3 b

f. 'Michelin'

Target crop load (no. fruit/cm^2 TCSA)	2016 FC ($mg \cdot L^{-1}$ GAE)	2017 FC ($mg \cdot L^{-1}$ GAE)	2018 FC ($mg \cdot L^{-1}$ GAE)
0	—	—	—
3	1.7	2.0	2.1 a
6	1.7	1.9	1.7 b
9	1.5	2.0	1.7 ab
Control	1.4	2.2	1.5 b

g. 'Geneva Tremlett'

Target crop load (no. fruit/cm^2 TCSA)	2016 FC ($mg \cdot L^{-1}$ GAE)	2017 FC ($mg \cdot L^{-1}$ GAE)	2018 FC ($mg \cdot L^{-1}$ GAE)
0	—	—	—
3	2.2 a	2.6	2.1 ab
6	2.1 ab	2.5	1.9 b
9	1.9 bc	2.8	2.0 b
Control	1.8 c	—	2.4 a

Table A3-11. Average pH of juice from seven apple cultivars in a three-year hand-thinning experiment harvested at LynOaken Farms in Lyndonville, NY 2016-2018

a. 'Binet Rouge'

Target crop load (no. fruit/cm^2 TCSA)	2016 pH	2017 pH	2018 pH
0	—	—	—
3	3.97	4.21 b	3.92
6	4.00	4.20 b	3.96
9	3.98	4.36 a	3.96
Control	3.98	—	3.96

b. 'Brown Snout'

Target crop load (no. fruit/cm^2 TCSA)	2016 pH	2017 pH	2018 pH
0	—	—	—
3	4.11	4.21	3.96 ab
6	4.05	4.19	4.00 ab
9	4.11	4.15	3.93 b
Control	4.10	—	4.05 a

c. 'Chisel Jersey'

Target crop load (no. fruit/cm^2 TCSA)	2016 pH	2017 pH	2018 pH
0	—	—	—
3	4.41	4.52	4.43 ab
6	4.42	4.47	4.30 ab
9	4.34	4.48	4.27 b
Control	4.43	4.51	4.45 a

d. 'Dabinett'

Target crop load (no. fruit/cm^2 TCSA)	2016 pH	2017 pH	2018 pH
0	—	—	—
3	4.63	5.05	4.64
6	4.57	4.98	4.65
9	4.61	4.84	4.70
Control	4.62	4.95	4.78

e. 'Harry Masters Jersey'

Target crop load (no. fruit/cm^2 TCSA)	2016 pH	2017 pH	2018 pH
0	—	—	—
3	4.65 a	4.33 b	4.05 b
6	4.59 ab	4.26 b	4.07 b
9	4.51 bc	4.25 b	4.02 b
Control	4.41 c	4.79 a	4.46 a

f. 'Michelin'

Target crop load (no. fruit/cm^2 TCSA)	2016 pH	2017 pH	2018 pH
0	—	—	—
3	4.29 a	4.69	4.18
6	4.27 a	4.73	4.12
9	4.21 a	4.74	4.05
Control	4.02 b	4.70	4.00

g. 'Geneva Tremlett'

Target crop load (no. fruit/cm^2 TCSA)	2016 pH	2017 pH	2018 pH
0	—	—	—
3	3.20	3.17	3.18 b
6	3.20	3.14	3.24 ab
9	3.21	3.12	3.25 a
Control	3.24	—	3.27 a

Table A3-12. Primary Amino Nitrogen (PAN) of juice from seven apple cultivars harvested at LynOaken Farms in Lyndonville, NY 2016-2018

a. 'Binet Rouge'

Target crop load (no. fruit/cm^2 TCSA)	2016 PAN (mg N·L^{-1})	2017 PAN (mg N·L^{-1})	2018 PAN (mg N·L^{-1})
0	—	—	—
3	93.8 a	190.8	71.5 a
6	78.0 ab	194.0	62.5 ab
9	70.9 ab	171.3	46.7 ab
Control	54.9 b	—	29.2 b

b. 'Brown Snout'

Target crop load (no. fruit/cm^2 TCSA)	2016 PAN (mg N·L^{-1})	2017 PAN (mg N·L^{-1})	2018 PAN (mg N·L^{-1})
0	—	—	—
3	153.6 a	111.2	119.4 a
6	77.5 bc	104.6	88.7 ab
9	126.1 ab	89.0	44.6 bc
Control	43.8 a	—	14.1 c

c. 'Chisel Jersey'

Target crop load (no. fruit/cm^2 TCSA)	2016 PAN (mg N·L^{-1})	2017 PAN (mg N·L^{-1})	2018 PAN (mg N·L^{-1})
0	—	—	—
3	60.7 a	55.4	25.4 a
6	44.3 ab	40.14	20.2 ab
9	43.8 ab	41.2	13.4 ab
Control	40.1 b	52.3	6.6 b

d. 'Dabinett'

Target crop load (no. fruit/cm^2 TCSA)	2016 PAN (mg N·L^{-1})	2017 PAN (mg N·L^{-1})	2018 PAN (mg N·L^{-1})
0	—	—	—
3	84.2 a	103.0	27.4
6	48.5 ab	85.5	12.7
9	45.1 b	73.1	38.2
Control	20.6 b	100.4	1.0

e. 'Harry Masters Jersey'

Target crop load (no. fruit/cm^2 TCSA)	2016 PAN (mg N·L^{-1})	2017 PAN (mg N·L^{-1})	2018 PAN (mg N·L^{-1})
0	—	—	—
3	80.2 a	112.7	49.3
6	78.7 a	90.0	58.2
9	63.3 ab	77.5	44.7
Control	43.9 b	115.1	31.5

f. 'Michelin'

Target crop load (no. fruit/cm^2 TCSA)	2016 PAN (mg N·L^{-1})	2017 PAN (mg N·L^{-1})	2018 PAN (mg N·L^{-1})
0	—	—	—
3	127.7 a	210.6	109.1 a
6	127.4 a	215.2	100.0 a
9	112.8 a	199.4	66.0 ab
Control	57.6 b	198.7	40.3 b

g. 'Geneva Tremlett'

Target crop load (no. fruit/cm^2 TCSA)	2016 PAN (mg N·L^{-1})	2017 PAN (mg N·L^{-1})	2018 PAN (mg N·L^{-1})
0	—	—	—
3	161.5 a	195.9	120.0 a
6	138.3 ab	128.3	130.2 a
9	132.0 ab	153.9	104.5 ab
Control	80.8 b	—	49.9 b

Table A3-13. Extraction volume (% of total pomace weight) of seven cultivars harvested at LynOaken Farms in 2018.

Target crop load (no. fruit/cm^2 TCSA)	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
0	—	—	—	—	—	—	—
3	69.1	67.3	72.4	74.9	65.2	55.8	69.1 ab
6	68.6	69.8	73.0	74.4	64.3	53.1	67.4 b
9	65.3	70.9	71.9	76.9	63.0	64.5	70.9 ab
Control	69.4	73.7	77.3	75.9	67.4	63.7	73.7 a

Table A3-14. Starch pattern index (SPI), flesh firmness, peel color, soluble solid concentration (SSC), pH, titratable acidity (TA), and Folin-Ciocalteu total polyphenols (FC) from 'Chisel Jersey' apples harvested from a one-year hand-thinning experiment (Exp. 2) at LynOaken Farms in 2017.

Target crop load (no. fruit/cm^2 TCSA)	SPI (1-8)	Flesh firmness (N)	Red peel color (%)	SSC (°Brix)	pH	TA (g·L^{-1})	FC (mg·L^{-1} GAE)	Post-harvest mean fr wt (g)	Internal Browning (% present)	ΔA
0	—	—	—	—	—	—	—	—	—	—
3	6.8	78.0 c	42.9 c	17.3 a	4.53	2.8	3.7	187.6 a	2.0	0.49 b
6	6.4	89.3 b	71.8 a	16.7 a	4.47	2.8	3.2	170.9 b	2.0	0.54 b
9	6.3	84.8 bc	68.2 ab	16.2 a	4.45	2.5	3.2	181.1 ab	0.0	0.49 b
Control	5.8	101.5 a	50.4 bc	14.6 b	4.44	2.5	2.9	129.8 c	0.0	0.67 a

Table A3-15. Starch pattern index (SPI), flesh firmness, peel color, soluble solid concentration (SSC), pH, titratable acidity (TA), and Folin-Ciocalteu total polyphenols (FC) from 'Dabinett' apples harvested from a one-year hand-thinning experiment (Exp. 2) at LynOaken Farms in 2017.

Target crop load (no. fruit/cm^2 TCSA)	SPI (1-8)	Flesh firmness (N)	Red peel color (%)	SSC (°Brix)	pH	TA (g·L^{-1})	FC (mg·L^{-1} GAE)	Post-harvest mean fr wt (g)	Internal Browning (% present)	ΔA
0	—	—	—	—	—	—	—	—	—	—
3	7.8	69.0 b	79.7	15.7	5.07 a	1.6	2.2	176.2 b	0.00	—
6	7.8	84.5 ab	79.1	15.7	5.04 ab	1.6	2.4	221.0 a	0.20	—
9	7.4	88.0 a	83.1	15.4	5.00 ab	1.6	2.3	176.5 b	0.10	—
Control	7.0	76.5 ab	84.9	15.2	4.91 b	1.6	2.2	125.3 c	0.00	—

Table A3-16. Starch pattern index (SPI), flesh firmness, peel color, soluble solid concentration (SSC), pH, titratable acidity (TA), and Folin-Ciocalteu total polyphenols (FC) from 'Harry Master's Jersey' apples harvested from a one-year hand-thinning experiment (Exp. 2) at LynOaken Farms in 2017.

Target crop load (no. fruit/cm^2 TCSA)	SPI (1-8)	Flesh firmness (N)	Red peel color (%)	SSC (°Brix)	pH	TA ($g \cdot L^{-1}$)	FC ($mg \cdot L^{-1}$ GAE)	Post-harvest mean fr wt (g)	Internal Browning (% present)	ΔA
0	—	—	—	—	—	—	—	—	—	—
3	7.5 a	69.0 b	97.0 a	16.1 a	4.7	2.4	3.0 a	208.3 a	0.0	0.33 c
6	6.8 b	73.2 b	93.9 ab	15.0 ab	4.5	2.6	2.8 ab	175.4 b	0.0	0.55 bc
9	6.5 b	73.3 b	91.3 b	14.5 bc	4.5	2.6	2.7 ab	171.9 b	0.0	0.63 b
Control	5.2 c	85.4 a	83.6 c	13.2 c	4.4	2.6	2.4 b	125.0 c	0.0	1.09 a

Table A3-17. Starch pattern index (SPI), flesh firmness, peel color, soluble solid concentration (SSC), pH, titratable acidity (TA), and Folin-Ciocalteu total polyphenols (FC) from 'Michelin' apples harvested at LynOaken Farms in 2017.

Target crop load (no. fruit/cm^2 TCSA)	SPI (1-8)	Flesh firmness (N)	Green peel color (1-5)	SSC (°Brix)	pH	TA ($g \cdot L^{-1}$)	FC ($mg \cdot L^{-1}$ GAE)	Post-harvest mean fr wt (g)	Internal Browning (% present)	ΔA
0	—	—	—	—	—	—	—	—	—	—
3	7.7 ab	55.7	1.5	13.9	4.7	2.0	2.2	108.2	77.1	—
6	8.0 a	49.2	1.6	13.9	4.8	2.0	2.2	106.1	81.4	—
9	7.3 b	59.3	1.5	14.0	4.6	2.3	2.1	100.4	61.7	—
Control	7.8 ab	50.6	1.5	14.2	4.6	2.3	2.3	105.0	65.6	—

Table A3-18. Comparison of yeast nutrient supplement costs ($/ha) based on 2016-2018 yield and juice PAN data from a three-year hand-thinning experiment at LynOaken Farms

	Cost of nitrogen supplement to achieve 140 mg/L N		
Variety	DAP	FermAid K	FermAid O
Binet Rouge			
3 fruit/cm^2	$7.96 c	$216.45 c	$186.39 c
6 fruit/cm^2	$17.28 bc	$469.65 bc	$404.43 bc
9 fruit/cm^2	$21.64 b	$588.04 b	$506.39 b
Un-thinned	$34.45 a	$936.06 a	$806.08 a
Brown Snout			
3 fruit/cm^2	$3.89 c	$105.79 c	$91.10 c
6 fruit/cm^2	$10.71 bc	$290.92 bc	$250.53 bc
9 fruit/cm^2	$19.24 b	$522.87 b	$450.26 b
Un-thinned	$36.78 a	$999.53 a	$860.74 a
Chisel Jersey			
3 fruit/cm^2	$35.12 b	$954.31 b	$821.81 b
6 fruit/cm^2	$69.67 ab	$1,893.16 ab	$1630.29 ab
9 fruit/cm^2	$71.87 ab	$1,952.92 ab	$1681.75 ab
Un-thinned	$99.93 a	$2,715.29 a	$2338.26 a
Dabinett			
3 fruit/cm^2	$45.29	$1,230.79	$1059.89
6 fruit/cm^2	$85.26	$2,316.75	$1995.06
9 fruit/cm^2	$41.31	$1,122.51	$966.64
Un-thinned	$69.45	$1,887.12	$1625.09
Harry Masters Jersey			
3 fruit/cm^2	$15.77 b	$428.58 b	$369.07b
6 fruit/cm^2	$26.12 ab	$709.76 ab	$611.21 ab
9 fruit/cm^2	$33.27 ab	$904.03 ab	$778.50 ab
Un-thinned	$40.39 a	$1,097.39 a	$945.01 a
Michelin			
3 fruit/cm^2	$2.93 c	$79.70 c	$68.63 c
6 fruit/cm^2	$6.16 bc	$167.51 bc	$144.25 bc
9 fruit/cm^2	$16.15 b	$438.77 b	$377.85 b
Un-thinned	$40.02 a	$1,087.49 a	$936.49 a
Geneva Tremlett's Bitter			
3 fruit/cm^2	$1.42 b	$38.60 b	$33.24 b
6 fruit/cm^2	$4.18 b	$113.64 b	$97.86 b
9 fruit/cm^2	$10.80 b	$293.51 b	$252.75 b
Un-thinned	$24.00 a	$652.12 a	$561.57 a

Table A4-1. Estimated full bloom (>50% of blossoms open) dates at LynOaken Farms, 2016-2018.

	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
Full bloom 2016	20th May	26th May	27th May	27th May	26th May	22nd May	23rd May
Full bloom 2017	12th May	28th May	18th May	17th May	17th May	17th May	16th May
Full bloom 2018	16th May	26th May	24th May	20th May	20th May	19th May	18th May

Table A4-2. Hand-thinning dates and number of days after full bloom at LynOaken Farms, 2016-2018.

	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
June 21st 2016 DAFB	32	26	25	25	26	30	29
June 30th 2017 DAFB	49	33	43	44	44	44	45
June 15th 2018 DAFB	30	20	22	26	26	27	28

Table A4-3. PGR spray dates and number of days after full bloom, LynOaken Farms, 2016-2018.

	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
29 June 2016	40	34	33	33	34	38	37
8 July 2016	49	43	42	42	43	47	46
15 July 2016	56	50	49	49	50	54	53
24 July 2016	65	59	58	58	59	63	62
22 June 2017	41	25	35	36	36	36	37
30 June 2017	49	33	43	44	44	44	45
14 July 2017	63	47	57	58	58	58	59
28 July 2017	77	61	71	72	72	72	73
21 June 2018	36	26	28	32	32	33	34
5 July 2018	50	40	42	46	46	47	48
19 July 2018	64	54	56	60	60	61	62
2 August 2018	78	68	70	74	74	75	76

Table A4-4. Harvest dates and number of days after full bloom, LynOaken Farms, 2016-2018.

Cultivar	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
Harvest date 2016	3rd Oct.	11th Oct.	26th Sept.	11th Oct.	26th Sept.	3rd Oct.	9th Sept.
No. DAFB	136	138	122	137	123	134	109
Harvest date 2017	2nd Oct.	16th Oct.	2nd Oct.	16th Oct.	15th Sept.	25th Sept.	11th Sept.
No. DAFB	143	141	137	152	121	131	118
Harvest date 2018	4th Oct.	16th Oct.	16th Oct.	25th Oct.	13th Sept.	24th Sept.	6th Sept.
No. DAFB	141	143	145	158	116	129	111

Table A4-5. Estimated full bloom (>50% of blossoms open), hand thinning, and harvest dates at Cornell University Orchard in Lansing, NY, 2016-2017.

	Full bloom	Hand-thinning	Spray 1	Spray 2	Spray 3	Spray 4	Harvest
Chisel Jersey, 2016	28 May	5 July (38 DAFB)	8 July (41 DAFB)	22 July (55 DAFB)	5 August (69 DAFB)	—	14 Oct (139 DAFB)
Chisel Jersey, 2017	24 May	26 June (33 DAFB)	29 June (36 DAFB)	13 July (50 DAFB)	28 July (65 DAFB)	10 August (78 DAFB)	3 Oct. (132 DAFB)
Brown Snout, 2017	22 May	26 June (35 DAFB)	29 June (38 DAFB)	13 July (52 DAFB)	28 July (67 DAFB)	10 August (80 DAFB)	10 Oct (139 DAFB)

Table A4-6. Proportion of hand-thinned trees at LynOaken Farms with sufficient bloom in 2019 to reimpose crop load, from a three-year PGR experiment at LynOaken Farms

	Binet Rouge	Brown Snout	Chisel Jersey	Dabinett	Harry Masters Jersey	Michelin	Geneva Tremlett's Bitter
Proportion of trees with sufficient bloom to achieve 6 fruit/cm^2	0.8	0.4	1.0	1.0	1.0	1.0	1.0

Table A4-7. Return bloom of seven cultivars treated at LynOaken Farms in Lyndonville, NY, 2016-2018. Treatment averages compared using Dunnett's Test. Asterisks indicate significant difference from control (*=p<0.05, **=p<0.01, ***=p<0.001)

a. Binet Rouge

Treatment	May 2017 flower no./tree	May 2017 Flower density (flower cluster no.·$TCSA^{-1}$)	June 2018 fruit clusters/ tree	June 2018 fruitlet density (cluster no. ·$TCSA^{-1}$)	May 2019 flower cluster no./tree	May 2019 flower density (cluster no. ·$TCSA^{-1}$)
Control	0.0	0.0	469	37.1	0.6	0.1
Hand-thin (6 fruit/cm^2)	29.2*	5.9*	144	24.2	192.8***	24.2***
NAA, NAA, NAA, NAA	1.2	0.4	153	26.8	1.6	0.2
Eth, NAA, NAA, NAA	0.2	0.1	168	28.3	1.2	0.2
Eth, Eth, NAA, NAA	8.0	2.0	124	22.8	14.2	2.8

b. Brown Snout

Treatment	May 2017 flower no./tree	May 2017 Flower density (flower cluster no.·$TCSA^{-1}$)	June 2018 fruit clusters/ tree	June 2018 fruitlet density (cluster no. ·$TCSA^{-1}$)	May 2019 flower cluster no./tree	May 2019 flower density (cluster no. ·$TCSA^{-1}$)
Control	0.0	0.0	114	24.3	89.6	22.8
Hand-thin (6 fruit/cm^2)	42.0***	10.8***	103	23.9	54.0	10.2
NAA, NAA, NAA, NAA	0.0	0.0	147	24.7	0.0	0.0
Eth, NAA, NAA, NAA	0.0	0.0	118	24.0	0.2	0.1
Eth, Eth, NAA, NAA	0.0	0.0	71	19.9	14.2	6.7

c. Chisel Jersey

Treatment	May 2017 flower no./tree	May 2017 Flower density (flower cluster no.·$TCSA^{-1}$)	June 2018 fruit clusters/ tree	June 2018 fruitlet density (cluster no. ·$TCSA^{-1}$)	May 2019 flower cluster no./tree	May 2019 flower density (cluster no. ·$TCSA^{-1}$)
Control	7.4	1.4	167	28.1	0.6	0.1
Hand-thin (6 fruit/cm^2)	95.4***	15.9***	126	27.5	281.2***	31.0***
NAA, NAA, NAA, NAA	12.6	2.9	149	26.9	0.6	0.1
Eth, NAA, NAA, NAA	44.0	6.4	135	21.4	16.6	2.5
Eth, Eth, NAA, NAA	29.2	5.7	152	23.4	6.0	0.8

d. Dabinett

Treatment	May 2017 flower no./tree	May 2017 Flower density (flower cluster no.·$TCSA^{-1}$)	June 2018 fruit clusters/ tree	June 2018 fruitlet density (cluster no. ·$TCSA^{-1}$)	May 2019 flower cluster no./tree	May 2019 flower density (cluster no. ·$TCSA^{-1}$)
Control	10.2	1.9	171	22.8	0.0	0.0
Hand-thin (6 fruit/cm^2)	113.6***	20.6***	176	24.3	189.0***	20.9***
NAA, NAA, NAA, NAA	6.5	1.4	155	25.5	4.3	0.5
Eth, NAA, NAA, NAA	8.4	2.0	146	21.9	4.2	0.6
Eth, Eth, NAA, NAA	5.4	0.9	199	23.8	0.4	0.1

e. Harry Masters Jersey

Treatment	May 2017 flower no./tree	May 2017 Flower density (flower cluster no.·TCSA^{-1})	June 2018 fruit clusters/ tree	June 2018 fruitlet density (cluster no. ·TCSA^{-1})	May 2019 flower cluster no./tree	May 2019 flower density (cluster no. ·TCSA^{-1})
Control	12.8	3.1	110	24.1	84.0	12.9
Hand-thin (6 fruit/cm^2)	103.6***	22.8***	86	16.8	228.4***	32.9***
NAA, NAA, NAA, NAA	17.4	5.0	96	21.1	78.4	14.5
Eth, NAA, NAA, NAA	36.6	8.6	104	21.4	101.2	16.3
Eth, Eth, NAA, NAA	15.8	3.4	139	24.5	74.8	9.8

f. Michelin

Treatment	May 2017 flower no./tree	May 2017 Flower density (cluster no. ·TCSA^{-1})	June 2018 fruit clusters/ tree	June 2018 fruitlet density (cluster no. ·TCSA^{-1})	May 2019 flower cluster no./tree	May 2019 flower density (cluster no. ·TCSA^{-1})
Control	0.8	0.2	174	31.7	0.4	0.1
Hand-thin (6 fruit/cm^2)	86.0***	16.6***	220	32.5	217.0***	26.0***
NAA, NAA, NAA, NAA	7.8	1.9	149	26.9	7.6	1.3
Eth, NAA, NAA, NAA	21.6	5.2	151	28.0	13.2	1.9
Eth, Eth, NAA, NAA	1.2	0.3	164	30.4	0.6	0.2

g. Geneva Tremlett's Bitter

Treatment	May 2017 flower no./tree	May 2017 Flower density (flower cluster no.·TCSA^{-1})	June 2018 fruit clusters/ tree	June 2018 fruitlet density (cluster no. ·TCSA^{-1})	May 2019 flower cluster no./tree	May 2019 flower density (cluster no. ·TCSA^{-1})
Control	0.0	0.0	100	22.7	0.0	0.0
Hand-thin (6 fruit/cm^2)	13.6***	3.5***	125	26.4	100.6***	17.1***
NAA, NAA, NAA, NAA	0.0	0.0	70	21.2	0.0	0.0
Eth, NAA, NAA, NAA	0.0	0.0	90	22.3	0.0	0.0
Eth, Eth, NAA, NAA	0.0	0.0	109	24.7	0.0	0.0

Table A4-8. Yield and biennial bearing indices of seven cultivars treated at LynOaken Farms in Lyndonville, NY, 2016-2018. Treatment averages compared using Dunnett's Test. Asterisks indicate significant difference from control (*=p<0.05, **=p<0.01, ***=p<0.001)

a. Binet Rouge

Treatment	2016 Yield (fruit/tree)	2016 Yield (kg/tree)	2017 Yield (fruit/tree)	2017 Yield (kg/tree)	2018 Yield (fruit/tree)	2018 Yield (kg/tree)	2016-2018 Cumulative Yield (kg)	BBI (yield wt. basis)
Control	90.6	6.3	0.4	0.0	215.6	11.1	17.4	1.00
Hand-thin (6 fruit/cm^2)	35.4***	3.6*	25.8*	2.7*	60.4***	5.4**	11.7*	0.34***
NAA, NAA, NAA, NAA	70.8	4.9	3.2	0.2	209.0	12.4	17.6	0.93
Eth, NAA, NAA, NAA	81.6	6.1	0.6	0.1	206.4	12.1	18.3	0.98
Eth, Eth, NAA, NAA	69.6	4.7	10.6	1.0	184.6	11.9	17.6	0.88

b. Brown Snout

Treatment	2016 Yield (fruit/tree)	2016 Yield (kg/tree)	2017 Yield (fruit/tree)	2017 Yield (kg/tree)	2018 Yield (fruit/tree)	2018 Yield (kg/tree)	2016-2018 Cumulative Yield (kg)	BBI (yield wt. basis)
Control	133.4	3.7	0.0	0.0	245.4	7.8	11.5	1.00
Hand-thin (6 fruit/cm^2)	24.4***	1.8	14.2 ***	1.3***	32.6**	3.0*	6.1*	0.31***
NAA, NAA, NAA, NAA	154.4	5.4	0.0	0.0	277.0	9.1	14.5	1.00
Eth, NAA, NAA, NAA	116.2	3.8	0.0	0.0	249.8	8.8	12.6	1.00
Eth, Eth, NAA, NAA	131.0	3.6	0.0	0.0	192.8	6.6	10.2	1.00

c. Chisel Jersey

Treatment	2016 Yield (fruit/tree)	2016 Yield (kg/tree)	2017 Yield (fruit/tree)	2017 Yield (kg/tree)	2018 Yield (fruit/tree)	2018 Yield (kg/tree)	2016-2018 Cumulative Yield (kg)	BBI (yield wt. basis)
Control	96.8	6.5	17.0	3.3	264.8	14.9	24.0	0.65
Hand-thin (6 fruit/cm^2)	51.2**	5.0	52.4	5.8	46.0***	6.8*	17.6*	0.12***
NAA, NAA, NAA, NAA	96.8	6.1	31.2	4.1	238.2	14.3	24.4	0.40
Eth, NAA, NAA, NAA	104.2	5.5	67.0	7.0	246.0	14.9	27.4	0.42
Eth, Eth, NAA, NAA	105.0	7.6	31.2	4.4	290.6	17.3	29.2	0.54

d. Dabinett

Treatment	2016 Yield (fruit/tree)	2016 Yield (kg/tree)	2017 Yield (fruit/tree)	2017 Yield (kg/tree)	2018 Yield (fruit/tree)	2018 Yield (kg/tree)	2016-2018 Cumulative Yield (kg)	BBI (yield wt. basis)
Control	105.8	7.1	19.0	3.9	383.0	20.7	30.9	0.65
Hand-thin (6 fruit/cm^2)	40.0***	4.6	33.0	4.9	50.8***	7.8***	17.3*	0.35***
NAA, NAA, NAA, NAA	110.0	6.6	14.0	3.6	242.8	12.8	24.5	0.77
Eth, NAA, NAA, NAA	114.2	6.6	18.0	3.1	269.4	14.4	23.5	0.68
Eth, Eth, NAA, NAA	101.4	6.7	79.0 **	10.3*	353.6	19.4	36.4	0.25

e. Harry Masters Jersey

Treatment	2016 Yield (fruit/tree)	2016 Yield (kg/tree)	2017 Yield (fruit/tree)	2017 Yield (kg/tree)	2018 Yield (fruit/tree)	2018 Yield (kg/tree)	2016-2018 Cumulative Yield (kg)	BBI (yield wt. basis)
Control	66.2	6.4	35.4	5.0	160.4	9.7	21.1	0.47
Hand-thin (6 fruit/cm^2)	35.0	3.4	40.2	5.0	58.8*	5.1*	13.5*	0.20***
NAA, NAA, NAA, NAA	69.0	4.1	44.4	5.2	129.6	7.8	17.1	0.34
Eth, NAA, NAA, NAA	64.8	5.3	64.8	7.1	165.4	10.7	23.1	0.18
Eth, Eth, NAA, NAA	102.6	7.5	40.4	5.6	190.6	10.8	24.0	0.35

f. Michelin

Treatment	2016 Yield (fruit/tree)	2016 Yield (kg/tree)	2017 Yield (fruit/tree)	2017 Yield (kg/tree)	2018 Yield (fruit/tree)	2018 Yield (kg/tree)	2016-2018 Cumulative Yield (kg)	BBI (yield wt. basis)
Control	123.8	5.4	1.2	0.1	305.0	12.6	18.0	0.98
Hand-thin (6 fruit/cm^2)	35.2***	2.6*	19.6**	1.9***	52.4***	6.5**	10.9*	0.44***
NAA, NAA, NAA, NAA	92.8	5.0	8.0	0.6	278.4	13.6	19.2	0.86
Eth, NAA, NAA, NAA	105.2	4.8	18.8**	1.3*	294.0	13.8	19.9	0.70
Eth, Eth, NAA, NAA	107.8	4.6	0.8	0.6	293.8	11.5	16.2	0.98

g. Geneva Tremlett's Bitter

Treatment	2016 Yield (fruit/tree)	2016 Yield (kg/tree)	2017 Yield (fruit/tree)	2017 Yield (kg/tree)	2018 Yield (fruit/tree)	2018 Yield (kg/tree)	2016-2018 Cumulative Yield (kg)	BBI (yield wt. basis)
Control	64.6	4.4	0.0	0.0	173.2	10.2	14.6	1.00
Hand-thin (6 fruit/cm^2)	24.4***	2.5	12.4***	1.4***	42.8***	5.0*	8.8*	0.42***
NAA, NAA, NAA, NAA	63.8	3.4	0.0	0.0	125.8	6.8	10.2	1.00
Eth, NAA, NAA, NAA	49.0	3.3	0.0	0.0	165.6	9.0	12.3	1.00
Eth, Eth, NAA, NAA	57.0	4.0	0.0	0.0	178.6	10.8	14.9	1.00

Table A4-9. Crop density, yield efficiency, and Biennial Bearing Indices (yield efficiency basis) of seven cultivars treated at LynOaken Farms in Lyndonville, NY, 2016-2018. Treatment averages compared using Dunnett's Test. Asterisks indicate significant difference from control (*=p<0.05, **=p<0.01, ***=p<0.001)

a. Binet Rouge

Treatment	2016 Crop Density (fruit no. ·TCSA^{-1})	2016 Yield efficiency (fruit wt. ·TCSA^{-1})	2017 Crop Density (fruit no. ·TCSA^{-1})	2017 Yield efficiency (fruit wt. ·TCSA^{-1})	2018 Crop Density (fruit no. ·TCSA^{-1})	2018 Yield efficiency (fruit wt. ·TCSA^{-1})
Control	24.5	1.69	0.1	0.00	52.9	2.10
Hand-thin (6 fruit/cm^2)	7.8***	0.81***	4.1	0.43	15.8***	0.72***
NAA, NAA, NAA, NAA	17.6*	1.21*	0.5	0.04	51.5	1.97
Eth, NAA, NAA, NAA	20.2	1.52	0.1	0.01	50.7	1.86
Eth, Eth, NAA, NAA	17.4*	1.19*	2.5	0.23	45.3	1.98

b. Brown Snout

Treatment	2016 Crop Density (fruit no. ·TCSA^{-1})	2016 Yield efficiency (fruit wt. ·TCSA^{-1})	2017 Crop Density (fruit no. ·TCSA^{-1})	2017 Yield efficiency (fruit wt. ·TCSA^{-1})	2018 Crop Density (fruit no. ·TCSA^{-1})	2018 Yield efficiency (fruit wt. ·TCSA^{-1})
Control	43.2	1.18	0.0	0.00	67.6	1.65
Hand-thin (6 fruit/cm^2)	6.6***	0.49**	3.4***	0.32***	11.3***	0.54**
NAA, NAA, NAA, NAA	41.7	1.42	0.0	0.00	80.7	1.45
Eth, NAA, NAA, NAA	34.8	1.12	0.0	0.00	71.8	1.99
Eth, Eth, NAA, NAA	40.4	1.09	0.0	0.00	55.4	1.50

c. Chisel Jersey

Treatment	2016 Crop Density (fruit no. ·TCSA^{-1})	2016 Yield efficiency (fruit wt. ·TCSA^{-1})	2017 Crop Density (fruit no. ·TCSA^{-1})	2017 Yield efficiency (fruit wt. ·TCSA^{-1})	2018 Crop Density (fruit no. ·TCSA^{-1})	2018 Yield efficiency (fruit wt. ·TCSA^{-1})
Control	21.6	1.42	2.4	0.46	54.4	2.07
Hand-thin (6 fruit/cm^2)	8.4***	0.82**	10.2	1.22	8.7***	0.74***
NAA, NAA, NAA, NAA	22.4	1.37	6.2	0.80	54.5	2.20
Eth, NAA, NAA, NAA	19.7	1.38	9.3	1.00	40.0	2.05
Eth, Eth, NAA, NAA	19.7	1.42	5.7	0.69	60.1	2.40

d. Dabinett

Treatment	2016 Crop Density (fruit no. ·TCSA^{-1})	2016 Yield efficiency (fruit wt. ·TCSA^{-1})	2017 Crop Density (fruit no. ·TCSA^{-1})	2017 Yield efficiency (fruit wt. ·TCSA^{-1})	2018 Crop Density (fruit no. ·TCSA^{-1})	2018 Yield efficiency (fruit wt. ·TCSA^{-1})
Control	21.9	1.44	2.8	0.57	63.5	2.46
Hand-thin (6 fruit/cm^2)	7.0***	0.81***	4.4	0.64	10.9**	0.86***
NAA, NAA, NAA, NAA	27.1	1.60	2.4	0.61	56.2	2.37
Eth, NAA, NAA, NAA	23.4	1.35	2.9	0.50	59.4	2.17
Eth, Eth, NAA, NAA	20.1	1.29	10.5*	1.35	74.4	2.27

e. Harry Masters Jersey

Treatment	2016 Crop Density (fruit no. ·TCSA^{-1})	2016 Yield efficiency (fruit wt. ·TCSA^{-1})	2017 Crop Density (fruit no. ·TCSA^{-1})	2017 Yield efficiency (fruit wt. ·TCSA^{-1})	2018 Crop Density (fruit no. ·TCSA^{-1})	2018 Yield efficiency (fruit wt. ·TCSA^{-1})
Control	18.8	1.89	6.6	0.95	43.2	1.64
Hand-thin (6 fruit/cm^2)	7.3*	0.71*	7.8	0.96	15.8*	0.76***
NAA, NAA, NAA, NAA	20.0	1.16	9.2	1.07	31.4	1.39
Eth, NAA, NAA, NAA	15.6	1.27	13.8	1.51	38.4	1.67
Eth, Eth, NAA, NAA	22.6	1.66	6.9	0.95	44.6	1.44

f. Michelin

Treatment	2016 Crop Density (fruit no. ·TCSA^{-1})	2016 Yield efficiency (fruit wt. ·TCSA^{-1})	2017 Crop Density (fruit no. ·TCSA^{-1})	2017 Yield efficiency (fruit wt. ·TCSA^{-1})	2018 Crop Density (fruit no. ·TCSA^{-1})	2018 Yield efficiency (fruit wt. ·TCSA^{-1})
Control	25.0	1.10	0.2	0.01	61.5	1.94
Hand-thin (6 fruit/cm^2)	6.2***	0.46**	3.1	0.29**	11.2**	0.81***
NAA, NAA, NAA, NAA	22.4	1.21	1.5	0.10	76.6	2.09
Eth, NAA, NAA, NAA	24.3	1.11	3.8	0.26*	64.2	2.09
Eth, Eth, NAA, NAA	27.0	1.16	0.1	0.01	75.5	1.92

g. Geneva Tremlett's Bitter

Treatment	2016 Crop Density (fruit no. ·TCSA^{-1})	2016 Yield efficiency (fruit wt. ·TCSA^{-1})	2017 Crop Density (fruit no. ·TCSA^{-1})	2017 Yield efficiency (fruit wt. ·TCSA^{-1})	2018 Crop Density (fruit no. ·TCSA^{-1})	2018 Yield efficiency (fruit wt. ·TCSA^{-1})
Control	18.4	1.23	0.0	0.00	48.4	2.07
Hand-thin (6 fruit/cm^2)	6.1***	0.62***	2.7***	0.30***	12.8 ***	0.86***
NAA, NAA, NAA, NAA	24.6*	1.31	0.0	0.00	41.5	1.89
Eth, NAA, NAA, NAA	16.9	1.09	0.0	0.00	49.5	2.02
Eth, Eth, NAA, NAA	16.8	1.16	0.0	0.00	62.6	2.30

Table A4-10. Mean fruit weight (g) of seven cultivars harvested at LynOaken Farms 2016-2018. Treatment averages compared using Dunnett's Test. Asterisks indicate significant difference from control (*=p<0.05, **=p<0.01, ***=p<0.001)

a. Binet Rouge

Treatment	2016 Mean fruit weight (g)	2017 Mean fruit weight (g)	2018 Mean fruit weight (g)
Control	69.2	—	53.2
Hand-thin (6 fruit/cm^2)	103.4***	101.6	88.8***
NAA, NAA, NAA, NAA	68.2	48.9	59.4
Eth, NAA, NAA, NAA	74.6	19.3	59.0
Eth, Eth, NAA, NAA	66.2	18.4	65.8

b. Brown Snout

Treatment	2016 Mean fruit weight (g)	2017 Mean fruit weight (g)	2018 Mean fruit weight (g)
Control	27.8	—	31.5
Hand-thin (6 fruit/cm^2)	74.6***	91.7	91.2***
NAA, NAA, NAA, NAA	33.0	—	33.6
Eth, NAA, NAA, NAA	31.8	—	35.3
Eth, Eth, NAA, NAA	27.4	—	34.6

c. Chisel Jersey

Treatment	2016 Mean fruit weight (g)	2017 Mean fruit weight (g)	2018 Mean fruit weight (g)
Control	66.2	166.2	55.5
Hand-thin (6 fruit/cm^2)	98.8**	116.3	144.7***
NAA, NAA, NAA, NAA	62.6	129.1	60.2
Eth, NAA, NAA, NAA	54.8	127.7	63.8
Eth, Eth, NAA, NAA	72.4	157.3	59.7

d. Dabinett

Treatment	2016 Mean fruit weight (g)	2017 Mean fruit weight (g)	2018 Mean fruit weight (g)
Control	67.6	174.7	54.2
Hand-thin (6 fruit/cm^2)	116.8***	120.1	154.0***
NAA, NAA, NAA, NAA	59.5	188.6	53.0
Eth, NAA, NAA, NAA	57.2	122.0	53.6
Eth, Eth, NAA, NAA	65.4	138.4	55.1

e. Harry Masters Jersey

Treatment	2016 Mean fruit weight (g)	2017 Mean fruit weight (g)	2018 Mean fruit weight (g)
Control	106.0	113.0	63.2
Hand-thin (6 fruit/cm^2)	103.0	127.1	99.6**
NAA, NAA, NAA, NAA	64.2	137.8	61.9
Eth, NAA, NAA, NAA	82.8	117.6	66.0
Eth, Eth, NAA, NAA	71.4	142.3	58.9

f. Michelin

Treatment	2016 Mean fruit weight (g)	2017 Mean fruit weight (g)	2018 Mean fruit weight (g)
Control	43.4	58.3	41.7
Hand-thin (6 fruit/cm^2)	70.0*	96.4	85.2***
NAA, NAA, NAA, NAA	54.2	73.6	49.5
Eth, NAA, NAA, NAA	48.8	71.1	46.8
Eth, Eth, NAA, NAA	43.0	100.0	39.5

g. Geneva Tremlett's Bitter

Treatment	2016 Mean fruit weight (g)	2017 Mean fruit weight (g)	2018 Mean fruit weight (g)
Control	67.2	—	58.3
Hand-thin (6 fruit/cm^2)	100.6**	106.7	119.1***
NAA, NAA, NAA, NAA	53.6	—	54.4
Eth, NAA, NAA, NAA	68.2	—	54.8
Eth, Eth, NAA, NAA	68.6	—	59.3

Table A4-11. Trunk cross-sectional area (TCSA) of seven cultivars at LynOaken Farms 2016-2018. Treatment averages compared using Dunnett's Test. Asterisks indicate significant difference from control (*=p<0.05, **=p<0.01, ***=p<0.001)

a. Binet Rouge

Treatment	Dec. 2016 TCSA (cm^2)	Nov. 2017 TCSA (cm^2)	April 2019 TCSA (cm^2)
Control	3.8	4.7	5.5
Hand-thin (6 fruit/cm^2)	4.6	6.0	7.5
NAA, NAA, NAA, NAA	3.9	5.9	6.6
Eth, NAA, NAA, NAA	4.0	5.7	6.6
Eth, Eth, NAA, NAA	4.0	5.4	6.2

b. Brown Snout

Treatment	Dec. 2016 TCSA (cm^2)	Nov. 2017 TCSA (cm^2)	April 2019 TCSA (cm^2)
Control	3.2	4.5	4.7
Hand-thin (6 fruit/cm^2)	3.7	4.3	5.6
NAA, NAA, NAA, NAA	3.6	5.6	6.4
Eth, NAA, NAA, NAA	3.4	4.8	4.5
Eth, Eth, NAA, NAA	3.3	3.5	4.5

c. Chisel Jersey

Treatment	Dec. 2016 TCSA (cm^2)	Nov. 2017 TCSA (cm^2)	April 2019 TCSA (cm^2)
Control	4.6	6.1	7.2
Hand-thin (6 fruit/cm^2)	6.0	5.5	8.8
NAA, NAA, NAA, NAA	4.5	5.5	6.5
Eth, NAA, NAA, NAA	5.7	6.5	7.3
Eth, Eth, NAA, NAA	5.5	6.5	7.1

d. Dabinett

Treatment	Dec. 2016 TCSA (cm^2)	Nov. 2017 TCSA (cm^2)	April 2019 TCSA (cm^2)
Control	4.9	7.9	8.5
Hand-thin (6 fruit/cm^2)	5.7	7.2	9.2
NAA, NAA, NAA, NAA	4.2	6.1	7.0
Eth, NAA, NAA, NAA	4.9	6.8	6.7
Eth, Eth, NAA, NAA	5.2	7.9	8.7

e. Harry Masters Jersey

Treatment	Dec. 2016 TCSA (cm^2)	Nov. 2017 TCSA (cm^2)	April 2019 TCSA (cm^2)
Control	3.6	4.7	6.0
Hand-thin (6 fruit/cm^2)	4.6	5.2	6.9
NAA, NAA, NAA, NAA	3.5	4.5	5.5
Eth, NAA, NAA, NAA	4.2	4.8	6.4
Eth, Eth, NAA, NAA	4.6	6.0	7.7

f. Michelin

Treatment	Dec. 2016 TCSA (cm^2)	Nov. 2017 TCSA (cm^2)	April 2019 TCSA (cm^2)
Control	5.0	5.6	6.6
Hand-thin (6 fruit/cm^2)	5.3	6.8	8.9
NAA, NAA, NAA, NAA	4.2	5.6	6.5
Eth, NAA, NAA, NAA	4.4	5.5	6.8
Eth, Eth, NAA, NAA	4.0	5.4	6.1

g. Geneva Tremlett's Bitter

Treatment	Dec. 2016 TCSA (cm^2)	Nov. 2017 TCSA (cm^2)	April 2019 TCSA (cm^2)
Control	3.5	4.5	5.0
Hand-thin (6 fruit/cm^2)	3.9	4.7	5.9
NAA, NAA, NAA, NAA	2.6	3.3	3.6
Eth, NAA, NAA, NAA	3.0	4.1	4.5
Eth, Eth, NAA, NAA	3.3	4.3	4.7

Table A4-12. Pre-harvest drop of seven cultivars harvested at LynOaken Farms 2016-2018. Treatment averages compared using Dunnett's Test. Asterisks indicate significant difference from control (*=p<0.05, **=p<0.01, ***=p<0.001)

a. Binet Rouge

Treatment	2016 Pre-harvest drop (%)	2017 Pre-harvest drop (%)	2018 Pre-harvest drop (%)
Control	34.8	100.0	45.2
Hand-thin (6 fruit/cm^2)	12.9**	25.2*	26.6
NAA, NAA, NAA, NAA	26.1	20.0*	42.8
Eth, NAA, NAA, NAA	31.6	33.0	34.3
Eth, Eth, NAA, NAA	27.0	17.0*	36.7

b. Brown Snout

Treatment	2016 Pre-harvest drop (%)	2017 Pre-harvest drop (%)	2018 Pre-harvest drop (%)
Control	30.3	—	79.8
Hand-thin (6 fruit/cm^2)	43.3	77.7	49.5***
NAA, NAA, NAA, NAA	33.4	—	86.9
Eth, NAA, NAA, NAA	34.1	—	77.6
Eth, Eth, NAA, NAA	32.7	—	77.4

c. Chisel Jersey

Treatment	2016 Pre-harvest drop (%)	2017 Pre-harvest drop (%)	2018 Pre-harvest drop (%)
Control	14.6	44.6	33.9
Hand-thin (6 fruit/cm^2)	34.7	58.2	65.6***
NAA, NAA, NAA, NAA	12.5	14.4	27.5
Eth, NAA, NAA, NAA	10.6	21.2	30.7
Eth, Eth, NAA, NAA	17.4	36.8	29.2

d. Dabinett

Treatment	2016 Pre-harvest drop (%)	2017 Pre-harvest drop (%)	2018 Pre-harvest drop (%)
Control	25.4	81.8	71.7
Hand-thin (6 fruit/cm^2)	28.7	70.3	52.2*
NAA, NAA, NAA, NAA	11.5	83.0	72.3
Eth, NAA, NAA, NAA	14.6	77.8	66.8
Eth, Eth, NAA, NAA	18.9	83.2	63.0

e. Harry Masters Jersey

Treatment	2016 Pre-harvest drop (%)	2017 Pre-harvest drop (%)	2018 Pre-harvest drop (%)
Control	75.2	66.3	38.9
Hand-thin (6 fruit/cm^2)	88.3	47.0	46.2
NAA, NAA, NAA, NAA	59.3	38.2*	38.9
Eth, NAA, NAA, NAA	54.6	36.8*	35.7
Eth, Eth, NAA, NAA	67.3	42.6	26.2*

f. Michelin

Treatment	2016 Pre-harvest drop (%)	2017 Pre-harvest drop (%)	2018 Pre-harvest drop (%)
Control	65.9	50.0	24.0
Hand-thin (6 fruit/cm^2)	94.9**	84.6	91.5***
NAA, NAA, NAA, NAA	78.6	69.8	38.0
Eth, NAA, NAA, NAA	78.8	61.8	38.9
Eth, Eth, NAA, NAA	78.8	75.0	23.1

g. Geneva Tremlett's Bitter

Treatment	2016 Pre-harvest drop (%)	2017 Pre-harvest drop (%)	2018 Pre-harvest drop (%)
Control	21.6	—	33.1
Hand-thin (6 fruit/cm^2)	4.5**	9.6	7.6**
NAA, NAA, NAA, NAA	22.7	—	37.0
Eth, NAA, NAA, NAA	17.3	—	32.1
Eth, Eth, NAA, NAA	16.1	—	25.0

Chapter 5 Suvery Questions

1. Today’s date

2. Cidery/orchard name

3. Year your cidery was/will be established?

4. Is your orchard/cidery in an urban or rural location? (Choose one)

5. Are you primarily a… (Choose one)
    - Cidery
    - Brewery
    - Distillery
    - Eatery
    - Meadery
    - Winery
    - Other: __________

6. Location by state/province (Drop-down menu)

7. Cidery distribution scale (Choose one)
    - Not currently selling cider
    - Local/on-site
    - Multi-county or state/province-wide
    - Multi-state/province or regional
    - National/international

8. Where do you sell most of your cider? (Choose one)

    Mostly on-premise 1 2 3 4 5 Mostly off-premise

9. Do you have a taproom/tasting room?
    - Yes
    - No
    - Planning to/building one

10. Current scale of cider production (just cider)
    - Below 1,000 gallons (3,800 liters) per year
    - 1,000-5,000 gallons (3,800-19,000 liters) per year
    - 5,000-10,000 gallons (19,000-38,000 liters) per year
    - 10,000-50,000 gallons (38,000-190,000 liters) per year
    - 50,000-250,000 gallons (190,000-950,000 liters) per year
    - 250,000-500,000 gallons (950,000-1.9 million liters) per year
    - 500,000-1,000,000 gallons (1.9-3.8 million liters) per year
    - Over 1 million gallons (3.8 million liters) per year

11. Do you use, or plan to use, bitter apple varieties (including juice/concentrate) in your cider?
    - Yes *(skip to question 14)*
    - No *(skip to question 12)*
    - Plan to use *(skip to question 12)*

Cideries Not Using High-Tannin Varieties

12. If you don't use bitter apples/juice, why? (Check all that apply)
    - Lack of availability
    - Not interested
    - Lack of experience working with these varieties
    - Use tannin supplement instead
    - Looking to plant/supply bitter varieties in the future
    - Other: _________

13. What (range) is your estimated cost per gallon of non-bitter juice, or per pound of non-bitter fruit? ________________

Cideries and growers using bitter varieties

14. Do you buy non-bitter (culinary/dual purpose) juice from elsewhere? (Check all that apply)
    - Yes
    - No
    - Occasionally/open to doing so
    - Forage wild/abandoned trees

15. What proportion of the fruit/juice you use in all your ciders comes from bitter cider varieties? (Estimates are okay)
    - 10% or less
    - 11-25%
    - 26-50%
    - 51-75%
    - 76-100%

16. Do you grow some of all of the bitter apples that you use in your cider? (Choose one)
    - Yes
    - No *(skip to question 33)*
    - Will be in future
    - N/A
    - Other:_________

For growers

17. How many bittersweet or bittersharp varieties do you grow? _______________
18. What bittersweet or bittersharp varieties do you grow? _____________________________________
19. How many acres of bitter apples do you have planted? (enter as a number) __________________
20. How many years ago did you plant your bitter cider trees?
    - 1
    - 2
    - 3
    - 4
    - 5
    - 6
    - 7
    - 8
    - 9
    - 10
    - 11 or more years ago
21. Have your bitter varieties come into production? (Choose one)
    - Yes
    - No
    - Some
22. Would you characterize your bitter apple planting as currently 'experimental'?
    - Yes
    - No
    - Started that way
23. Do you pay your pickers a higher rate per bin to harvest smaller-fruited bitter cider apples?
    - Yes
    - No
    - Prefer not to say
24. If you pay a different rate per bin based on fruit size, would you be comfortable sharing what the different rates are? ______________________
25. Do you thin your bitter varieties to improve… (Choose all that apply)
    - Sugar content (Brix)
    - Tannin content
    - Acid content
    - Don't thin bitter varieties
    - Tried thinning and stopped
    - Other: ____________

26. Do you sell bitter fruit/juice to other cideries?
    - Yes
    - No
    - Have done so but no longer do
    - Other: __________

27. If you do sell bitter fruit/juice, what (range) price do you charge per unit of bitter juice or fruit?

28. Do you buy culinary apples/juice for your cider from other companies?
    - Yes
    - No

29. Do you buy bitter apples/juice for your cider from other growers?
    - Yes
    - No
    - I have in the past

30. If you buy bitter apples/juice, what range of price have you paid? __________________

31. If you buy or sell bitter fruit/juice from elsewhere, do/would you use a contract to guarantee a price, a buyer, or a seller?
    - I do
    - I plan to
    - I don't but would be open to it
    - I don't and wouldn't be open to it
    - N/A

32. Do alternate/biennial yields affect your apple supply?
    - Yes *(skip to question 40)*
    - No

For non-growers

33. How many sources do you buy bitter fruit/juice/concentrate from? _______________
34. What bitter varieties are you working with? ____

35. Where do you source bitter fruit/juice/concentrate? (Choose all that apply)
    - In-state/province
    - Out-of-state/province
    - Out-of-country

36. Do you/would you use a contract with a grower to guarantee bitter apple/juice supply?
    - I do
    - I don't
    - I would
    - I wouldn't

37. What form do you buy your bitter cider apples? (Choose all that apply)
    - Juice (fresh or frozen)
    - Concentrate
    - Fruit

38. What price (range) have you paid for bitter fruit/juice? ____________________

39. Has biennial/alternate bearing ever been an obstacle to your sourcing bitter fruit/juice/concentrate?
    - Yes *(skip to question 42)*
    - No

Biennial/alternate bearing (growers)

40. If alternate/biennial bearing in bitter varieties is an issue for you, do you… (Choose all that apply)
    - Try to manage it in-field through horticultural means (thinning, PGR sprays, etc.)
    - Use whatever fruit you have for that year's blend
    - Store fruit/juice longer
    - Ferment what you have and save some for subsequent years

41. If you could guarantee more consistent yields from year to year in your bitter apple varieties, would you accept lower cumulative yields?
    - Yes
    - No
    - Maybe

Biennial/alternate bearing (non-growers)

42. If bitter fruit/juice/concentrate is unavailable, do you… (Check all that apply)
    - Try to source from another grower/supplier
    - Not use bitter fruit/juice that year
    - Ferment what you have and save some to blend the next year
    - Freeze juice for future years
    - Use tannin supplements